

Practical Development of Control Technology for the More Electric Engine

MORIOKA Noriko : Manager, Control Systems Engineering Department, Research & Engineering Division, Aero-Engine & Space Operations
KAKIUCHI Daiki : Control Systems Engineering Department, Research & Engineering Division, Aero-Engine & Space Operations
OZAWA Kanji : Manager, Engine Technology Department, Research & Engineering Division, Aero-Engine & Space Operations
SEKI Naoki : Engine Technology Department, Research & Engineering Division, Aero-Engine & Space Operations
OYORI Hitoshi : Manager, Electrical Technologies Office, Technologies Development Department, IHI AEROSPACE Co., Ltd.

The More Electric Engine (MEE) is a next generation turbofan engine that will lead engine control for MEA (More Electric Aircraft) in the 21st century. Recently, IHI has started investigations and studies in order to meet the challenge of creating “an ECO-friendly engine for the future.” This paper overviews the IHI MEE and reveals details of IHI’s “Green Innovations.”

1. Introduction

In the aviation industry, improving the efficiency of aircraft and their engines has become an important issue from the standpoint of the environment, specifically the prevention of global warming. MEE (More Electric Engine) is a technology that will bring about reductions in engine weight and improvements in engine efficiency in conjunction with the elimination of engine bleed from engines and the electrification of flight control systems, which are introduced by MEA (More Electric Aircraft).

IHI MEE is aimed at developing control systems to improve fuel system efficiency and reducing the size and weight of components with high voltage electrification technology. Electrification of engine control systems improves fuel consumption and reduces CO₂ emissions from aircraft, making it possible to achieve flight operating cost reduction, which is a customer requirement.

2. Overview of MEE development

2.1 Background of development

This study is aimed at the practical application of MEE control technology, which focuses on fuel systems, power systems, and other engine control systems, to improve fuel consumption and reduce CO₂ emissions. Aircraft manufacturers have already introduced high voltage electric power systems for practical application of MEA and employed a starter generator, which combines an electric engine starter and generator, electric actuator, and electric ECS (Environment Control System) in their Boeing 787 (The Boeing Company, U.S.) or Airbus A380 (Airbus S.A.S., France).

Key concepts of MEA are the integration of electric power management and the elimination of engine bleed. It provides ① improved fuel consumption, ② improved on-time departure rate, ③ improved passenger satisfaction with cleaner cabin air, and ④ easier maintenance and inspection.⁽¹⁾ MEE is a technology that improves engine efficiency and reduces engine weight in conjunction with MEA.

2.2 Benefits of MEE

(1) Improvement of engine efficiency

To reduce the circulation of excess fuel, the rotational speed of the fuel pump driven by an electric motor is directly controlled to adjust the fuel flow. This provides improved engine efficiency with less engine power being consumed by the fuel pump.

(2) Elimination of accessory gearboxes, hydraulic systems, and pneumatic systems

In the present system, components such as pumps and generators are driven by engine power, which is mechanically extracted from the engine via an accessory gearbox. In addition, the engine is started by a pneumatic engine starter installed in the accessory gearbox. Electrification of these components enables the reduction of mechanical power transmission mechanisms such as accessory gearboxes as well as the reduction of hydraulic and pneumatic lines.

(3) Reduction of air resistance on aircraft

In addition to the elimination of the accessory gearbox, a starter generator is installed inside the engine. It reduces air resistance on aircraft with a reduced frontal projected area.

- (4) Optimization of idle engine rotational speed on the ground

During an engine run-up or while an aircraft is taxiing on the ground, a large portion of the engine output power is consumed by the aircraft system. To absorb this fluctuation in the load demand by the aircraft system, the engine rotational speed must be set high. If the load fluctuation can be compensated for by electric power management, the engine rotational speed on the ground can be set lower.

- (5) Facilitation of accessory maintenance work

Electrification reduces the installation and removal work of hydraulic pipes, making it possible to replace accessories in a shorter time. In addition, electrification reduces the amount of oil drained, enabling environmentally friendly, clean maintenance work.

2.3 IHI MEE development steps (Fig. 1)⁽²⁾

- (1) Step 1: Electric fuel system

An electric motor-driven fuel pump is introduced, and a generator is installed in the accessory gearbox, which was conventionally used to drive the fuel pump. The electric power from the generator is used to drive the electric fuel pump. In addition, the hydraulic actuators used to drive variable geometries, such as variable stator vanes, are electrified (Fig. 1-(a)).

- (2) Step 2: Starter generator and full electrification

Full electrification eliminates the need for the accessory gearbox, so the engine output shaft is connected to the generator without the accessory gearbox. The generator is used as a starter generator to ① start the engine, ② generate electric power for the aircraft, and ③ generate electric power for the engine accessories (Fig. 1-(b)).

- (3) Step 3: Embedded starter generator

The starter generator is embedded inside the engine. The engine components are distributed, providing the highest engine efficiency with the smallest projected engine area (Fig. 1-(c)).

3. Concepts of IHI MEE

3.1 Fuel system

Figure 2 shows a comparison between the IHI MEE fuel system and a conventional fuel system. The fuel system using a fixed displacement fuel pump driven by an accessory gearbox is used mainly for commercial aircraft engines. The accessory gearbox-driven fuel pump discharges fuel in proportion to the engine rotational speed and when the pump discharge flow exceeds the engine required fuel flow, the system bypasses and circulates excess fuel to the pump inlet. Such recirculation unnecessarily consumes engine horsepower, causing the fuel temperature to increase due to the consumed energy. As the fuel temperature increases, it causes a decrease in the cooling performance of the fuel-cooled oil cooler, which uses fuel as coolant. To compensate for the decrease in performance, an air-cooled oil cooler, which uses fan discharge air as its cooling medium, is needed. However, the air-cooled oil cooler exhausts the fan discharge air into the atmosphere, resulting in deteriorated fuel consumption (SFC) with reduced engine fan efficiency.

