Efficiency Map Evaluations Considering Harmonic Loss

1. Background

With electromagnetic machines increasing in efficiency, increasing accuracy for loss analyses poses important challenges for electromagnetic field analyses. Permanent magnet synchronous motors and induction motors are often driven by inverters such as PWM inverters for variable speed operation. It is known that inverters generate time harmonic components (hereinafter referred to as carrier harmonics) derived from the carriers in the current of the motor, increasing iron loss. In recent years, examples of using hairpin coils with rectangular wires for the purpose of improving fill factor, dielectric strength, etc. have been increasing. It is known that when a rectangular wire is used, the current has a distribution in the wire during high speed rotation of the motor, increasing copper loss (AC copper loss). It is important to take into account the carrier harmonics and AC copper loss in order to accurately calculate the efficiency of a rotating machine performing variable speed operation. In this paper, a method is proposed to calculate efficiency taking into account the effects of carrier harmonics and AC copper loss using electromagnetic field / circuit / control coupled analysis.

2. Proposed Method

Fig. 1 shows the flow from material measurement to performing an analysis. The process consists of computing a simple efficiency map, determining operating points, and performing coupled analysis.

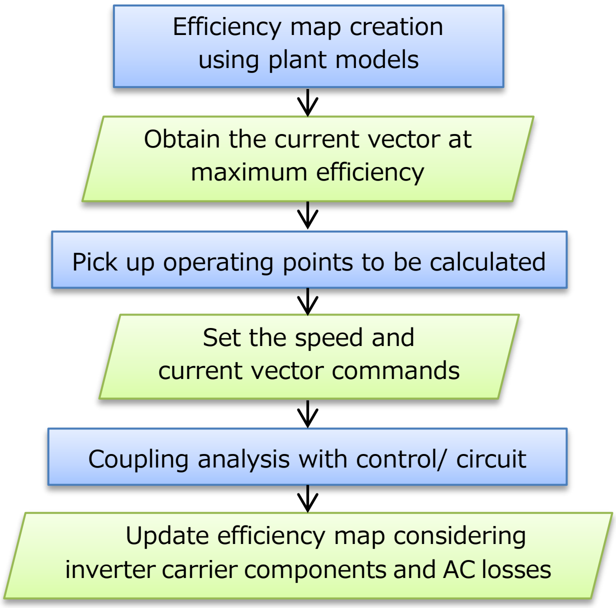


Fig. 1 The flow of efficiency calculations taking into account the influence of carrier harmonics and AC copper loss

It is assumed that the current vector providing the highest efficiency does not change due to the presence or absence of carrier harmonics and AC copper loss.

First, in order to determine the operating points for calculating the efficiency, an efficiency map is computed using a plant model. In this case study, the efficiency is determined without taking into account carrier harmonics and AC copper loss in the inverter. Next, several operating points for calculating the efficiency taking into account carrier harmonics and AC copper loss are selected. These are selected considering the operating points most frequently used, important operating points, etc. in the target device. Coupled analysis is performed by using the current vector of the last selected operating point as a command value, from which the efficiency is computed. The loss takes into account copper loss, iron loss in electromagnetic steel sheets, eddy current loss generated by magnets, and mechanical loss.

3. Analysis target

The FEA model of the permanent magnet synchronous motor to be analyzed is shown in Fig. 2, and specifications including specifications for the inverter are shown in Table 1.

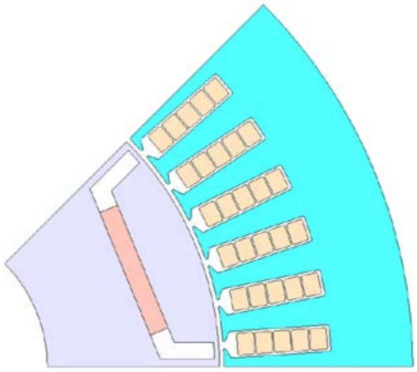


Fig. 2 Analysis target (permanent magnet synchronous motor)

Table 1 Analysis target specifications

Item	Value
Poles	8
Slots	48
Rated output power	80 kW
Core material	35H270
Magnet	Sintered neodymium magnet
DC voltage	600 V
Max. phase current	250 Apeak
Carrier frequency	6 kHz
Mechanical loss	20 W/(krpm)

4. Efficiency map computataion and selection of operating points

Fig. 3 shows an efficiency map computed using a plant model. Four operating points are selected using this efficiency map.

