DEVELOPMENT OF AIRCRAFT SYSTEM ELECTRIFICATION AND HYBRID ELECTRIC PROPULSION

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Abstract

To achieve the decarbonization of air transportation in 2050, the aviation industry must pursue all options. While alternative fuels, which are Sustainable Aviation Fuel (SAF) and hydrogen, are seen as major contributors to decarbonization measures, carbon-free supply of these fuels in sufficient quantities is still far from certain. Therefore, it is mandatory not only to convert fuel types, but also to introduce more energy-efficient systems to air transportation. One method to improve system efficiency is electrification of the aircraft, and the development of electrification both in the aircraft system and in the propulsion system is being considered. IHI has been conducting research and development activities with the contract of Japanese national funding to improve energy efficiency by applying hybrid electric propulsion and aircraft system electrification targeting to the single-aisle aircraft class, which has the largest section of air transportation volume and highest CO2 emissions. In this paper, the concept, expected benefits, technical issues, and technical development efforts for the development of aircraft electrification systems in IHI is presented.

Keywords: Aircraft System Electrification, Hybrid Electric Propulsion, Electric Power System, Air & Thermal Management System

1. Introduction – The Way for the Decarbonization of the Aviation Industry

At the 41st ICAO Assembly, the long term global aspirational goal (LTAG) was adopted and the decarbonization of air transportation by 2050 becomes a global commitment. The main means to achieve the goal is the application of SAF, and in some cases, the application of hydrogen is also considered. In any case, the key to decarbonization of air transportation is believed to be the shift to alternative 'green' fuels that do not emit carbon.

It is a logical conclusion because there is no way other than applying green energy storage to directly eliminate or significantly reduce the CO2 emissions, and there is no alternative green energy storage which is applicable to large commercial aircraft other than alternative fuels. However, unfortunately, alternative fuels are not almighty. In the LTAG Report, the CO2 reduction effect of SAF, including manufacturing and transportation processes, is limited to around 75% reduction for SAF derived from biomass or waste [1]. In addition, the cost of SAF is expected keeping very high, and there is no prospect of securing a sufficient supply. Hydrogen has a larger CO2 reduction effect; the reduction is expected about 94% through the lifecycle [1]. However, it is also has a supply chain issue to gather enough amount of CO2-free green hydrogen. Also, when applying hydrogen as fuel to the aircraft, although the weight energy density of hydrogen is higher than that of hydrocarbon fuel, the volume energy density is lower, so the tank becomes larger; it is considered difficult to have the same operating range as conventional aircraft [2]. In addition, extensive development of airport facilities and hydrogen supply infrastructure is necessary. Therefore, it is expected that hydrogen aircraft will be introduced for relatively short-distance routes and intra-regional aircraft where infrastructure development is possible [2].

From these facts, it is important to continue improving aircraft fuel efficiency, and the development of technologies that can be applied to various aircraft regardless of their size is desired. In the LTAG

Report, while it is depending on the scenario, fuel efficiency improvement through technology is expected to be around 20% compared to 2020. The electrification of aircraft systems, including hybrid electric propulsion, is a technology that exactly matches this, and IHI has been engaged in this research and development for more than 10 years.
In the technology development activities, IHI set the target as the next generation singe aisle aircraft. It is based on market forecasts considering the timing of the implementation of the next generation of aircraft and the proportion of CO_2 emissions by aircraft sector. The sector handled by single-aisle aircraft accounts for 50% of CO_2 emissions [2], and it is important to develop technologies that can be applied here, considering the contribution to the decarbonization of air transport by 2050.

2. Methodology of Implementing Electrification in Aircraft

2.1 Prior research of EAP (Electric Aircraft Propulsion)

While various methods of electrification can be considered for the small and short-range aircraft such as Urban Air Mobility (UAM), when considering the cruising range of over 1000-2000km and more than 150 passengers that single-aisle aircraft handles, the only applicable current means of electrification is the aircraft system electrification and/or a relatively low electrified hybrid (So called Micro-Hybrid). Due to the increased occurrence of discharge phenomena at high altitudes, the voltage that can be applied to aircraft is currently limited to ±270VDC (differential voltage of 540V). When considering the future, the implementation of the 800V system (±400V) that is currently starting the implementation in the automobile industry, or the application of the 1kV system (±500V) which is twice the current voltage, is being discussed. Voltages higher than this level does not seem feasible in the next generation aircraft. The voltage restriction cause the motor size restriction, so many companies and organizations put the development target of the motor around up to 1MW.

