Innovative Waste Heat Recovery Systems in Rotorcrafts

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Abstract- **Research in modern helicopters is targeted into the increase of their efficiency due to economical and ecological pressures. This paper introduces two innovative methods of absorbing a ratio of the energy remains of the main engine exhaust gases and converting it to electrical energy. The recovered power is then injected to the electrical bus of the helicopter through power electronics converters. The first one uses thermoelectric generators whereas the second one an electromechanical generator. Both of these systems are analyzed, candidate power converter configurations and topologies are depicted and the results of simulations using SABER are evaluated.**

Index terms- **More electric aircraft, thermoelectric generator, supercapacitor, dc/dc step-up converters, ac/dc rectifiers, pfc converters**

I. INTRODUCTION

In the last years, helicopters have grown to become very popular, not only for special missions, such as medical emergencies, law enforcement and civil protection, but also for general transportation use. Under this context, the improvement of their efficiency as well us the idea of a “more electric aircraft” (MEA) [1] have been promoted.

The electrical grid of a rotorcraft is used to supply a variety of different loads, such as avionic equipment, radar, autopilot, flight instruments, heating resistors, anti-ice components, searchlights etc. As a first approach, much research has been done in the use of a high voltage 270V DC bus which has already been implemented in other types of aircrafts, under the MIL STD 704 F standard [2]. This voltage level is easily obtained by rectifying the output of the standard 3-phase alternator already used. However, no speed regulation is required, as in AC voltage systems, and due to lower currents, the power supply efficiency is increased whereas its weight is reduced. For existing loads that are powered by lower voltages small power converters are used.

The use of higher voltages in helicopters has facilitated the concept of the MEA, because the electrical grid of the helicopter has to support the growing load demands introduced by the conversion of instruments, which were priory powered mechanically or hydraulically. Furthermore the electrical power generation efficiency now plays a significant role to the whole helicopter efficiency, fuel usage and carbon impact. In current helicopters, for reliability reasons, at least two electrical generators operating at half their nominal power are used to supply the necessary power to the grid. These machines are connected to the main gear box, which has a direct cost in fuel burning. As a result new and more efficient power supply methods are needed. Waste heat energy recovery systems, which take advantage of the main engine exhaust gases have already been applied in ground vehicles. However they have never been used before in aircrafts, where the requirements are very strict. In this paper two innovative methods of energy recovery will be introduced, the static and the dynamic. The description of these new systems as well as the candidate topologies which can be used will be thoroughly described and the first simulation of the systems will be presented.

The exhaust gases contain a great amount of energy in the form of heat, as their temperature is around 570^{o}C under normal operation. A fraction of this energy remains can be exploited with the use of thermoelectric generators [3], which are semiconductor devices that convert heat into electrical energy using the Seebeck effect. The energy is then injected to the DC bus through a power electronics converter, which has a double role, as it will be described in the next section. What is more the gases exit at a pressure of around 15,8psi which is higher than the atmospheric pressure[4]. The energy contained in the form of mechanical power can be used to rotate an electrical generator. For reasons of weight and volume, the permanent magnet generator is the more suitable option. The electrical power is then transferred to the DC bus through another power electronics converter connected in between. This dynamic waste heat recovery system will be analyzed in section 3 of this paper.

II. Static Waste Heat Recovery System

Thermoelectric modules can convert electrical energy into thermal energy (thermoelectric heat pumps, which use the Peltier effect), or vice versa, can convert heat to electrical energy (thermoelectric generators - TEGs, which use the Seebeck effect). The equivalent electrical circuit of the TEG is a DC voltage source connected in series with a resistor [5]. The resistor remains constant while in operation, whereas the voltage of the DC source is a function of the difference of temperature between the two sides of the module. In order to achieve a higher voltage output, many TEGs would need to be connected in series, which would also increase the series resistance, diminishing the power output. Therefore, a dc-dc voltage step-up converter is needed. A Maximum Power Point Tracking (MPPT) algorithm [6] is implemented in the converter, for impedance matching, in order to achieve maximum power harvesting at any environmental conditions. Waste heat energy recovery systems using TEGs have already been designed for automotive applications [7]-[10].

Another problem in modern helicopters, due to the increase of the number of electrical loads, is the existence of high peak currents, which create as a result a voltage fluctuation at the DC bus, due to the parasitic inductance of the bus lines. Moreover, the generator is overstressed. On the other hand, an energy storage device, i.e. a battery or a capacitor, connected to a power electronics bidirectional dc-dc converter can supply and absorb the energy necessary in order to compensate these transient currents. A supercapacitor bank can be used to store this energy, because of its high energy density, crucial for this application, as well as its low ESR, which allows high current values. Supercapacitors is a new trend already applied in the case of regenerative braking systems in electric drive systems [11]-[14]. With the implementation of such a system, the voltage fluctuation of the DC bus can be lower and the main generator does not have to be oversized.