The IHI MEE fuel system uses an electric motor to drive a gear pump type fuel pump and controls the fuel flow based on the motor rotational speed. This can reduce engine power extraction as shown in Fig. 3.⁽³⁾ In addition, the fuel temperature can be prevented from increasing, and the cooling performance of the fuel-cooled oil cooler increases, eliminating the extraction of fan discharge air by the air-cooled oil cooler. Figure 4 shows a heat management analysis model. The above enables the provision of a high-efficiency engine system.⁽³⁾ In comparison with other pump systems for which efforts are being made to improve the efficiency, as shown in Fig. 5, the IHI MEE fuel system has higher efficiency than other fuel systems with a variable displacement pump⁽⁴⁾ and a centrifugal pump.⁽⁵⁾ In other words, the IHI MEE fuel system is the most efficient fuel system with optimized heat management. In addition, the

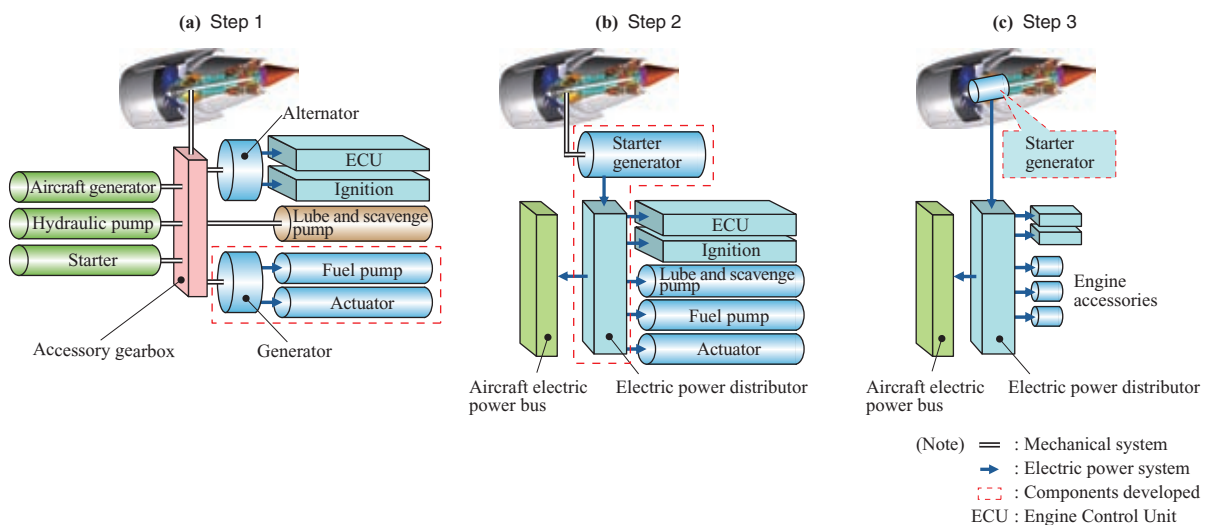


Fig. 1 Steps in development of IHI MEE

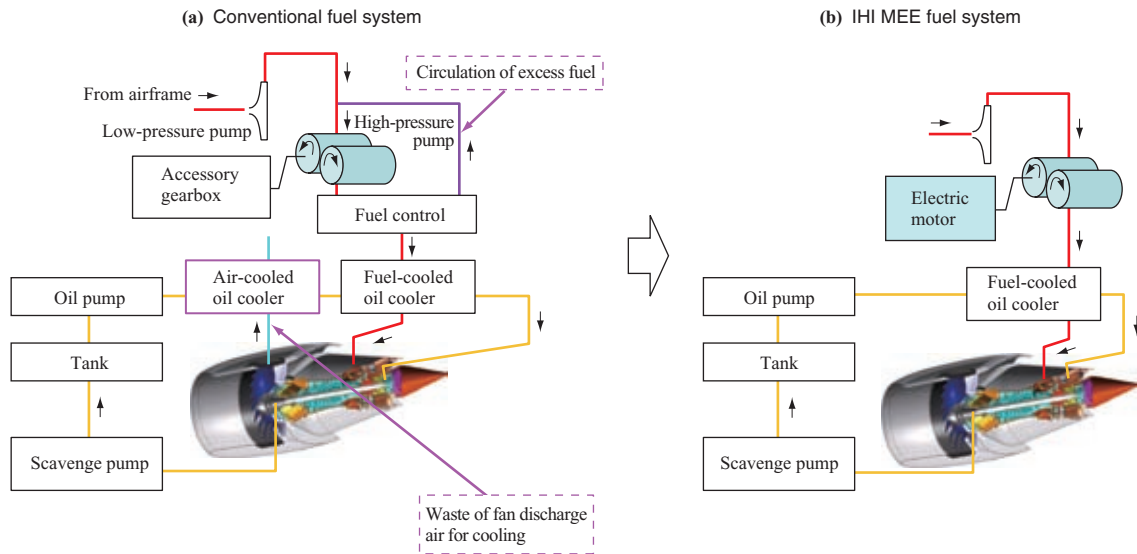
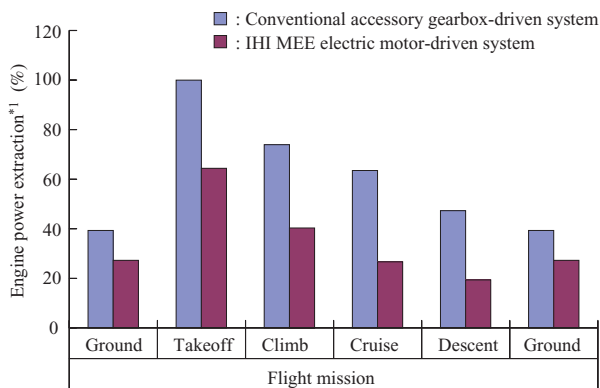


Fig. 2 Schematic of the proposed IHI MEE system



(Note) *1 : The engine power extraction when an aircraft with an accessory gearbox taking off is taken to be 100%.

Fig. 3 Reduction in power extracted from engine

IHI MEE fuel system, unlike conventional systems with a fuel metering mechanism, does not require complicated mechanisms involving metering valves and pressure control valves, and therefore has a simple construction, which contributes to improved reliability and maintainability with fewer components and hydraulic lines.

We calculated the improvement effect of the improved fuel system efficiency on the fuel consumption with a typical small engine,⁽⁵⁾ and found that the fuel consumption decreased by about 0.4% through the reduction of engine power extraction with an optimized fuel pump drive, and by about 0.6% through the reduction of fan discharge air loss by the elimination of the air-cooled oil cooler, which means that the total fuel consumption reduction is about 1%.⁽³⁾ Figure 6 shows the SFC improvement effect in IHI MEE step 1.

