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The implications of aerospace requirements on the design-space of a permanent magnet starter/generator system

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ABSTRACT

Starter/generator units based on PM machines are generally not considered due to their inherent safety risks. This technology can, however, prove advantageous for aerospace applications where mass, volume, efficiency and low maintenance costs play a significant role. A safety analysis is performed in order to identify the safety and mitigation measures required to realise such a system which conforms to aerospace requirements. These measures define the design-space and boundary conditions within which a design may be realised. It is found that not all the measures are unique to PM based SGUs and that their degree of influence on the mass and volume is highly dependent on the starting and generating specifications.

1 INTRODUCTION

In the past decade a trend towards more electric aircraft was initiated in an effort to improve efficiency and decrease system weight and cost of ownership [1] [2] [3]. To this end innovative technologies are required and in the case of rotating electrical machines, permanent magnet (PM) machines are a leading contender, due to their high power density, high efficiency and low maintenance cost [4] [5]. However, due to the strict safety requirements imposed by the aerospace environment, PM machines are normally only considered for motors and seldom for generators, as they are pose an inherent safety risk under fault conditions (specifically short circuits) due to the inability to remove the magnetic field from the rotor [1].

In order to identify, quantify and mitigate the risks of a PM based generator a safety analysis was performed. Through this safety analysis the two main objectives will be met: 1) The identification of the safety and mitigation measures required for the safe operation of a PM generator within the aerospace environment, and 2) obtain a relationship between an incremental decrease of the failure rate (FR) and the steps required to realise such a decrease. The results of this second objective can be used as a starting point for the design of the safety and mitigation concept of a similar system with equal or lower safety requirements. In such a case it allows for the qualitative, or first-order, identification of which safety and mitigation measures are truly needed without having to necessarily apply all the (or similar) safety and mitigation steps identified here.

The PM generator in question is in actuality a starter/generator unit (SGU) for gas turbines, which acts as a motor/starter during the starting phase (or mode) and as a generator once the turbine is started (known as generator phase/mode). Figure 1 gives a high level overview of the system during starting and generating modes. The safety analysis must therefore incorporate both modes of operation, along with all the power and control electronics required to realise this SGU. A first-order design was performed in order to identify all the functional components and obtain a baseline from which the safety analysis could be performed. These are highlighted by the blue blocks in Figure 2. As

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can be seen, the system consists of an electric motor/generator (EM), cables and an ECU (electronic control unit). The ECU in turn consists of an inverter and a DC/DC converter. The DC/DC converter is required as the voltage available during starting is significantly higher than the voltage the ECU must supply during generating. This difference is too large for the inverter to realise, with the result that a separate DC/DC converter is required. Consequently, if the baseline design is changed the resultant safety analysis and conclusions would also change. This specific baseline design was selected as it is felt that it provides the best solution to the functional requirements.

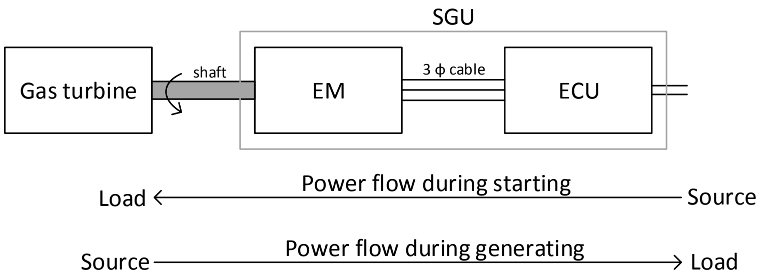

Figure 1. Power flow during starting and generator modes

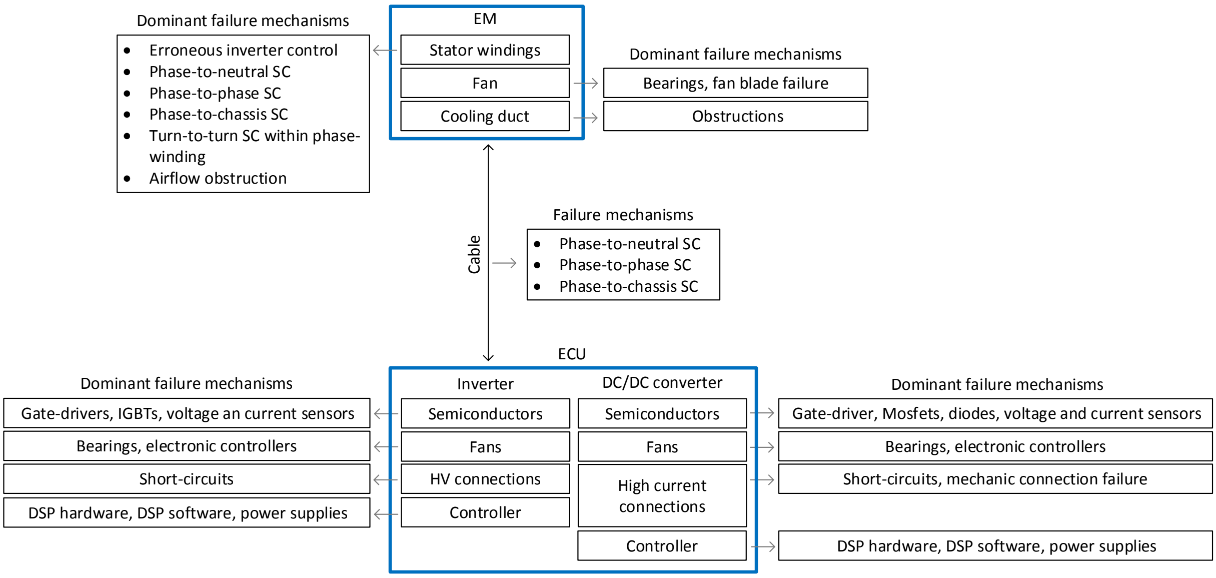
Dominant failure mechanisms
Erroneous inverter control
Phase-to-neutral SC
Phase-to-phase SC
Phase-to-chassis SC
Turn-to-turn SC within phase-winding
Airflow obstruction
EM
Stator windings
Fan
Cooling duct
Dominant failure mechanisms
Bearings, fan blade failure
Obstructions
Cable
Failure mechanisms
Phase-to-neutral SC
Phase-to-phase SC
Phase-to-chassis SC
ECU
Dominant failure mechanisms
Gate-drivers, IGBTs, voltage an current sensors
Bearings, electronic controllers
Short-circuits
DSP hardware, DSP software, power supplies
Inverter
Semiconductors
Fans
HV connections
Controller
DC/DC converter
Semiconductors
Fans
High current connections
Controller
Dominant failure mechanisms
Gate-driver, Mosfets, diodes, voltage and current sensors
Bearings, electronic controllers
Short-circuits, mechanic connection failure
DSP hardware, DSP software, power supplies

