

Article

Early-Stage Design for Reliability Assessment Considering Electrothermal Modeling in High-Speed Integrated Motor Drives

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Abstract

The electrical drive and the electrical motor share the same housing in Integrated Motor Drives (IMDs), which directly affects the reliability of failure-prone components in such a system. Existing studies are often conducted without considering system-level electrothermal reliability interactions in IMDs. This paper proposes a framework for electrothermal modeling for reliability analysis of IMDs during the early design phase. The framework is based on a back-to-back converter as an emulation platform adaptable to different high-speed electrical machines through software reconfiguration alone. It follows two stages: first, it converts the real-world mission profile, including high-speed operation, into load current commands and motor power loss. Secondly, the thermal network modeling accounts for thermal coupling between the components and the motor, which affects the junction temperature and the hot-spot temperature of the DC link capacitor. The parameters of the thermal network of the electrical motor can be the result of a multiphysics simulation or a real available motor. This framework enables reliability assessment considering motor thermal effects in the early design phase without requiring a physical motor prototype, while providing a fast and cost-effective approach for reliability evaluation. The experimental tests are performed to validate an electrothermal modeling framework capable of thermal modeling and reliability analysis. In addition, the reliability analysis of the power device is carried out by doing the simulation results using data from a real motor, selected for integrated power converter applications. The results demonstrate that the thermal interaction between the motor and the electrical drive causes an 11.5% reduction in the predicted B_{10} lifetime compared with the non-integrated configuration. The non-integrated configuration exhibits approximately 20,000 km longer lifetime than the integrated configuration, highlighting the importance of considering motor-drive thermal coupling in IMD reliability assessment.

Keywords: Integrated Motor Drives (IMDs); reliability; lumped thermal networks; SiC; DC link capacitor



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1. Introduction

1.1. Background and Motivation

Integrated Motor Drives (IMDs) have drawn interest in E-mobility applications due to the potential for higher power density and reliability compared to non-IMDs [1–3]. While this provides more space in the critical applications, there are some challenges in the design of high-speed reliable IMDs: the thermal couplings, which are one of the main failure sources for fatigue on the power devices, and the DC link capacitors, are challenging

parts [4,5]. It is important to analyze the mutual thermal effect effectively because thermal stress is the primary driver of component failure in integrated systems. In the design of a converter for a reliable IMD, the mutual impact of thermal interaction and mechanical vibration from the electrical motor must be addressed [2,6]. The excessive thermal effect from the electrical motor can diminish the lifetime of the susceptible components of the integrated power converter, as they are highly affected by the surrounding temperature [7].

Such a framework allows both motor and power electronics designers to perform a multiphysics-based reliability assessment under real mission profiles.

1.2. State of the Art and Related Works

There are two main categories of IMD: (i) non-modular IMDs, in which a single power converter drives the electrical machine, and (ii) integrated modular motor drives (IMMDs), in which the converter is composed of multiple power converter modules. In both configurations, the power converter and the electrical machine share the same housing [2,8]. The current literature is categorized into two domains: electrical machine design and power converter design in the IMD where the thermal design is a major challenge in the overall design [9]. In [10], a design procedure for a module of an IMD using GaN H-bridge has been presented. The procedure consists of thermal studies by analyzing the number of parallel devices and also the switching frequency. In [11], the design of the electrical drive based on GaN for low-power integration has been proposed. The final design is in a circular shape which is mounted to the end cap of the electrical motor. Also, there is a high-power and high-voltage IMD, which reduces dv/dt and demonstrates an improved thermal management to obtain higher reliability for the more-electric aircraft applications [1].

However, in an integrated system, the coupling effect between the subsystems must be taken into account in the design [12]. In [13], a lumped thermal network for a drive system has been introduced to monitor the temperature of the critical components. A multi-objective design considering electromagnetic–thermal coupling has been introduced in [14] to identify the most sensitive parameters influencing the IMD performance. In some studies, the feature cooling sharing in IMMDs has been utilized to have a better thermal management for the power converter and the electrical motor [15,16]. In [16], a modular inverter with two series-connected units was designed for a pre-existing commercial induction motor, specifically focusing on minimizing the DC-link capacitor size.

1.3. Research Gap, Contribution and Roadmap

In spite of the advancement in the design analysis of the IMD, there is a gap in analyzing the effect of electrothermal coupling on the susceptible components of the power converter during the early stage, without requiring the physical motor of the IMD in practice.

This paper proposes a unified simulation and test framework for early-stage design for reliability assessment, taking into account the thermal coupling for high-speed IMDs. The framework employs a back-to-back (B2B) converter to emulate the motor behavior electrically and thermally. The main contributions of the proposed framework are as follows:

- It is a cost-effective, and fast approach;
- It does not require additional software or hardware reconfiguration and a physical motor prototype for different motor types;
- It is adaptive to various types of electrical motors and their control algorithms;

The remaining parts of this paper are as follows: Section 2 introduces the proposed framework and algorithm to convert mission profile into control references. Section 3 discusses the thermal model to analyze the temperature of the two most prone components

in an IMM. Sections 4 and 5 explain the simulations and experimental results for reliability analysis following the conclusions.

2. Electrothermal Reliability Assessment of Integrated Motor Drives

2.1. Reliability Assessment and Thermal Coupling in IMDs

The reliability and lifetime of the power electronics components are determined by their thermal behavior because temperature is one of the dominant stresses affecting the strength of failure-prone components, such as power semiconductor devices and DC-link capacitors.

