Technical Paper

Verification of Electric Motor using First Adopted Winding and its Feasibility Study

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In motors for construction machinery, there is a need to increase power density by increasing power or reducing motor size. Komatsu is working on the development of a motor with increased winding density (fill factor). Increasing the fill factor of a coil not only allows a motor to be more powerful or smaller, but also improves its cooling performance. This paper reports on the performance of a motor using a winding called "flat wire" winding, which we used for the first time in our motors, and its effects.

Key Words: *Electric motor, Switched reluctance motor, Winding*

1. Introduction

In recent years, hybrid or electric cars have entered the market in response to global warming and rising fuel prices. In the construction equipment market, Komatsu has been selling hybrid hydraulic excavators since 2008. Our hybrid hydraulic excavators are equipped with two types of electric motors: a swing motor for swinging a machine body, and a generator motor for generating electricity from the engine power and assisting acceleration. In particular, the generator motor is mounted between the engine and the hydraulic pump. It must provide high power in a limited space, which means it requires higher power density.

To meet the above requirement, Komatsu is working on the development of a motor with increased winding density (fill factor). Increasing a winding fill factor not only allows a motor to be more powerful or smaller, but also improves the cooling performance of a motor. This paper reports on the performance of a motor using a winding called "flat-wire" winding, which we used for the first time in our motors, and its effects.

2. Construction of generator motor

The generator motor uses a SR (switched reluctance) motor. The SR motor does not use permanent magnets and therefore has superior heat resistance. This superior heat resistance improves the reliability of the built-in motor between the high temperature engine and the hydraulic pump. In addition, the absence of permanent magnets means that the amount of loss in drag turning is very small when the motor is racing without engine assistance and power generation, which helps reduce fuel consumption.

As shown in **Fig. 1**, the SR motor is mainly composed of electromagnetic steel sheets and coils. When an electric current passes through the winding wire wound around the electromagnetic steel plate of the stator, an electromagnetic force is generated. When the electromagnetic force attracts the rotor, torque is generated. As the electric current flowing through the winding is repeatedly turned on and off, the electromagnetic force is also turned on and off accordingly, causing the rotor to rotate continuously. This phenomenon can be explained by the following torque formula [1]:

$$T = \frac{1}{2} i^2 \left(\frac{\partial L}{\partial \theta}\right) \quad (1)$$

where T is the torque, i is the current flowing through the winding, L is the inductance, and θ is the rotor angle. The SR motor loss is given by the following formula:

$$P = P_{dc} + P_{ac} + P_i + P_m \quad (2)$$

where P is the motor loss, P_{dc} is the DC copper loss in the winding, P_{ac} is the AC copper loss in the winding, P_i is the iron loss generated in the electromagnetic steel plate, and P_m is the mechanical loss. This paper reports the results of the study that we conducted by focusing on the losses, P_{dc} and P_{ac}, in the winding.

First, based on the winding resistance and the current flowing through the winding, the copper loss is given by the following formula:

$$P_{dc} = Ri^2 \quad \text{......(3)}$$

$$= \rho \frac{l}{S} i^2 \quad \text{......(4)}$$

where R is the winding resistance, ρ is the resistivity of the wire material, l is the length of the wire, and S is the cross-sectional area of the wire.

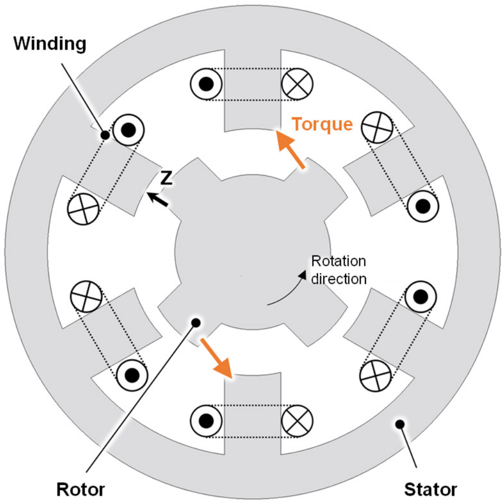


Fig. 1 Construction of SR motor

Next, the AC copper loss is the loss caused by changes in the magnetic flux linkage in the windings. Similar to the eddy current loss in iron loss, it is given by the following formula [2]:

$$P_{ac} = k_e \frac{(tfB_m)^2}{\rho} \quad \text{......(5)}$$

where k_e is an eddy current loss constant, t is the thickness of the windings in the direction perpendicular to the magnetic flux, B_m is the maximum magnetic flux density, and f is the frequency. From formulas (4) and (5), the winding losses can be roughly classified into the following three types:

- Losses that depend on the operating point of the motor: i, f, B_m
- Losses that depend on the winding wire material: ρ, k_e
- Losses that depend on the winding geometry: B_m, l, S, t

Based on these classifications, we studied the flat-wire winding structure suitable for use in a generator motor.

3. Flat-wire winding

3.1 Features of flat-wire winding

Figure 2 shows a comparison of the cross-sectional structures between conventional winding and flat-wire winding. The conventional winding wire has a round cross section and leaves unnecessary spaces in a section called the slot where the wires are arranged. These spaces result in a low fill factor and consequently deteriorate the overall cooling performance of the motor. In contrast, the flat-wire winding uses a rectangular wire and leaves smaller spaces. These smaller spaces result in a higher fill factor and are expected to improve the cooling performance of the motor.

In addition, the flat-wire winding is advantageous in that, among the parameters that depend on the winding geometry, the wire cross-sectional area, S, can be changed to any value. Assuming that the thickness of the windings, t, is constant, the winding widths A and B, shown in the schematic drawing (**Fig. 3**) viewed in the Z-direction in **Fig. 1**, can be individually designed to their own dimensions. With this advantage, we can expect to create many kinds of added value, such as an ultra-flat small motor with the smallest winding width A, an improved cooling performance with a large winding width A, or increased motor power. This paper reports on the comparison of the cooling performance with respect to the differences in the winding structure.

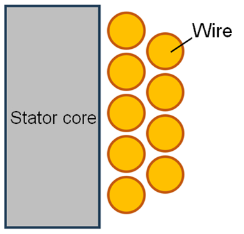
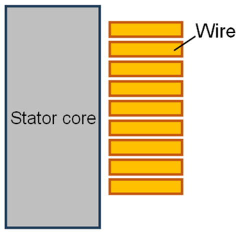
	Conventional winding	Flat-wire winding
Slot cross section		
Stator core	Lower	Higher
Heat dissipation	Lower	Higher

Fig. 2 Comparison of conventional winding and flat-wire winding

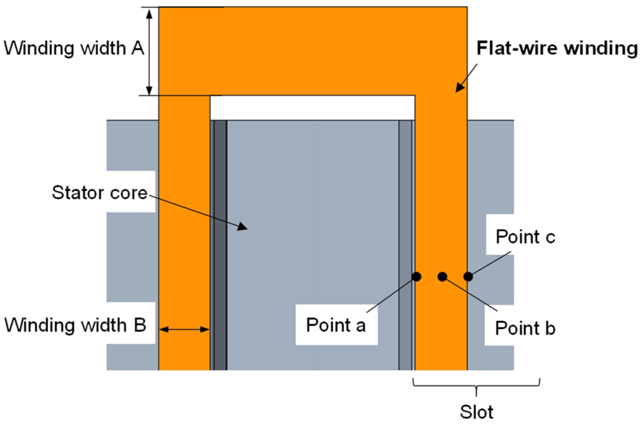


Fig. 3 Schematic drawing of winding geometry

3.2 Winding design

To compare the cooling performance, the winding was designed so that the torque given by formula (1) and the loss given by formula (2) are equivalent to those of the mass-produced motor. The AC copper loss P_{ac} was studied under the condition that the shape of the electromagnetic steel sheet, the winding material, and the electric current were the same as those of a conventional motor. The winding was designed by setting individual levels for the maximum magnetic flux density, B_m, and the winding thickness, t, among other parameters that depend on the winding geometry. For calculations requiring the finite element method, we used JMAG-Designer, an electromagnetic field analysis software.