3.2 Effects on engine performance

3.2.1 Effects of the elimination of the fuel metering mechanism on engine response

The conventional system, which uses a metering valve and pressure control valve in the fuel metering mechanism to measure the fuel flow, responds extremely quickly to

change the fuel flow as compared to the required response time of the engine rotational speed. However, the IHI MEE system controls the fuel flow based on the motor rotational speed, which drives the pump, and therefore, the fuel flow response time is affected by the motor acceleration/deceleration time response. Because electric motors have a greater moment of inertia than the moving parts of valves, electric motors are considered inferior in terms of quick response. Figure 7 shows the results of analysis of the time response of fuel flow rate carried out for this evaluation.

The analysis results show that the control with a motor responds as quickly to changes in the fuel flow as the control with a conventional fuel metering mechanism, and has an adequate response for engine control. In other words, the IHI MEE system is believed to have the same engine control response as conventional systems.

3.2.2 Effects of increases in the required electric power on engine performance

It is estimated that MEA and MEE increase the electric power required by aircraft, which significantly increases the engine power extraction for power generation. A generator with increased capacity has been employed to deal with increases in the required electric power, and as shown in Fig. 8, the larger generator can work as an engine starter, instead of a conventional pneumatic starter.

However, increased engine power extraction could make engine control unstable. Figure 9 shows the effect of increased engine power extraction. As suggested by the analysis result in Fig. 9-(a), if the engine power is extracted from the high-pressure shaft as in conventional engines, as the power extraction increases, the low-pressure compressor operating line moves up and closer to the surge line (boundary line of the area where the balance between the flow of air flowing into the compressor and the pressure ratio becomes unstable and the compressor malfunctions), causing the surge margin to decrease. As a solution to this, the authors are studying a method by which the power is

