Novel Winding Concept for MEA Actuators

03/02/2015
Auteurs : Puvan Arumugam, Tahar Hamiti, Chris Gerada
Publication MEA 2015 More Electric Aircraft
OAI : oai:www.see.asso.fr:10638:20112
DOI :

Abstract

Collection

Authors

Chris Gerada

Saliency Tracking-based Condition Monitoring for Electromechanical Actuators
Comparison of multi-physics optimization methods for high speed synchronous reluctance machines

Novel Winding Concept for MEA Actuators

The Impact of Additive Manufacturing on the Development of Electrical Machines for MEA Applications: A Feasibility Study

Aircraft Starter-Generator System based-on Permanent-Magnet Machine fed by Active Front-End Rectifier

Puvan Arumugam

Power loss Analysis of a Permanent-Magnet Machine Based - Starter/Generator Fed by an Active Front-End Rectifier

Novel Winding Concept for MEA Actuators

Tahar Hamiti

Novel Winding Concept for MEA Actuators

Metrics

Downloaded: 6
Viewed: 4
Size: 335.76 KB
Type: application/pdf
URI: bitcache://3047e60a57693fbfbee0450938a0835d8acd7bdb

License

La SEE (Société de l'Electricité, de l'Electronique et des Technologies de l'Information et de la Communication – Association reconnue d'utilité publique, régie par la loi du 1er juillet 1901) met à la disposition de ses adhérents et des abonnés à ses publications, un ensemble de documents numériques accessibles à partir de son portail des publications. Ces documents incluent notamment les articles des revues REE, 3 EI et e-STA disponibles sous forme numérique ainsi que des publications additionnelles regroupées dans l'espace eREE. Les présentes conditions précisent les conditions de diffusion et d'utilisation de ces documents et des informations qu’ils contiennent. L’accès à ces documents, qu’il se fasse de façon gratuite ou dans le cadre d’abonnements ou d’achats faits à titre onéreux, implique l’acceptation sans restriction de ces dispositions.

Droits de propriété et de diffusion des contenus téléchargés sur le portail des publications

Les contenus rendus accessibles sur le portail des publications sont, en règle générale, protégés par le droit d’auteur. En tant que producteur, et le cas échéant d’auteur, des informations rassemblées dans les contenus accessibles par ce portail, SEE se réserve l'exclusivité des droits de copie et de diffusion de tout ou partie de ces contenus.
Les contenus sont rendus accessibles à titre individuel, pour les besoins de la personne en détenant des droits d'accès en cours de validité. Aussi, la modification, la reproduction et/ou la diffusion via Internet ou le Web, intranet, extranet ou toute autre forme numérique ou imprimée, de tout ou partie des contenus téléchargés sont interdites. Une tolérance est consentie quant à la reproduction d'extraits limités de ces contenus, dans le cadre de travaux ou d'activités auxquels ils sont utiles, à la condition que l'origine de ces reproductions partielles soit mentionnée de façon lisible et sans ambiguïté. Figureront en particulier : la REE (ou toute autre revue accessible sur le portail) en tant que la source, la référence de la publication et le nom de l’auteur (s’il figure dans la revue).
Ces dispositions s’appliquent également aux figures, illustrations, logos ou images.

**Publication externe des contenus du portail des publications**

Tout extrait des contenus du portail destiné à être utilisé dans des publicités, des communiqués de presse ou du matériel de promotion nécessite un accord préalable écrit de la SEE. Une version préliminaire du document proposé contenant ces extraits doit accompagner chacune de ces demandes. SEE se réserve le droit de refuser un tel usage externe pour quelque raison que ce soit.

**Responsabilités**

La SEE apporte tout le soin possible à la préparation des informations délivrées dans les contenus produits. Cependant elle ne peut être tenue pour responsable d’aucune perte ou frais qui pourrait résulter d'imprécisions, d'inexactitudes, d'erreurs ou de possibles omissions portant sur des informations publiées, ni des résultats obtenus par l'utilisation et la pratique des informations délivrées.

