BUILDING ELECTRIC MOTORS FOR SPACE, WITH REDUNDANCY AND HIGH RELIABILITY

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ABSTRACT

Many experiments and mechanisms in space require the assistance of electronic Motion Control based on an electric motor. Typical applications are scanners, de-spin drives, reaction wheels, as well as antenna and laser beam pointing systems, shutters and filter wheels etc.

This paper presents the design process of such electric motors, starting with the target performance criteria and the selection of the best motor technology. The main topic of the paper however is to present techniques to maximize reliability by the introduction of redundancy into the motor and into its drive and control electronics. The possible ways of implementing such functional redundancy are considered along with the compromises they entail.

1. MOTOR DESIGN REQUIREMENTS

1.1. Torque/speed

The fundamental user requirements on an electrical machine (not only in space) are the:

- torque-speed characteristics
- available dimensions
- minimum operating voltage
- speed and positioning accuracy

These lead to the choice of motor technology and to the base-line design:

- motor types
- motor topologies
- number of poles (and slots)
- slot geometry etc.
- winding scheme
- integrated HE- and temperature sensors
- position feedback sensors

In space the most commonly used electric motor types are:

- brushless DC servomotors
- hybrid stepper motors
- limited-angle torquers
- solenoids
- shutter motors (combined electro-magnetic and mechanical spring actuation)

Topologies, which may be considered, are such as:

- inner/outer rotor configurations
- surface, embedded magnets
- axial, radial flux machines
- multiple and independent winding systems

The actual design process proceeds in steps, which may need to be iterated several times before reaching an acceptable design:

- electro-magnetic, analytical motor design (Fig.1)
- thermal analysis for the given environmental conditions
- dynamic system modeling
- electro-magnetic, finite-element design
- mechanical, including choice of bearings

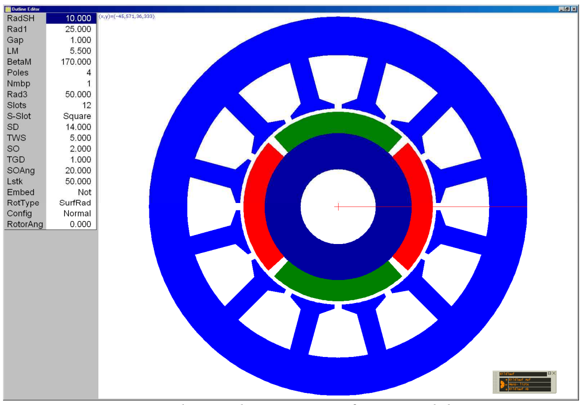

Figure 1: Analytical Design of a Brushless Motor using SPEED

1.2. The Special Demands on space-rated Motors

There are however some special issues, which must also be considered when designing space-rated motors:

- torque safety margins, defined by the ECSS E-30 standard, Part 3A
- full mechanical motor integration into the mechanism
- low mass
- high efficiency, minimization of losses and heat dissipation

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- use only of permissible materials:
  - no or very limited out-gassing
  - temperature range
  - corrosion coatings
  - acceleration/vibration
- radiation sensitivity
- stray magnetic fields
- life and reliability

One part of the motor or mechanism, which contributes significantly to life and reliability, is the bearing and lubrication system. This issue is however not considered further in this paper.

1.3. Life and Reliability

The specified life-time of the mission is probably the greatest demand on the design (as well as on the manufacture and qualification) of space-rated motors. Long life and reliability are achieved by employing conservative and proven designs as well as the best possible quality levels of material and workmanship.

However one further measure can significantly improve the life-time of a motor-based, space mission; that is the implementation of intrinsic redundancy by duplicating magnetic and winding sub-systems. If one of these fails, at least one further sub-system is available to maintain operation, either with full performance or with some given de-rating.

The next chapter considers the basic issues of fault-tolerance within an electrical machine and approaches to implement redundancy.

2. FAULT TOLERANCE IN AN ELECTRICAL MOTOR DRIVE

Examples of fault-tolerant electrical drives can be found in the literature for all major types of motors. The procedures described are applicable for most types of electric machines, particularly if parts of the motor, such as the stator windings, are similar.