Figure 2. Outline of components of the SGU and dominant failure mechanisms

The system is purely considered from a safety analysis perspective, with each component decomposed only into the elements which are significant from a safety perspective. The electric machine (EM) therefore consists of the stator windings, fan and cooling duct (the fan is connected to the rotor shaft). The inverter consists of the power semiconductors, cooling fans, high voltage (HV) connections and controller, while the DC/DC converter consists of the power semiconductors, cooling fans, high current connections and its controller. The inverter and DC/DC converter are enclosed within the same housing. Components which do not pose a significant failure risk, such as the rotor or EMI filter, are not listed or considered.

Objectives one and two are both addressed in section 2 through a stepwise approach of the safety and mitigation measures. During this approach care is taken to select the safety and mitigation

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measures which are best suited to the aerospace optimization goals of efficiency, volume and mass. Where appropriate comparisons to other machine topology based systems are made in order to place the choices made in perspective. Section 3 discusses each of the required mitigation methods in the necessary detail (as allowed in the context of this paper). Section 4 gives a qualitative examination and discussion of the implications of the selected methods on the optimization goals, while section 5 presents an overview of the final system which was constructed as proof of this concept.

2 IMPLICATIONS ON THE DESIGN SPACE AS DRIVEN FROM THE SAFETY ANALYSIS

Since the focus is on the implications on the design space as a result of the safety analysis, and not on the safety analysis itself, only the most relevant information from the safety analysis will be presented. The safety analysis was performed together with NLR (Dutch National Aerospace Laboratory) using the commercial software 'Fault Tree+'. Even though significant effort was placed on realising a representative safety analysis, some limitations could not be avoided. Firstly, the failure rate (FR) of individual components were based on statistical data, where available, and experience where not. In order to err on the side of caution, very conservative numbers were used were statistical data was not available. Secondly, some common-cause (or common-mode) failures were not considered.

The result is that even though the FR numbers are given in the analysis below, they are very specific to this system. Since the details of the system and the safety analysis is outside the scope of this paper the provided FR numbers should rather be used for a comparison between incremental improvements than an absolute quantifying value. Focus should therefore instead be placed on the devised solutions, with the FR as an indication of their effectiveness.

From the aerospace requirements a number of failures were identified as 'catastrophic' and are given in Table 1 below, along with their maximum allowed failure rates. These failures have the lowest associated failure rates and define the boundaries of the design space, as will be shown below.

Table 1: Critical events

Undesired events defined as critical	**Objective (/FH)**
Fire in EM	10^{-9}
Fire in ECU	10^{-9}
Uncontained rotor burst	10^{-9}

Through a mechanically sound rotor design and a proper containment structure is was possible to lower the failure rate of an 'uncontained rotor burst' to well below the requirement of 10^{-9} and as a result will not be considered in the analysis below.

In order to identify the most vulnerable components, from a FR perspective, an initial analysis was performed on the basic functional system. This baseline system does not have any monitoring or fault mitigation measures in place and provides a reference from which to work. Figure 2 shows this basic system, along with the failure mechanisms associated with each component. From the initial analysis the most significantly contributing components to the failure rate were identified. These are given in Table 2, along with their associated failure rates.

Table 2: Components which significantly contribute to the FR

Contributing component	**Associated failure rate**
Loss of the cooling fans in the ECU	$4.99 \text{x} 10^{-3}$
Undetected overheat due to erroneous inverter control in the ECU and EM	$1 \text{x} 10^{-5}$
Short-circuit leading to overheating or fire within EM	$2 \text{x} 10^{-6}$

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In line with objectives one and two, a solution will be approached by step-wise remedying the contributors to the failure rate until a small enough value is reached. As the design is to be optimized for volume, mass and efficiency, efforts are made to start with solutions which have the lowest impact on these criteria. Each remedying step is identified by a 'condition' number, with 'condition' referring to the conditions needed to realise the calculated failure rate. A graphical overview of this approach is given in Figure 3 and Figure 4, with the actual failure rates given in Table 3 below.