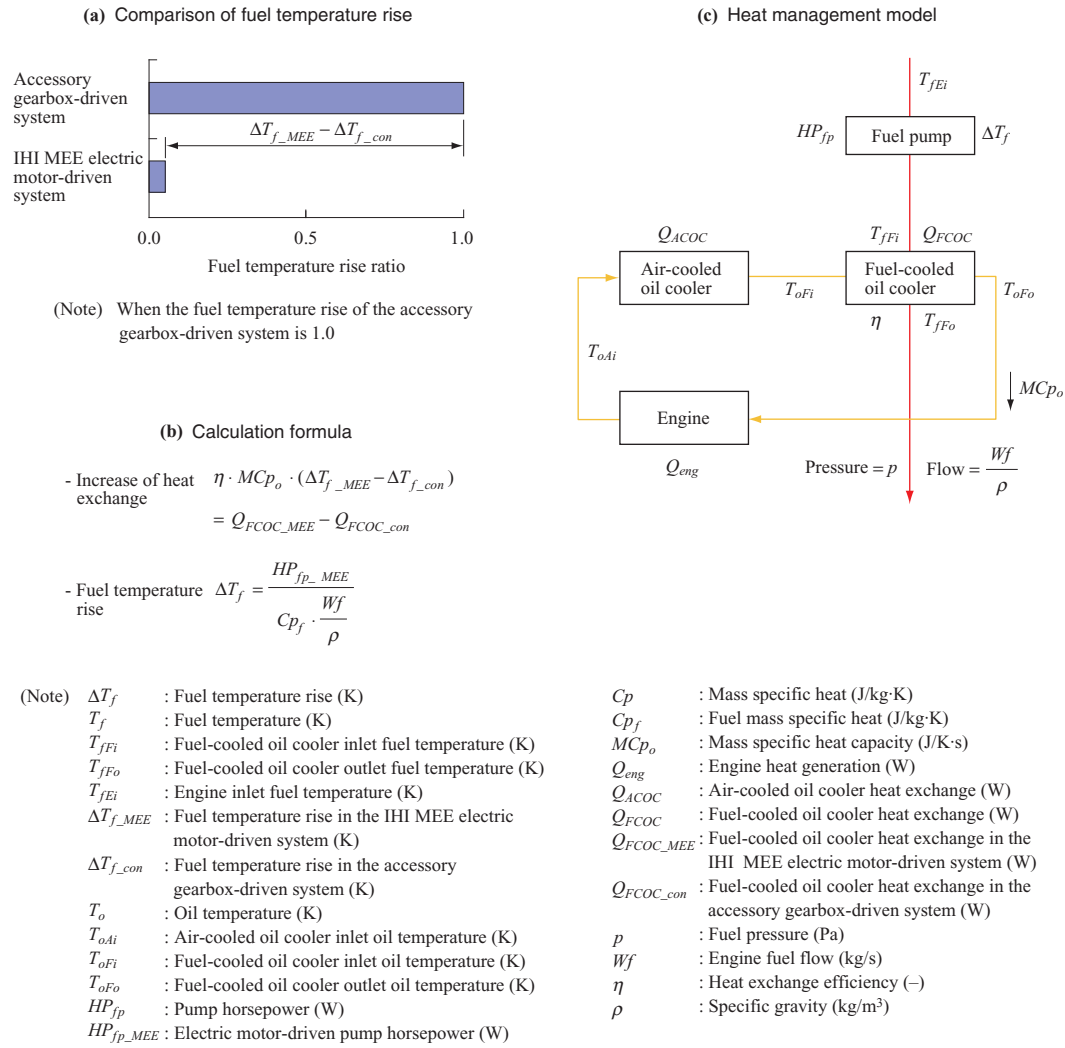


Fig. 4 Heat-management analysis model

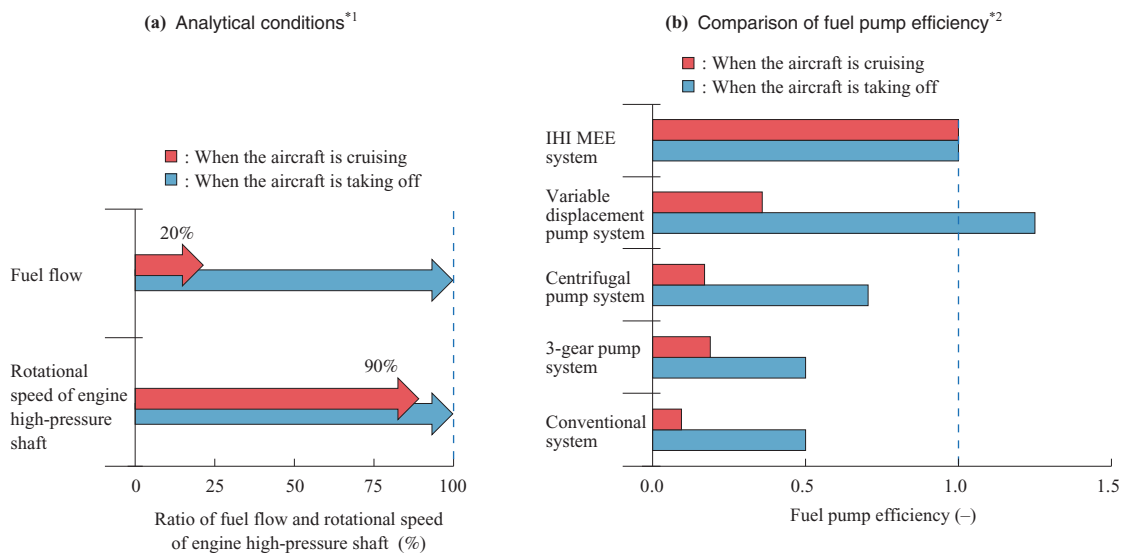
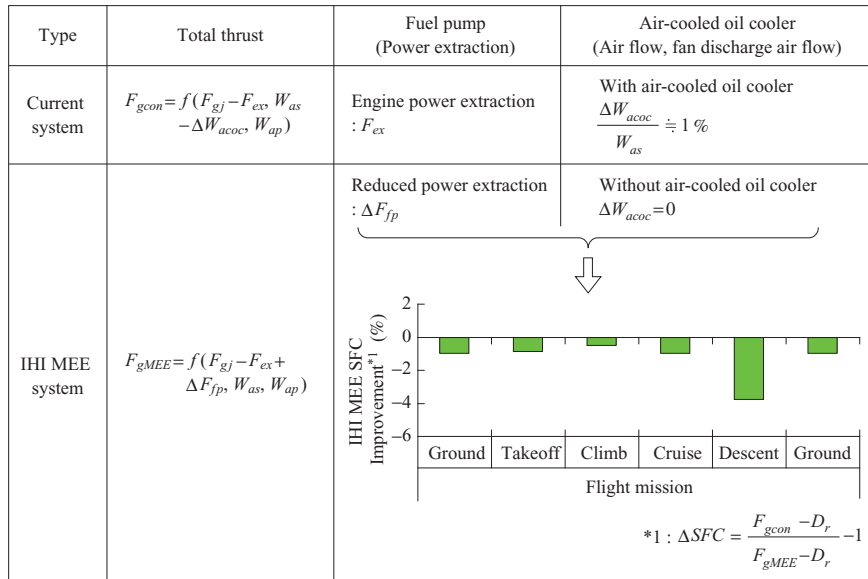


Fig. 5 Calculated efficiency of various fuel systems



(Note) F_{gcon} : Current system total thrust
 F_{gMEE} : IHI MEE total thrust
 D_r : Drag
 ΔF_{fp} : Power extraction reduction
 F_{gj} : Core total thrust
 W_{ap} : Core air flow
 W_{as} : Bypass air flow
 ΔW_{acoc} : ACOC (air-cooled oil cooler) fan discharge air flow

Fig. 6 SFC reduction accomplished by using IHI MEE step 1

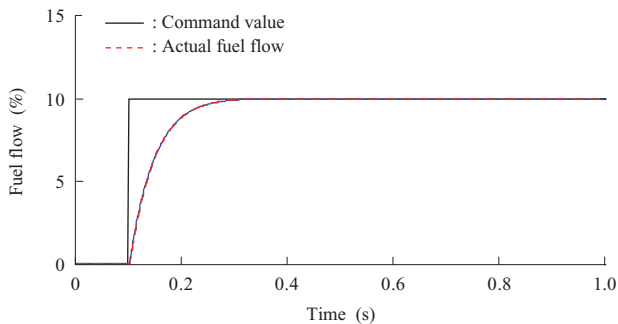


Fig. 7 Engine transient simulation of the IHI MEE metering system

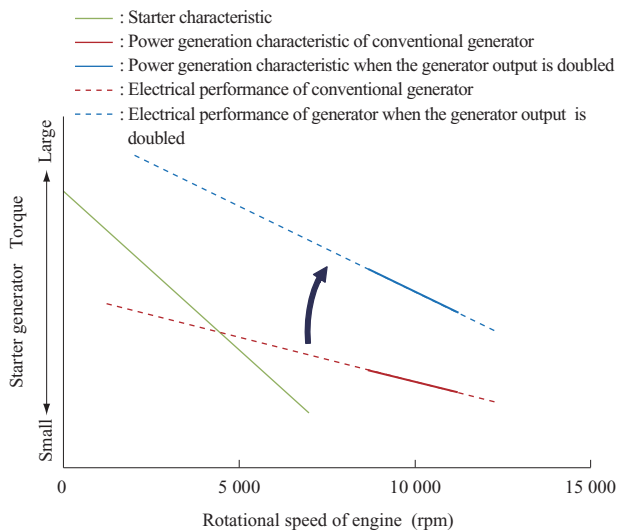


Fig. 8 Torque-speed characteristics of engine starter and aircraft generator

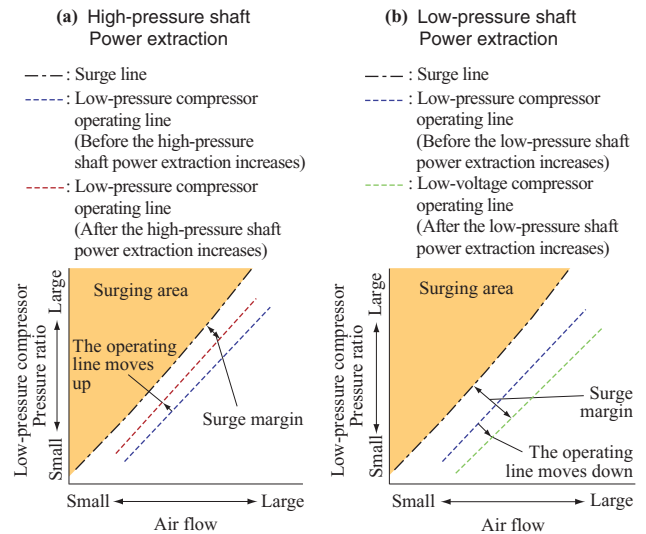


Fig. 9 Analysis of effect of increase in power extraction from engine

extracted from the low-pressure shaft.

