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Urban Air Mobility Electric Motor Winding Insulation Reliability: Challenges in the Design and Qualification of High Reliability Electric Motors and NASA's Research Plan

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Abstract

This work was motivated by the needs of the emerging Urban Air Mobility (UAM) concept. Guided by analyses of concept vehicles, electric motor winding insulation reliability was identified as a subsystem limiting the vehicle reliability. This paper covers NASA's understanding of the current state-of-the-art for electric motor winding insulation reliability, life modeling and qualification testing in the context of UAM. The needed improvements to the accepted practice for qualification of high reliability UAM motors are highlighted. NASA's Revolutionary Vertical Lift Technologies Project strives to develop new testing methods to support the rating and qualification of UAM motor winding insulation. We describe assumptions used to frame a research approach, and we outline a NASA RVLT research plan for motor winding insulation.

Introduction

This reported work was motivated by the research goals and focus of NASA's Revolutionary Vertical Lift Technologies (RVLT) Project. The vision of the project is the creation of a future where vertical take-off and landing (VTOL) configurations operate quietly, safely, efficiently, affordably, and routinely as an integral part of everyday life. Toward that vision, the project seeks to develop and validate concepts, technologies, testing methods, and analysis tools to overcome key barriers. Currently, the RVLT project is focused on the Urban Air Mobility (UAM) concept, which is a subset of the NASA Advanced Air Mobility (AAM) Mission. UAM is projected to have the greatest economic impact and the most difficult technological challenges of the concepts in AAM (Ref. 1).

Urban Air Mobility (UAM) is a developing market for electric and hybrid-electric vertical take-off and landing vehicles (eVTOL). For UAM to realize its expected potential, eVTOL will need to achieve a safety and reliability record comparable to today's commercial airliners. To that end, the NASA RVLT Project sponsored a hazards and failure analysis of four NASA-developed UAM concept vehicles (Ref. 2). Results of that analysis identified electromechanical drivetrains as being a limiting subsystem for the overall reliability of the concept vehicles. In particular, the reliability of electric motors and generators was shown to be a major contributor to lower than desired reliability estimates for the electromechanical drivetrain subsystems. Guided by these results, NASA's RVLT project established a "Reliable Electric Propulsion Components for UAM Vehicles" Technical Challenge. The goal of the technical challenge is to improve the reliability of electric propulsion for UAM vehicles by improving design tools and test methods and providing component technology demonstrations addressing vehicle propulsion system electrical power quality, thermal management, and component reliability. Results will support standards development for certification needs. The exit criteria of the Technical Challenge is to demonstrate 2 to 4 orders of magnitude improvement in electric motor reliability.

Past surveys of electric motor failure modes identified electric motor winding insulation and bearings as the dominant causes of motor failure (Refs. 3 to 13). This paper covers NASA's understanding of the current state-of-the-art for electric motor winding insulation reliability, life modeling and qualification testing relative to UAM. The needed improvements to accepted winding insulation lifetime testing practices are highlighted relative to qualification of high-reliability motors for UAM. In this report, a plan to develop new testing methods to support the rating and qualification of UAM motor winding insulation is outlined.

The subsequent sections treat the following topics in sequence:

1. Assumptions relative to defining the needed research for winding insulation in the UAM motor context
2. Key aging and failure mechanisms for UAM motor windings
3. Combined stress winding aging models
4. Present methods for motor winding life testing per standards
5. NASA's research plans to improve winding insulation testing and ratings for UAM eVTOL propulsion systems

Assumptions and UAM Context

Due to the vast design space that exists for electric motors, motor windings, and winding insulation systems, it is impractical to address every possible scenario for motor winding reliability in one research program. To that end, assumptions were made to frame motor winding reliability in the context of propulsion motors for UAM vehicles and their expected missions. The following subsections outline the assumptions and provide the corresponding rationale. With the assumptions established, the remainder of this paper outlines the needed research for the development of methods for characterizing the capabilities of insulation systems and quantifying high reliability motor winding lifetimes.

