

Electric Drives for Electric Green Taxiing Systems

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ABSTRACT

This paper addresses the implementation of electric taxiing without the use of main engines by using electric propulsion of the landing gears. Substantial progress in this area has been achieved by Honeywell Aerospace and Safran in a joint initiative for developing an electric green taxiing system (eTaxi). Considerable analysis, design, fabrication, and testing have already been completed, which culminated in a demonstration at the Paris Air Show (PAS) in 2013. The eTaxi system has been installed on an A320 airplane that uses the auxiliary power unit (APU) to generate electric power to provide propulsion to two wheels of the main landing gear. The main advantages of such a system are reduction of fuel consumption and audio noise, reduction of CO₂, carbon and nitrous emissions, reduced engine foreign object damage (FOD) exposure and fast-turn time savings by elimination of the ground tractor for pushback operation.

The electric drive system (EDS), which comprises an alternating current (AC)-to-direct current (DC) converter, a wheel actuation control unit (WACU) and a traction motor (TM), is the heart of the system. It performs high power conversion of electrical to mechanical energy. At least one EDS is required to perform eTaxi functions. In this paper, the focus will be on the EDS and its components. The following topics will be covered:

- Definition of the major requirements and functions of the system.
- The requirements and functions related to the three components AC-to-DC converter, the WACU, and the TM.
- Architectural options and trade study results.
- Various possible implementations at the component level, along with a description of optimizations.
- The interfaces between the major components.
- Environmental challenges and potential solutions.
- Cooling designs and thermal challenges in the light of installation difficulties.
- EMI and power quality management approaches.
- Control and protection methodology as a part of the EDS and beyond.
- Data from development testing.
- Results from the PAS demonstration.
- Analytical results and correlation to the test results.
- System performance, as a part of typical operational duty cycles.

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BACKGROUND

The more electric architecture (MEA) and energy-optimized aircraft (EOA) initiatives continue to be dominating trends in the aerospace industry, as they have for the last two decades. The commercial aircraft business is increasingly using no-bleed air environmental control systems (ECS), variable-frequency (VF) and DC power distribution buses, and electrical actuation. A typical example is the Boeing 787 platform. The next-generation Boeing and Airbus narrow-body airplanes will most likely use MEA. Some military

aircraft already utilize MEA for both primary and secondary flight controls. Substantial progress in replacing hydraulic and pneumatic systems with electric ones has been achieved.

The aerospace industry and the airlines have expressed interest in performing a taxiing operation without the use of the main engine. Fuel savings and environmental benefits are expected. The other advantages are reduction of brake wear and the elimination of ground tug operation. The next logical step is the implementation of electric taxiing using the electric power generated by the existing APU or alternative sources like fuel cell or battery. Analysis and estimates

have been performed by different companies and universities to justify various approaches. Some of the results have been shared in the public domain.

For the first time, Reference 1 provides results of a comprehensive study of the technical feasibility of an electric wheel-drive taxiing system using publicly available aircraft and runway coefficient data. The study shows the potential for overall mission fuel burn reductions, particularly for short haul aircraft with a relatively long taxi time. The study also highlights that the wheel-drive system needs to be considered as an integral part of the design of the next generation of MEA as it has implications for other systems onboard the aircraft. Another important conclusion is that the main wheel drive configuration offers greater applicability than the nose-wheel-drive configuration due to its better traction.

A tool to assess the global benefits in terms of fuel consumption and emissions is presented in Reference 2. A concept of an aircraft-integrated ground propulsion system is considered and its performances and weights are determined, assuming the APU or a zero-emission device like a fuel-cell as the power source for the system. A model of the propulsion system integrated into an object-oriented, mid-sized aircraft is generated, capable of precisely simulating an entire aircraft mission. The results show a potential overall fuel savings of up to 2.6%, depending on the flight mission and the duration of the taxi phases. The associated CO₂ emissions may decrease by the same amount. Furthermore, NO_x, CO, and HC emissions might be reduced by 64 to 80% compared to conventional ground operations. The aircraft model used in this work has proved a powerful tool for assessing the performance of an electrical taxiing system and comparing it with different real-world scenarios.

Reference 3 focuses on electric taxiing that does not require the use of jet engines or the APU during taxiing, either from the departure gate to take-off or from landing to the arrival gate. The proposed approach examines these systems and proposes an ecologically-sound solution for reducing aviation emissions at airports for a 3% fuel burn reduction.