Table 3: Conditions required to realise an aerospace compliant SGU

Condition	**Predicted failure rate (/FH)**		
	System	**ECU**	**EM**
Cond. 1: Basic system: • **No monitoring** • **No protection**	$5x10^{-3}$	$4.99x10^{-3}$	$1.2x10^{-5}$
Contributing components		Loss of cooling fans ($4.99\ x10^{-3}$)	
Cond. 2: • **ECU fans are monitored** • **Hardware protection layer**	$1.71x10^{-5}$	$5.1x10^{-6}$	$1.2x10^{-5}$
Contributing components			Undetected overheat due to erroneous inverter control ($1\ x10^{-5}$)
Cond 3: • **Cond 2** • **Temperatures are monitored**	$2x10^{-6}$	$5.11x10^{-12}$	$2x10^{-6}$
Contributing components			Short-circuit leading to overheating or fire ($2x10^{-6}$)
Cond 4: • **Cond 3** • **EM designed to operate under phase-to-phase, phase-to-neutral and phase-to-ground faults**	$1.7x10^{-6}$	$5.11x10^{-12}$	$1.7x10^{-6}$
Contributing components			Turn-to-turn short-circuit leading to overheating or fire ($1.7x10^{-6}$)
Cond 5: • **Cond 4** • **Fault detection system present (detects remaining fault in machine)** • **Protection-mode present**	$3x10^{-10}$	$1.41x10^{-11}$	$2.9x10^{-10}$
Contributing components			Inability to activate protection mode (1.89e-10)
Cond 6: • **Cond 5** • **Extra independent aux. voltage bus**	$1.3x10^{-10}$	$1.41x10^{-11}$	$1.2x10^{-10}$
Contributing components			Bearing grease overheat ($1\ x10^{-10}$)

In the basic system (condition 1, Table 3) the largest FR contributor was identified as a loss of the cooling fans associated with the inverter or the DC/DC converter. Through monitoring of the fans' speed, and thereby whether they are active, the failure rate can be reduced by a factor of 200 (condition 2). In the event of a fan failure one of two actions are taken, depending on whether the system is in starting or generating mode. In starting mode the entire system is turned off (EM stopped), as this is still possible since the turbine is still dependent on the torque from the EM. In generating mode the turbine is, however, actively turning the EM and a traditional shut down is not possible. In such a case the load of the DC/DC converter is discarded and the IGBTs of the inverter are opened. The inverter and associated components need to be rated for the full back-emf of the machine, since the internal DC-bus of the inverter will be charged up to this potential. However, once fully charged no current will flow and no power dissipation will take place.

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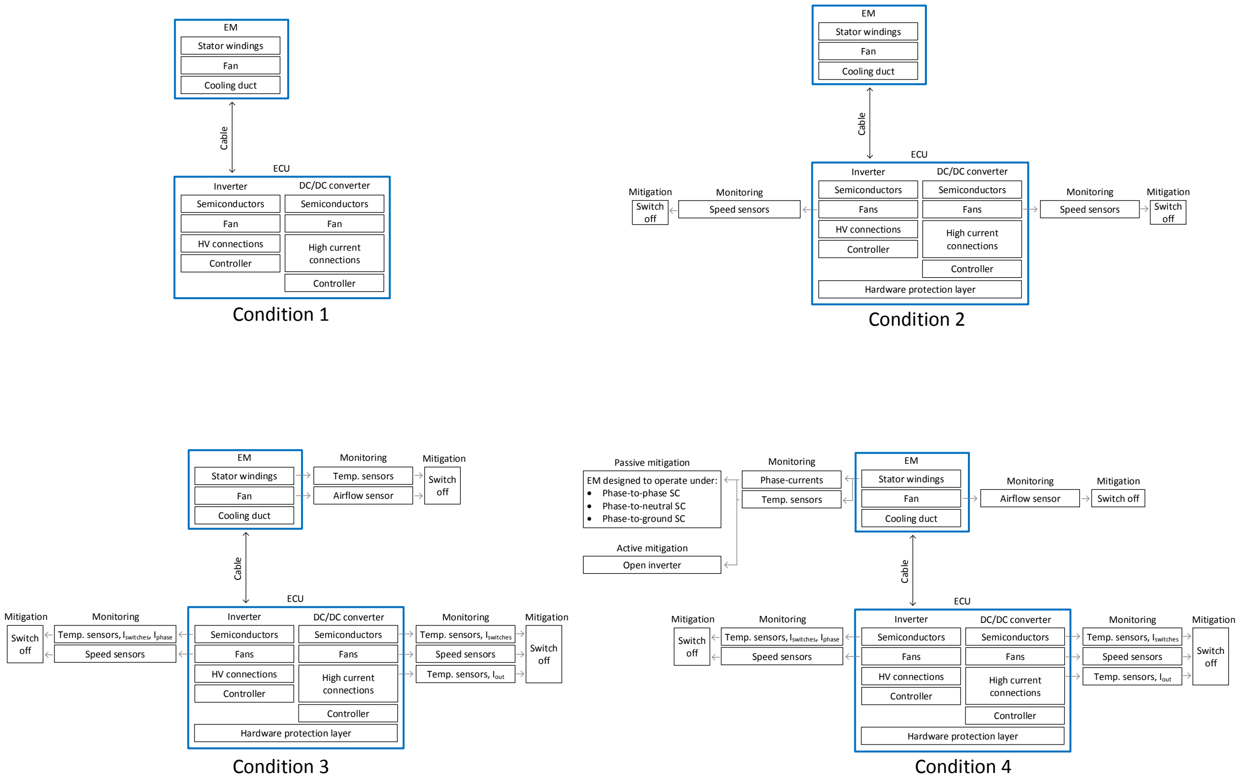
A large number of the measures employed, from condition 2 onwards, entails active monitoring and mitigation in the event that a problem has been detected. This can either be done through software, running on the DSPs which controls the system, and/or through dedicated analog hardware. Due to a number of reasons, including both redundancy and safety, the decision was made to use both dedicated analog hardware, from here on known as the hardware protection layer, along with software to monitor and mitigate any problems. The hardware protection layer is discussed in section 3.1.