Motor Driven by Frequency Converters

For an electric motor to produce a given torque at a certain speed, electric power is supplied to the motor with an appropriate magnitude, waveform, and frequency. For UAM vehicles, power converters transform power from the vehicle power grid to the required power form at the motor terminals. Most power converter technologies used for vehicle motors are based on some form of switching device (Ref. 14). Pulse Width Modulated (PWM) voltage source inverters are expected to be the dominant form of motor drive for electric aircraft applications (Ref. 15). These devices operate by applying high-frequency square-wave-form voltage to the motor winding circuit. Wide band gap switching devices with switching frequencies between 20 and 100 kHz are expected to become the prominent switching devices for electric aircraft motor drives because their high switching frequencies and operating temperatures enable higher overall motor drive power density and efficiency (Ref. 16). The use of high-frequency wide band gap devices creates new and difficult challenges for the insulation technologist and motor designer (Ref. 17). The new challenges include: Nonlinear voltage distributions through the motor windings and significant turn-to-turn electrical stresses caused by the short switch rise times (Ref. 18); Changes in how electrical stress is distributed through the insulation due to high voltage gradients (dV/dt's) (Ref. 19); and short life times of insulation in the presence of repetitive partial discharges (PD) at the converter switching frequency. Herein it is assumed that the motor windings will be powered by a PWM voltage source inverter with switching frequencies in the 20 to 100 kHz range and voltage waveform rise times on the order of 10's of nanoseconds. In general, insulation systems and motor winding coils should be tested with appropriate waveforms consistent with the specifications for the motor drive that will power the motor.

Type 1 Insulation

International Electrotechnical Commission (IEC) standards categorize motor winding insulation into two types (Refs. 20 and 21). Type 1 insulation is defined as winding insulation that is required to be free of PD throughout its operating life due to its rapid degradation in the presence of PD (Refs. 19, 20, and 22). Prominent examples of Type 1 insulation are common magnet wire organic film insulation like polyimide or polyethylene. Type 2 insulation is defined as insulation which is PD resistant and therefore can have suitable design life or "safe life" in the presence of PD (Ref. 21). The prominent example of Type 2 insulation is mica-based insulation tape (Ref. 19).

The lower design electrical stress capability of Type 2 insulation relative to Type 1 insulation results in thicker insulation layers for Type 2 insulation. Correspondingly, the use of Type 2 insulation for motor windings limits the achievable motor specific power as compared to Type 1 insulation (Ref. 23). A simple comparison of mica-based insulation dielectric strength at ~20 kV/mm to the dielectric strength of polyimide insulated magnet wire at >130 kV/mm illustrates the required insulation thickness difference (Ref. 19). Type 1 insulation is therefore selected as the insulation type of interest for this research program. Polyimide magnet wire films and vacuum pressure impregnated resins will be used as the insulation system in the research effort.

If desired, the NASA RVLT winding reliability research effort for characterizing insulation and certifying motor windings could be extended to include Type 2 insulation. Characterization with Type 2 insulation will be conservative since Type 2 insulation will have longer lifetimes in the presence of PD.

Voltage Magnitude

Commonly, Type 1 insulation is limited to voltages less than 750 V to achieve desired PD-free operation (Refs. 19, 20, 22, and 24). Increasing the operating voltage of Type 1 insulation would have significant benefits to overall aircraft mass and is the target of ongoing research (Ref. 25). The objective of this proposed research effort however is to develop modeling and testing methods for improved reliability of motor winding insulation systems and not necessarily to advance the state-of-the-art for motor winding technology. Therefore, 750 V is assumed as the maximum motor power supply voltage for the research effort. Extending voltage beyond this magnitude is being studied by the broader research community and may be an objective of future NASA work.