Reference 4 provides a top-level comparison between the Honeywell/Safran eTaxi approach and the front-wheel-driven hybrid approach of WheelTug.

This paper is concentrated primarily on the EDS and its components rather than the entire eTaxi.

ELECTRIC DRIVE SYSTEM

The commercial aircraft business is moving toward more fuel efficient and environmentally friendly operations. The high-power EDSs will play a significant role in this trend. In the eTaxi applications, an Airbus A320 airplane is utilized to demonstrate use of the APU to power EDS to taxi in and/or out of a runway. The EDS is the heart of the eTaxi. The function of the EDS is to utilize power from the APU electric generator and drive the wheels on each of the

main landing gear. Hence, it propels the aircraft in either the forward or the reverse direction as commanded by the pilot. The EDS is commanded by the system controller so that the aircraft can move at a constant commanded speed or constant commanded acceleration. The pilot is not required to constantly adjust the main engine throttles and/or ride the brakes to control taxiing speed. Consequently, control of the aircraft is more efficient.

The EDS contains an AC-to-DC power converter in the form of an autotransformer rectifier unit (ATRU), a motor controller (DC-to-AC converter) with clutch control called also WACU, and a TM. Detailed description of these components is included in the following sections.

EDS Major Requirements

The EDS receives electrical power from the APU generator and converts it to mechanical power for the aircraft movements of taxi-in, taxi-out and pushback. The EDS control system operates in 3 quadrants: forward and reverse drive and reverse braking. The EDS must perform reverse braking since, the pilot, using mechanical brakes, could apply them too abruptly and potentially lift the nose gear off the ground. The resulting regenerated power is dissipated in a resistor bank. The EDS supplies the necessary torque to breakaway the aircraft from a stationary state, accelerating it to a speed of up to 20 knots within 90 seconds and maintains the speed control as the pilot commands. The EDS has a torque/speed profile requirement that calls for very high torque at zero and low-speed operation and is power limited at high speed due to the APU generator power capability. The system should operate in constant torque mode and/or constant power mode as required by the operation taxiing profile. The speed control mode and torque control mode are required for the eTaxi. The torque control mode is generally implemented by the motor controller in the EDS. The speed control can be implemented in a separate system controller or optionally in the WACU.

The torque/speed profiles for the EDS functional requirements are shown in [Figure 1](#). The characteristic points are defined with required speed, torque and time of duration.

The aircraft's APU generator provides power for hotel loads while the aircraft is on the ground and when the main engines are not operating. For aircraft equipped with eTaxi, the APU power generation system also provides the power for the EDS. The EDS converts the high-voltage AC (115 Vac, 3 phase, 400 Hz power) from the generator into high-voltage DC power (± 270 Vdc nominal) and distributes it to the motor controllers. The motor controllers with high-frequency switching commands AC voltage into the traction motor based on the speed and torque required by the system controller. There are cable harnesses which carry high voltage AC and DC power. All the EDS components must comply with strict power quality and electromagnetic interference (EMI) requirements to prevent any contamination on the aircraft power distribution bus. The power drawn by the EDS is limited by the eTaxi system controller to prevent an overloading of the APU generator.

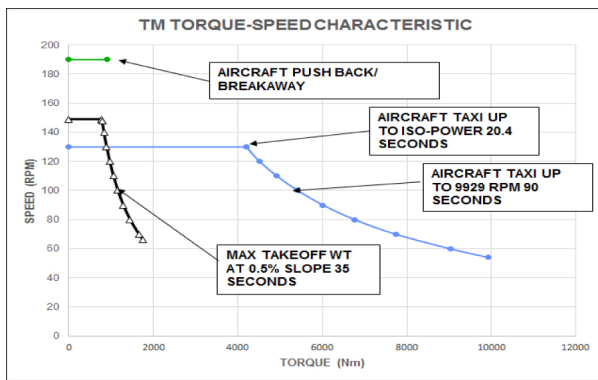


Figure 1. EDS torque/speed curves

The intention is for EDS to be implemented in a new platform as well as retrofitted to an existing airplane. All the high-power components of the EDS must be air cooled since a liquid cooling system is not available in the existing aircraft at the targeted installation areas. A dedicated new cooling system would increase overall system weight. All key components might be installed far apart from one another and, therefore can have different environmental requirements. The traction motor must fit into the existing landing gear space without compromising the integrity of the landing gear and wheel braking system. The EDS will need to have high-bandwidth data processing capability to implement the motor control and protection algorithms and to monitor the health of the entire system. In the section “EDS Architecture,” the major requirements of each individual component are introduced.