As a result of analysis with a typical small engine, it was found that when the engine power extracted from the low-pressure shaft is increased, the operating line moves in a direction such that the surge margin increases (Fig. 9-(b)), but the efficiency has a reverse characteristic, which means that power extraction from the low-pressure shaft is not necessarily the best solution. Selecting which shaft to extract engine power from for the generator will be an important design issue for MEA and MEE to address increases in the required electric power.

4. Advanced technologies and future tasks for IHI MEE

Our future task for IHI MEE is to improve efficiency, reduce size and weight, and further improve reliability and safety of the aircraft engines. To accomplish this task, we are developing technologies to make higher voltage available and simplify fuel metering systems and power generation systems.

4.1 Introduction of high-voltage active-active control

The technology to increase the voltage to 270 VDC, which has been applied to MEA to improve the efficiency, is an essential technology for IHI MEE as well. In the 1990s, the IHI Group developed and put to practical use a high-voltage (270 VDC) electric control system for ELVs (Expendable Launch Vehicles).⁽⁶⁾ For IHI MEE, in order to apply this technology to aircraft engines, redundant system design is required for increased safety.

IHI MEE employs active-active control to increase safety and minimize weight increment.⁽²⁾ Active-active control, unlike active-standby control, instantaneously avoids a loss of control when a failure occurs and allows all redundant systems to operate in a normal state so as to distribute loads, reduce current loss, and contribute to improving the efficiency and reducing the weight of the entire system. The following describes key technologies being studied for practical use.

(1) Current control of multi-wound motors⁽⁷⁾

This uses the servo theory and is an electric current control technology that uses active-active control with a redundant configuration where two windings are

used such that if one of them fails, the current flowing in the other is doubled. The sum of the current flowing in the two windings is fed back to the current servo to instantaneously compensate for the current decrease and reduce the fail-over time (Fig. 10).

(2) Current phase control of a faulty motor⁽⁷⁾

IHI MEE employs digital technology for current phase control of three-phase motors to increase the motor safety and provide a fail-safe system where, if one phase fails, control is provided by the other two phases. Three-phase motors have an oval-shape current vector when one phase fails, but digital control is provided so that they have a circular current vector, which enables smooth motor rotational speed control (Fig. 11).

(3) Speed summing actuator⁽⁸⁾

Electromechanical actuators have a simple structure without hydraulic devices, but require handling of a jamming failure, which is typically seizure of the reduction gears. Typically, the clutch is disengaged if a gear gets seized, but the reliability and weight of the clutch mechanism itself become issues. In addition, when active-active control is configured, if two output motor shafts are directly connected to each other, each servo system has an error and the calculated output torque of one system contradicts that of the other system, which causes the two forces to fight with each other, resulting in vibration.

To solve this problem, IHI MEE employs a technology that connects the motor output shafts not based on the force, but based on the speed. A speed summing