The static waste heat recovery system presented addresses both points; the energy acquired by the TEG is supplied to the DC bus through a power converter, whereas another converter supplies or absorbs the power of the transient loads. The nominal power rating of this system is 1kW.

There are two different connection configurations that can be applied. In the first configuration (fig. 1), the two converters are connected in series, with the supercapacitor bank in between charged at an intermediate voltage, acting as a buffer between the two. The first converter steps-up the voltage of the TEG and stores the energy to the supercapacitor bank, whereas the second bidirectional converter supplies a constant amount of energy generated from the TEG as well the energy to compensate the current of the transient loads. In the second configuration (fig. 2) the first converter is directly connected to the DC bus, whereas the second converter acts as a Parallel Active Filter (PAF) [15]. The main advantage of this configuration is that, as the two converters are independent, the voltage fluctuation of the supercapacitor bank can be much higher, leading to a smaller capacitance needed, which increases the power density of the system. However, because of the higher step-up voltage needed for the first converter, which will need to connect the TEG directly to the DC bus, switching losses become higher, due to higher voltage stresses of the semiconductors.

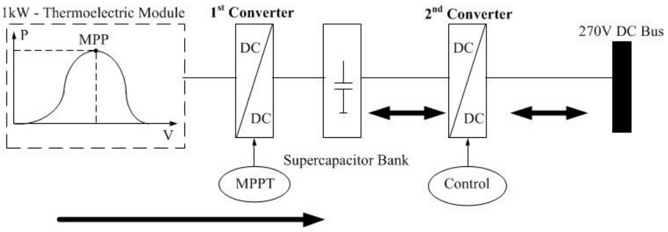

Fig. 1. First candidate SWHR system configuration

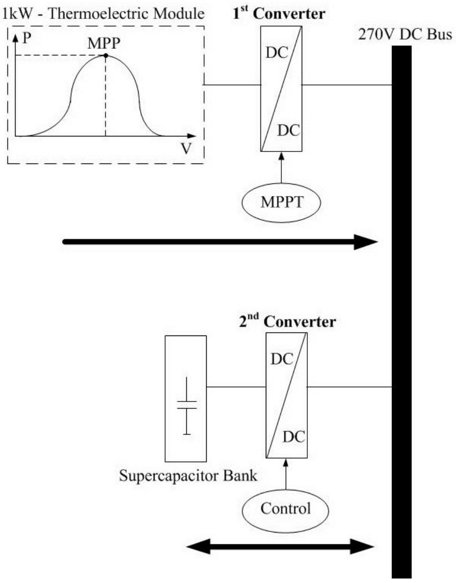

Fig. 2. Second candidate SWHR system configuration

Though numerous different topologies of dc-dc step-up converter topologies exist, only the topologies suitable for medium and high power ratings with high power efficiency can be used in this application. Voltage step-up topologies that include a transformer, as well as topologies that have a high number of devices should not be an option, due to low power density and reliability reasons. There are still many transformer-less candidate topologies, such as the Boost converter [16], the Cuk converter [17], the SEPIC [18], as well as the family of the switching converters with wide dc conversion range [19]. The same requirements apply to the selection of the second bidirectional converter. Candidate topologies for this converter, which can be used in both proposed architectures, are the two switch buck/boost converter [16] and the bidirectional Cuk converter [20].

For these candidate topologies, simulations were carried out in SABER, with real semiconductor devices in order to categorize the topologies based on the expected efficiency. Simulation results have shown that, for the selected operating voltage levels, the boost topology has the higher efficiency for use in the first converter, whereas the buck/boost topology has the higher efficiency for use in the second converter. Moreover, the first configuration has a slightly higher overall expected efficiency than the second one. The weight of the final converter primarily depends on the core of the inductor as well as the heatsink used. Based on the elements selected, the two topologies mentioned above have also the lowest expected weight.

It is also essential to implement a modular design approach for this system, in order to be used in different types of helicopters. Moreover, interleaved converters with current sharing can be used, which will also increase the efficiency of the system. This configuration is validated by SABER simulation results.

Finally, it is possible to compensate current peaks more efficiently by connecting multiple converters at the feeder of each load (fig. 3). As a result the voltage fluctuation of the DC bus will be significantly decreased.