・A: Low speed, large torque (1,200 rpm, 260 N·m)

・B: Low speed, low torque (1,200 rpm, 40 N·m)

・C: Medium speed, large torque (4,500 rpm, 110 N·m)

・D: High speed, low torque (9,000 rpm, 25 N·m)

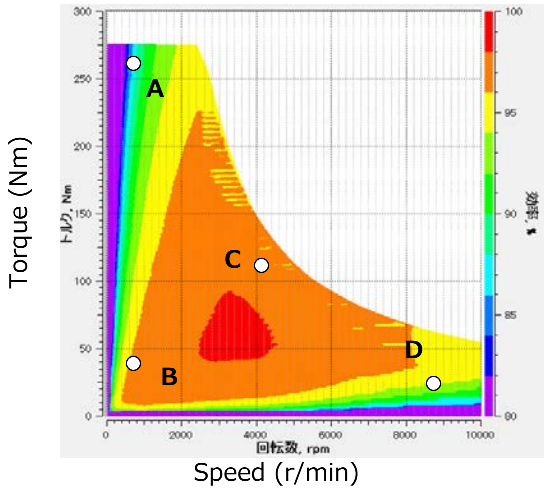


Fig. 3 Efficiency map and selected operating points

5. Coupled analysis

The layout of the coupled analysis used in this paper is shown in Fig. 4. Magnetic field analysis (FEA) for the motor and circuit analysis are performed using strong coupling. This makes it possible to fully consider the mutual interference between the motor and the inverter. The current vector controller performs weak coupling with the motor/inverter.

The difference between an efficiency map taking into account inverter harmonics and AC copper loss obtained by coupled analysis and the efficiency map in Fig. 3 is shown in Fig. 5.

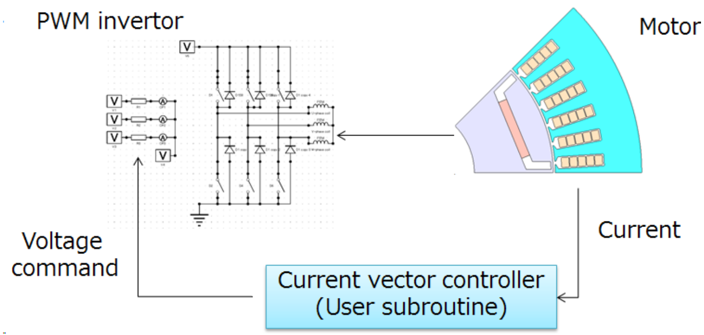
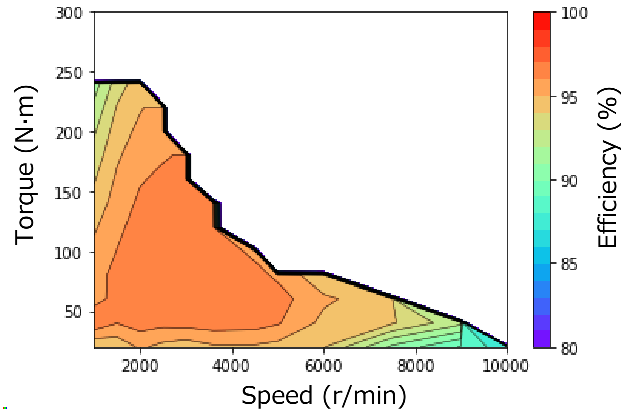
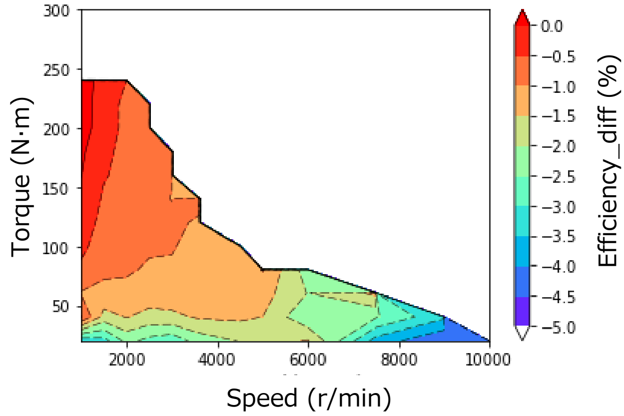


Fig. 4 Layout of the coupled analysis

The current vector controller receives current from the motor and inputs voltage command values to the inverter