Condition 2 mitigated the risk associated with the fans failing, which results in the second contributing component in Table 2 becoming dominant. Erroneous inverter control refers to a failure within the inverter's DSP hardware or software, or within the inverter itself, which leads to incorrect and damaging currents within the machine. An example is if a software fault produces spurious high frequency currents within the machine, resulting in increased hysteresis and eddy current losses, leading to overheating.

Considering that the EM has a large thermal inertia and that the losses associated with this fault are evenly distributed, the detection can be realised through a finite number of temperature sensors distributed throughout the machine. For the inverter the temperature sensors are placed next to the semiconductors and on its heatsink itself. The results are reflected under condition 3. Again, during the starting phase shutting down refers to turning off the entire system (including the EM). Whereas during generating mode, the load is again discarded and the inverter rendered inactive. If the fault is a result of the DSP software, it follows that the DSP may not be able to turn the inverter off, in which case the analog hardware protection layer takes this task over.



Condition 1

Condition 2

Condition 3

Condition 4

Figure 3. Representation of conditions 1 – 4

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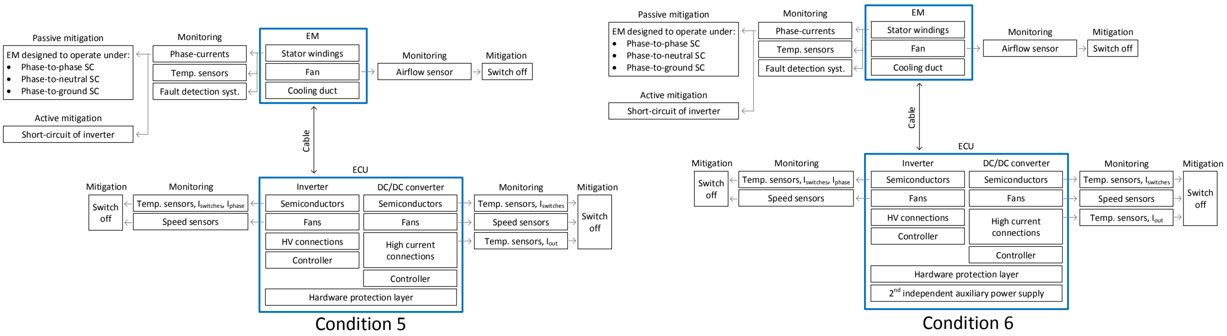

Condition 5

Condition 6

Figure 4. Representation of the conditions 5 and 6

With the third component from Table 2 now being dominant, a method to prevent overheating or fire within the EM during an internal short-circuit is needed. As discussed in section 3.2, a short-circuit can manifest itself in a number of different ways, depending on the exact location of the fault. The four that were identified are phase-to-phase, phase-to-neutral, phase-to-chassis and turn-to-turn within a phase-winding. By designing the machine to have a higher inductance (as compared to its minimum value) it is possible to limit the current under the first three short-circuit conditions to below a chosen safe value [6] [7] [8]. Consequently, in the event of a short-circuit (one of the first three) the inverter is opened and the current within the short-circuit is limited by the machine's inductance. The machine must, however, be designed, from a thermal perspective, to be able to handle this selected short-circuit current. The impact of this is mitigation measure is given under condition 4 in Table 3.

This mitigation measure does not, prevent fire in the case of a turn-to-turn short-circuit, as the current is predominantly limited by the winding resistance and not the inductance [9]. Given that turn-to-turn short-circuits are by definition localised, the thermal inertia and potential distance between such a fault and the nearest temperature sensor, along with the magnitude of the currents involved, renders to efficacy of temperature sensors to detect such a fault (within the allowed time) uncertain. This problem can therefore be addressed by either physically separating the windings through constructional means, or by detecting the fault through an alternative detection method. Since the first solution is in conflict with the optimization goals, the second method is preferred and implemented through a dedicated fault detection system (section 3.3). By comparing the difference between the neutral point of the machine and an artificial neutral point at the inverter, the probability of detecting a turn-to-turn short-circuit is significantly increased. In addition, this fault detection system can also detect all of the other short-circuit conditions, which in turn lowers the FR of the complete short-circuit detection system and in turn the FR of the EM. It may be tempting to reduce or remove the EM's temperature sensors based on the presence of the fault detection system, but doing so will significantly increase the FR of the EM. This is because the FR of the fault detection system is not low enough to substitute the temperature sensors and bring the FR of a short-circuit (of any kind) to a low enough value. It is the redundancy resulting from both the temperature sensors and the fault detection system being present which pushes the FR low enough.

Once the fault has been detected a means to limit the current is required. By short-circuiting all the phases the resultant electromotive force (emf) in the turn-to-turn short-circuit is reduced, which reduces the turn-to-turn short-circuit current to within safe limits [10]. This short-circuit is achieved by closing all the bottom (or top) semiconductors of the inverter. This may, however, adjusts the boundaries of the inverter's design space, since it must now be able to withstand the short-circuit current rating of the machine. It is worthwhile to note that for the first three short-circuit conditions a symmetrical short-circuit of all the phases results in comparable or lower losses within the EM under consideration (as compared to opening the inverter, condition 4). Since the inverter is now also rated

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for the EM's short-circuit current the more generic mitigation measure of short-circuiting the phase-windings will be employed, since no distinction between the different short-circuit conditions needs to be made. As a side note, this inverter short-circuit mitigation measure does increase the FR of the ECU from $5.11x10^{-12}$ to $1.41x10^{-11}$ and is a result of the increased risk of accidentally activating this mitigation method when a cooling fan failure is present at the inverter. This act of short-circuiting the phases together is from here on known as "protection mode". The FR associated with this detection and mitigation method can be found under condition 5 in Table 3.