2.1. Classification of Redundancy

A classification according to characteristics of redundancy leads to three groups [1]:

(1) structural redundancy can be achieved in a drive by duplicating the electrical machine and the power electronics according to the order of redundancy, which is requested. This leads to so called main and additional redundant drive(s). From the electrical machine point of view these can be realized in the same motor (the main and redundant windings sharing one stator in combination with one rotor) or in completely separated stators and rotors.
In general there two possibilities to structure redundancy within a single motor with the help of the main and redundant windings. One is to multiply the number of phases to the redundancy level of the system; the other is to choose a winding structure which achieves the order of redundancy by multiplying the number coil groups of each phase. In both cases the inverter(s) can still use the classical 3-phase topology.
Anyhow these machines must be overrated in such a way that even in the event of a fault the machine is capable to run with the minimum specified performance. If the redundancy of the motor is to be realized by multiplying the number of phases, their number n must be greater than the minimum number of phases (n-f) which is required to achieve that performance. Thus these machines are over-rated with the ratio of $n/(n-f)$, if f is the number of faulty phases. For the second configuration described the over- rating factor is equal the multiplying factor of the coil groups.

(2) functional redundancy is achieved by handling errors or failures in the drive with completely different machine control schemes.

(3) the third group combines structural and functional redundancy by leading out the neutral point of the machine and connecting this to the appropriate point to the inverter in order to gain additional degrees of freedom in motor control.

In this paper we will focus on the structural redundancy option and the permanent-magnet excited synchronous machine.

2.2. Faults

There are many potential faults which can occur in a drive system, only a few main ones are listed [2] below:

(i) Mechanical faults in electrical machines are mainly attributed to the bearings, and are predictable but generally infrequent.

(ii) Electrical faults, on the other hand, are much more difficult to predict and are more frequent.

The main categories of fault in electrical machines are:

- Open-circuited phase
- Single phase short-circuit
- Phase-to-phase short-circuit

Within the power converter the faults to consider are:

- power device open circuit
- power device short circuit
- power device phase-leg short-circuit
- DC link capacitor failure.

2.3. Fault Tolerance

The term fault–tolerance has two different meanings [3].

(1) to support a temporary fault without being damaged. To achieve that, the motor is specifically designed

with an inductance high enough to limit the short–circuit current to a given threshold. This design approach does have a disadvantage; it leads to a high inductance, which implies a low power factor during the healthy operations.

(2) to work even under faulty operating conditions. In this case the designs of the motor and the inverter cannot be kept distinct, and different solutions can be adopted. A multi–phase motor drive can be designed. For these solutions, the motor cost does not increase significantly; however the inverter cost can even be double that of the conventional three–phase inverter.

Thus a fault-tolerant machine must, either inherently or specifically, be designed to incorporate the following features [3], [4]:

(1) If it can be realized in the motor design there should be physical separation of phase windings, to minimize the possibility of a fault or physical damage in one phase propagating to other phases, and to limit the likelihood of phase-to-phase short-circuits, which would dramatically compromise the achievable performance. This can be achieved by using a fractional-slot motor design with non overlapping coils and one coil side per slot (Fig. 2). In design cases where it is not possible to have physical separation of the winding system (for example classical LAT motors or stepper motors with a slot to pole combination where both winding system are wound on the same tooth) attention should be paid to the insulation between the winding sub-systems.

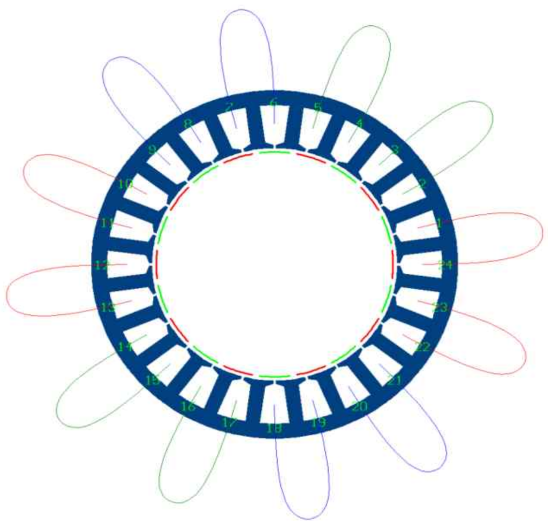

Figure 2: Physical separation of windings by winding every coil on a single tooth