(1) Study of magnetic flux density

As mentioned earlier, B_m increases or decreases depending on the operating point of the motor. The magnetic flux density is distributed in the slot, which causes losses. We have studied the wiring arrangements to minimize the losses. A point where the power output reached its maximum was used as the operating point for the calculation. Assuming that the magnetic flux density is not distributed in the axial directions, the radial and circumferential components of the cylindrical coordinate system were calculated, respectively. Measurements were taken at the three points in the slot shown in **Fig. 3**.

- Point a: Near the stator core
- Point b: Midpoint between point a and point c
- Point c: Point farthest from the stator core

Figure 4 shows the results of the magnetic flux density calculation. The magnetic flux densities of the windings are expressed as a percentage of the circumferential component in the magnetic flux density at point a, which is 100%. The figure shows that the closer a point is to the stator core, such as point a, the higher the magnetic flux density becomes. At point c, the farthest from the status core, the magnetic flux density is reduced to half of the highest. Both the radial and circumferential components showed the same results as above. The figure also shows that the magnetic flux density in the radial component is low, 40% of the circumferential component. In other words, the loss due to the magnetic flux density in the circumferential component is dominant, and a winding structure that minimizes the loss is required. Based on the above, we designed the winding structure so that the winding is arranged at a distance from the stator core with a small winding thickness, t, in the circumferential direction.

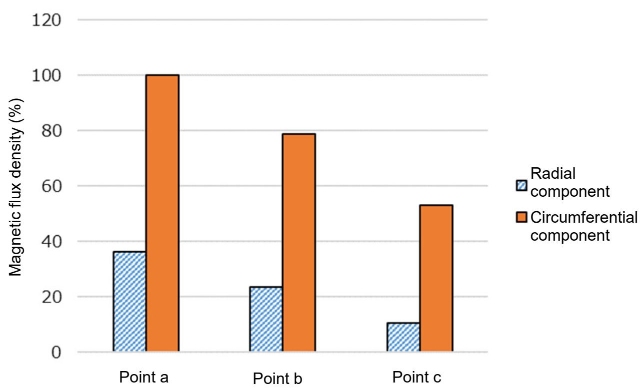


Fig. 4 Magnetic flux density in winding

(2) Study of winding thickness

Losses were compared for different winding thicknesses t. We adjusted the winding widths A and B so that the DC copper loss was equivalent to that of the conventional winding, and changed the cross-sectional area S. A point where the power output reached its maximum was used as the operating point for the calculation. **Figure 5** shows the result of the loss analysis in the winding for each thickness. The losses are expressed as a percentage of the DC copper loss, which is 100%. The figure shows that the AC copper loss increases or decreases as the thickness, t, changes. The figure also shows that the AC copper loss is minimized when the winding thickness is 1.5 mm for the motor designed in this study. From the above, we determined the winding thickness to be 1.5 mm and designed the winding to have a geometry away from point a.

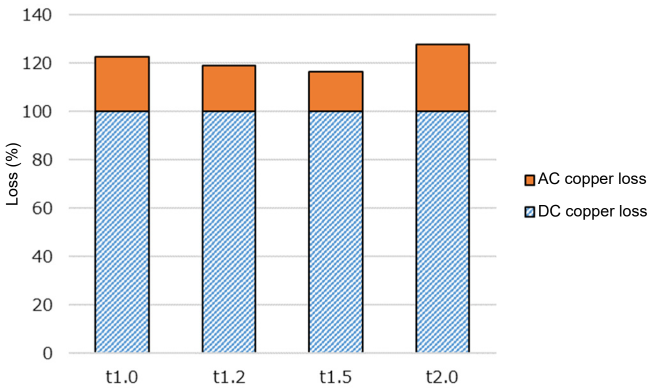


Fig. 5 Comparison of winding losses

4. Results of actual motor evaluation

We evaluated the two types of actual motors: our mass-produced motor with conventional windings and the developed motor with flat-wire windings. This paper reports on the insulation performance, motor performance, and cooling performance of these motors. In general, there is a trade-off between insulation performance and cooling performance. Therefore, we first report that the developed motor has the same insulation performance as our mass-produced motor. Next, in terms of motor performance, we report that the developed motor and the mass-produced motor have the same level of motor losses, i.e., the same level of heat generation. Then, we report that the developed motor has better cooling performance than the mass-produced motor.