Motor Requirements for UAM Missions

The NASA RVLT project defined several UAM reference vehicle concepts to aid in the development of technologies and certification processes for UAM vehicles (Refs. 1, 26, and 27). One assumed design mission for these vehicles is shown graphically below with the mission profile broken into hover, climb, and cruise mission segments. The design mission consists of two 37.5 nmi flights with a short time in between for unloading and loading. After the second flight it is assumed a longer down time is needed for refueling and/or recharging.

The assumed mission in Figure 1 is only one potential UAM mission case that was defined for the vehicle sizing studies in (Ref. 26). The motor power required for each of the design mission segments and the length of each mission segment is valuable information for understanding the thermal loading electric motors will experience in UAM applications. From the vehicle design study results, motor power requirements during cruise are approximately 50 percent of the peak power required for either hover or climb. Since motor winding resistive losses trend proportionally with the square of torque, the power requirements can result in four times the heat load in hover or climb relative to cruise. NASA has been assessing motor designs for the mission of Figure 1 (Ref. 28). A predicted motor winding hotspot thermal profile from those studies is shown in Figure 2 as an example of the thermal transient that UAM motor windings might experience in hover/climb and the winding temperature difference between cruise and hover/climb conditions. In addition to the winding thermal profile in Figure 2, short-term motor power requirements for flight maneuvers and control such as response to wind gusts will create additional, but smaller motor winding thermal cycles within a given mission segment.

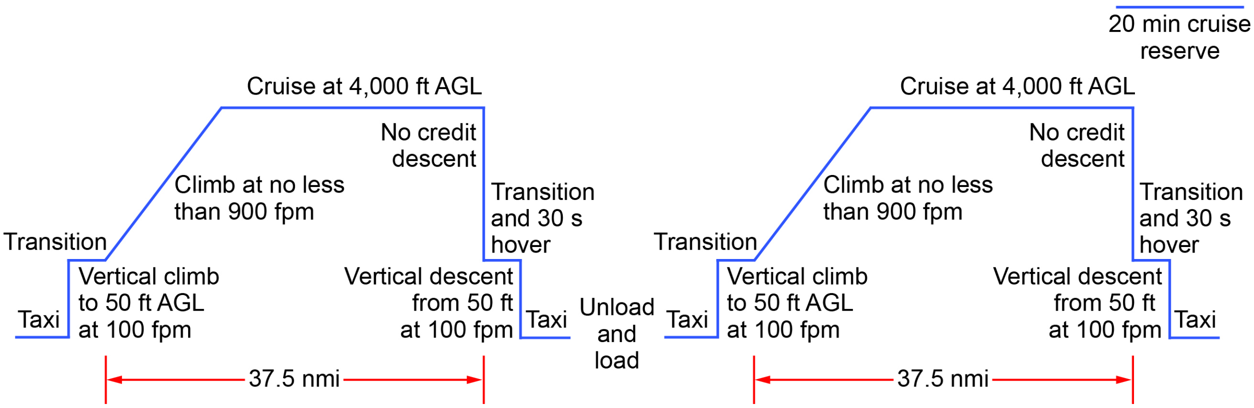

Figure 1.—NASA RVLT UAM vehicle design mission.