A block diagram for reliability analysis of an integrated electrical drive is shown in Figure 1. It requires the system specifications, including the motor speed, load torque, and ambient temperature from the mission profile, as well as the electrical motor and prone component types. By having the power loss of the power device and the DC link capacitor over its mission profile, in addition to the thermal mutual effect from the electrical motor, the strength can be estimated based on the junction temperature and the hot-spot temperature. The power loss based on, e.g., SiC MOSFET can be expressed as (1) [12,17]

$$\begin{aligned} P_{\text{loss,SiC}}(t) &= P_{\text{cond,SiC}}(t) + P_{\text{switch,SiC}}(t) \\ &= R_{ds}(I, T_j) I_{abc}^2(t) d_{abc}(t) \\ &\quad + \left(E_{on}(I, T_j, V_{dc}) + E_{off}(I, T_j, V_{dc}) \right) f_{sw}, \end{aligned} \quad (1)$$

where R_{ds} is the on-state resistance of the SiC MOSFET, I_{abc} is the phase current, d_{abc} is the duty cycle, E_{on} and E_{off} are the turn-on and turn-off energies obtained from the datasheet, respectively, and f_{sw} is the switching frequency [12].

The internal power loss of the DC-link capacitor is estimated as (2)

$$P_{\text{loss,C}} = i_{c,\text{rms}}^2 R_{\text{ESR}}, \quad (2)$$

where $i_{c,\text{rms}}$ is the RMS capacitor current and R_{ESR} is the equivalent series resistance of the capacitor.

However, in practical motor drive systems, the power converters and the controller are typically housed within a common enclosure. Hence, there is a thermal coupling between the susceptible components, such as power devices and DC link capacitors. As a result, it affects the reliability of the susceptible power electronic components [12]. However, this analysis requires a physical prototype of the electrical motor for reliability and thermal analysis to capture the thermal interaction between the motor and the electrical drive. Such approaches increase both development time and cost during the early design for the reliability phase [2].

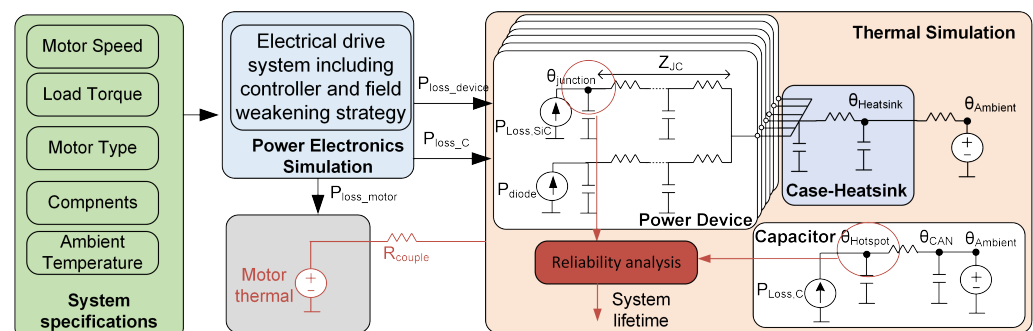


Figure 1. Block diagram for reliability analysis of prone components in an Integrated Motor Drive.

2.2. Proposed Electrothermal Framework Based on a Back-to-Back Converter

An electrothermal framework able to emulate the thermal influence of the motor on the power converter can contribute to the thermal and reliability analysis in the early design phase of IMDs. Although other stress factors, such as mechanical vibration and humidity, exist in IMDs [18], the proposed framework focuses on a single stress factor, namely thermal stress, which is considered one of the dominant factors affecting component reliability.

The whole proposed electrothermal framework is shown in Figure 2, which consists of two main stages: (1) software parts and (2) hardware parts. The software stage maps a real-world mission profile, including a wide speed range of the motor and four-quadrant operation, into the required dq axis current for a back-to-back converter to generate 12 gate signals. The back-to-back converter include six half-bridges, one of which is the device under test, and the other one is the load under test. The power module of the device under test is physically mounted to a programmable temperature source, thereby being able to program it. The profile of the heatsink temperature source is obtained based on the thermal loading of the electrical motor.

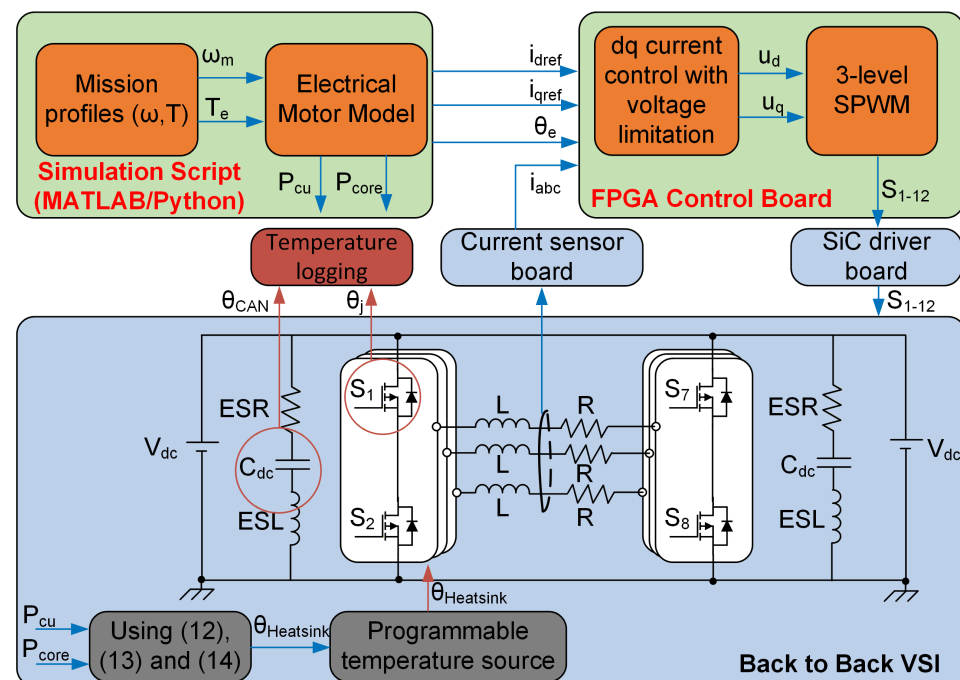


Figure 2. An electrothermal framework for reliability analysis of susceptible components in an Integrated Motor Drive.

