Electromagnetic Design of Electric Motor for Crankshaft-mounted Integrated Starter-Generator System of 48V Hybrid Vehicles

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Recently, electric vehicles (EVs) and hybrid electric vehicles (HEVs) have been rapidly spreading in the automobile market for reducing CO_2 emissions. In line with this trend, Mitsubishi Electric Corporation has developed and released a small and lightweight high-efficiency crankshaft-mounted 48V-integrated starter-generator (ISG) system for mild-HEVs. This paper describes the characteristics of this system and the electromagnetic design of electric motors.

1. Characteristics of the Crankshaft-Mounted 48V-ISG System

1.1 Outline of the crankshaft-mounted 48V-ISG system

Figure 1 illustrates the configuration of this system. As the structure of this system, an electric motor is installed between the engine and transmission. The electric motor rotor is directly connected to the crankshaft, which enables the driving force of the electric motor to be directly transmitted, resulting in high torque transmission and shorter response time of the torque. However, the magnetic circuit needs to be formed in a thin, flat, and cylindrical limited space due to the layout restrictions of the engine room and for weight reduction.

1.2 Outline of electric motors for the 48V-ISG system

HEVs powered by engines and electric motors are broadly divided into full-HEVs and mild-HEVs depending on the functions. Full-HEVs can drive only on the electric motor with the engine stopped, which is expected to significantly improve the fuel economy. On the other hand, mild-HEVs do not drive only on the electric motor, and have a torque assist and other functions for energy regeneration from decelerating vehicles. Mild-HEVs are characterized by a simple system. The total cost of 48V mild-HEVs in particular is lower compared to high-voltage systems and they are expected to spread more rapidly.

The 48V-ISG system for mild-HEVs can improve the fuel economy by performing restart of the engine, energy regeneration from the decelerating vehicle, and torque assist under acceleration. Figure 2 shows our 48V-ISG system. The electric motor is thin and flat and the inverter is mounted to the electric motor housing.

2. Electromagnetic Design of Electric Motors for the 48V-ISG System

2.1 Performance requirements

Figure 3 shows the performance requirements for electric motors for the 48V-ISG system. To restart an engine, high torque is required in the low-speed range. For torque assist under acceleration, the efficiency needs to be higher in the low-torque range from the low- to medium-speed ranges for higher fuel economy. During energy regeneration from decelerating vehicles, high power regeneration from the low- to medium-

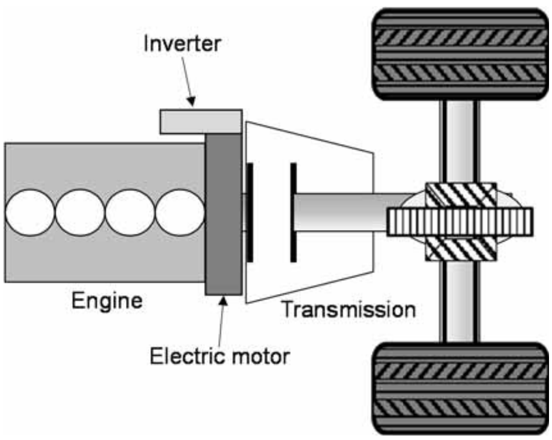

Fig. 1 Engine crankshaft direct-driven system

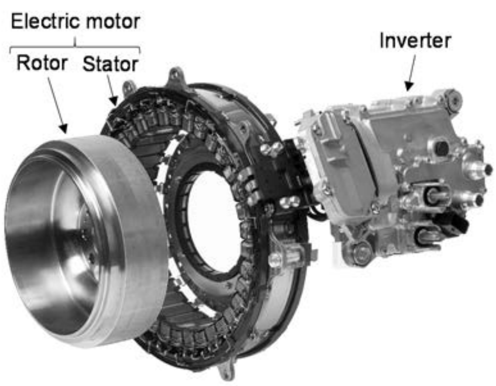

Fig. 2 Crankshaft ISG system for 48V hybrid

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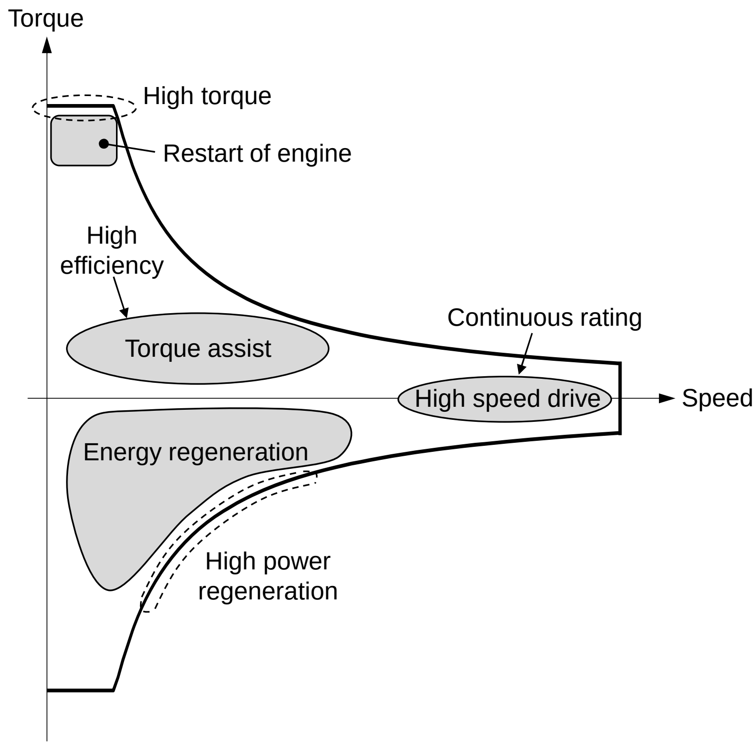