(a) Efficiency map obtained



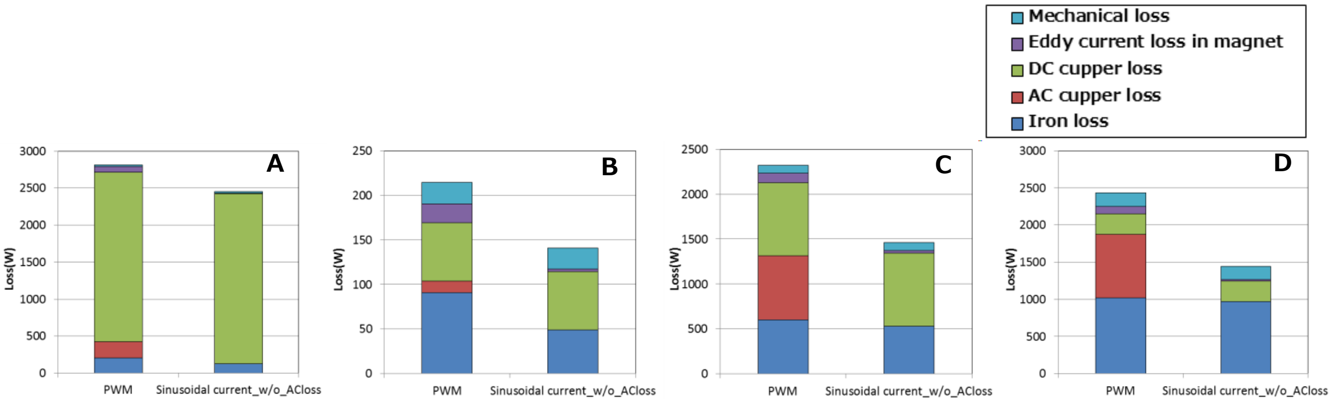
(b) Difference from the efficiency map where sinusoidal waves and AC copper loss are not taken into account

Fig. 5 Efficiency map taking into account inverter harmonics and AC copper loss

When taking into account inverter harmonics and AC copper loss, the efficiency at low load and high revolutions drops.

6. Loss and efficiency analysis

In Fig. 6 the loss and efficiency obtained at each operating point is compared with the loss and efficiency for the case when the current is an ideal sine wave and there is DC copper loss only. Since it can be seen that the copper loss ratio is low and the iron loss ratio is high at the low torque operating point B, the influence on loss and efficiency with or without carrier harmonics was relatively highest. It can be seen that the iron loss of the core has increased by 1.9 times. For the high-speed operating point D, the AC copper loss is much greater, and the total copper loss is 4 times greater, than the DC copper loss, so taking into account AC copper loss significantly reduces the efficiency. Fig. 7 shows the ratio (%) of core loss due to carrier harmonics to the total core loss of the core. Since the operating points A and B are for low speed, the iron loss due to the fundamental component is small and the iron loss due to the carrier harmonics is very large.



Eff. (%) 92.1 93.1 96.3 97.2 95.6 97.2 91.0 94.3

Fig. 6 Loss breakdown and efficiency comparisons

At the low speed and low torque operating point B, the effect on iron loss is greatest. For operating point A, as with operating point B the carrier harmonics significantly increase the iron loss, but since the DC copper loss is dominant the influence on the total loss is small. For the high speed and low torque operating point D, the effect on iron loss due to carrier harmonics is small, but the influence of AC copper loss is very large.

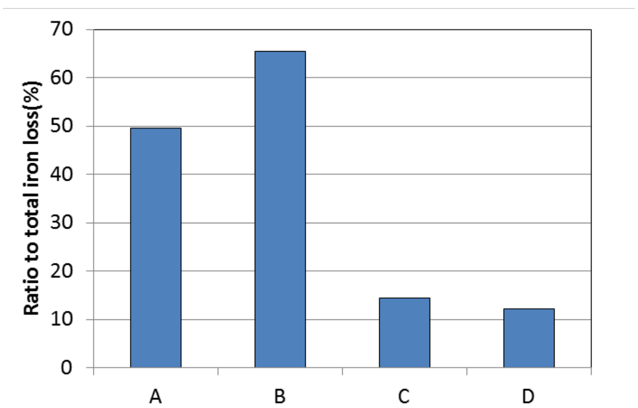


Fig. 7 Percentage of loss from carrier harmonics on the total loss

It can be seen that consideration of carrier harmonics is indispensable for computing iron loss, because the percentage of loss due to carrier harmonics is high at low rotation.

7. Computation time

Table 2 shows the PC and model information used in this analysis, the number of analysis steps required for the computations, and the computation times. In addition, in order to calculate the efficiency map (105 points) shown in Fig. 5, simulataneous execution was performed using 24 cores taking approximately 18 hours.

Table 2 PC environment used, model information, number of analysis steps, time

Since the number of analysis steps for one carrier period is fixed, the number of total analysis steps is larger for low rotation.

Item	Value
CPU	Xeon E5-1660 v3 3.0GHz
Used memory（MByte)	150
Number of parallel process	4
Elements	15,652
Nodes	9,121
Time steps	A: 4,500 A: 4,500 C: 1,200 D: 600
Computation time (min)	A: 235 B: 227 C: 65 D: 34

8. Conclusion

In this paper, the loss taking into account the carrier harmonics of an inverter and the AC copper loss of rectangular wire was obtained by magnetic field / circuit / control coupled analysis. It was confirmed that the influence from carrier harmonics at low speed and low torque and from AC copper loss at high speed are large and cause the efficiency to decrease.

Contact
JMAG Div.
info@jmag-international.com