In the following, the mission profile to current command mapping is explained, where Maximum Torque Per Ampere (MTPA) and Field Weakening (FW) regions are identified, which are then used to control the back-to-back converter.

2.3. Mission Profile to Electrical and Control Reference Mapping

A permanent magnet synchronous motor (PMSM) is selected to demonstrate the proposed framework. However, the proposed framework can be adapted to different types of electrical motors by modifying the motor model in the first stage of the framework to generate the corresponding dq -axis current references and motor power losses [19].

For an interior PMSM, the dq axis voltage equations, considering the core loss resistance as displayed in Figure 3 and the torque equation in the rotor reference frame, can be explained as follows:

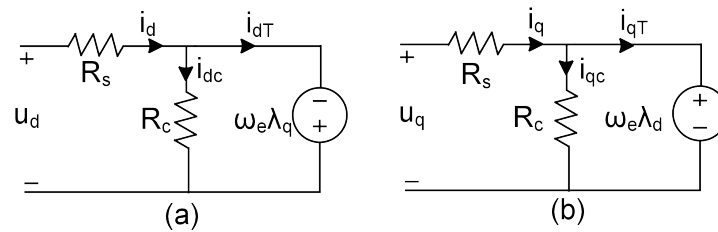


Figure 3. Equivalent circuit of the interior permanent magnet synchronous motor in (a) d – and (b) q – references frame.

$$\begin{cases} u_d = R_s i_d - \omega_e \lambda_q, & \lambda_q = L_q i_{qT} \\ u_q = R_s i_q + \omega_e \lambda_d, & \lambda_d = L_d i_{dT} + \lambda_m \\ T_e = \frac{3p}{2} (\lambda_m i_{qT} + (L_d - L_q) i_{qT} i_{dT}), \end{cases} \quad (3)$$

where R_s , λ_m , L_{dq} , and p are the stator resistance, flux linkage of permanent magnet, d – q axis inductances, and number of pole pairs, respectively. The optimal d -axis current under the MTPA operation is obtained by solving $\frac{\partial T_e}{\partial i_d} = 0$, resulting in (4).

$$i_{dTMTA} = -\frac{\lambda_m}{2(L_d - L_q)} - \sqrt{\frac{\lambda_m^2}{4(L_d - L_q)^2} + i_{qTMTA}^2} \quad (4)$$

For surface-mount PMSM, the d axis current is zero below rated speed because $L_d = L_q$. Also, the optimal d -axis current under the FW condition, which is limited by the inverter voltage, can be obtained as shown in (5).

$$\begin{cases} u_d^2 + u_q^2 = u_{\max}^2 \\ i_{dTFW} = -\frac{\lambda_m}{L_d} + \frac{1}{L_d} \sqrt{\frac{u_{\max}^2}{(\omega_e)^2} - (L_q i_{qTFW})^2} \end{cases} \quad (5)$$

The optimal d -axis current in the FW region is identical for both types of PMSMs.

The optimal dq -axis currents are obtained from (6) and (7), where the electrical speed ω_e and torque T_e are determined by the mission profile. For each operating point (ω_e, T_e) obtained from the mission profile, the optimal q -axis current is computed by solving the corresponding nonlinear equations in (6) and (7).

$$f(i_{qTMTA}; \omega_e, T_e) = (L_d - L_q)^2 i_{qTMTA}^4 + \frac{2|T_e| \lambda_m}{3p} i_{qTMTA} - \frac{4|T_e|^2}{9p^2} = 0 \quad (6)$$

$$f(i_{qTFW}; \omega_e, T_e) = a^2 L_q^2 i_{qTFW}^4 + \left(\lambda_m^2 b^2 - \frac{a^2 u_{\max}^2}{\omega_e^2} \right) i_{qTFW}^2 - \frac{4|T_e| b \lambda_m}{3p} i_{qTFW} + \frac{4|T_e|^2}{9p^2} = 0 \quad (7)$$

where $a = \frac{L_d - L_q}{L_d}$ and $b = 1 - a$. It must be noted that only the real solution of the fourth-order equations within the rated current is meaningful.

Equations (6) and (7) give the optimal dq -axis current for positive torque due to the symmetry of the PMSM operating point [12]. However, to handle the negative torque, the sign of the electrical torque must be considered for q -axis current, while the d -axis current

remains unchanged. Once i_{dqT} are obtained, the currents i_{dq} and i_{dqC} can be determined, and as a result, the core loss and copper loss of the motor can be calculated as (8) [12]

$$\begin{aligned} P_{cu} &= \frac{3}{2} R_s (i_d^2 + i_q^2) \\ P_{core} &= \frac{3}{2} R_c (i_{dc}^2 + i_{qc}^2) \end{aligned} \quad (8)$$

The whole flowchart to generate dq axis current, and motor loss with more details over a wide speed range, including MTPA and FW regions, is depicted in Figure 4.