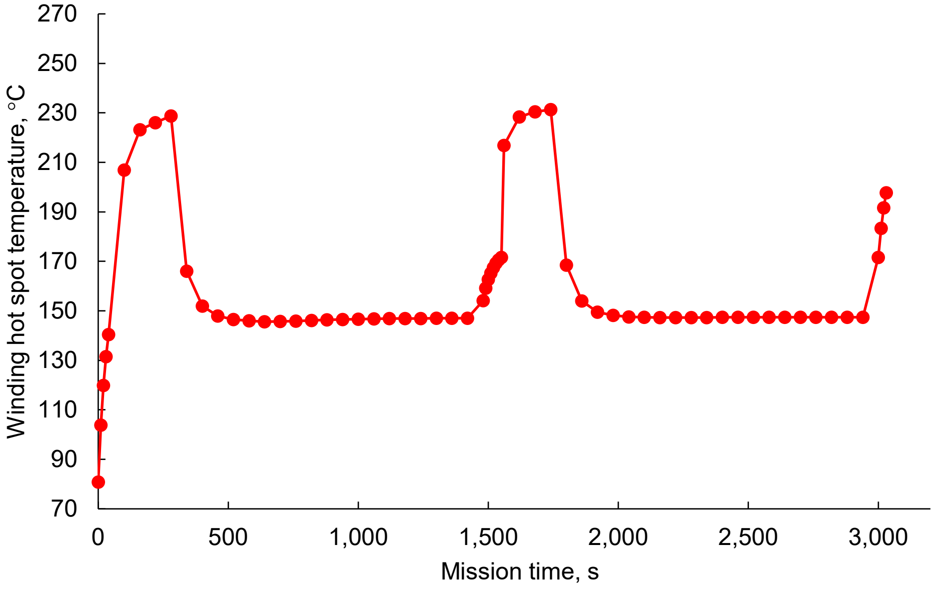

Figure 2.—Example motor winding hotspot temperature mission profile.

Cleanliness

Harsh chemicals, e.g., acids or ozone, can chemically react with the insulation systems to cause degradation of the insulation system and premature breakdown. Similarly, conductive material contacting motor windings and electrically coupling to the windings can lead to PD and premature winding failure (Ref. 19). To achieve high electric motor reliability, this document assumes that cleanliness concerns have been mitigated by motor design features and manufacturing quality processes that appropriately seal the motor and keep the windings clean during manufacturing and flight operations. Methods to mitigate the effects of harsh chemicals and conductive debris is therefore considered beyond the scope of the near-term RVLT research efforts. Harsh chemicals that are the byproduct of winding insulation degradation, for example ozone produced by PD, will be included in this research efforts.

Humidity and Altitude

Humidity and altitude both affect the initiation of PD for a given electrical stress condition in a motor winding insulation system (Ref. 19). Humidity and water in general can adversely affect some insulations, and epoxy resins that are susceptible to water absorption. The expected altitude of operation for UAM motors is modest compared to many fixed-wing missions, i.e., approximately 1.2 km (4,000 ft) above ground level. The proposed research efforts will include considerations for how to account for air pressure and humidity conditions for a target UAM mission.

Aging and Failure Mechanisms of Winding Insulation

Four primary stresses affect the aging of insulations systems: 1) Electrical through partial discharge and insulation breakdown; 2) Thermal through thermal-chemical aging; 3) Mechanical through mechanical fatigue and crack initiation; and 4) Environmental/contamination effects as was previously discussed. The following subsections discuss electrical, thermal, and mechanical stresses individually in the context of the above assumptions and the UAM mission. The effects of each stress are highly-interactive with each other, and it is the combination of stresses that can lead to failure of UAM motor insulation systems.

Electrical Stress

Electrical insulators prevent the flow of electrical current along undesired paths. The electric field stress to which an insulating material is subjected to is numerically equal to the voltage gradient across the material. Galvanic isolation of conductive components in a motor stator is the primary purpose of motor winding insulation. Correspondingly, motor insulation design and failure are strongly influenced by electrical stress. Abnormal and very high voltage surges can produce immediate breakdown and failure of healthy motor winding insulation. More commonly however, failure of insulation is preceded by electrical aging caused by a series of PD’s burning “electrical trees” through the insulation material (Ref. 19).

For electrical aging, the traditional life models are the inverse power model

$$L = cE^{-n}$$

and the exponential model

$$L = ae^{bE}$$

where L is lifetime, E is electrical field, and a, b, c, and n are constants obtained from experimental data. Many materials exhibit an electrical stress threshold below which electrical stress degradation can be neglected. The power laws can be written with the threshold term E_t included as

$$L = L_0 \left(\frac{E - E_t}{E_t - E_0} \right)^{-n}$$

where L_0 and E_0 are constants corresponding to an insulation's estimated life, L_0, at a given electrical stress E_0. The exponential power law can be expressed with a threshold as

$$L = \frac{ae^{bE}}{E - E_t}$$

where L_0 is the life at $E = E_0$ (Ref. 29).