(2) Magnetic isolation between phases, so as to minimize electromagnetic coupling effects (resulting in a low mutual inductance), and thereby limit the effects of fault current flowing in one phase on the capability of other phases, and in turn on the performance of the machine. For a surface mounted magnet design with a non-magnetic retaining sleeve the mutual coupling is insignificant because of the reduction of the air gap component of the armature reaction field.

(3) Thermal isolation between phases, in order to limit the effect of localized heating due to a fault on one phase on the thermal performance of other phases. If the stator outer surface is well cooled then the dominant temperature rise in the machine is within each slot.

(4) Electrical isolation between phases, in order to maintain rated performance capability in the event of a power electronic device failure or a winding short-circuit. Each motor phase is fed by a full-bridge converter and is therefore independent (no common star point), see Fig. 3.

(5) A phase inductance high enough to limit the short-circuit current to less than the rated full-load current of the machine, and thereby enable it to operate with a short-circuited phase winding for an indefinite period. This, however, reduces the power factor, and therefore necessitates an increase in the Volt-Amp rating of the power electronic converter.

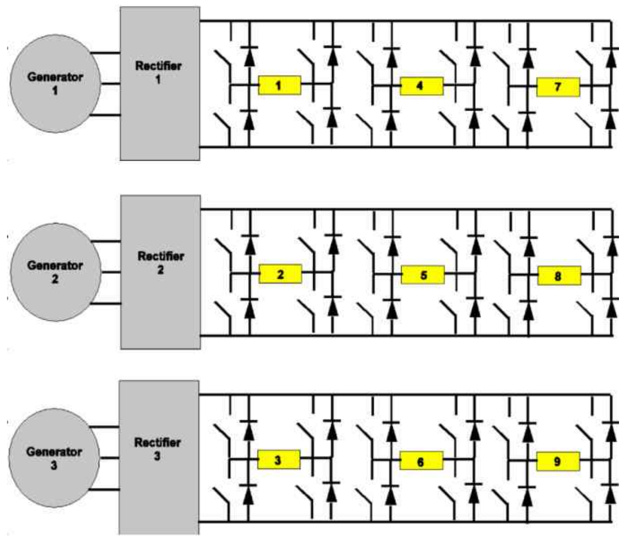

Figure 3: Full electrical isolation for a 9 phase drive with 2-level power supply redundancy

2.4. Fault Tolerance Summary

With regard to the machine design, the essential conclusions are that the machine should have
(1) a surface mounted magnet rotor design,
(2) high armature self inductance,
(3) each winding wound around a single tooth and
(4) only one phase winding per slot.
For designs where physical separation of the winding system is not possible additional insulation measures must be taken.

The first two conclusions appear to be in conflict because the windings of a surface mounted magnet machine generally have a lower reactance. However, the key to meeting these requirements is to design for a large leakage inductance by modifying the depth and width of the slot opening, commonly called the stator reactance slot. In the event of a phase winding short-circuit one half of the magnet flux, which normally passes up one tooth, is shunted across each reactance slot. To avoid undue saturation the depth of the tooth slot opening is designed to be approximately one half of the tooth width, with the reactance slot width being chosen according to the value of inductance required.

3. THE BEPI COLOMBO MMO ANTENNA DESPIN MOTOR

3.1. Mission

The Bepi Colombo Mercury Magnetospheric Orbiter (MMO) will be launched 2014/5. It will investigate:

- the origin and evolution of a planet close to the parent star
- Mercury as a planet: form, interior, structure, geology, composition and craters
- Mercury's vestigial atmosphere (exosphere): composition and dynamics
- Mercury's magnetized envelope (magnetosphere): structure and dynamics
- Origin of Mercury's magnetic field
- Polar deposits: composition and origin
- Einstein's theory of general relativity (an experimental verification)

The motor example described here is used in the MMO Antenna Despin Mechanism (Fig. 4). This mechanism has the task of maintaining the orientation of the High Gain Antenna towards the earth while the rest of the satellite is spinning – to minimise its outer surface heating due to the high level of radiation received from the sun.