The output power of the single-aisle aircraft engine is about 20MW at takeoff and about 5MW at cruising when considering twin engine configuration. Even if 1MW electric motors are introduced as a hybrid electric system to the engine, it is difficult electric assist become a major power contributor of the hybrid engine, which is so-called Strong-Hybrid configuration. Current technology only allows Micro-Hybrid for large commercial aircraft engine.

Also, the batteries as a main power source can be applied the aircraft which has operating range up to 200NM [2]. This situation basically does not change even if it considers hybrid propulsion, not fully electric propulsion. If assuming a single-aisle aircraft class, batteries are not suitable option for the energy source of the main propulsive power.

2.2 Aircraft electrification concept of IHI

Based on these preliminary studies, IHI set the following aircraft electrification concept.

- Implementing aircraft system electrification and micro-Hybrid Electric Propulsion (HEP).
- Regarding HEP, reduced idle from LP spool to HP spool, electric fan taxiing and takeoff assist is considered.
- Considering the implementation of fuel cell to Auxiliary Power Unit (APU); it has higher efficiency than the conventional turbine APU.
- Considering lithium-ion batteries as the secondary energy source. It is only considered for conforming system level safety requirements and short-duration power sharing.
- Apply a electrified and integrated thermal and air management system; it consists of the electric Environmental Control System (ECS) with energy recovery by Electric Turbo Compressor (ETC) and with elimination of ram-air intake by Fuel Cooled Air Cooler (FCAC), and the air-cooling system for the power electronics which augment the energy recovery.
- Boundary Layer Ingestion (BLI) with electric fan is one of the option.

The diagram of entire aircraft electrification concept is shown in Figure 1, and the diagram of HEP concept is shown in Figure 2.

Currently, IHI is conducting research and development as a commissioned project based on the

Green Innovation (GI) fund from NEDO (New Energy and Industrial Technology Development Organization), with the aim of technology development and system-level demonstration based on this aircraft electrification concept. In this project, we are developing with the goal of achieving TRL6 by conducting demonstration tests at the system level, along with the development of core technologies in the electrification concept. MW-class electric motor and high-output electric turbo compressor is selected as the core technology component in the project. The details of this research and development is presented in section 5.