This mitigation measure (protection mode) in turn couples the EM's failure rate to that of the inverter and associated electronics, thereby placing lower failure rate requirements on the inverter. From the safety analysis a failure of the auxiliary power supply was identified as the main contributor to this problem. This supply is responsible for powering all gate drivers, monitoring and safety electronics, such as the fault detection system and the activation of the inverter. If this supply fails, then the entire monitoring and protection systems fail. By supplying a second parallel independent auxiliary voltage bus the FR can be adequately reduced (condition 6).

As can be imagined, the development of this system can be approached in any number of alternative ways, with each reaching the required failure rate. The choices made and solutions devised were felt to provide the best design space for an optimal solution based on the initial selection of a PM based SGU. However, the choices made are as much objective as subjective, based on the experience of the people involved. The only true way to determine if this is the optimal solution is to quantify each possible solution and place them all in an optimisation algorithm. This is an extensive and long term task and is outside the scope of this paper.

3 RESULTANT FAULT MITIGATION MEASURES

3.1 Hardware protection layer

It was chosen to realize all critical monitoring and mitigation functions through a concurrent combination of analog hardware (HW) and software (SW) (implemented on the DSPs). The reason is that each method (hardware or software) has its own advantages and disadvantages, while neither method possesses all the requirements to realize the necessary failure rate. In particular, the analog hardware excels at fast detection and mitigation, which is comparable to the timeframe of the switching devices, while software is far better suited to realize a more intelligent and corrective control. The difference is better understood with the help of Figure 6 and Figure 7.

Figure 6 gives a conceptual overview of how the hardware and software protection domains (or layers) interact. The hardware protection domain directly monitors the SGU power processing hardware (the hardware which makes power transfer possible) and in the event of a failure the system is either switched-off or placed into protection mode (short-circuiting of inverter), depending on which fault occurs. The software protection domain encases both the power processing hardware, as well as the SGU controller software running on the DSPs. This allows for interaction with the control software, which in turn provides for a softer and more corrective mitigation approach. If a fault is detected the software protection will first attempt to correct the problem, before reverting to switching the system off or placing it in protection mode.

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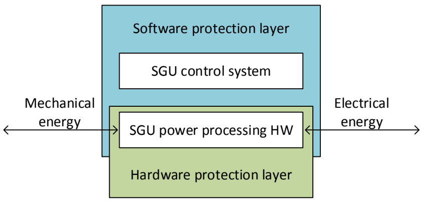

Figure 6. Monitoring and protection methodology

In order to ensure that the protection is performed in a logical and controlled manner each protection system has a predefined area, or safe operating area (SOA), in which it can operate. This is illustrated in Figure 7 for the phase currents and the DC/DC converter output current. As can be seen, the boundaries of the software protection are below that of the hardware protection for both the phase current and DC/DC converter output current.

In the event that the current exceeds the SW boundary the software will first attempt to reduce the current and if this fails it will mitigate the problem through switching off or entering protection mode. The SW protection is best suited for slow faults where the software has enough time to implement corrective action. The HW protection on the other hand, is meant as a last resort to prevent catastrophic failure (such as fire) and is meant to stop faults that propagate far faster than what the SW protection can respond to. In the event of the current increasing as a result of a short-circuit, the SW protection is too slow and the current level will reach the HW protection level before the software can respond. In such a case the HW protection will place the system in protection mode.

Staggering the protection values in this way allows the SW protection to attempt corrective action first. If the corrective action fails then either the SW will mitigate the fault, or if the value has reached the HW protection value, the HW protection act to keep the system safe. It follows that a SOA diagram was defined for every event identified in the safety analysis which requires active monitoring and mitigation.

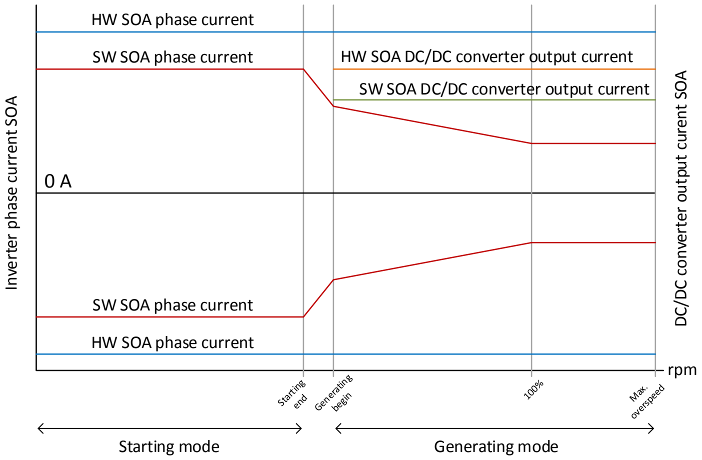

Figure 7. Safe operating area of the inverter and DC/DC converter as defined by the hardware and software limits

In order to guarantee complete autonomy of the two protection layers no interaction between them may be permitted, as a fault in the one may compromise the operation of the other. A dedicated hardware fault bus is therefore needed which connects all the hardware monitoring events together over both the inverter and the DC/DC converter (thereby creating the hardware protection layer). The hardware fault bus is in essence a communication bus dedicated to the hardware monitoring

