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

Serhiy Bozhko, Chris Gerada, Marco Degano, Zeyuan Xu, Antonino La Rocca, Puvaneswaran Arumugam, Steve Pickering, Pat Wheeler
The University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom
serhiy.bozhko@nottingham.ac.uk

Abstract This paper deals with the development of an electric starter-generator system that exploits recent advances in modern power electronics. These advances allow the designer to consider novel machine types and introduce of controlled power electronics into the main path of energy flow. Development of such system is a complex multi-disciplinary task that includes definition of the best system topology, electrical machine and power electronic converter design, thermal management and cooling arrangements, development of control techniques, health monitoring and fault management systems. The paper describes the main challenges and solutions proposed within these key areas, as well as addresses manufacturing aspects and overviews the test program and the test results achieved.

Introduction
The global move towards environmentally friendly technologies results in major changes in transportation systems, including aviation. The state-of-the art technologies in the field become more fuel efficient, very safe, simpler in servicing and of easier maintenance. The way towards this goal is identified as a move towards “more electric” aircraft [1], [2] by replacement of hydraulic and pneumatic sources of power with electrical counterparts. This results in an increased reliance on electrical power for a range of primary functions including actuation [2], de-icing, cabin air-conditioning, and engine start. An electric power generation system plays a key role in this technological trend.

The current starter/generator (S/G) technology employs a three-stage wound field synchronous generator [2]. This machine has been extensively adopted for different platforms and has proved to be highly reliable, inherently safe with voltage control achieved by varying the excitation current. However performing a starting function requires employing of an extra winding hence the design cannot be regarded as optimal. Advances in power electronics result in the possibility to consider other machine types for the starter/generator operation which have the potential of a substantial improvement in power density (kW/kg), overall system performance, functionality, reliability, diagnostics, and availability for the overall system compared to the previous or existing solutions. The paper reports the research project targeting the development of such a novel system.

Consideration of many design aspects is required for this complex multi-disciplinary task including definition of the best system topology, electrical machine and power electronic converter design, thermal management and cooling arrangements, development of control techniques, health monitoring and fault management systems. The paper will report the major achievements of the project in these key areas.

Employing active rectification for starter-generation function
In the full paper, this Section will review the core idea of the proposed system in details. Basic idea of voltage-source converter and way of controlling an electric machine for performing controlled power flow in both starter and generation modes will be considered. Figure 1 shows the configuration of the proposed system and the operational principle will be discussed in the full paper version.

Fig. 1: AC Electric Machine - Active Front-End Rectifier system

Trade-off studies and selection of system topology
The research started with the selection of the best possible system topology. Different machine types and converter topologies for S/G drive concepts and their associated thermal management, control and sensing requirements were considered. The machine types and topologies were assessed based on the required load and speed duty cycles and a comparison matrix was created in an effort to identify the most promising solutions. The main aspects of evaluation were included machine size, profile and weight, converter complexity and reliability, sensing requirements, peak torque, torque ripple, extended speed range, system safety, adaption to cooling, technological maturity, material cost and availability.
As a result of initial considerations, the following topologies were selected for further detailed trade-off study:

- a) Based on Induction Machine
- b) Based on Switched Reluctance Machine
- c) Based on Permanent-Magnet Machine (with surface-mounted magnets and with interior magnets)

Each of the short-listed topology candidates has been subject of the detailed design process that will be described in the full paper and will be discussed during the conference presentation. As the trade-off study result, for the further detailed development, the topology “permanent-magnet machine with surface-mounted magnets (SPM) with three-level IGBT converter” was selected.

**Electric Machine**

In this Section the full paper will consider the design and optimisation of SPM machine that satisfies the basic system requirements. The basic requirements are as follows:

- an extended speed range (in motoring mode: up to 12,000rpm; in generation mode - between 19,000rpm and 32,000rpm)
- maximum torque in a starting mode: 40Nm
- maximum electrical output in generating mode – 45kW into 270V dc bus.

An SPM candidate was chosen considering mechanical and thermal constrains at high speed, power density, reliability and size. In the design process, fault tolerance is considered by adopting a redundancy solution in the event of a failure. This allows a distributed winding to be adopted, consequently minimizing rotor losses in both PM and the rotor back-iron. Different slot-pole combinations were investigated in view of the overall losses and performance and the compromise in the design of the machine for operating as an engine starter and as generator. Implications of different magnet's retention material and magnetic materials were studied as well and will be reported in the full paper.