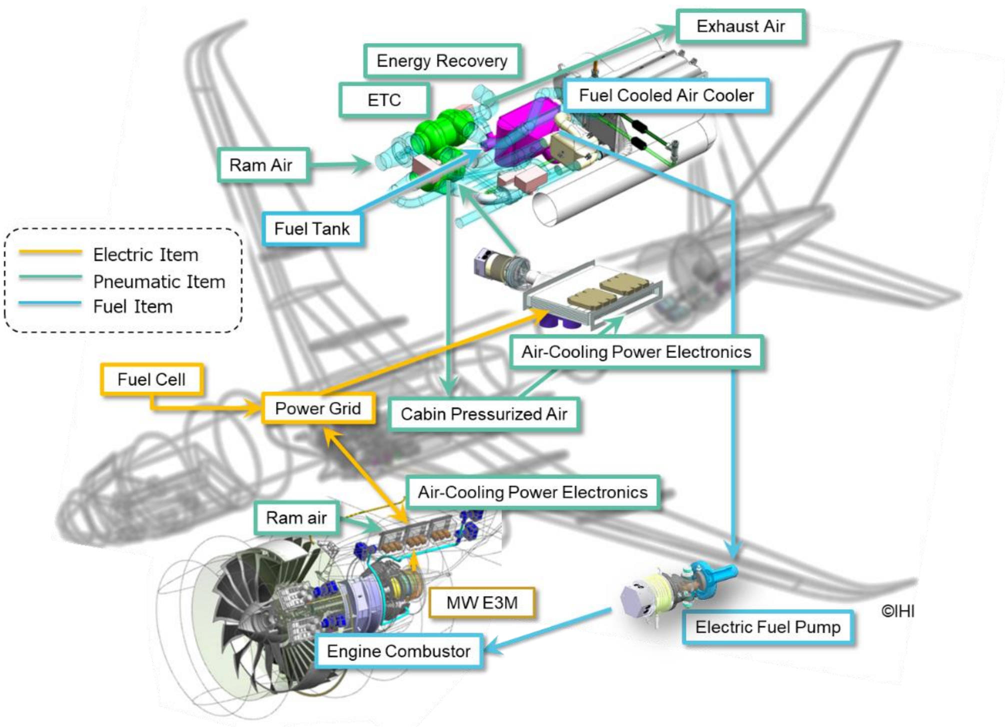


Figure 1 – Aircraft electrification concept of IHI.

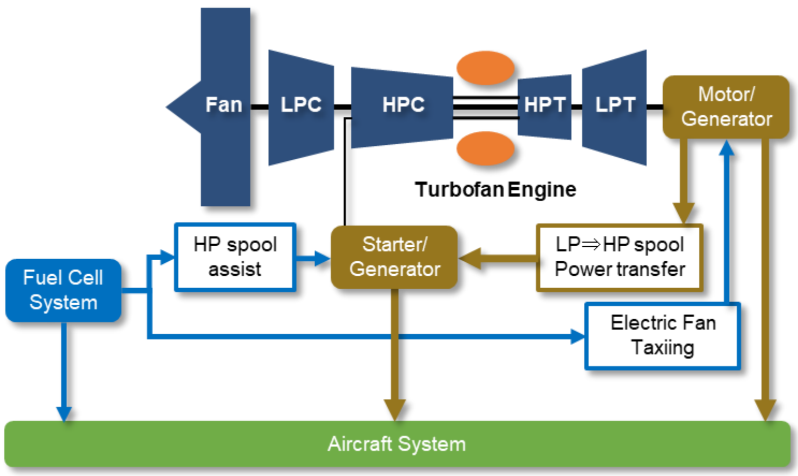


Figure 2 – HEP concept of IHI.

2.3 Expected Benefits

Based on the aircraft electrification concept mentioned above, IHI estimated the CO2 emissions through the mission. It does not contain the assessment of CO2 emission through the fuel production. As a premise for this estimation, we assumed that a 200-seat class single-aisle aircraft with two Turbofan engine, assuming the technology level of the 2030s, and that the electric system mentioned in the previous section would be applied. Hydrocarbon fuel, kerosine or SAF, is assumed for the primary fuel for turbofan engine, and gaseous hydrogen is assumed for the APU fuel. With this assumption, IHI estimated that around 5% total reduction in CO2 emissions can be achieved, with 3% due to the effect of HEP and 2% due to the effect of electrification of the aircraft system that we call the thermal and air management system.

One of the important points of this study is that these benefits will be very limited if each device or subsystem is implemented alone. Although the power weight density of the electric power system equipment has been improved drastically over the past 20 years, they are still heavy, and if a full set of electrical drive systems from generation to distribution, energy storage, and motor drive for one purpose are installed, the weight penalty of them will eat up the benefit obtained by installing it in almost all use cases. However, if various electrification means and devices with different usage phases during operation can be combined and the power supply system is time-shared, multiple benefits can be obtained with one penalty. In the aircraft electrification, it is necessary to challenge this difficult task of systems integration.

3. Technical Challenges and Main Focus of Development

3.1 Technology development in component level

3.1.1 Technology development of high heat-resistant electric motor

In the aircraft flying through the low pressure environment at high altitudes, the electrical discharge phenomena greatly constrains the applicable voltage of electrical system. In particular, the partial discharge resistance characteristics of the electric motor are a bottleneck, and it is assumed that the applicable voltage will not exceed around 1000V in DC link voltage even when looking at the 2030s. Due to the voltage constraint, in the 1MW class electric motor that supports the electrified aircraft including HEP, the current exceeds 1000A and it generates a large loss. The motor design will be aiming for high power density for aircraft application, the loss density will also increases and it makes the inside of the electric motor extremely hot. High heat resistance is important both for managing this high loss density and also achieving the concept of an engine embedded generator that aims for system integration of the engine and the high-power electric motor.