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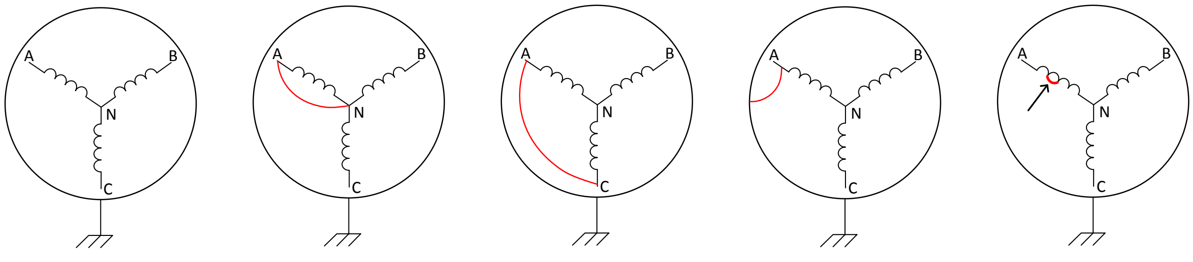
components. If any of these components detect a fault the bus is latched high, which places both the inverter and converter in the appropriate protection mode.

3.2 Current limiting under short circuit conditions

Electrical Machine

As was discussed in section 2, four different short-circuit conditions were identified in the machine. As illustrated in Figure 8 these are phase-to-neutral, phase-to-phase, phase-to-chassis and turn-to-turn within a winding. Since these failure mechanisms are stator phenomena it follows that they are not unique to PM machines, but can occur in any machine topology.



Healthy EM Phase-to-neutral Phase-to-phase Phase-to-chassis Turn-to-turn

Figure 8. Identified short-circuit possibilities within EM

In the event that one of these short-circuit faults occur a means to limit the current is required. For PM machines, where it is not possible to switch off the flux, current limiting for the first three faults can be realised by using a method commonly employed in fault-tolerant machines, where the machine is designed with a one per unit inductance [6] [7]. In the case of a terminal fault the current is limited by the inductance to a value which the machine is thermally designed to withstand.

A similar concept is employed for this fail-safe machine. Fail-safe meaning that the machine must be safe (no fire hazard) under fault conditions, but does not have to continue operating (as opposed to fault-tolerant). For this specific starter-generator unit the torque requirements under starting conditions are significantly higher than under generator conditions (5 – 6 times higher). This has the result that a 1 p.u. inductance would have significant negative implications on the V.A. rating of the inverter and required DC bus voltage [11]. Optimization of the machine from an electrical and thermal perspective yielded a lower system volume by selecting a p.u. inductance of 0.27. The result is that such high starting specifications leads to the EM being unavoidably over dimensioned for generator mode. The machine is given in Figure 9. The complexity surrounding the optimization of the EM and inverter and the selection of an appropriate p.u. inductance is further discussed in section 4.

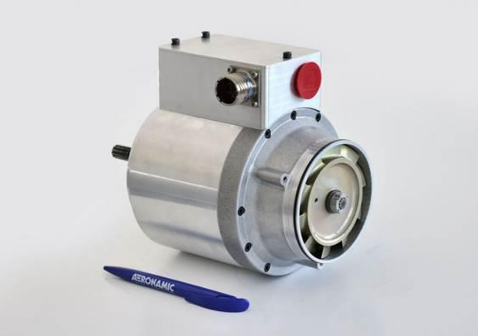


Figure 9. PM machine

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As was mentioned in section 2, a symmetrical short-circuit will result in similar or lower losses as compared to a single short-circuit and opening of the inverter. This is reflected in Table 4 below, where all the values are normalised (for comparison) against the single phase-to-neutral short-circuit. These values are specific to the selected EM (Figure 9) and the possibility of each short-circuit scenario occurring is highly dependent on the exact details of the machine's construction. The trend reflected in the table, with a three-phase short-circuit having similar losses to a single phase-short circuit, is characteristic of the machine configuration under consideration, where the windings' mutual inductance is in the order of -½ their self-inductance.

Details on the optimization and selection process can be found in [11] for an aerospace SGU with similar specifications. It is worthwhile to mention that the exact method of protection in the case of a phase-to-chassis fault is dependent on the chosen grounding scheme. One of three options can be selected: a.) If the chassis is connected to the neutral point of the machine then the fault current will be identical to that of phase-to-neutral fault. b.) If the chassis is connected to the negative (or positive) of the inverter's DC link then the inverter will see an overcurrent and turn-off. c.) If the chassis is connected to the midpoint of the inverter's dc-link then a significant current will flow through the inverter's y-capacitors. This in turn will be detected by the fault detection system which will initiate protection mode.

Table 4: Losses within the EM under different short-circuit conditions

Short-circuit case	**Normalised phase current**	**Normal Cu losses**	**Normalised Cu-loss per phase**	**Normalised iron losses**	**Normalised rotor losses**	**Normalised total losses**
1 phase-to-neutral	1	1	1	1	1	1
2 phases-to-neutral	1.03	2.13	1.06	0.29	0.33	1.27
3 phases-to-neutral	0.71	1.51	0.5	0.28	0.44	0.96
Phase-to-phase (star-connection)	0.61	0.75	0.38	1.16	1.14	0.92

Turn-to-turn short-circuits specific to this machine are extensively analysed and modelled in [10], while [12] extends this investigation through experimental determination of the failure mechanisms involved in the different short-circuit scenarios. Reference [10] outlines that for a machine incorporating parallel strands (which is the case here) a three-phase terminal short-circuit will reduce the losses within the turn-to-turn fault to below safe values. Therefore, irrespective of the type of EM short-circuit, an external three-phase short-circuit will be used to mitigate the losses.