4.1 Insulation performance

First, the results of the insulation performance evaluation are shown in **Fig. 6**. The figure shows the partial discharge inception voltages after three types of environmental durability tests on construction machinery. They are expressed as a percentage of the criterion, which is 100%. The figure shows that the partial discharge inception voltages are higher than the criterion in all tests, and the motor with the flat-wire windings has the same insulation performance as the mass-produced motor.

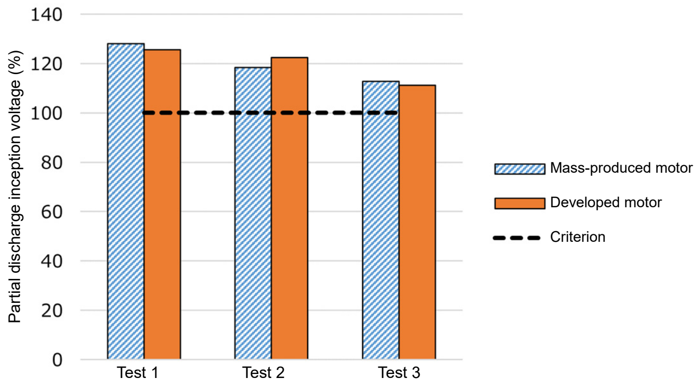


Fig. 6 Results of insulation performance evaluation

4.2 Motor performance

Next, we report the result of the motor performance evaluation by bench testing. **Figure 7** shows the bench test system configuration. The mass-produced motor and the developed motor were tested under the same voltage and electric current conditions. A power analyzer was used to measure the motor loss, P, which is the difference between the input and output of the motor. The following three operating points were used:

- Operating point 1: Low speed and high torque
- Operating point 2: Medium speed and high torque
- Operating point 3: High speed and medium torque

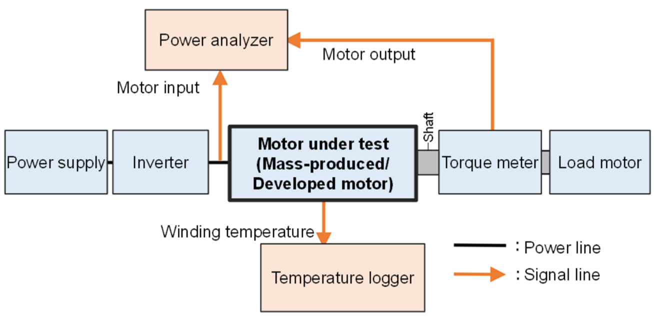


Fig. 7 Bench test system configuration

Figure 8 shows the results of the measurements. The loss at each operating point is expressed as a percentage of the corresponding criterion, which is 100%. The figure shows that the loss of the developed motor increases by a few percent at operating points 1 and 2. We were able to design the motor to have the same level of losses, P_{dc}, P_i, and P_m, except for the loss, P_{ac}, in formula (2), as the mass-produced motor. The possible reason for this is that although we have designed the motor to have the lowest P_{ac} at the operating point where the power output was maximum, the other factors, speed or torque, prevented P_{ac} from reaching the same level as the mass-produced motor. In particular, the value of B_m in formula (5) changed when the torque was high, which caused the developed motor to have a higher loss than the mass-produced motor. Although the developed motor had the higher heat generation than the mass-produced motor by a few percent, we conducted the cooling performance evaluation under the above mentioned operating conditions.