3.1.2 Technology development of ultra-high-speed motor with gas bearing application

For making the aircraft systems efficiency higher, it is necessary to improve the efficiency of the air system which is the largest power consumer in the aircraft system. It is also important to enhance and the system capability of Thermal Management System (TMS) to cope with the increased heat load in the aircraft due to the increase in electric power equipment. In many cases, TMS is considered as a secondary system; typical design process is that after designing equipment that satisfies the necessary functions for the other main systems, appropriate coolers are chosen like patchwork for cooling them. In IHI's aircraft electrification concept, we have established a concept of a thermal and air management system that first expands the limits of air cooling and unifies all the equipment in the aircraft with air cooling, and then combines it with energy recovery by ETC turbine to manage the heat and air in the aircraft in an integrated manner. At the center of this concept are the power electronics air cooling system and the electric ECS which combines energy recovery and fuel cooling. Both have ultra-high-speed motors with gas bearing applications as their core technology. Gas bearings, by principle, have low bearing load capacity because they hold the shaft by air film, which further decreases in a low-pressure environment. Therefore, when increasing power of motor compressor, it is essential to reduce the weight of the rotor; we are working on technology development with the basic strategy of multipolarization and high-speed rotation up to 200,000 rpm.

3.2 Technology development in system level

In the electrified aircraft, in order to fully obtain the expected benefits, it is very important to optimize the system design matching with the actual use case and it should be validated by the system level integration test, along with technology development at the element and component levels. The CO2 reduction effect presented in the previous section assumes a so-called typical mission, but the effect of electrification is greatly influenced by the flight mission profile, and the optimal system configuration is expected to be different depending on it. In addition, the design of the protection system also has a large influence. It has a large impact on the system weight. MW class high-power electric system obviously requires reliable protection system, but no one have experience to implement it in the aircraft; It is still not flight proven. Therefore, it is important to conduct test demonstrations considering failure scenarios. The development of test facilities to respond to these is also one of the focuses in technology development..

4. Prior Technology Development Funded by the Japanese Government and Remaining Technical Challenges

IHI has conducted three commissioned projects from NEDO and has been working on technology development. The overview is described below.

4.1 First project: Research and Development Project for Advanced Aircraft Systems toward Practical Application / Research and Development for Next Generation More-Electric Engine System

In the research and development conducted from 2016 to 2020, IHI developed a 250kW Engine-Embedded Electric Machine (E3M) applying high heat resistance technology. For the proof of the concept, elemental testing and component testing was done, and the cooling structure and high heat-resistant insulation coating was tested. The picture is shown in Figure 3. In addition, for the proof of the concept of thermal and air management system, three activities were done: the first is the elemental testing of Fuel Cooled Air Cooler (FCAC) which is the structurally high reliable heat exchanger, the second is the concept verification of thermal integration of the aircraft and engine through fuel by simulator, and the third is elemental testing of power electronics air-cooling. The picture is shown in Figure 4.