**Utilisation des informations recueillies lors du téléchargement de contenu**

Le portail des publications est susceptible d'utiliser des « cookies » afin notamment de permettre l'utilisation de paniers d'achat et de personnaliser les parcours sur le site. SEE se réserve la possibilité d'utiliser les informations recueillies lors des téléchargements pour ses besoins internes et notamment pour l’amélioration de ses services, sans qu’elles puissent être cédées à des partenaires commerciaux. Conformément à la loi "informatique et libertés" du 6 janvier 1978, chaque utilisateur du portail dispose d'un droit d'accès et de rectification aux informations qui le concernent. Pour exercer ce droit, les utilisateurs doivent s’adresser à SEE – 17 rue de l’amiral Hamelin – 75783 Paris Cedex 16, par simple lettre ou en utilisant le formulaire de contact disponible sur son site.

Paris, le 28 avril 2013

**Sponsors**

**Organizers**
Novel Winding Concept for MEA Actuators

Puvan Arumugam, Tahar Hamiti, Chris Gerada

Power Electronics Machine and Control Group, Faculty of Engineering, University of Nottingham, Nottingham, UK

e-mail: puvan.arumugam@nottingham.ac.uk

Abstract

This paper proposes a novel winding concept for Permanent Magnet (PM) machines used for more electric aircraft actuators where reliability is a concern. The proposed winding concept is called vertical winding that has inherent fault current limiting capability than conventional round structure arrangement. A 12 slot, 10 pole surface mounted, concentrically wound PM machine particularly designed for rotorcraft swashplate actuation is used for the analysis. The impact of the winding arrangement for such machine
Introduction