Fig. 3 Performance requirements for electric motor of 48V ISG system

speed ranges is required. In addition, since the engine power is transmitted via the rotor in this system, the system needs to function throughout the entire operation range of the engine and continuous rating is required even in the high-speed range. Thus, the system requires high torque and high power regeneration and must also be highly efficient in the low-torque range from the low- to medium-speed ranges. Therefore, the system uses permanent magnet synchronous motors for a motor system since such motors deliver high torque and high power regeneration. However, to enable continuous rating of a permanent magnet synchronous motor to the maximum engine speed at a low voltage of 48 V, current needs to be supplied to decrease the induced electromotive force (magnetic flux-weakening control). Therefore, reducing the current for performing magnetic flux-weakening control is a key point in the electromagnetic design of this system.

2.2 Consideration of the winding structure

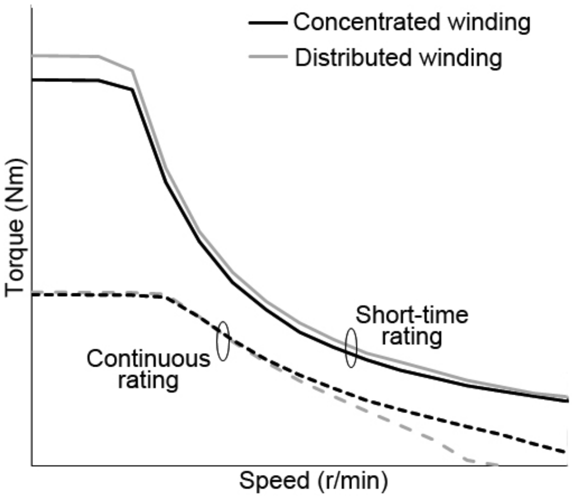
The winding structure of electric motors is broadly divided into concentrated winding where a coil is formed around one tooth and distributed winding where a coil is formed around multiple teeth. This section describes the appropriate winding structure for electric motors for the 48V-ISG system.

Figure 4 shows the electromagnetic field analysis results of systems with each winding structure. The short-time rating in Fig. 4(a) shows the speed-torque characteristic at the maximum current. The continuous rating in Fig. 4(a) shows the speed-torque characteristic at the same current density supposing continuous rating. The figure shows that the short-time rating on the distributed winding is higher than that of the concentrated winding at any speed. The reluctance torque on the distributed winding is higher than that on the concentrated winding and as a result, the distributed winding can realize high torque and high power. However, in terms of the continuous rating, the torque is higher on the concentrated winding in the medium- to high-speed ranges. This is because the current for performing magnetic flux-weakening control could be reduced. This result is also seen in the efficiency characteristics in Fig. 4(b) and 4(c). On the concentrated winding, the high efficiency range could be enlarged to the high-speed range by reducing the copper loss due to the current for performing the magnetic flux-weakening control.

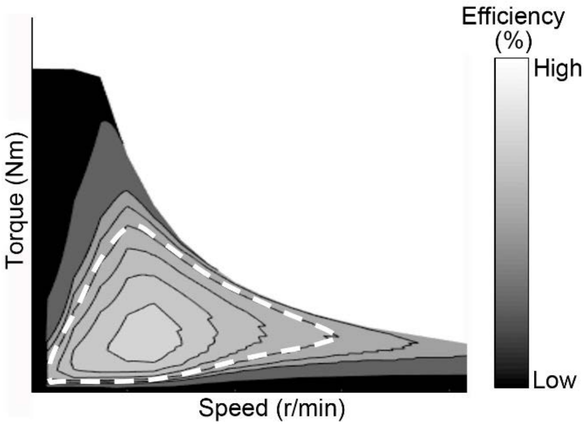
2.3 Consideration of increasing number of pole pairs

Adopting concentrated winding can shorten the coil end. In addition, increasing number of pole pairs can further reduce the height of the coil end and the area of the iron core necessary for forming a magnetic circuit. Therefore, to satisfy the performance requirements in a limited space like in this system, it may be effective to use the concentrated winding and increasing number of pole pairs. However, since increasing number of pole pairs increase the electrical angular frequency of electric motors, the increase in iron loss is of concern. Since the number of poles is thus an important parameter in the electromagnetic design, this section describes the relationship between the performance requirements and number of poles.