Under the assumptions of this paper, for UAM motors that are inverter fed and use Type 1 insulation, IEC 60034-18-41 (Ref. 20) requires that the motor windings be designed and qualified such that they are PD-free throughout their operating life. Put another way, IEC 60034-18-41 requires that the electrical stress remain below the insulation system's electrical stress threshold value. This requirement is primarily due to Type 1 insulation being susceptible to damage and extremely short life in the presence of PD, especially when it occurs as the result of high-frequency PWM voltage waveforms (Refs. 19 and 24). Example lifetimes for Type 1 insulation in the presence of PD can be found in (Refs. 18, 24, and 30). The life values are on the order of 1 to 10 million cycles. At inverter PWM frequencies anticipated for UAM vehicles, the time to failure for these insulation materials in the presence of PD is on the order of a few minutes. Correspondingly, the onset of PD can be considered the end-of-life for inverter fed Type 1 insulation windings, and electrical aging degradation can be neglected in the prediction of UAM motor lifetimes or maintenance intervals.

Understanding electrical aging of Type 1 insulation is important for high reliability UAM electric motor drivetrains for two reasons. First, since the onset of repetitive PD signals the approaching end-of-life for a UAM motor's electrical insulation, understanding the time from repetitive PD initiation to actual breakdown can be a factor in defining emergency landing requirements and procedures. Second, abnormal voltage events due to fluctuations in the power quality of the aircraft electrical system or abnormal motor-inverter interactions are likely to occur at some point in the life of a UAM motor. PD may occur due to either of these events. However, if the PD is not repetitive then the motor may continue to have substantial remaining life. A suitable method for predicting remaining insulation life after a single abnormal PD event may be important for managing unnecessary maintenance (Refs. 23 and 31).

Accurate prediction of the electrical stress in a UAM motor's insulation is important for designing a PD-free system. For inverter fed windings, electrical stress prediction is not a straightforward task. The short voltage waveform rise time associated with high-frequency PWM switching can result in significant voltage overshoot at the motor terminals and produce nonlinear voltage distribution through the motor winding turns (Refs. 18, 22, 32 to 34). Additionally, as mentioned above, high dV/dt's associated with these high switching-frequency short rise times alter the electrical stress distribution in the insulation system (Ref. 19). Correspondingly, motor windings must be tested and modeled with voltage waveforms appropriate for the power converter that will power the motor.

Thermal-Chemical Stress

Thermal stresses in insulation systems refer to the temperature of the insulation and the boundary conditions provided by the surrounding environment. Thermal stresses cause gradual degradation of insulation systems by accelerating chemical reactions. The rate of degradation of the insulation is dependent on both the temperature and the chemical composition of the environment.

The traditional model (Ref. 35) for thermal degradation of insulation is Arrhenius's law:

$$L = Ae^{\frac{B}{T}}$$

where L is insulation life, T is temperature, and A and B are constants obtained from experimental data. Stone et al. (Ref. 19) point out two flaws with using Arrhenius's law for winding thermal degradation. The first flaw is that degradation only occurs at temperatures high enough for the dominant chemical reactions to occur. Similar to electrical aging thresholds, temperature thresholds exist for materials below which certain chemical aging reactions do not occur, but a threshold is often not included in this model. The second flaw is that the model is meant for only one chemical reaction while often multiple reactions are ongoing between the insulation and the environment. The model has, however, been the basis for accelerated aging testing and rating of insulation systems for many years. For example, it is the basis for the testing procedures and data analyses in (Refs. 36 to 38).