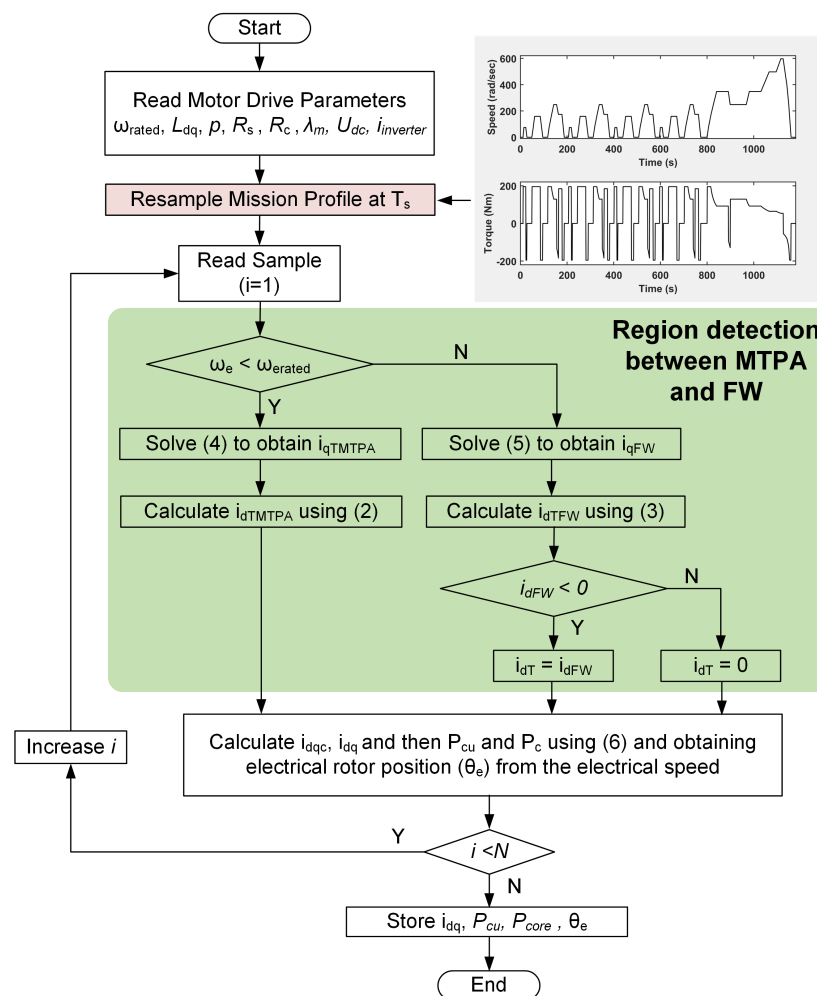


Figure 4. Algorithm to generate i_{dq} , P_{cu} , P_{core} , θ_e based on a mission profile.

2.4. Control of Back-to-Back Converter

The control block diagram is shown in Figure 5. There are three inputs, which are dq -axis currents and the electrical rotor position obtained from the mission profile mapping. Initially, the reference current must be limited to the rated current as one of the requirements for high-speed operation. Then, there are two PI current controllers with external anti-windup whose signals are derived from the voltage limit circle as another requirement for the FW region. The Park transformation, followed by symmetrical PWM and a gate signal generator, produces the gating signals for the 12 switches of the back-to-back converter. In the integrated case, the heatsink temperature depends on the mission profile, and the method for obtaining the corresponding temperature profile is presented in the following section.

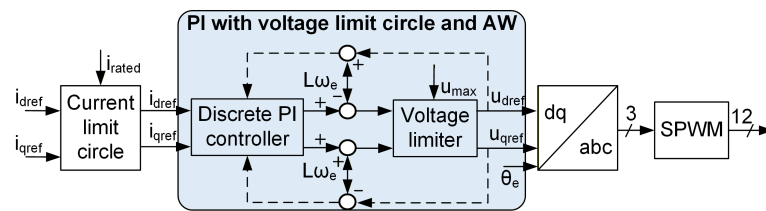


Figure 5. Control scheme to generate gate pulses for the back-to-back converter shown in Figure 2.

3. Thermal Lumped Network of the Integrated Modular Motor Drive

3.1. Temperature Estimation of Susceptible Components

The electrical drive in the IMMD is physically embedded inside the electrical motor, either axially or radially [2]. The approximate thermal lumped model of the IMMD using a second-order lumped thermal network for the electrical motor is depicted in Figure 6. The order of power devices mostly relies on the specification provided by the manufacturer. Based on the thermal model, the junction temperature (θ_j) can be obtained as follows:

$$\theta_{j,k}(t) = \theta_{\text{Heatsink}}(t) + P_k(t)Z_{\text{JC},k}(t) + \sum_{m=1}^6 P_m(t)Z_{\text{CH}}(t), \quad (9)$$

where $\theta_{j,k}$ is the junction temperature of the k th power device, θ_{Heatsink} is the heatsink temperature, P_k is the power loss of the selected device, $Z_{\text{JC},k}$ is the junction-to-case thermal impedance, P_m is the loss of the m th device thermally coupled through the heatsink, and Z_{CH} is the case-to-heatsink thermal impedance. For reliability design, the widely maximum continuous junction temperature is 150°C .