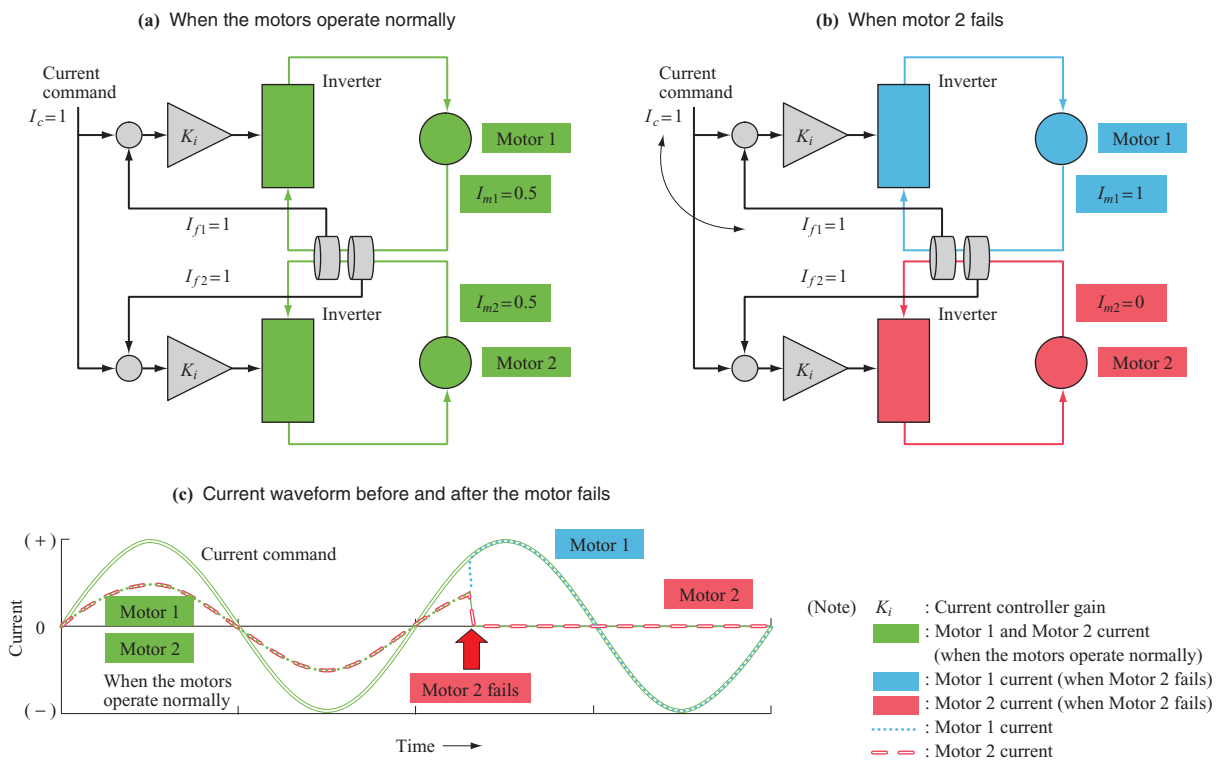


Fig. 10 Schematics of redundant motor current control system

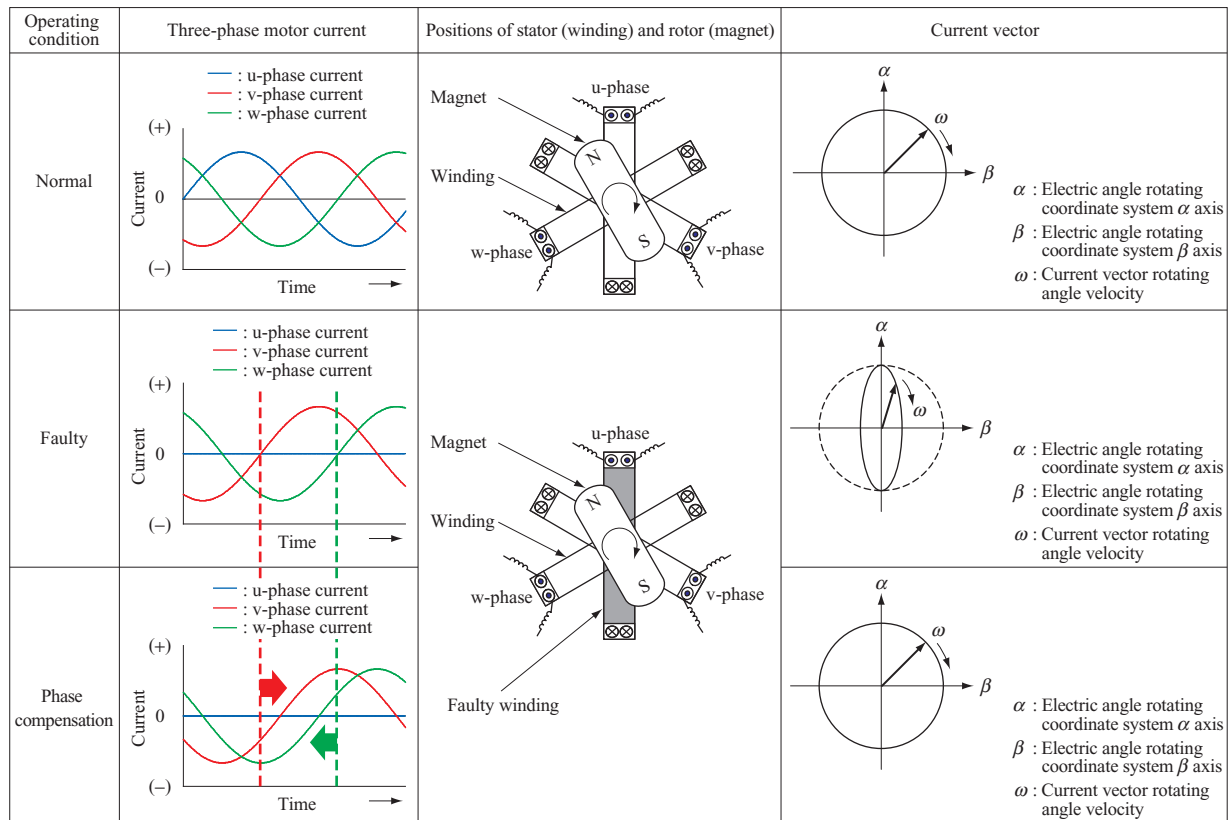


Fig. 11 Phase control for faulty motors

mechanism (the sum of the input speeds is equal to the output speed) is configured with a ball screw mechanism. One of the motor output shafts is attached to a screw lead, and the other is attached to a ball nut. The result is that the total output speed from the actuator is equal to the sum of the speed of the two output shafts, which allows for weight reduction (Fig. 12).

4.2 Development of a new fuel metering system⁽³⁾

IHI MEE uses an electric motor to drive a fuel pump and controls fuel flow by changing the motor rotational speed. Conventional systems use a hydraulic mechanism with a metering valve and pressure regulating valve to control the fuel flow, providing high response and accuracy. In the IHI MEE system, the fuel flow response and metering accuracy depend on the motor response characteristics and fuel flow feedback accuracy, respectively (Fig. 13). To improve motor response, a direct-drive motor is used to drive the fuel pump, and in addition, the motor-driven pump is designed to have improved reliability.

In order to accurately measure the fuel flow with an electric motor-driven fixed displacement fuel pump, there is a need to compensate for changes in the pump volumetric efficiency due to changes in the fuel temperature or long operation times. The most reliable method is feed-back control of the fuel flow to the motor rotational speed control. One way to measure the fuel flow is using a high-accuracy flow sensor to directly measure fuel flow, but in this case, there is a need to prevent pressure loss caused

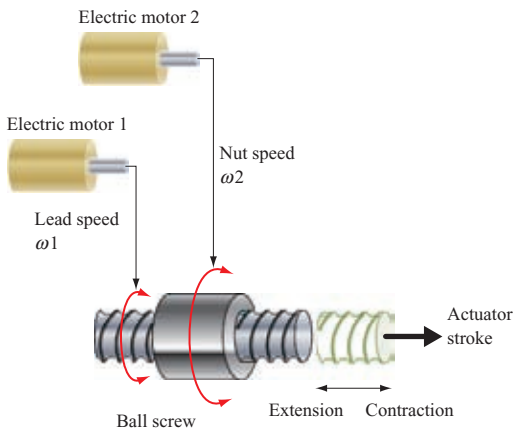
by installing a flow sensor in the fuel passage, which means that the sensor must be a non-contact sensor. At the present time, however, there are many issues in terms of measurement accuracy and installability regarding the non-contact sensors.

In order to simplify the fuel system configuration to the maximum extent possible, IHI MEE places a valve mechanism downstream of the pump and measures the pressure difference between the upstream and downstream of the valve mechanism to reflect the measured data in the fuel flow control. In this measuring system, the valve mechanism is designed so that the differential pressure can be measured accurately in all ranges from the low flow range to the high flow range. In the low flow range, the valve mechanism produces sufficient differential pressure so as to ensure high measurement accuracy by a differential pressure sensor. In the high flow range, the valve mechanism maintains the pump outlet pressure so that it does not get too high, meaning that both measurement accuracy and high efficiency of the pump system can be achieved. This is a new fuel control system that eliminates complicated fuel metering units, which is to say, it is a simple, reliable fuel system, which is one of the key concepts of IHI MEE.