This reduction can be seen in Figure 10, where a turn-to-turn short-circuit (during generator mode) was simulated by placing an external short-circuited turn around one of the teeth of the machine. The blue line gives the current density within the turn with the inverter opened, while the green line is realised with the inverter short-circuiting the machine.

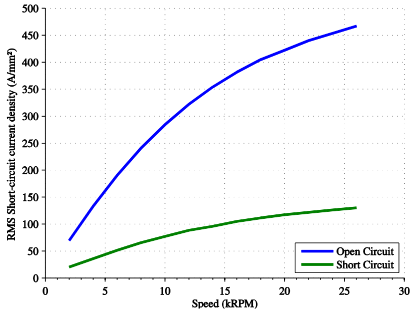

Figure 10. Turn-to-turn short-circuit current

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Figure 11 below gives the phase-currents and temperatures under a three-phase short-circuit for the selected EM (Figure 9). Each of the lines in the temperature plot correspond to a temperature sensor within the machine. As can be seen, the currents during the short-circuit are clamped to constant values (smaller than those during the starting phase) and limits the steady-state short-circuit temperatures to safe values.

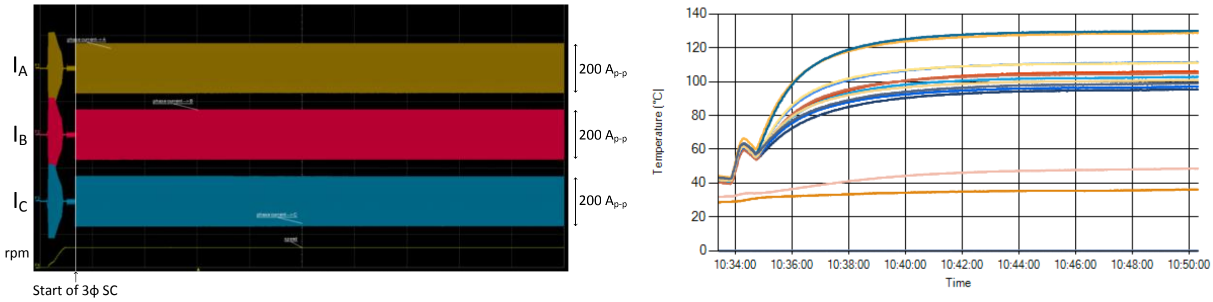

Figure 11. Current and temperatures within the EM under a three-phase short-circuit

External three-phase short-circuit implementation

An external short-circuit can either be implemented by a dedicated short-circuit circuit, or alternatively, the inverter. Whichever solution is chosen, it will need to be able to withstand the short-circuit current thermally, as well as have a very low failure rate. Given that volume and mass are such important optimization goals, it logically follows that the inverter was selected to realise the short-circuit function.

3.3 Fault detection system

Irrespective of what machine topology is chosen, a successful means to either prevent or detect a fault/fire is required. The measures required to realise the low failure rate solely through construction techniques of the machine (such as separation of the windings) is extensive and in direct conflict with aerospace requirements of reduced mass and volume. As a result the second option of detection and mitigation is preferred.

As was mentioned in section 2, detection can either be realised through placement of temperature sensors or through a dedicated fault detection system. Due to the thermal inertia between a sensor and fault an impractically large number of sensors would be required to bring the detection time low enough to pacify a fault before it presents a fire hazard. A more reliable detection method can, however, be realised through a dedicated fault detection system. Once the fault has been detected the problem becomes machine topology specific. In the case of wound field DC, induction or variable-reluctance machine the excitation is simply removed. In the PM machine case, the terminals of the machine are shorted, as was discussed in the previous section.

The fault detection system is based on monitoring the difference between the neutral point of the machine (star-connected) and an artificially created neutral point at the inverter (created with three equal impedances). It was conceptually tested in software, after which it was implemented on a microcontroller and tested on the final SGU test bench. Figure 12a shows the software implementation of the fault-detection system, while Figure 12b shows the hardware implementation on a microcontroller.

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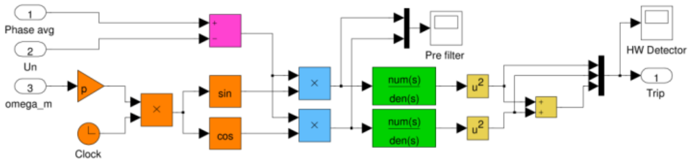

Figure 12a. SW fault detection system

Figure 12b. HW fault detection system

From the test it was concluded that a.) the time required to detect a fault is directly related to how small the fault is, and b.) the complexity is related to the sensitivity of the system. Detailed information on this system can be found in [9]. It is worthwhile to note that the hardware implementation given in Figure 12b was not constructed with volume reduction in mind, as it was a prototype system used for experimentation. A final implementation will be significantly smaller.

In order to test the system the same turn which was used to simulate a turn-to-turn short-circuit (Figure 10) was connected through a contactor. The fault detection system was subsequently tested by closing the contactor and measuring its response, as shown in Figure 13.

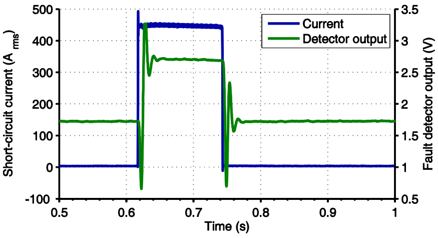

Figure 13. Detector output

4 BOUNDARY CONDITIONS IMPOSED ON THE DESIGN SPACE

From the above discussion it is clear that these fault detection and mitigation measures place hard boundaries/requirements on the design space. All of these requirements are, however, not uniquely attributable to the use of PM technology. For instance, a safety analysis of a non-PM based SGU, with the mass, volume and efficiency as optimization goals, would still identify the hardware protection layer and fault detection system as essential components (or at least something similar would be needed to reduce the FR). Table 5 below gives a summary of the fault mitigation measures, their impact on the optimization goals and whether they are only applicable to PM-based SGUs.