The reliability and lifetime of the DC-link capacitor in the electrical drive are of high importance [20]. The usual representation of the DC link capacitor is first order, which is the thermal characteristics from the hot-spot temperature to the can-temperature. The temperature of the DC link capacitor, the other susceptible failure component in a drive, are highly influenced by the surrounding thermal environment, which is determined by both the power loss of the devices and the electrical motor. Although there is no direct thermal connection between the heatsink and the capacitor, the capacitor temperature is mainly influenced by the surrounding temperature, in addition to a small contribution from its internal losses. Accordingly, the function of the capacitor temperature with respect to the heatsink temperature, loss of devices, and coupling loss, by ignoring the thermal capacitance, is given in (10):

$$\theta_{\text{CAN}} = \theta_{\text{Heatsink}} - R_{\text{CAP-H}}[\sum P_s + P_{\text{coupled}}], \quad (10)$$

where $R_{\text{CAP-H}}$ represents thermal resistance between the heatsink thermal node and the capacitor CAN, showing how much heat flows between these two thermal nodes. As seen, the temperature of the capacitor is affected by the heatsink and the heat coupling between the electrical motor and the converter. In IMMDs, a portion of the motor losses is transferred to the converter through the thermal coupling path represented by the thermal resistance (R_{couple}). The resulting heatsink temperature profile can be used to emulate the motor thermal influence by means of a programmable temperature source, eliminating the need for a dedicated motor prototype during the early design phase.

3.2. Motor Temperature Estimation

The heat of the electrical motor and power devices is taken away by the coolant and heatsink, respectively. Due to the integration of the electrical drive inside the motor housing, a thermal coupling exists between the stator and the heatsink. The heat flow of the

coupling ($P_{coupled}$) represents the portion of heat that is not dissipated through the motor cooling system. Based on the thermal coupling model shown in Figure 6, the heat flow coupling is expressed as (11)

$$P_{coupled} = \frac{\theta_s - \theta_{Heatsink}}{R_{couple}}, \quad (11)$$

where θ_s is the stator temperature, and R_{couple} represents the thermal coupling resistance between the motor stator and the converter heatsink. A higher R_{couple} leads to less heat flow in the coupling path, but reduce the integration advantage. The heatsink temperature based on the stator temperature can be estimated as (12)

$$\theta_{Heatsink} = \theta_s - R_{couple} P_{coupled}. \quad (12)$$

$$\begin{bmatrix} \dot{\theta}_w \\ \dot{\theta}_s \end{bmatrix} = \begin{bmatrix} -\frac{1}{R_{w-s}C_w} & \frac{1}{R_{w-s}C_w} \\ \frac{1}{R_{w-s}C_s} & -\left(\frac{1}{R_{w-s}C_s} + \frac{1}{R_{s-coolant}C_s}\right) \end{bmatrix} \begin{bmatrix} \theta_w \\ \theta_s \end{bmatrix} + \begin{bmatrix} \frac{1}{C_w} & 0 \\ 0 & \frac{1}{C_s} \end{bmatrix} \begin{bmatrix} P_{cu} \\ P_{core} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{R_{s-coolant}C_s} \end{bmatrix} \theta_{Coolant} \quad (13)$$

A key variable, which must be determined, is θ_s . Due to the fact that the proposed framework aims to emulate the thermal influence of the motor without requiring a physical motor prototype, the motor thermal behavior must first be estimated independently by using the mission-profile-based calculated motor losses.

The motor thermal behavior is represented by a second-order lumped-parameter network. The housing and cooling jacket are not modeled as separate dynamic states; instead, their thermal effect is incorporated into an equivalent outer thermal resistance connected to a constant coolant-temperature boundary. The state space model explaining the thermal network of the electrical motor is as shown in (13), which allows for obtaining the stator temperature of the electrical motor. The initial condition for the two states, which are winding and stator temperature, is the coolant temperature.

The heat transfer between two thermal nodes of the electrical motor, i.e., winding (θ_w) and stator (θ_s), is governed by the thermal resistance R_{w-s} . The copper loss is partly transferred to the stator and partly stored in the winding by its thermal capacitance, while the core loss is directly generated at the stator node.

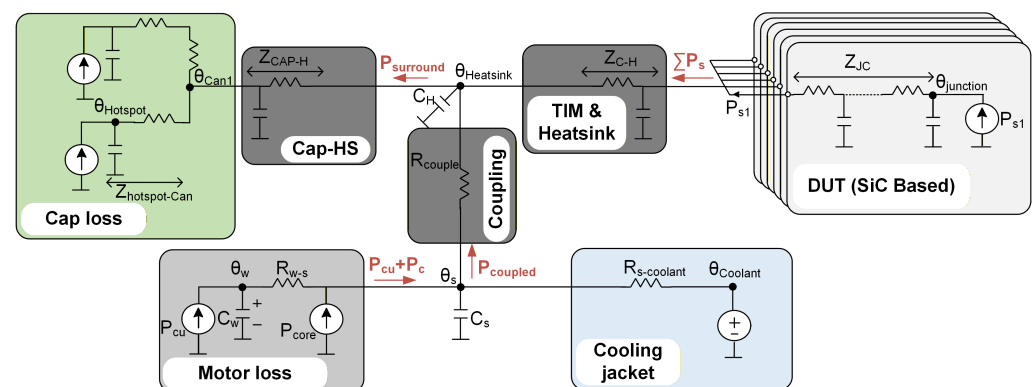


Figure 6. Lumped thermal network of the integrated modular motor drive, including coupling between the susceptible components in the electrical drive and electrical motor.

By ignoring the temperature derivatives $\dot{\theta}_w$ and $\dot{\theta}_s$, the heat flow through the coupling branch can be expressed as (14)

$$P_{coupled} = P_{cu} + P_{core} - \left(\frac{\theta_s - \theta_{coolant}}{R_{s-coolant}} \right) \quad (14)$$

where P_{cu} and P_{core} are the copper and core losses of the electrical motor, $\theta_{coolant}$ is the coolant temperature, and $R_{s-coolant}$ is the thermal resistance between the stator and the cooling jacket. Replacing (14) into (12) results in the heatsink temperature as a function of the motor thermal states. This enables thermal and reliability analysis of the electrical drive in the early design phase of IMMD without requiring a physical prototype.