Thermal-chemical aging of insulators in air environments is the most well documented and studied form of thermal-chemical degradation. Most insulators are assigned a thermal classification based on the temperature in air at which they are estimated to have 20,000 h of life. The NEMA publication (Ref. 39) on magnetic wire defines the thermal classification of common magnet wire film insulations. The test method used to define the thermal classification of the insulation is ASTM D2307 (Ref. 36). ASTM D2307 specifies a process for accelerated thermal aging of multiple samples of twisted wire pairs in air. Arrhenius's law and statistical methods are applied to estimate the temperature at which the insulation will have 20,000 h of life. The 20,000 h lifetime is a measure of the central tendency of the probabilistic nature of insulator lifetime data. In this rating process, an electrical stress of roughly 12 kV/mm is used to proof test the insulation after each aging cycle. Breakdown at this electrical stress is used to define end of life. The common thermal classification of insulators is therefore a temperature index of insulation life as measured using electrical stresses of 12 kV/mm for aging in air environments. The temperature rating is an index for design but is not a direct measure of motor winding temperature capability or temperature limit.

In air environments, oxidation is the dominant thermochemical degradation mechanism for most insulators. Oxidation causes most insulations to become brittle and, correspondingly, more readily cracked or delaminated by mechanical action (Ref. 19). These cracks or delaminations act as defects for initiation of PD, and eventually final electrical breakdown of the insulation. In the absence of sufficient mechanical stress, thermal aging can still cause insulation failure. For example, recent work by Madonna et al. (Ref. 40) and Cavallini (Ref. 17) have suggested that oxidation alone leads to loss of the insulation thickness and associated loss of dielectric strength that eventually leads to electrical breakdown. Wang et al. (Ref. 41) measured reductions of insulation thickness during thermal cycling experiments and proposed the idea that creep phenomena may contribute to the measured reductions. Researchers at University of Nottingham have been developing thermal aging correlations based on normalized insulation capacitance as a correlating marker of the thermal age of insulation (Refs. 40 and 42). Such a marker may be valuable as a tool for accelerated life test ratings of an insulation material as well as for insulation health monitoring.

In the absence of oxygen, as would be the case for direct liquid-cooled stators or inert gas environments, the thermochemical life of the insulator will be driven by a chemical reaction other than oxidation, and as a result the thermomechanical life is likely longer at a given temperature. Khazaka et al. (Ref. 43) aged polyimide films in air and nitrogen environments at 360 °C. The films in air degraded completely in 100's of hours. No notable degradation in film thickness occurred for the films in nitrogen after 1,000 h. The use of direct liquid cooling or other methods of putting a motor winding in a nonreactive environment may be a path to enabling longer motor lives or increasing motor specific power.

Accelerated aging tests and extrapolation to estimate life based on Arrhenius's Law is the current accepted and practical approach for winding insulation thermal chemical life prediction (Ref. 19). However, the UAM mission presents a unique and challenging thermal profile relative to ground-based generators which motivated and influenced the development and application of current insulation test standards. In Reference 28, motor design for the example UAM mission profile in Figure 1 was studied, and the design was constrained by thermo-chemical aging. It was found that the high-power, short-duration hover and climb portions of the mission profile dominated the thermal chemical aging of the insulation. The lower-power, long duration cruise portion of the mission had only a minimal contribution to the thermal chemical aging of the insulation. Correspondingly, depending on the motor, its mission, and its corresponding winding thermal profile, it may be practical to complete thermal-chemical aging for the full life of a UAM motor at temperatures representative of the peak temperatures of the motor during hover/climb. The accelerated-life-test approach and the uncertainties and approximations associated with extrapolation of such experimental data may be unnecessary for the UAM motor application.

Mechanical Deformation Cycling and Stress

Mechanical deformations and associated stresses of insulation systems can cause cracks, wear, or delamination of the insulation system. These then act as defects in an insulation system and allow PD activity to occur in an insulation system that was originally PD-free. Mechanical stresses in UAM motor windings can be caused by electromagnetic forces, vehicle-maneuver accelerations, vibrations from both within the motor and other sources on the aircraft, and thermal-mechanical stresses caused by differing coefficients of thermal expansion between materials in the system, or nonuniform temperature distributions in the stator. As mentioned in the subsection above, thermo-chemical degradation of insulation typically causes the insulation to deteriorate in strength and to become more brittle. Thermochemical aging correspondingly lowers the threshold for the mechanical stresses to create PD-initiating defects in an insulation system.