Ideally, the design and optimization of an EM and the selection of its p.u. inductance and short-circuit current should be done in conjunction with that of the inverter (which must carry its short-circuit current) [13]. Their respective impacts on the mass, volume and efficiency are therefore inherently interlinked and will depend on a large number of factors. The most important being the duration and frequency of the transients, the difference between the transient and steady-state requirements and the chosen p.u. inductance.

Fundamentally, both an EM and inverter can be decomposed into a power conversion component, magnets and windings for the EM and semiconductors for the inverter, and passive cooling

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components. For a design based on steady-state operation both their mass and volume can be related to their VA ratings, based on chosen technologies and cooling methods. However, during transient operation, where the thermal inertia of the cooling system is used, the extent of this relationship is very much dependent on the details of the transients.

This can be better understood by considering the limits of the transient requirements. The one extreme is when the generating (or steady-state) requirements completely overshadow the starting requirements. It can then be argued that the EM and/or inverter will be oversized since both of them must be able to withstand the short-circuit current. The short-circuit current will again depend on the chosen p.u. inductance. An inductance of one p.u. will lead to the inverter being oversized (its VA rating will increase) [11], while a lower p.u. inductance will lead to both the EM and inverter increasing (due to higher thermal and VA requirements). The other extreme is where the starting-requirements dominate to such an extent that it can be considered as steady-state (i.e. very large and long transients). In such a case the short-circuit current during generating mode can be chosen equal to or smaller than the starting-current, since the EM and inverter are already designed to operate under this condition. The subsequent impact on the optimization goals will therefore be zero. This argument is therefore reflected in Table 5 as a potential increase of the impact on the optimization goals.

Table 5: Fault mitigation measures of the SGU

Impacted/required elements	**Impact on volume/mass/efficiency**	**Applicable to PM SGU**	**Applicable to all SGUs**
Hardware protection layer	Small	Yes	Yes
Fault detection system	Small	Yes	Yes
Inherent current limiting EM design	Potential increase	Yes	No
Inverter rated for short-circuit current	Potential increase	Yes	No

5 RESULTANT SYSTEM

The resultant system is shown in Figure 14, with Table 6 giving the mass, volume and power rating of the ECU and PM machine. The ECU contains the inverter and converter, along with the aforementioned detection and mitigations measures. The fault-detection system is, however, not included as this was developed in parallel with the remainder of the system. This will be included in the next iteration. It may be tempting to determine the power density in order obtain a comparison to similar systems. It needs, however, to be remembered that this can only be done for systems with identical power and transient requirements, since the transient requirements played a dominant role in the design of this SGU.

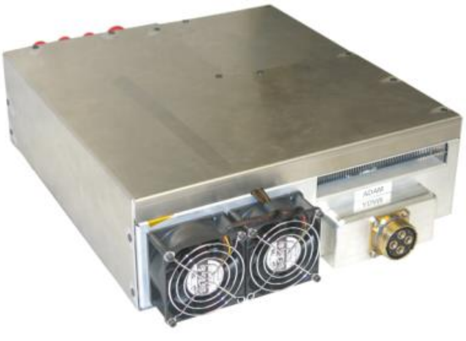

Figure 14a. ECU

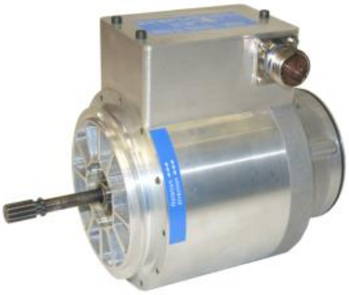

Figure 14b. PM EM

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Table 6: Power rating and resultant mass of the ECU

Component	Mass (kg)	Volume (litres)	Max. transient power (kW)	Steady-state power (kW)
ECU	16.4	18.2	25	9
PM machine	7.6	2.8	23	17

6 CONCLUSION

The safety analysis plays a dominant role in the design of any system with reasonably high safety requirements (such as for aerospace) and should be taken into account from the very start of such a project. In the initial stages it serves as an indicator of where effort should be placed and solutions are required, while at the end it is required to show compliance with the safety requirements and for eventual certification.

When considering the SGU system presented here a number of elements were identified that are required, irrespective of the chosen electrical machine topology, such as the hardware protection layer and the fault detection system. If these particular measures were not selected then something else would have been required to reduce the failure rates. The hardware protection layer and the fault detection system were particularly chosen as they have a very limited impact on the SGU, as opposed to other possible failure reduction methods (such as separation of the windings).

The use of PM machine technology does, however, require additional mitigation measures. These measures place additional constraints on the design space and may negatively impact the design objectives of volume, mass and efficiency. The impact is, however, highly dependent on the relation between the transient and steady-state requirements and no clear conclusion can be drawn on the impact before an optimized design is realised.

Lastly, an incremental investigation of the safety analysis, as was done here, can be used as a starting point for future systems where larger or smaller failure rates are required.

7 FUTURE WORK

This safety analysis can be extended to include the common cause failures which were initially omitted, as well as other fault mitigation measures. Further work can also include a dual safety analysis and optimization of an SGU with an induction machine, switched reluctance and/or synchronous reluctance machine.

8 ACKNOWLEDGEMENTS

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