4. Results and Discussion

4.1. Experimental Validation of Electrothermal Model

The first part of the results will confirm the behavior of the proposed framework experimentally. The experimental setup is based on the SiC B2B converter as shown in Figure 7. It consists of an optical fiber to acquire the junction temperature, while a PT1000 temperature sensor is mounted on the top of the DC link capacitor to observe the CAN temperature (θ_{CAN}) of the capacitor. The sample time of the optical fiber is 1 ms, and the PT1000 sensor is 1 s. In addition, the heatsink temperature is controlled by a programmable thermal source to emulate different thermal boundary conditions associated with the mission profile.

The purposes of the experimental tests are as follows:

- Assess the junction temperature by using an optical fiber for reliability analysis;
- Evaluate the temperature of the capacitor for reliability analysis;
- Validate the coupling between the temperature of the capacitor and the heatsink as shown in Figure 6 based on the lumped thermal network.

Four operating conditions with different speeds, torques, and heatsink temperatures are selected as representatives to emulate the mutual effect from the electrical motor to the electrical drive. The results from the measured junction temperature and the CAN of the capacitor are shown in Figure 8. Additionally, a zoomed-in view of the junction temperature profile is shown to demonstrate the captured junction temperature swing. The thermal effect from the motor changes the magnitude of the temperature swing (ΔT) for reliability analysis [12]. The temperature of the capacitor shows that it is strongly affected by the surrounding environment [7] because it follows the behavior of the heatsink as well.

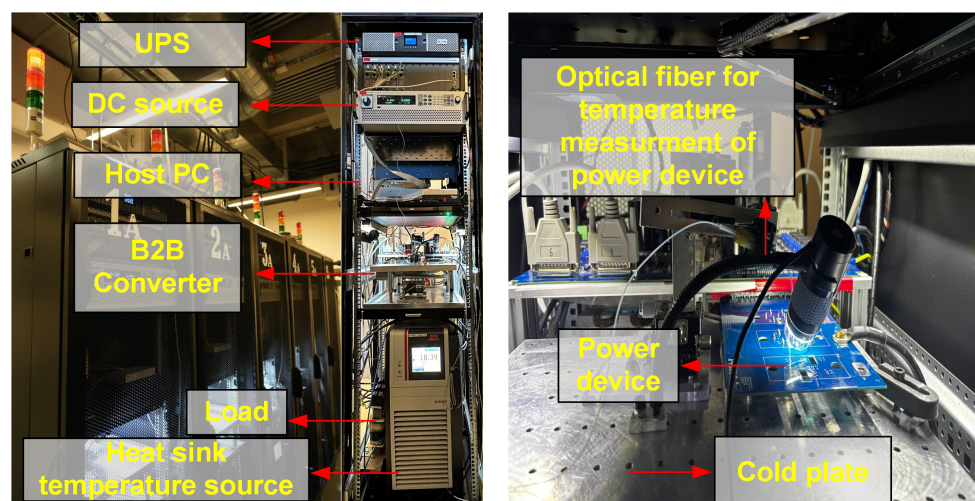


Figure 7. Experimental setup based on a back-to-back converter, detailed configuration of the converter, including optical fiber for temperature measurement of power devices.

The proposed experimental setup allows reliability engineers to validate the electrothermal and reliability models for IMDs during the early design phase.

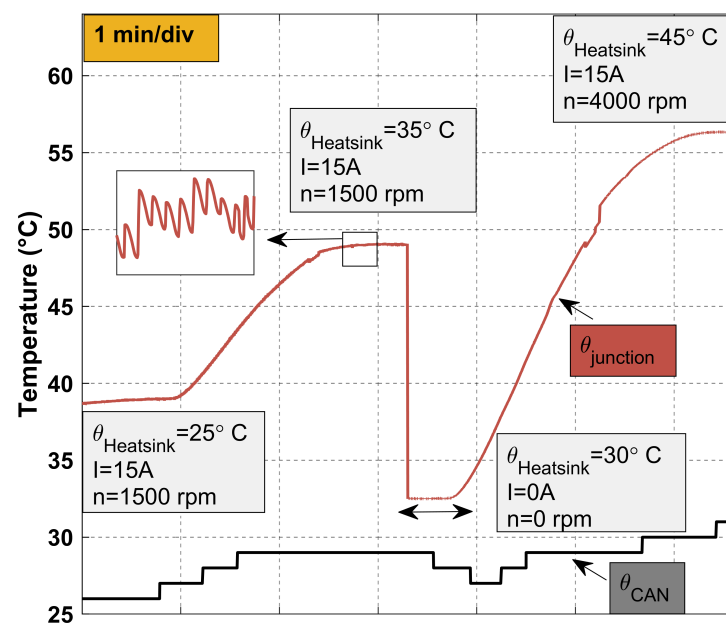


Figure 8. Experimental results of the junction temperature and capacitor CAN temperature under different operating conditions (1500, 0, 4000 rpm).

4.2. Simulation Results for Reliability Analysis

The data motor under study to integrate the electrical drive is given in the Table 1 [21,22]. The New European Driving Cycle (NEDC) is used as the mission profile for the analysis. The speed and torque are as shown in Figure 9. Using the proposed algorithm shown in Figure 4, the references dq axis currents, which are displayed in Figure 9, are generated for the closed-loop control. The reference current generation can be adapted to different electrical motor types through the corresponding machine equations. The corresponding core and copper losses, which are presented in Figure 10, are calculated to estimate the heatsink temperature using stator temperature and (12). The thermal coupling is assumed to be $R_{couple} = 0.01$ K/W. However, it can be optimized based on the reliability and thermal requirements of the system.