EDS Architecture

Figure 2 shows a conceptual block diagram of the eTaxi EDS architecture.

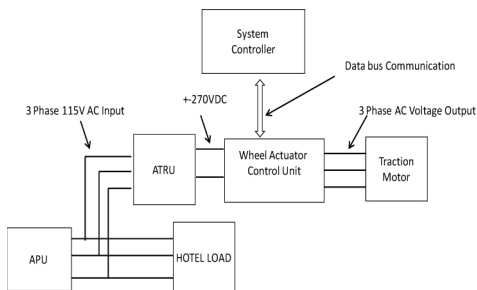


Figure 2. EDS architecture

The electric drive system of the eTaxi contains the following key high-power components:

- An ATRU serves to convert the electrical AC power source to DC voltage. For example, it is used to convert and boost 3 phase 115 Vac at 400 Hz from the APU generator to ± 270 Vdc. A single ATRU can be used to feed both WACUs or each WACU can have a dedicated ATRU. The second option was used at the PAS.
- The motor controller, also referred to as the WACU, is used to generate AC voltage to drive the TM. High current is required to deliver high torque (such as breakaway torque) and accelerate the airplane to reach the desired taxiing speed.

- A high-torque/high-power traction motor needs to be installed on the wheel actuation system to deliver the required torque. The motor must accommodate severe environments like shock and vibration. The motor will be exposed to a heavily contaminated environment as well.
- High power cable harness to deliver electric power from the motor controller to the traction motor. These harnesses need to be capable of carrying high current and flexible enough to be routed to the motor mounted on landing gears.

Some key requirements of the ATRU are listed in Table 1.

Table 1. ATRU key requirements

Power Input	115Vac, 400Hz, 3 phase, nominal, per ABD 100.1.8
Power Output	Nominal +/-270Vdc, +/-255Vdc minimum at full load
Power rating	40KW continuous, 150% overload for 1 minute
Rectification	18-pulse ATRU
Inrush Current	4X nominal current
Cooling	Forced Air (self cooled)
Environment	Non pressurized area, DO160G
Efficiency	>95% at full load
I/O	Temperature Monitoring and Signals
Power Factor	No less than 0.85 lagging at full load

Some key requirements of the WACU are listed in Table 2.

Table 2. WACU key requirements

DC Bus	+/- 250 Vdc minimum
Output Power	60 kW at 20Kt of aircraft speed
Communication	Databus, Discrete and Analog I/Os, Resolver
Environment	Pressurized Area
Power Quality	ABD100.1.8.1
Cooling	Forced Air (self cooled)
Electromagnetic Interference (EMI)	DO-160 Rev F
Control	DSP, Built-in-test

Some key requirements of the TM are listed in Table 3.

Table 3. TM key requirements

Winding Configuration	3 Phase Y connected
Connection	Two parallel cables for equal power splitting
Shaft position sensor	Resolver
Physical	Fit into the existing allocated space near landing gear
Performance	Breakaway torque at zero speed, rated power at 20Knt aircraft speed
Cooling	Forced Air (self cooled)

Figure 3 shows the entire EDS being integrated and tested in the lab environment at the Honeywell facility in Torrance, California.

EDS Protection and Controls

Protection mechanisms are built in the EDS to prevent component failures from propagating to other components, including upstream to the power distribution bus. The thermal management and protection of the EDS is necessary due to the high-power nature of the hardware. Overcurrent and overvoltage protection for the components

is also required for safety. The components of the electric drive system will be installed at various aircraft locations. The harness for connecting these components can be up to 60 to 70 feet long.

In addition, the number of power cables can be doubled due to power sharing. The EDS needs to detect and isolate a failure in the harnesses and the components as well. A large number of sensors and their associated circuitry may be required which could lead to degradation of system reliability. An innovative way to protect the system with a minimum number of sensors is highly desirable.