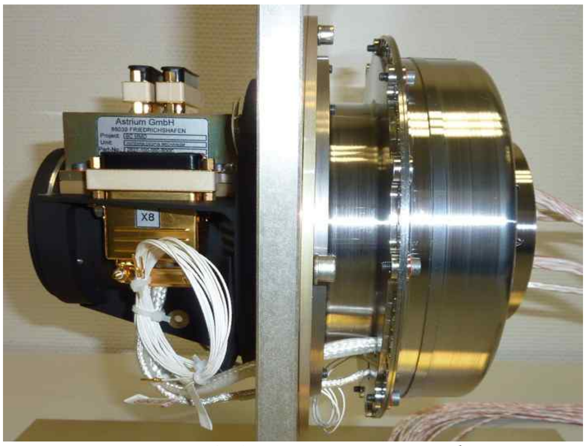

*Figure 4: MMO Antenna Despin Mechanism
Photo: Astrium, D*

3.2. Choice of Motor Topology

A surface permanent magnet synchronous machine with a fractional slot winding scheme with single tooth coils was chosen. Single-level redundancy is achieved in this case by duplicating the stator; a single rotor passing through both stators. The two independent stators are shifted by half a slot pitch with respect to each other in order to minimize the cogging ripple. Only one machine is activated at the same time.

*Figure 5: Main and redundant stator,
potted as one unit*

3.3. Choice of Materials

In addition to the redundancy issue in the design and manufacturing process of the electrical machine the question on the materials is of high importance in particular due to the stringent space requirements on the out-gassing of materials. Close cooperation with the material specialists of the Space Agency helped to choose the right materials.

4. THE SENTINEL-3 SCAN DRIVE MOTOR

4.1. Mission

The Sentinel-3 is an environmental research satellite. It will carry a suite of four instruments, designed to combine oceanography and monitoring of land vegetation. One of these is the Sea Land Surface Temperature Radiometer (SLSTR), which is a conical imaging radiometer with a dual view capability: a near-nadir view and an inclined view.

In operation infrared and visible energy is reflected off the mmirror of the Scan Mechanism onto a parabolic mmirror. From there, the energy is then focused and reflected to the infrared and visible focal planes. Focal Plane Assemblies detectors convert the radiant energy into electrical signals. These low level signals are amplified, digitized, processed and passed onto other systems on the satellite for transmission back to the Earth.

In addition to the earth, the SLSTR detectors also view calibration targets for the visible and thermal channels during each circular scan. Two stable high-accuracy blackbody targets provide calibration of the IR channels for every scan, whilst an on-board visible calibration system Visual Calibration Unit is viewed once per orbit.

4.2. Choice of Motor Topology for the Scan Drive Motor

In this project the redundancy concept allows for main and redundant motor winding sub-systems in a single stator, each being driven by their own motor driver electronics and feedback encoder.
Again a 3- phase surface, permanent magnet synchronous motor with a fractional slot winding scheme was chosen, with single tooth coils (compare Fig. 2). In this case single-level redundancy is achieved in this case by winding every phase onto a single stator tooth. The back EMF curves of two winding systems are in phase.

To achieve the physical separation of the main and redundant winding only one slot of adjoining 4 slots of a coil group for one phase of the main and redundant winding system is used (Fig. 6).