Permanent magnet machines are gaining a considerable attention in more electric aircraft technologies such as actuators, fuel pumps and starter-generators. This is due to their higher torque and consequently higher power density. This is an important advantage in the aircraft industry because a reduction in weight increases fuel efficiency and significantly impacts emissions and cost. One of the key issues with PM machines is their reliability, especially in safety-critical applications. The main challenge with PM machines stems from the fact that the field cannot be de-excited in an event of a fault. In such applications the necessary reliability and safety levels can be achieved in two ways. One approach is to design the machine such that it can tolerate faults; the other is to design the machine in such a way that the likelihood of faults occurring is reduced up to an acceptable level. Both approaches have their respective disadvantages and this paper will illustrate the application of these methodologies to two different environments. It will be noted that for different application performance requirements either of the two approaches might be more suitable. Adopting a machine with Fault Tolerant (FT) features [1-3] that facilitate a degree of operation under a fault condition is the first option. The second is to reduce the probability of failure through operation with less stressful conditions (for example lower winding operating temperature) as well as to implement prognostics and health monitoring techniques to reduce the probability of a sudden failure to acceptable levels. Machines adopting fault tolerant features can be designed to tolerate various faults such as winding open circuit faults [4], phase to phase Short-circuit (SC) faults and phase to ground SC fault [5]. Winding turn-turn SC faults however remain problematic [2]. This paper addresses an approach to deal with internal winding failures by adopting a novel winding concept. For the investigation a 12 slot/10 pole machine with concentrated tooth windings used for a rotorcraft swashplate actuator is considered. Analytical tools are adopted for the analysis. The performance implications during both healthy and faulty conditions of utilising the fault tolerant winding will be modelled and discussed. It is shown that the proposed winding concept has inherent fault limiting capability. Fig 1: A cross sectional view of a 12-slot 10-pole FT-PM machine FT-PM Machine for rotorcraft swashplate actuator. This section describes a FT-PM machine (Fig.1) designed for a rotorcraft swashplate actuator. This being a primary flight control actuator, very high reliability is required. Failing to move the swashplate to a desired position or holding it in a particular position can be catastrophic for the rotorcraft [6]. Thus, the machine was designed to satisfy the fault tolerant criteria to avoid catastrophic damages in the system at the event of single fault. Where, 1. Dual star windings supplied through different converter units were adopted to introduce redundancy under an event of fault. 2. Concentrated windings are used to provide physical and magnetic isolation between the phases. 3. To limit the SC current to a safe value as well as to minimize the resulting breaking torque at operation under the fault, the phase winding is designed to have an appropriate inductance [2]. 4. The machine is oversized to handle the increased current loading and thus provide required torque during faulted operation. The specifications of the machine that satisfy the abovementioned FT criteria are presented in Table I. The machine is capable of operation under any type of winding failure (open-circuit/SC fault) with a continuous torque of 1.25 Nm and a continuous speed of 180 rpm. In addition a peak torque of 8 Nm and a maximum speed of 5250 rpm are also needed to be delivered under fault conditions. Rated current (rms) 5.6 A Back-emf at 180rpm (rms) 32.5 V Number of phase 3 (with dual channel) Phase inductance 1.25 mh Phase resistance 306 mΩ Airgap 1.2 mm Axial length 99.5 mm Outer Diameter (OD) 58.0 mm Magnet height 3.2 mm Table I: Specification of 12-slot 10-pole PM machine Concept of vertical winding As previously mentioned turn-tum faults are the most difficult to handle in PM machines both from a timely detection point of view and from a machine design point of view if the machine is to tolerate such failures. Indeed, if an inter-turn fault is left undetected and uncorrected, the resulting current can be excessively high due to the low impedance of the SC turn. This may in turn lead to further uncontrolled failure modes eventually resulting in lack of motor output, possibly a motor jam or excessive motor temperatures or fire. To avoid this failure mode, these faults must be detected with adequate speed so that the drive system can be reconfigured before the initial fault causes collateral damage and hence results in secondary faults. To accommodate this SC fault several post-fault control methods can be adopted within the system. The most common post-fault methods are: faulted phase/machine terminals shorting [7], current injection [8], mechanical shunts and sleeves [9] and electrical shunts/ special wire [10] techniques. Amongst them phase/machine terminals shorting is popular since it can be implemented easily via the power converter terminals without requiring any additional arrangements. This method forces all the turns in the phase to share the net winding magneto motive force (mmf) under the turn-turn SC fault. As a result the current in the shorted turn reduces. However, it has been reported in [1] that this method is not effective for all single turn SC fault cases. This is due to the variation of the shorted turn inductance with respect to its position in the slot; consequently the magnitude of the SC current varies according to the fault location. Thus, a significantly high fault current compared to the rated current may still persist [2]. Fig 2: Proposed vertical winding To overcome this, a winding concept known as vertical conductors winding [2], placed along the slot height can be employed (Fig 2). This winding concept is a solution to position-dependent fault current and allows for safe operation under SC faults. The next two subsections present an analytical study of the effectiveness of such a winding when compared to the conventional winding (using round conductors) for the swash plate actuator motor. Analysis of the SC fault current In order to investigate the implication of the SC current under fault an analytical model proposed in [2] is adopted. The method evaluates the flux linking each turn within the slot and subsequently the inductances that determine the SC current. It is worth noting that the model is only valid for FT machines where mutual coupling between the phases are negligible since the phase windings are segregated from each other. Under this assumption steady-state SC fault current (Is) before and after application of post-fault remedial stagey (terminals shorting) can be estimated using equations (1) and (2), respectively [2]. The detailed modelling process can be found in [2]. This winding concept is a solution to position-dependent fault current and allows for safe operation under SC faults. The next two subsections present an analytical study of the effectiveness of such a winding when compared to the conventional winding (using round conductors) for the swash plate actuator motor. Analysis of the SC fault current In order to investigate the implication of the SC current under fault an analytical model proposed in [2] is adopted. The method evaluates the flux linking each turn within the slot and subsequently the inductances that determine the SC current. It is worth noting that the model is only valid for FT machines where mutual coupling between the phases are negligible since the phase windings are segregated from each other. Under this assumption steady-state SC fault current (Is) before and after application of post-fault remedial stagey (terminals shorting) can be estimated using equations (1) and (2), respectively [2]. The detailed modelling process can be found in [2].
self-inductances of the Nh turns; \( \cdot \) Ls: self-inductances of the Ns turns; \( \cdot \) Lm: mutual inductance between the Nh and the Ns turns; \( \cdot \) RH: resistances of the Nh turns; \( \cdot \) R: resistances of the Ns turns; \( \cdot \) Q: angular velocity. Table II shows the obtained SC current for different fault locations (Fig.3) in the slot of the vertical conductors winding compared to the round conductors winding. From the results it is obvious that the vertical conductors winding limits the SC current inherently due to the arrangement of the conductors in the slots in a way that all the conductors share the slot-leakage flux almost equally. This is in contrast to the case for the round conductors winding where turn-turn SC faults located closer to the slot opening region exhibit potential SC currents up to six times the rated value. 1 46 23 (a) (b) Fig 3. Illustration of the fault location of (a) the round conductor and (b) the vertical conductor Round conductor Vertical Conductor Fault location SC current (A) Fault location SC current (A) 22.51 1 12.55 5 15.45 6 13.31 9 50.91 11 13.48 10 55.85 16 13.94 19 22.48 21 14.21 23 14.02 23 14.55 27 50.91 31 14.02 28 37.97 36 13.57 39 12.95 41 13.21 46 22.34 46 12.62 Table 2: Magnitude of turn-turn SC current vs fault location Eddy current loss computation Although the SC fault current can be limited to a safe value by adopting vertical conductors, winding eddy current losses (proximity effect and skin effect) associated with this winding will be considerably higher. On the positive side, the winding effective radial thermal conductivity is very high [1]. It was sown that even though the losses were high when compared to a round conductor winding, the vertical conductors winding experienced similar temperature hot spots as for the round conductors winding although its copper losses were twice as much as those of the round conductors. To ensure these losses are within acceptable margins, a method for their computation in a flexible way and reasonable time is proposed hereafter. An analytical model presented in [11] is adopted here. Two different formulations of the electromagnetic problem are considered since the conventional winding is less sensitive to skin effect than the vertical conductors. To calculate the losses in the round conductor winding the magnetic vector potential in the slot is estimated using the sub-domain field model itself based on the separation of variable techniques. The following Poisson’s equation is used in the computation of the vector potential in the slot domain: 