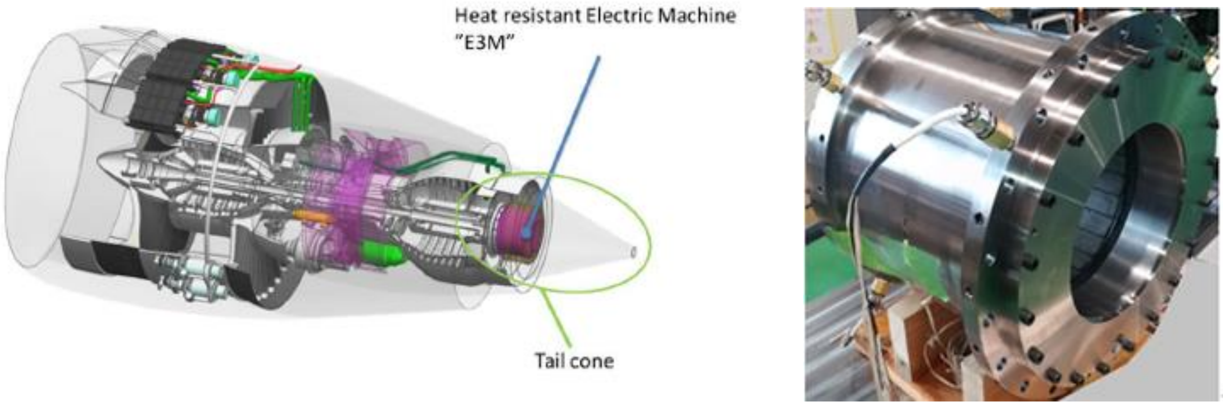


Figure 3 – 250kW E3M (Engine Embedded Electric Machine) [3].

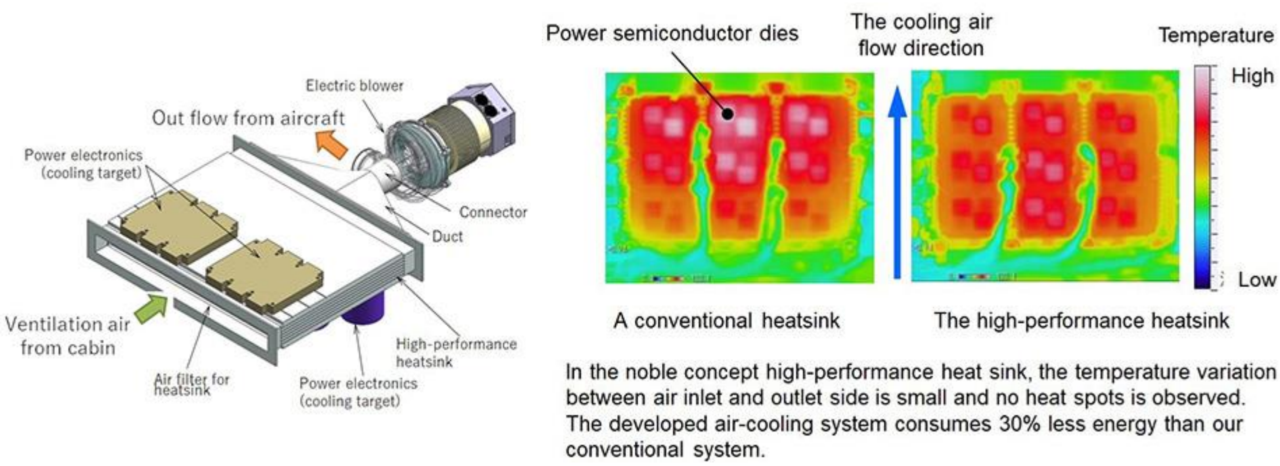


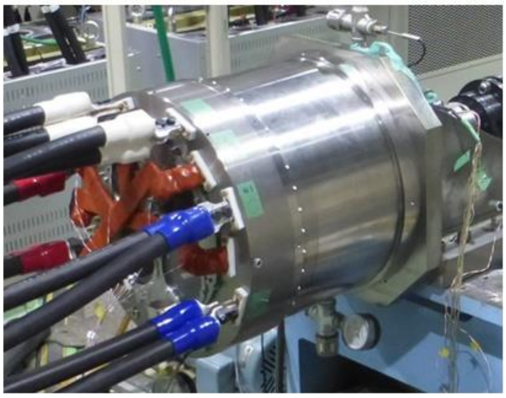
Figure 4 – Air-Cooling System for 100kW class Power Electronics [4].