4.3 Application of permanent magnet generator technology⁽⁷⁾

For IHI MEE, in order to develop a small, lightweight generator that can deal with increases in the required electric power output, the authors are studying permanent

(a) Principle of speed summing active-active control mechanism



(b) Operation test result of speed summing active-active control

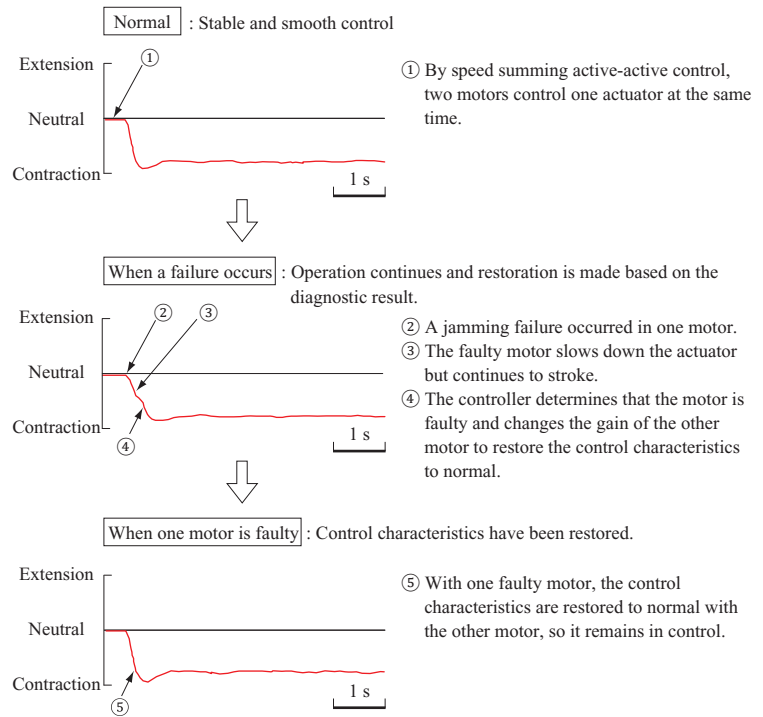
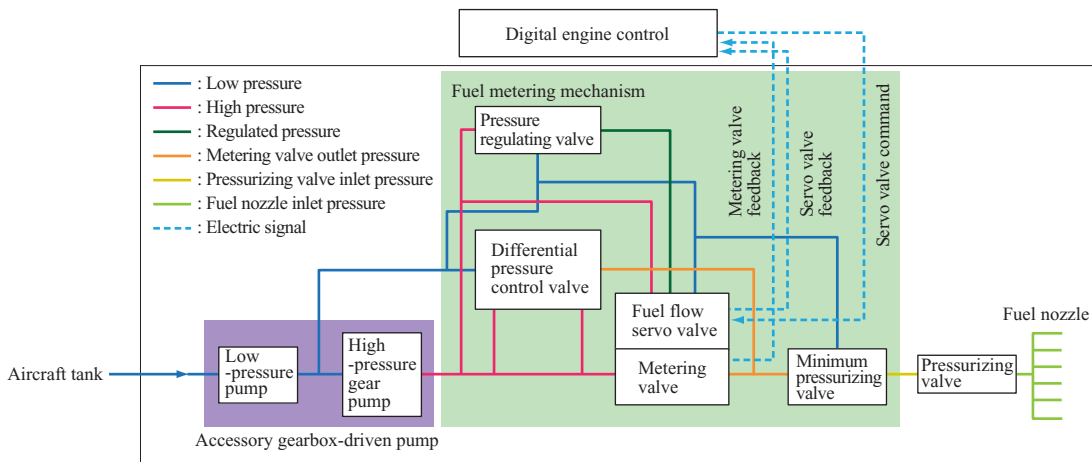


Fig. 12 Speed summing actuator

(a) Conventional system



(b) IHI MEE system

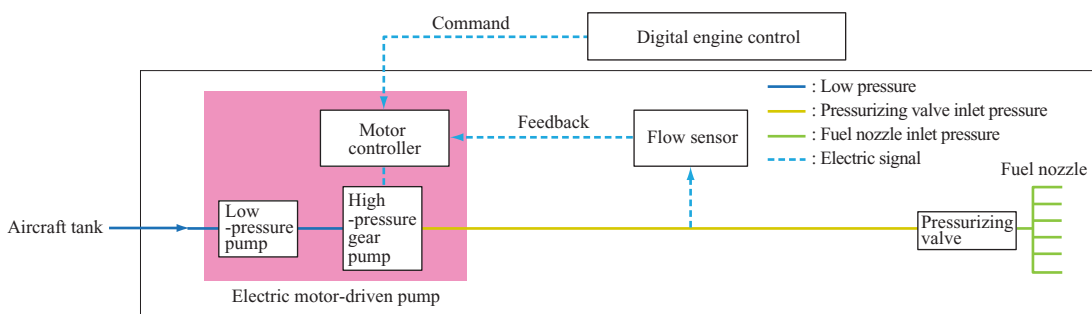


Fig. 13 Schematics of IHI MEE fuel metering system

magnet generators, which are expected to be lighter than conventional generators by 20%.

Conventional aircraft generators consist of ① an exciter generator, ② a generator that transfers the exciter power from the stator to the rotor via the generator controller, and ③ a main generator that uses the exciter power, and they have a function to cut off power if a short circuit failure occurs on the load side or inside the generator. The output current of each generator is monitored by the generator controller, and when an error occurs, the exciter power is cut off. When a permanent magnet generator is used, an alternative method for this cutoff function must be provided, which proved to be an issue.