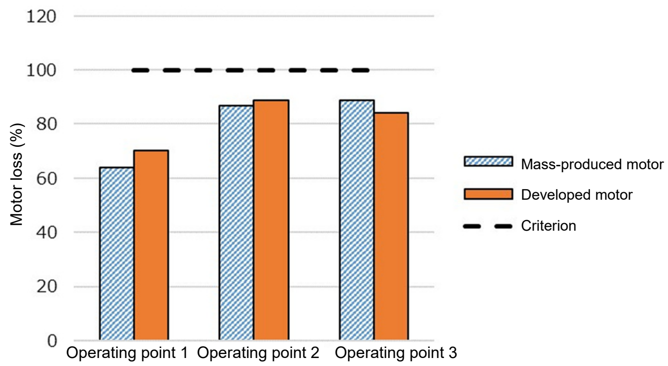


Fig. 8 Results of loss measurement

4.3 Cooling performance

Cooling performance was evaluated taking into account the results of the motor loss comparison. We attached several thermocouples to the winding and measured the winding temperatures with the temperature logger shown in **Fig. 7**. The test conditions used were operating point 2 above and constant speed. By varying the torque, the test was performed at different power output levels.

Figure 9 shows the test results. It represents the maximum temperatures of the windings when they have reached a state of heat balance after a long period of continuous power output. The figure shows that the winding temperatures of the developed motor are lower, up to 9% lower, than those of the mass-produced motor at all operating points from low to high power. We were able to demonstrate that the flat-wire winding has a high cooling performance because the winding temperature was kept low even though it generates more heat than the conventional wire. This paper only reports the results of the tests conducted at the same speed. We have obtained the similar results from the tests conducted at the other operating points. From the results mentioned so far, we were able to demonstrate that the developed motor with the flat-wire windings has improved cooling performance.

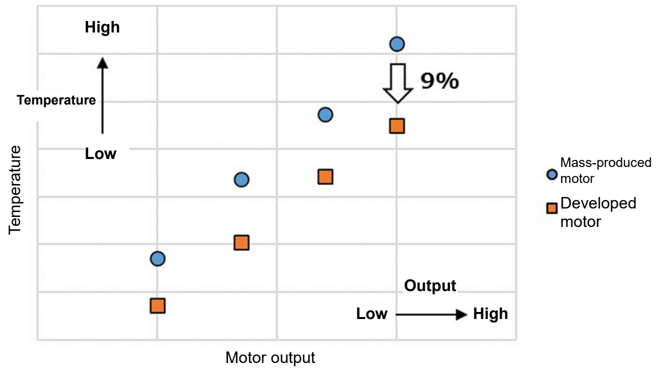


Fig. 9 Results of heat balance temperature measurement

5. Conclusion

This paper reports the results of a study on a generator motor for hybrid hydraulic excavators using our first adopted winding, a flat-wire winding. We have demonstrated that the flat-wire winding can achieve the same level as the conventional winding in terms of insulation performance and motor performance due to the advantage of the flat-wire winding that allows its wire cross-sectional area, S, to be freely varied. We have also demonstrated that the flat-wire winding allows the heat balance temperature to be better controlled for cooling performance, even though it generates a lot of heat.

To make accurate comparisons in this study, we designed the developed motor to have the same loss as the mass-produced motor and then compared the cooling performance between them. Further improvements can be expected by exploiting the potential of the flat-wire winding and designing it to minimize winding losses. By developing the motor evaluated in this study, we can expect to create many types of added value, such as extending the life of motors and other electrical components by taking advantage of temperature control, increasing the power of motors without changing their size or downsizing motors without changing their power by taking advantage of improved cooling performance, or reducing costs by simplifying cooling systems.

Recently, battery-powered electric construction machinery has been actively developed. Especially in Europe, small construction machinery for urban civil engineering requires smaller and less expensive electrical components. Future prospects for the flat-wire winding technology proposed in this paper include application to electric motors for the above-mentioned battery-powered construction machinery, in addition to hybrid hydraulic excavators. From now on, we will continue to study motors with flat-wire windings for their applicability to various types of electric construction machinery. The true results of this study will come from customer evaluations after the motor is launched. We are looking forward to the day we hear from customers.

References
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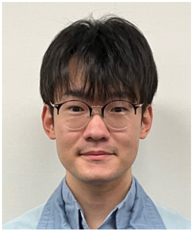

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[A comment from the authors]

It is essential to further increase the power, reduce the size, and lower the cost of electric motors, which have a lower power density than hydraulic motors. Although windings alone cannot solve these challenges, we want to contribute to the overall electrification of future construction machinery.