4.2 Second project: NEDO Feasibility Study Program / Advanced Research Program for Energy and Environmental Technologies / Research and Development of Innovative Hybrid Flight System

In the research and development conducted from 2018 to 2020, a feasibility study of hybrid propulsion system was done. Concept study and concept design of large power generator was conducted, confirming that the maximum 2MW class E3M can be installed in the tail cone with considering mounting structure and cooling capability. In addition, concept study of energy recovery in the thermal and air management system was conducted, and the feasibility of in-vehicle thermal management considering MW-class hybrid electric propulsion with the combination of the air cooling system, energy recovery and fuel cooling was confirmed by the simulator.

4.3 Third project: Research and Development Project for Advanced Aircraft Systems toward Practical Application / Research and Development for Next Generation Electric-Propulsion System / Electric Hybrid System

In the research and development conducted from 2020 to 2024, IHI developed an MW-class E3M applying high heat resistance technology. Based on the basic design of a 2MW output generator, we manufactured a 1MW output prototype by halving the axial length and conducted test evaluations for performance confirmation through component tests and profile operation of the power system assuming electric hybrid propulsion, and stability of power control during that time. In addition, as system design validation of the thermal and air management system, IHI prepared a sub-scale thermal and air management system rig and confirmed the feasibility of energy recovery through tests simulating a high-altitude, low-pressure and low-temperature environment. Energy recovery ratio was confirmed over 40% of ETC compression power. Also, we prototyped a 70kW-class electric compressor applicable to both aircraft ECS and fuel cell air supply systems, and conducted system tests as a fuel cell air supply system to confirm its performance. IHI also conducted the power electronics air-cooling system test assuming the thermal severest condition and confirmed its cooling capability. The pictures of MW class E3M and 70kW class ETC is shown in Figure 5.



MW class E3M [5]

70kW class ETC [6]

Figure 5 – MW class E3M and 70kW class ETC.

4.4 Remaining Technical Challenge

Through these three programs, the concept verification of aircraft system electrification including the hybrid electric propulsion proposed by IHI is generally complete, and test verification for the supporting elemental technologies is also completed. However, the following technical challenges remain:

- Due to the testing facility restriction, full-scale demonstration of 1MW has not been carried out for both the electric power system and the generator.

- Due to the testing facility restriction, full-scale demonstration of the thermal and air management system has not been conducted.
- Integrated system demonstration tests have not been conducted. It is required for systems optimization and validation considering the use case.
- Durability and environmental compatibility demonstrations in both system and components are not completed yet.

In response to these technical challenges, the next National funding development program has started.

5. Technology Development Plan under the GI Fund Project

The Japanese government and the Ministry of Economy, Trade and Industry have established a 2 trillion yen "Green Innovation Fund" (hereinafter referred to as the "Fund") in the NEDO in the fiscal year 2020 supplementary budget, in line with the 2050 carbon neutral goal. This Fund supports companies showing commitment to specific goals and their efforts towards their achievement in areas where policy effects are significant and long-term efforts are necessary, envisioning social implementation, for 10 years, from research and development and demonstration to social implementation. As part of this, from April 2024, the "Green Innovation Fund Project / Development of Next Generation Aircraft / Development of Power Control, Thermal and Air Management System and Electrification Rate Improvement Technology / Development of Power Control and Thermal and Air Management System Technology" has started, with IHI as the main contractor for research and development.

In this research and development, both technical development at the key component level and technical demonstration at the system level will be done. As technical development at the key component level, MW-class generators applicable to HEP and high-output electric turbo compressor applicable to thermal and air management systems and air supply systems for fuel cells have been selected as the main development targets. Their performance, environmental compatibility and durability will be confirmed by test. Full-scale system demonstration of power control systems and thermal and air management systems is planned for the fiscal year 2028, and integrated system demonstration is planned to be conducted by the fiscal year 2030.

In addition, in the GI Fund Project, not only technical development but also support for the development of testing facilities is planned. In introducing the testing facilities, IHI is joining the discussion of introducing infrastructure in conjunction with the future aircraft industry strategy led by the Ministry of Economy, Trade and Industry, and in sync with this discussion, IHI is making a plan to introduce a full-scale demonstration infrastructure for aircraft electrification system. The Joint Research Center of Electric Architecture of Akita University and Akita Prefectural University is being mentioned as a candidate for the testing site, and IHI is advancing the discussions in collaboration with them.