\[
\nabla \times \mathbf{A} = \mathbf{j} + \frac{\nabla \times \mathbf{J}}{\mu_0} \quad \text{at the slot entry region,}
\]

where, \( \mathbf{A} \) is magnetic vector potential, \( \mathbf{j} \) is the current density and \( \mu_0 \) is the permeability of free space. The detailed derivation for estimating the magnetic vector potential can be found in [12]. Hence, the eddy current density (Je) in the conductors and the associated copper losses (P) in the round conductors can be estimated using (4) and (5) respectively. 

\[
\begin{align*}
2.21122 & \cdot 0.2 & c c r m c r s t k e r l P J r d t d d r \quad (5) \\
& & (6)
\end{align*}
\]

The detailed process of solving (6) can be found in [11]. It is worth highlighting here that the problem is solved in the slot domain while assuming an equivalent current sheet at the slot-opening region. This current sheet is obtained using Ampere’s theorem. Hence, the total current density in the conductors can be expressed from complex magnetic vector potential by a ctual geometric considerations. 

Thus, the total copper loss in a conductor from the complex current density (7) can be rewritten as 

\[
\begin{align*}
2.2111 & \cdot 2 c c c r s t k a c t u a l a l r l P J r d d r \quad (8) \\
& (8)
\end{align*}
\]

The detailed derivation for

https://www.see.asso.fr/en/node/20112/landing