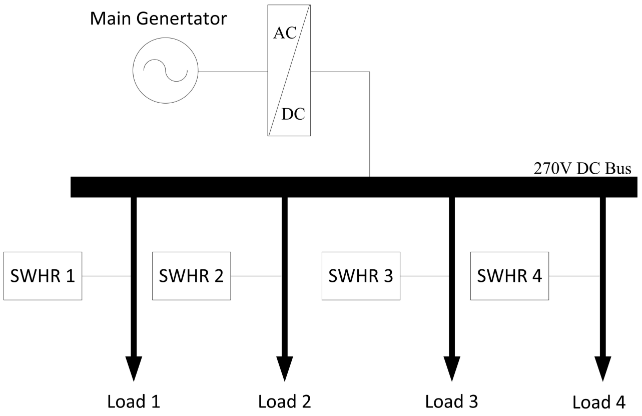

Fig. 3. Modular SWHR system design

III. DYNAMIC WASTE HEAT RECOVERY SYSTEM

The Dynamic energy recovery system (fig. 4) consists of a hot air engine, rotated by the exhaust gases, connected to a permanent magnet synchronous generator (PMG) and an ac/dc pfc converter which rectifies the voltage and supplies the energy to the DC bus, keeping the engine rpm constant. The PMG is selected, as it has a very high power density, low maintenance needs, which increases reliability, and because no external power supply is needed for operation. The nominal power rating of this system is 30kW. Because of its high power output, it is designed to run also as a backup system in case the main generator fails, increasing so the reliability of the helicopter electrical network.

The specifications that all candidate converter topologies should meet are: good pfc, high power density and efficiency, high reliability and low electromagnetic interference. Though, as in the previous system, there is a great number of rectifier topologies, only the ones that fulfill the above criteria are selected to be studied, which are: the cascade connection of the boost rectifier [21],[22] in series with a dc/dc buck converter, the cascade connection of the buck rectifier [23] in series with a dc/dc boost converter, the buck-boost pfc rectifier [24] and the parallel active filter [25]. The advantage of the last candidate topology compared to the previous ones is that the PAF handles only a fraction of the energy, because it acts as a compensator. Other topologies, such as the use of a full wave rectifier with firing angle control are still considered.

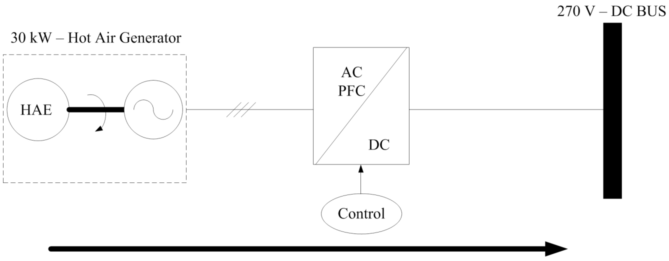

Fig. 4. Dynamic waste heat recovery system

Simulations are again carried out in SABER with real semiconductor devices, to measure the expected efficiency of each candidate topology, as well as its THD, in order to determine the level of pfc. Initial simulation results show that the boost pfc rectifier operating in discontinuous conduction mode (DCM) in series with a buck dc/dc converter has a very high expected efficiency with very low THD. Another advantage of this configuration is that no sensors are needed, reducing so the control complexity and improving the system reliability. A dc link capacitor is needed in the cascade connections, between the two converters to act as a buffer, which increases its volume and weight. On the other hand, the PAF configuration, as in the previous system, needs a much smaller capacitor, because of the high voltage fluctuation that is allowed. Therefore this remains a promising topology and is still under investigation at the moment.

As already mentioned in the static waste heat recovery system, a modular design approach is recommended, and is necessary because of the higher power rating of this system. This increases the overall efficiency and it significantly lowers the THD, as demonstrated in the initial simulation results.

IV. CONCLUSION

Two new energy regeneration systems have been presented which take advantage of the waste heat of the engine gases of helicopters. The first one utilizes the thermal energy of the gases, which is converted to electrical power through a thermoelectric generator. Two converters and a supercapacitor are used to supply the energy to the dc bus and compensate the current of various transient loads. The second one converts the mechanical energy into electrical energy through a hot air engine and a permanent magnet generator. The energy is then supplied to the dc bus through an ac/dc pfc rectifier.

In the final paper more detailed simulations will have been carried out, leading to final results about the architecture and converter selection. Moreover, the structure of the final system will be analyzed, as well as the energy management and control techniques that will be used.

ACKNOWLEDGMENT

This research is being conducted in the frame of CleanSky JTI Project, a FP7 European Integrated Project - http://www.cleansky.eu

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