In order to equip a permanent magnet generator with the cutoff function, we are studying the neutral point breaker system, which has a function equivalent to the power generation stop function. Using the configuration shown in Fig. 14, it becomes possible to cut off current when a short circuit failure occurs inside the generator, although it is not possible with conventional permanent magnet generators.⁽⁷⁾

4.4 Issues for larger systems⁽⁹⁾

It is estimated that application of IHI MEE to a typical small engine will not cause the weight to increase significantly, considering elimination of components and parts.⁽¹⁾ However, it is believed that application to medium

and large engines requires further weight reduction. Based on the current technology, as shown in Fig. 15, the weight of the electric fuel pump alone calculated for large engines is larger than the weight of the current accessory gearbox-driven pump. Methods are necessary to reduce the weight of the electric fuel pump system by increasing the motor rotational speed, to reduce the size of the controller, and at the same time, apply advanced power devices.⁽⁹⁾

5. Conclusion

This paper describes an overview of the development of IHI MEE, technical features, and efforts for introduction of advanced technologies. IHI MEE is expected to meet the environmental and economical requirements, which are global requirements, and represents the next generation of aircraft engine systems. IHI MEE will continue to make great contributions to the world with our technologies, focusing on the more electric engine control system architecture.

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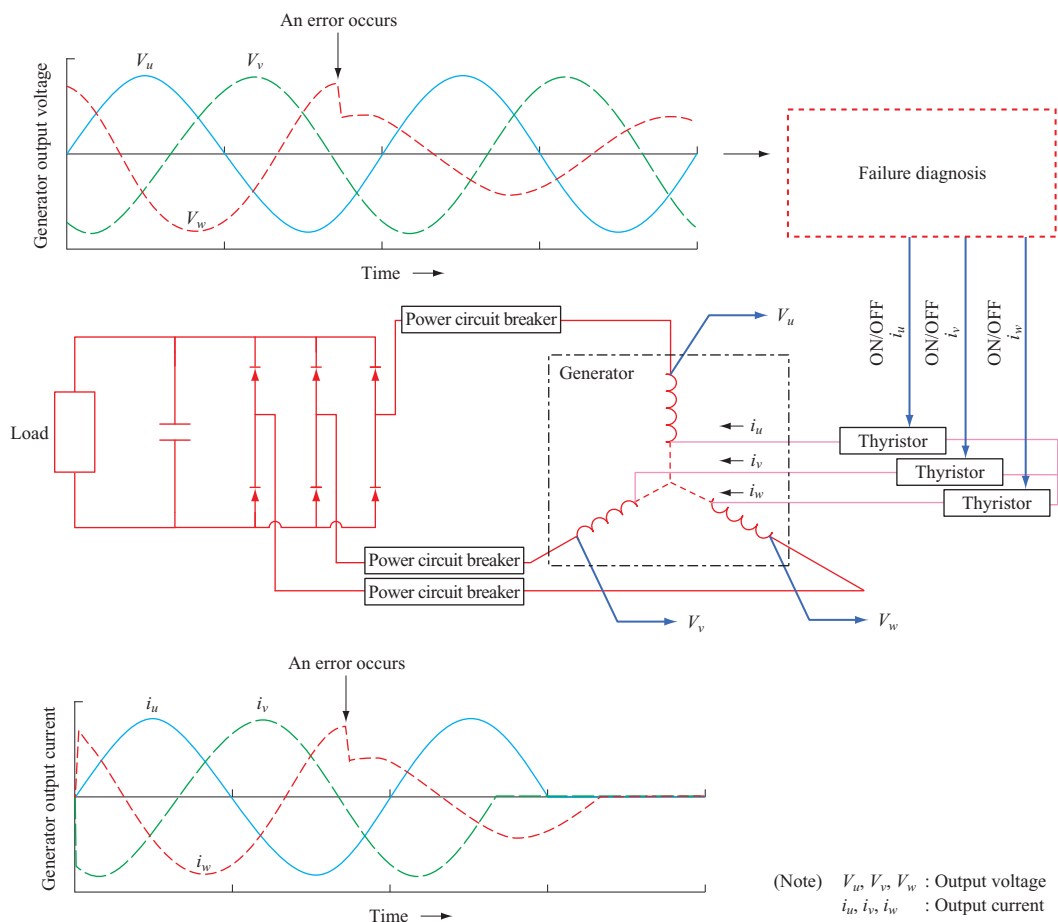


Fig. 14 Schematic of generator shutdown mechanism using permanent magnets

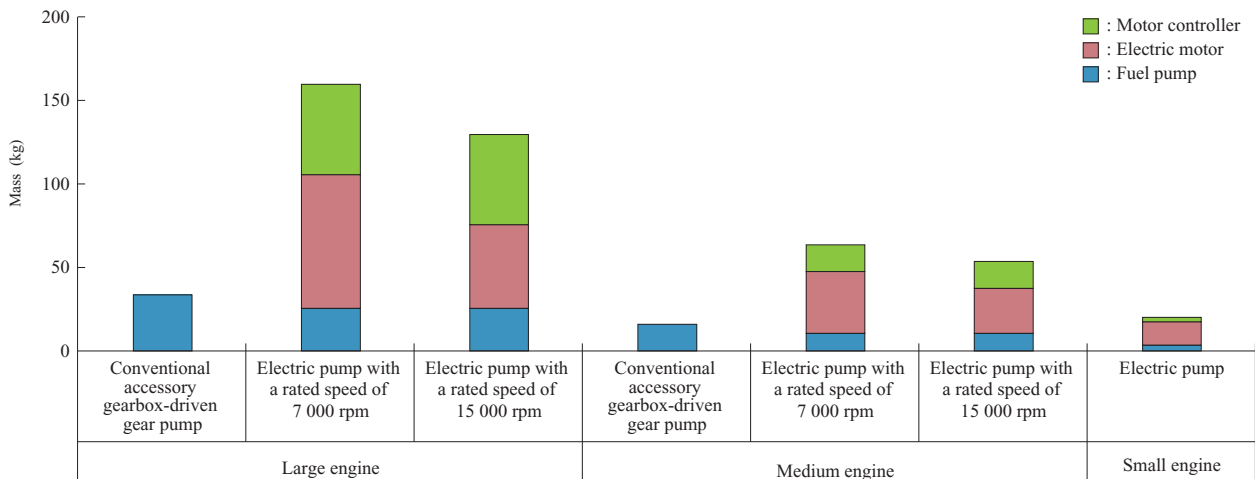


Fig. 15 Weight of fuel pump for medium and large engines

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