Another major pillar of the project is standardization. Reflecting on the insufficient promotion of standardization in Japanese aviation industry so far, it is included in the project to surely implement new technology in society and strengthen the competitiveness of Japanese aviation industry. Regarding standardization activities, it is discussed and prepared formulating an international standardization strategy in Japan and establishing domestic coordinating organizations in the new technology public-private council for aircraft decarbonization co-sponsored by the Ministry of Economy, Trade and Industry and the Civil Aviation Bureau of the Ministry of Land, Infrastructure, Transport and Tourism. IHI will promote standardization activities in sync with these activities.

Through these activities, the goal is to achieve TRL6 by the fiscal year 2028; it is in line with the technology development roadmaps announced in the other various countries, and it is intended to introduce the technologies into next-generation aircraft.

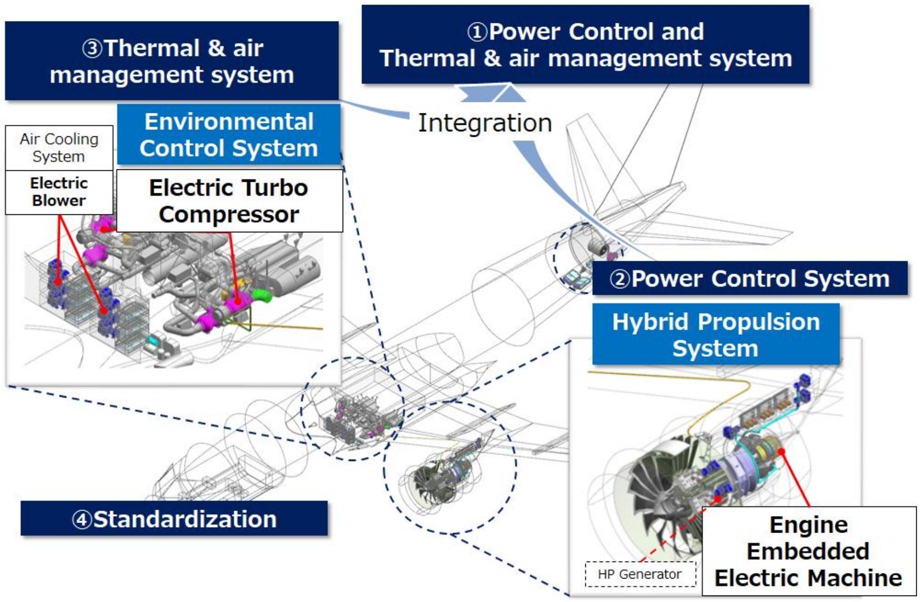


Figure 6 – Technology development items in GI fund project “Development of Power Control and Thermal and Air Management System Technology” [7].

Figure 7 – Development of System Testing Capability in Collaboration with Akita University and Akita Prefectural University

6. Future visions of the aircraft electrification

In the envisioned future of IHI’s aircraft electrification concept mentioned above, it was only shown a picture of incremental improvements. However, the technological developments conducted in the GI fund project can also be applied to disruptive future aircraft like hydrogen electric propulsion. It is important to note that electrification is a crucial technology underpinning them, and is an indispensable fundamental technology for future aircraft. IHI is working on research and development to realize a day when electrification systems using Japanese technology are widely applied and installed in aircraft flying around the world, and are recognized as significantly reducing carbon dioxide emissions.

7. Conclusion

To achieve decarbonization of air transportation by 2050, it is necessary to pursue all options for reducing fuel consumption. Electrification is one of the powerful means, and it has been analytically estimated that a combination of electric hybrid propulsion including the fuel cell APU and the thermal and air management system can reduce 5% of fuel consumption. Performance evaluations by the test have been done for the constituent technological elements. IHI has initiated technology development through the NEDO GI fund project, which is technology development in key component level and technology demonstration in system level, aiming to achieve TRL6 by 2028. This is for societal implementation towards the next-generation single-aisle aircraft expected in the 2030s.

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9. Copyright Statement

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