Table 1. Used electrical, thermal, and reliability parameters of the drive system.

Parameter	Value (Unit)	Parameter	Value (Unit)
Converter and Motor Parameters			
R_s	0.013 (Ω)	i_{max}	282 (A)
$R_c(\omega)$	100–80 (nm/6000) (Ω)	V_{dc}	180 (V)
L_{dq}	$[0.15 \ 0.25] \times 10^{-3}$ (H)	f_{sw}	20 (kHz)
λ_m	55 (mVs)	n_{max}	6000 (rpm)
p	8	T_{max}	206 (N.m)
Thermal Parameters			
C_w	2.62×10^3 (J/K)	C_s	8.5×10^3 (J/K)
R_{w-s}	0.0288 (K/W)	$R_{s-coolant}$	0.017 (K/W)
Reliability Parameters			
A	1.42×10^{12}	α	5.2

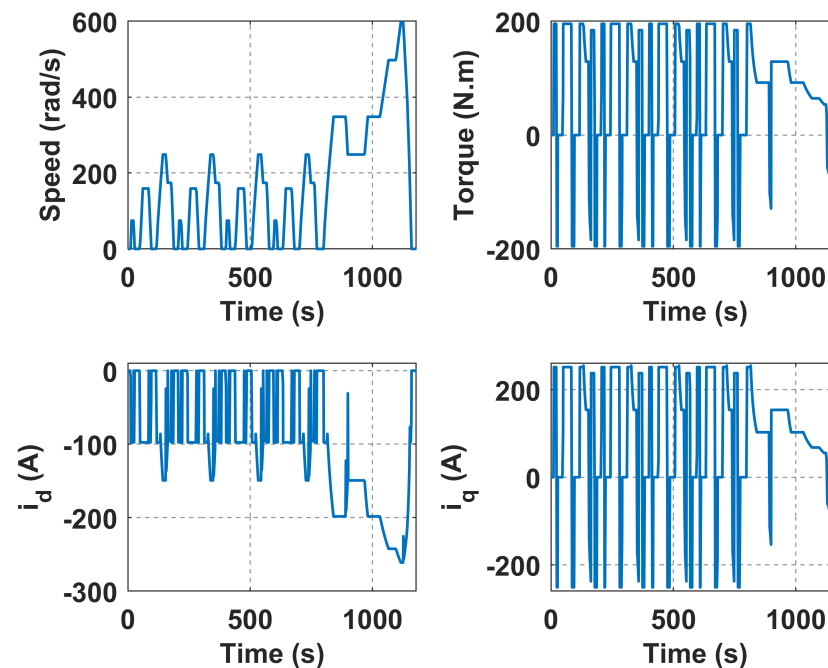


Figure 9. Speed and torque profiles of the New European Driving Cycle (NEDC) mission profile, corresponding current references dq -axis currents.

Above 200 rad/s, the motor operates in the FW region, where the core loss becomes dominant. Due to the shared housing configuration of the IMD, the heatsink temperature, as shown in Figure 10, reflects the thermal coupling between the motor and the power converter. The maximum heatsink temperature is above 90° due to the high-speed operation and the utilized FW strategy. This heatsink temperature is subsequently employed as the thermal of the motor for the estimation of the junction temperature over the mission profile, which is also displayed in Figure 10. The resulting junction temperature is because of the power loss of the device and the heatsink temperature.

The junction temperature profile is used as the thermal stress input for the reliability analysis to estimate the end of life of the power device. After applying rainflow counting and obtaining the junction temperature swing ($\Delta\theta_j$), the lifetime model presented in [12] is employed to estimate the number of cycles to failure (N_f), including the Accumulated Damage (AD), we have

$$N_f = A \Delta\theta_j^{-\alpha},$$

$$AD_{\text{Device}} = \sum \frac{n_{\text{cycle}}}{N_f}, \quad (15)$$

where A and α are constant values given in Table 1. To account for uncertainties in the reliability assessment, a Monte Carlo analysis is performed by considering a 5% variation in $\Delta\theta_j$, A , and α . This procedure enables the derivation of the unreliability functions at both the component and system levels while accounting for variations in these parameters under the New European Driving Cycle (NEDC) mission profile. The number of components for analyzing the system-level unreliability (F_{system}) are six [12], and it can be calculated based on the unreliability of single components ($F_{\text{component}}$) as follows:

$$F_{\text{system}} = 1 - (1 - F_{\text{component}})^6 \quad (16)$$

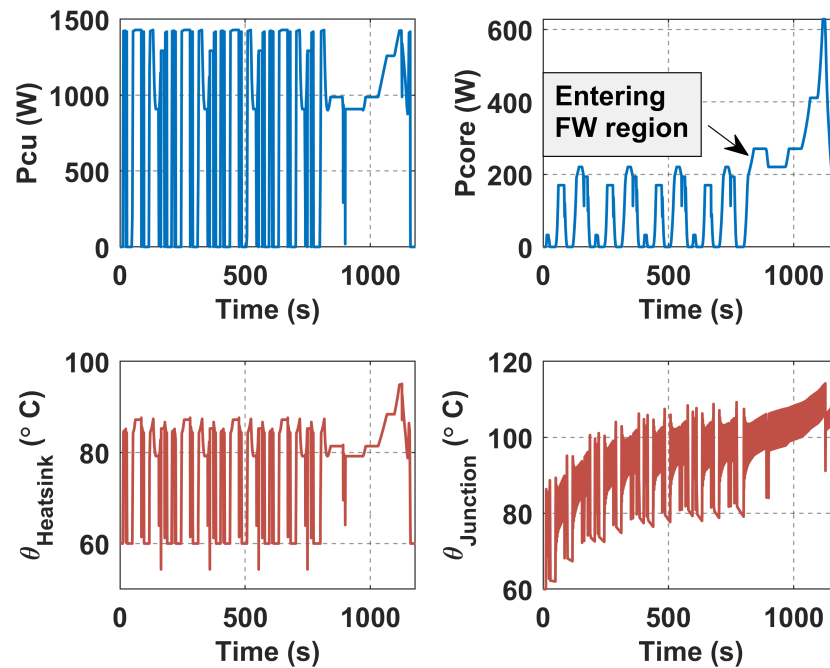


Figure 10. Copper loss, core loss, heatsink temperature, and junction temperature of the NEDC mission profile.