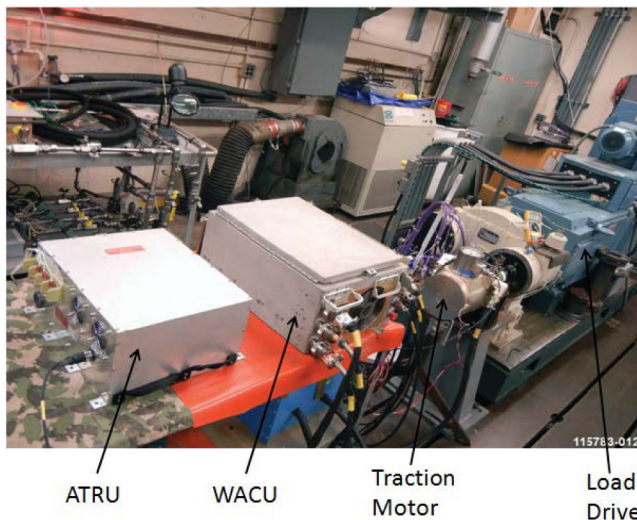


Figure 3. Integrated EDS in the lab environment

EDS Optimization and Stability

The EDS has to be optimized for weight, volume, efficiency, reliability and cost. The optimization should be conducted at the overall EDS level. The result will then dictate the EDS component-level requirements. For example, the EDS operation envelopes include a low-speed operation point with high-torque output and high-speed operation point with high-power output.

To minimize the weight of the motor controller and overall power loss, a flux weakening technique (Reference 5) is adopted. Without the optimization, the power loss and current, as well as the weight of the electrical drive system, would be very high. On the other hand, if too much flux weakening is used, the WACU will be penalized to absorb a high back emf voltage from the motor at high speed. Then the ATRU will be forced to boost the DC bus voltage to a higher level. Both the WACU and the ATRU will experience a weight penalty. Therefore, an optimization for flux weakening is implemented. The traction motor with flux weakening has a current speed curve as shown in Figure 4.

To perform a quantitative comparison between performance with flux weakening and performance without flux weakening, WACU power losses have been calculated over the operating profile. The chart on

the left of Figure 5 is the loss without employing flux weakening. The chart on the right of Figure 5 is the loss with an optimized flux weakening. Because of the flux weakening, WACU can be designed to dissipate 3.2 Kw peak power instead of 4.3 Kw peak power. This design strategy can improve power density up to 10%.

There are many design parameters that need to be optimized for the entire system performance like the inverter switching frequency. A frequency of 15 KHz has been selected based on optimization between EMI performance and losses. The efficiencies of the individual components must be properly allocated to achieve the overall EDS efficiency requirement.

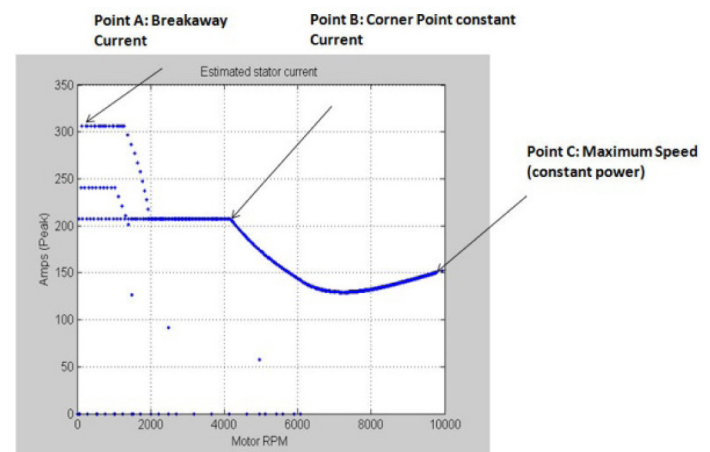


Figure 4. TM Current speed curve with flux weakening

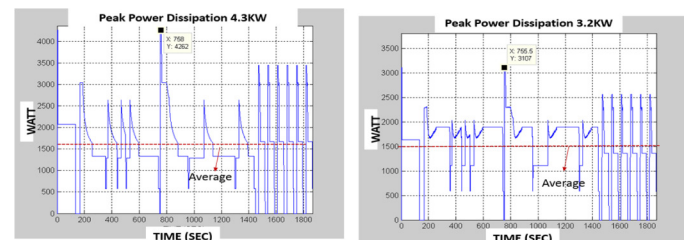


Figure 5. WACU power loss with no flux weakening and with flux weakening

The load of the EDS can be a constant power load (CPL) with negative impedance. The CPL is known for possibly degrading the system performance and causing instability. See Reference 6 and Reference 7. The long cable, the filter configuration in the components for power quality, the dynamics of the electric actuator, the parameter sensitivity of the motor and power electronics, and even the voltage dynamics of the generator and the generator control unit (GCU) can contribute to EDS internal voltage bus instability. There are several techniques such as generalized state space averaging, and dq frame modeling, which can help analyze the stability of the EDS and ensure stability over the entire operational envelope. This research is ongoing and will be a focus of future work.