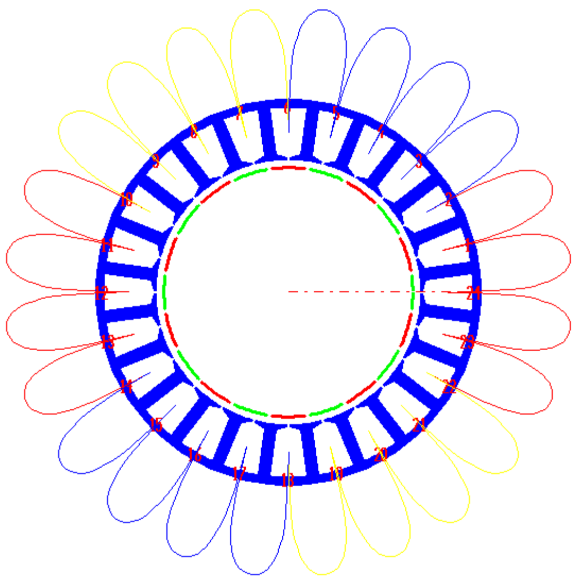

Figure 6: Winding scheme of Sentinel-3 Scan Drive Motor with 20 poles and 24 slots

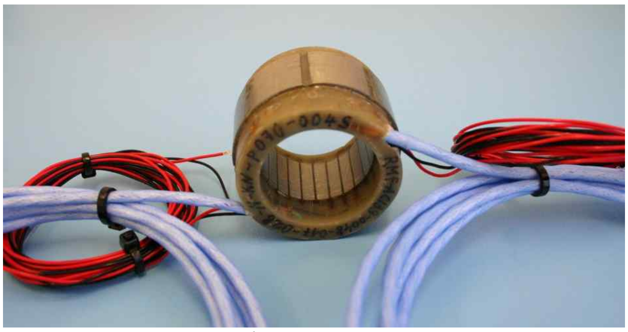

Figure 7: Sentinel-3 Scan Drive Motor stator with independent integral windings

5. CONTROLLER DESIGN

The implementation of redundancy in a space-motor automatically leads to redundancy being needed in the controller. In fact this commonly has the lower MTBF value and therefore has most to gain by duplication. Not only must the power stage be duplicated but also the command channel, controller and any motor feedback system in the mechanism (Fig. 8).
Last not least a fully independent electrical supply is needed for each of the redundant channels.

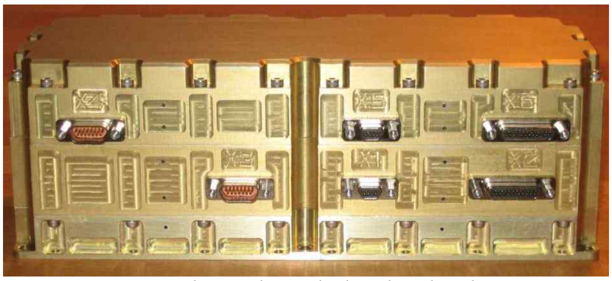

Figure 8: A 2-channel,single-level redundant Motor Control and Drive Unit with both dual motor, encoder and command channels

6. CONCLUSIONS

The reliability and availability of mechanisms can be increased considerably by applying redundancy techniques in the magnetic and winding design of the motor. However there are trade-offs.

The first issue is that of winding resistance. As the available copper volume within the motor must be shared between two or more winding sub-systems, the winding resistance of any single sub-system and therefore the continuous torque rating of the motor suffer. The peak torque rating need not however be reduced, as long as the supply voltage is sufficient to inject the current needed.

Secondly, when implementing independent winding sub-systems in the same stator, there can be serious magnetic interactions between them in the case of failure, which lead to high oscillations and a degradation of performance. This is particularly the case, when a single-phase short-circuit occurs (internal to the motor or in the controller or wiring harness). The effects of this can however be countered by shortening together all phases of the failed winding sub-system.

Thirdly, if the short-circuit condition is sustained, the failed winding sub-system will generate electro-magnetic damping within the mechanism. This in turn will increase the drive power requirement on the intact winding system and drive; the additional power requirement must be allowed for when dimensioning the drive system.

Finally however we wish to emphasise the main benefit of this approach. It is the reduction of the effects of electronic failure. Creating more than one electrical circuit in the motor(s) is the pre-requisite to duplicating the motor controller, which is mostly that part of the mechanism drive system with the lowest MTBF. This approach does require duplication of the power supply, command channels and sensor sub-systems.

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