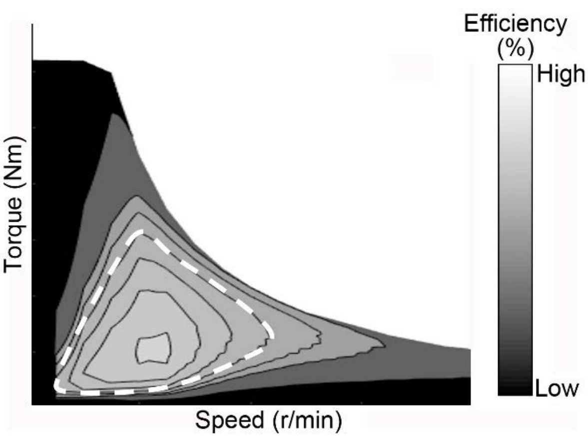
Figure 5 shows the electromagnetic field analysis results of the maximum torque and maximum generated power electric motors having different numbers of poles. The maximum torque shown in Fig. 5(a) increased due to the increasing number of pole pairs. However, the figure shows that when the number of poles reaches a certain number, the maximum torque no longer increases even when the number of poles is increased. Since increasing number of pole pairs can reduce the area of the iron core forming a magnetic circuit necessary for electric motors, the torque can be increased by relieving the magnetic saturation of each part and enlarging the rotor diameter. Meanwhile, increasing number of pole pairs increase the number of slots and thereby the leakage magnetic flux between the slots of the stator also increases. This trade-off results in the trend as shown in Fig. 5(a). Figure 5(b) shows that the maximum generated power is lower when the number of poles is large. As mentioned previously,



(a) Short-time rating and continuous rating

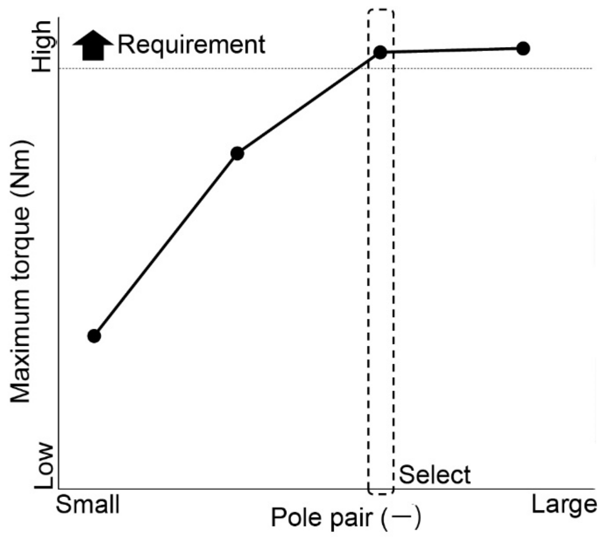


(b) Efficiency characteristics of concentrated winding

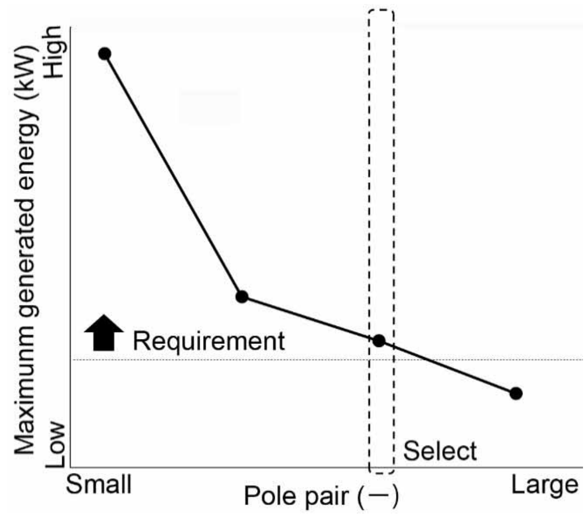


(c) Efficiency characteristics of distributed winding

Fig. 4 Comparison between concentrated winding and distributed winding



(a) Maximum torque



(b) Maximum generated power

Fig. 5 Maximum torque and maximum generated power increasing number of pole pairs increase the leakage magnetic flux between slots, so the inductance increases and as a result, the maximum generated power tends to decrease. Thus, the maximum torque and maximum generated power have a trade-off relationship with the number of poles. Therefore, this system uses the optimum number of poles that satisfies all the performance requirements.

3. Conclusion

This paper described the characteristics of the crankshaft-mounted 48V-ISG system and the electromagnetic design of the electric motors. In the electric motors for the 48V-ISG system, the current for performing magnetic flux-weakening control greatly affects the continuous rating and efficiency characteristics. Therefore, this system uses concentrated winding with increasing number of pole pairs, resulting in the 48V-ISG system that satisfies all the requirements over a wide operation range. We will continue to develop technologies to further reduce the size and weight and increase the power.