Thermal management of the machine is achieved by direct oil cooling. The core idea is to use ducts through the stator core along the stator outer diameter and slots existing between stator teeth. Such arrangements guarantee an even distribution of the coolant. Further enhancing cooling techniques have been identified for the stator and rotor regions aimed to effectively reduce the machine weight and improve system efficiency. Numerical simulations using a CFD code were conducted to investigate the fluid flow inside the machine. Another numerical method, based on the lumped parameters thermal network has allowed getting detailed information about the temperature distribution within the machine.

The machine was manufactured and currently is being tested to demonstrate its ability to produce the required torque-speed characteristic and validate the design. A view of manufactured stator and rotor are given in Fig.2.

**Power Electronic Converter**

In this Section the full paper will details a Power Converter Design, this short abstract reports only a major points.

The boundaries for the converter were defined as 400A peak output current, 1.2kV DC-link peak voltage and an electrical frequency equal to 1.6 kHz. The three-level converter topology was adopted due to advantages in terms of lower EMI emissions and higher fundamental frequencies for the same switching frequency. However the final decision came from the power losses comparison for the different topologies simulated for a similar load condition and THD. Minimizing the losses is important in aerospace because it will lead to a minimal heat-sink that has a significant influence on the overall mass. The results of these simulations will be reported and discussed in a full paper.

In terms of hardware, the chosen IGBTs were the Infineon F3L400R07ME4 rated at 400A/650V. In order to provide a stiff DC-Link, but at the same time a small and light solution, a custom design has been adopted: a single enclosure for the twin capacitors rated at 600µF, 650V/200Arms. The control board is based on the Texas Instruments DSK6713 running at 225MHz coupled with an Actel FPGA ProASIC3 A3P400. The gate drives boards use the Infineon driver 1ED02012-F, they have been specifically
designed to fit the layout of the power modules, minimizing the connections but at the same time providing single driver status and real time temperature monitoring for every power module. The design of converter thermal management was based on calculated losses in the thermally worst case of repeated start scenario (unsuccessful start). As a result, a forced air-cooled solution was employed and the heatsink for power modules was designed to guarantee an acceptable temperature at the end of the worst-case scenario. Following the calculations, the system will be able to provide an infinite number of repeated start attempts. A general view of the power converter manufactured for laboratory test is given in Fig.3.

Fig. 3: A view of the manufactured converter in a box frame

System Control
A control structure to ensure smooth system operation through the entire speed range was designed. The proposed approach expands flux-weakening operation into a generating mode and allows for the system to act as a stand-alone or paralleled source in an on-board electric power system. The developed general system control concept and detailed control loops design will be reported in the full paper version, here only the final control block-structure as depicted by Fig.4 is given.

Simulation of system performance
The designed system performance has been verified through time-domain simulation for which the corresponding models were developed in MATLAB/SimPower. Simulations of starter mode operation are given in Fig.5. As one can see, the system provides the same start-up time of 20s to the reference speed of 8,000rpm in both extreme environmental temperatures -40°C and +55°C. In both cases the machine current is well below its maximum value.

Fig.5. Starting mode performance: a) at -40°C, and b) at +55°C

Simulation of the S/G system in generating mode is reported in Fig.6.

Fig.6. System performance in generating mode
The scenario in Fig.6 assumes arbitrary change of engine speed within a specified range, and demonstrates that the machine voltage is controlled to its maximum allowable value whilst the dc-bus is controlled according to the required droop characteristic depending on a system load. Many other simulation scenarios demonstrating the system performance will be reported in the final paper and discussed during the conference presentation.

**System laboratory tests**

At the time if this abstract writing the system was manufactured and currently is being tested. Initial tests results are promising. By the time of full paper submission we expect the test campaign completed. The results achieved will be reported and presented at the Conference for discussion.

**Conclusions**

The paper reported development of aircraft starter-generator system based on a high-speed permanent magnet synchronous machine fed by an active front-end converter. Details of electric machine design, power electronic converter design, thermal management system and overall control design are reported. System design is confirmed by time-domain simulations and the overall system performance – by extensive testing in laboratory environment.

**References**