No commonly accepted or traditional model exists for mechanical degradation of insulation systems (Ref. 19) and rarely is data reported for the PD-initiation voltage (PDIV) of insulation systems as functions of both thermal and mechanical aging (Ref. 17). IEC 60505 (Ref. 44) suggests a power law could be used as an initial prediction for mechanical degradation of insulation, but from our literature review such an approach does not seem to be a widely utilized framework for degradation modelling.

Thermo-mechanical stress cycling of electric motors due to the relatively short high-power hover and climb segments of UAM missions are potentially significant influences on electric motor life. Thermal cycling may limit UAM and other aerospace motor specific power more so than thermo-chemical aging effects (Refs. 28 and 45). Some recent research, mostly motivated by electric aircraft, has begun to investigate the modeling of thermomechanical stresses and the resulting degradation and fatigue of motor windings (Refs. 46 to 50).

Mechanical stresses can also be caused by electrical stress in dielectrics. These stresses are of particular importance in DC insulation systems where space charge accumulates in defects (Ref. 51).

Space charge is not likely to accumulate in AC motor windings; however, inclusion of mechanical stresses caused by electrical stresses may be necessary to accurately predict motor winding failure.

Additional research is needed for the development of motor winding mechanical aging/degradation models.

Combined Stress Winding Aging Models

Very few aging insulation models for windings under combined stress states exist that include mechanical stress in their formulation. A detailed review of winding life models pre-2002 by Montanari (Ref. 29) indicates only models with combined electrical and thermal stresses. Mechanical stress models for the degradation of insulations systems have largely been neglected to date, and correspondingly combined stress models for mechanical and thermo-chemical degradation models are rare in the literature. Mazzanti et al. (Ref. 52) proposed a combined electrical-thermal-mechanical stress model. In their modelling approach, rate theory was used to combine three single factor aging models (Arrhenius and two power laws for electrical and mechanical) into a single empirical model for insulation degradation. Thermodynamics-based models for void growth in insulation that include a mechanical stress term can be found in Reference 51. The mechanical stress term in these models is written only for mechanical stress caused by electrical stress. However, the models outlined are a potential starting point for development of a combined thermochemical and mechanical stress aging model.

Present Stator Rating Processes

IEC 60034-18 (Ref. 53) specifies the qualification testing of motor winding insulation systems. IEC 60034-18-21 (Ref. 54) specifies thermal ratings based on thermal aging of windings. IEC-60034-18-41 (Ref. 20) covers the relevant electrical proof tests to use for Type 1 inverter fed insulation systems. IEC 60034-18-34 (Ref. 55) covers thermo-mechanical stress cycle testing for form wound motor windings and is the only part of the standard that covers mechanical aging testing. In all cases the standard requires that the test system be compared to a reference system with a known service life in the relevant target environment and application. This requirement presents a barrier for application of these standards to UAM motors as there exists no appropriate benchmark reference system for a UAM motor's insulation system. To enable the first UAM motors a new methodology for qualification of motor windings is needed.

Other limitations in applying the IEC standards for the UAM motor application are:

- IEC-60034-18-21 (Ref. 54) specifies thermal aging cycles based on assumption that Arrhenius's law applies for thermal aging of the insulation. This assumption, as mentioned above, may not be accurate because Arrhenius's Law considers only one chemical reaction, while UAM motors may experience multiple chemical reactions acting on a winding at a given time. This concern about multiple chemical reactions is more likely relevant for UAM motors than for some other applications given the expected elevated temperature operation resulting from the high-power density requirements for UAM motors.
- IEC-60034-18-34 (Ref. 55) specifies relatively slow thermal ramp rates for machines (between 30-60 min) and the minimum cycle count is 500 cycles. Both of these test procedure specifications are likely not relevant for UAM motors. The methodology would require significant adjustment for UAM motors.