Two operating scenarios are considered. In the first scenario, the heatsink temperature profile is obtained by considering the thermal interaction between the electrical motor and the electrical drive. In the second scenario, a constant heatsink temperature of 60 °C is assumed. The estimated lifetime distributions as a function of mileage are presented in Figure 11. The variation in heatsink temperature influences the junction temperature swing ($\Delta\theta_j$), which consequently increases the Accumulated Damage (AD) of the power devices.

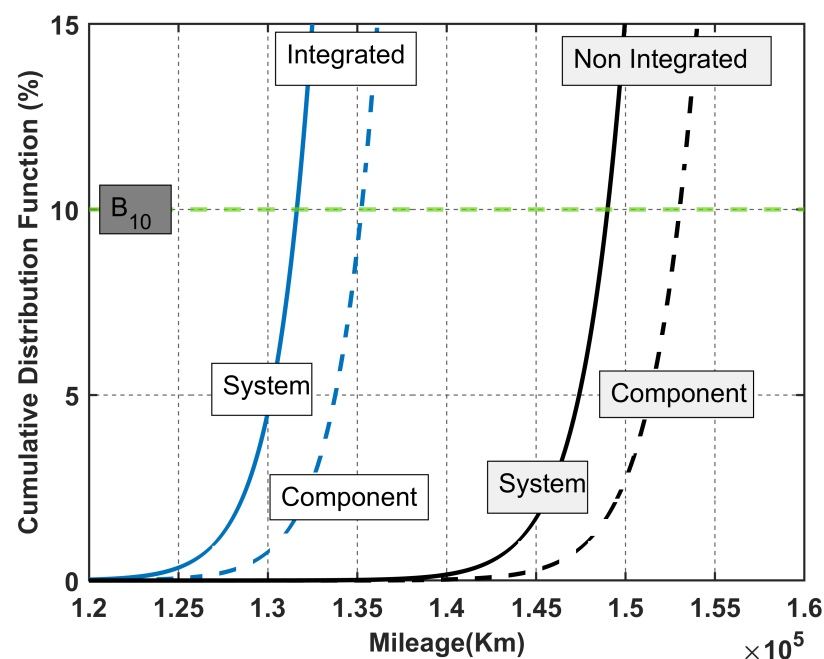


Figure 11. Cumulative distribution of the power devices at the component and system levels for integrated and non-Integrated Motor Drive configurations under the NEDC mission profile.

Based on the B_{10} reliability metrics, the predicted end of life of the integrated system occurs at approximately 1.345×10^5 km, whereas the non-integrated system reaches its end of life at approximately 1.52×10^5 km. These results highlight the importance of considering the thermal interaction between the electrical motor and the electrical drive when performing reliability analysis of IMD systems.

Table 2 is provided to compare the proposed framework with other methods, including Finite Element Analysis (FEA), fully electrothermal simulation, and the thermal simulation approach presented in [12]. As seen, the proposed work enables physical failure testing based on long mission profile analysis from a system-level perspective while considering the thermal coupling of the DC-link capacitor with other components. Furthermore, it does not require a detailed motor model and relies only on the electrical and lumped thermal parameters of the motor.

In spite of some advantageous, there are some limitations to the proposed framework, such as developing an experimental setup based on a B2B converter and ignoring other reliability stress factors beyond thermal interactions.

Table 2. Comparison of reliability assessment approaches for Integrated Motor Drives.

Description	3D/FEA	Electrothermal	[12]	This Work
Detailed motor model required?	Yes	No	No	No
Long mission-profile analysis	Impractical	Computationally intensive	Yes	Yes
Cost	Low	Low	Low	Moderate
Time	High	Low	Low	Moderate
Failure testing capability	No	No	No	Yes

5. Conclusions

Although other stressors, such as mechanical vibration and humidity, exist, the thermal effect of the electrical motor on the electrical drive is considered a dominant stress factor affecting the reliability of susceptible components and the system-level lifetime assessment of the IMD in this study. This study has proposed an electrothermal modeling framework for assessing the reliability of the power converter in an IMD using a back-to-back converter. This framework enables initial reliability assessment without requiring a detailed physical motor model.

The proposed framework is validated through simulation and experiment based on a high-speed IPMSM with the electrical and thermal parameters. The experimental test confirms the proposed thermal model and interaction between susceptible components of the electrical drive and the electrical motor. Reliability evaluation of the power devices was carried out for integrated and non-integrated configurations. Simulation results indicate that neglecting the thermal interaction between the electrical motor and the electrical drive results in an approximately 20,000 km longer predicted converter lifetime.

The key features of the proposed framework are a time-efficient reliability assessment based on a long mission profile, and a detailed motor model is not required. However, the framework has some limitations, including the need to develop an experimental setup based on a B2B converter and the exclusion of other reliability stress factors beyond thermal interactions.

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