- IEC 60034-18-41 (Ref. 20) provides enhancement factors for motor winding PD testing. These enhancement factors are specified for different categories of winding voltage overshoot. The numeric values selected for the enhancement factors can cover a fairly broad range depending on the experience and judgment of the individuals applying the standard. More precise and rigorous specification of the enhancement factors could enable either less overdesign or more reliable motor windings.

IEEE 117 (Ref. 37) provides a procedure for qualification of motor winding insulation systems in which thermal-chemical aging is the dominant aging mechanism. It lays out a method of sequential accelerated thermochemical aging, mechanical stress cycling, humidity exposure, and electrical proof testing. Thermochemical aging tests are conducted on motorettes or full-stators based on Arrhenius's law. Heating is conducted via a furnace environment. Mechanical stress is applied to the motorettes or full-stators via a 60 Hz shaker table with 0.2 mm of peak-to-peak displacement. The method, similar to the IEC method, requires a reference system and contains the qualifying statement that the test method does not enable an accurate prediction of an insulation systems life. The method provides only a relative comparison of capability to that of an insulation system already in use.

NASA Winding Reliability Research Plan

The current processes for motor winding qualification as presented in IEC and IEEE standards need modifications and enhancements for UAM motor qualification. The current standards' requirement of a reference motor with known life in the target application is a barrier for emerging UAM motors. Even if reference motors existed, the standards only enable a relative and comparative estimate of motor winding life and do not establish actual life or reliability estimates for the windings. Additionally, the current qualification processes have been primarily targeted toward ground-based generator type machines that typically have a more continuous duty cycle than UAM motors. The standards therefore do not provide methodologies for testing motors that experience frequent thermal transients and corresponding high thermal mechanical stress cycles, both of which are expected to be present in UAM motors. Furthermore, mechanical aging of motor windings may be the life limiting mechanism for winding life of some UAM motors. This aging mechanism has not received the degree of research and experimentation attention that thermochemical and electrical aging have. Current insulation material data and qualification processes assume thermochemical aging is the dominant aging mechanism.

To achieve high reliability UAM motor windings, two new processes need to be developed. First, a new process for characterizing the combined thermochemical and mechanical aging of insulation materials needs to be developed to enable design of high-reliability UAM motors. Second, a process for qualifying a UAM motor winding for a given life under combined thermochemical and mechanical aging needs to be developed to replace the current comparison-based lifing methods for motor windings. If possible, these processes must improve on the timeliness of the current processes for insulation and motor winding qualification to allow for faster and less costly development and certification of UAM motors (Ref. 56). NASA's RVLT project focuses on the development of these two processes to enable accomplishment of the corresponding RVLT technical challenge.

For the first process, an insulation system characterization test that incorporates mechanical, thermal-chemical, and electrical stress all applied to the same specimen (either simultaneously or sequentially) needs to be developed. The state-of-the-art for insulation characterization testing targeted at motor windings is a twisted wire-pair configuration. However, the twisted wire-pair specimen geometry does not allow mechanical loads to be applied to the insulation in a cyclic fashion (fatigue testing) and in a controlled manner. A new specimen configuration and testing method is under development that enables combined thermochemical and mechanical aging of insulation systems as well as PD testing. The proposed new method will enable UAM motor designers to consider and incorporate the information they need to design reliable electric machine windings for UAM applications.

The second process is a methodology for qualification of full machine-windings for UAM applications. This test configuration is intended to closely resemble current standard motorette testing with the added adaptation for the loading that motors will experience during UAM missions. Novel methods must be developed to enable qualification of windings for the frequent thermo-mechanical stress cycles anticipated during UAM motor operations. A key advancement that must be made is enabling the prediction of motor winding life in more absolute terms, perhaps with accelerated-rate test approaches and/or methods that enable more direct extrapolation of experimental findings rather than providing a relative rating comparison to an established reference system.

NASA's RVLT propulsion team is working towards development of these two processes to demonstrate a methodology for reliable UAM electric motor winding design.

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