Evaluation Method of Energy Consumption for Permanent Magnet Synchronous Motor Drive System

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***Abstract*— This paper discusses an evaluation method of electric energy consumption of a permanent magnet synchronous motor (PMSM) drive system. The calculation method of the energy consumption based on an efficiency map is proposed. First, it is confirmed that the error ratio between the calculation result and the measurement result is less than 5%. In addition, the energy consumption of the PMSM drive system for actual hybrid electric vehicles is calculated by the proposed method. As a result, it is clarified that when the three-level inverter is employed, the energy consumption decrease ratio compared with the two-level inverter in the light load region is higher than that in the heavy load region.**

Keywords*— Three-level inverter; Permanent magnet synchronous motor; Electric energy consumption; Efficiency map; Electric vehicle / Hybrid electric vehicle

I. INTRODUCTION

Recently, the drive systems applying the Permanent Magnet Synchronous Motor (PMSM) have been researched actively in order to improve the efficiency of the motor drive system. The systems applying PMSM have higher efficiency and power density than that applying the induction motor.

On the other hand, the multi-level inverter such as a three-level inverter is an alternative converter of a typical two-level inverter. The three-level inverter reduces both the harmonic loss of PMSM and the switching loss of the inverter. Therefore, in motor drive systems, high efficiency is expected by implementing the multi-level inverter.

In order to further improve the efficiency of the motor drive system, the analysis of the inverter loss or the PMSM loss has been individually reported in [1-4]. However, there is the trade-off relationship between the inverter loss and the PMSM loss [5]. For example, by increasing carrier frequency, the PMSM loss is decreased. On the other hand, the inverter loss is increased. Therefore, the efficiency evaluation method of the total drive system that includes the inverter and PMSM is necessary.

In general, the efficiency of the inverter or the PMSM is evaluated on constant speed and constant torque. Nevertheless, the speed and the torque changes continuously in a hybrid electric vehicle (HEV), an electric vehicle (EV), a flywheel energy storage system (FESS) and so on. Therefore, the drive system should be evaluated by not only the instantaneous loss or efficiency but also the energy consumption according to operation pattern. In [6-7], the reduction method of the energy consumption in PMSM is proposed by the identification of the parameters or the optimization of the PMSM structure. However, the energy consumption in the whole system included the inverter is not evaluated. Besides, the change of the energy consumption by the inverter topology is not also evaluated. Furthermore, the calculation method of the PMSM drive system is not compiled systematically.

In this paper, the calculation method of the energy consumption in the PMSM drive system based on the efficiency map is proposed. In addition, the energy consumption of the PMSM drive system applying the two-level inverter and the three-level inverter is evaluated. Thus, it clarifies the efficiency improvement effect of the drive system applying the three-level inverter when the PMSM is actually driven.

II. CHARACTERISTICS OF THREE-LEVEL INVERTER

Fig. 1 shows the circuit diagram three-level neutral-point-clamped inverter (T-type). The three-level inverter reduces the harmonic component of the output voltage comparing to the two-level inverter due to the possibility to output zero voltage level. In other words, the reduction of the harmonic loss in the PMSM is possible. In addition, the switching loss is reduced by the three-level inverter because the varying voltage on the switching is a half compared with the two-level inverter. Furthermore, when the switches which are connected to the neutral point of the DC bus are constructed by RB-IGBTs, the conduction loss is same as the two-level inverter. Therefore, the total efficiency of the system applying the three-level inverter is improved compared with the conventional system.

III. CALCULATION METHOD OF ENERGY CONSUMPTION

In this section, the calculation method for the energy consumption in the PMSM drive system based on the efficiency map is proposed. In the proposed method, the total efficiency map is made before calculation of the energy consumption. In addition, the calculation requires the operation command of the speed and the torque.

The efficiency of the drive system η which is a function of the speed N [r/min] and the torque T is expressed by (1).

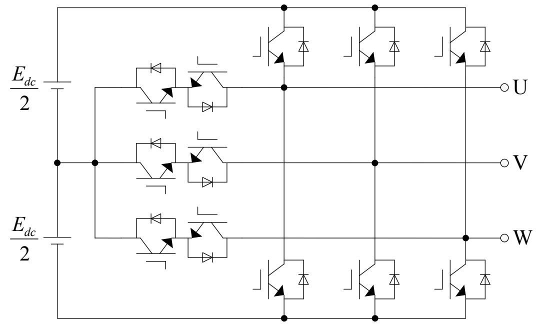


Fig. 1. Circuit diagram three-level neutral-point-clamped inverter (T-type). The total efficiency of the PMSM drive system applying the three-level inverter is improved compared with the conventional system.

$$\eta(N,T) = \frac{(2\pi N/60)T}{(2\pi N/60)T + P_{inv}(N,T) + P_{mot}(N,T)} \quad (1),$$

where, P_{inv} and P_{mot} are the losses of the inverter and PMSM, respectively and these are also the functions of the speed N and the torque T. The speed N and the torque T are the functions of time t because these are given by the operation command. Therefore, the energy consumption of the drive system W is expressed by (2).

$$W = \int \frac{\{2\pi N(t)/60\}T(t)[1-\eta\{N(t),T(t)\}]}{\eta\{N(t),T(t)\}\times 3600} dt \quad (2)$$

However, the mathematization of the actual efficiency or the complex operation command of the speed or the torque is impossible to derive. Thus, the look-up table is applied. Therefore, (2) is discretized and replaced by (3).

$$W = \sum_{n=0}^{T_o/T_s} \frac{\{2\pi N(n)/60\}T(n)[1-\eta\{N(n),T(n)\}]}{\eta\{N(n),T(n)\}\times 3600} T_s \quad (3),$$

where, T_o is the operation time and T_s is the sampling time of the operation commands.

Fig. 2 shows the calculation flowchart of the energy consumption using the efficiency map. As the input, the efficiency map $\eta(N, T)$, the operation command of the speed $N(t)$ and the torque $T(t)$, the operation time T_o and sampling time T_s are given. Then, the energy consumption is calculated by (3).

IV. Comparison between Calculation Result and Measurement Result of Energy Consumption

In this section, the proposed calculation method of the energy consumption is evaluated. Therefore, the measured energy consumption by the actual drive system is compared with the calculated one.

A. Configuration of actual PMSM drive system

Fig. 3 shows the configuration of the PMSM drive system for the energy consumption measurement. The inverter for the test motor is the three-level inverter. This inverter controls the speed of PMSM. In addition, if the inverter is driven as the two-

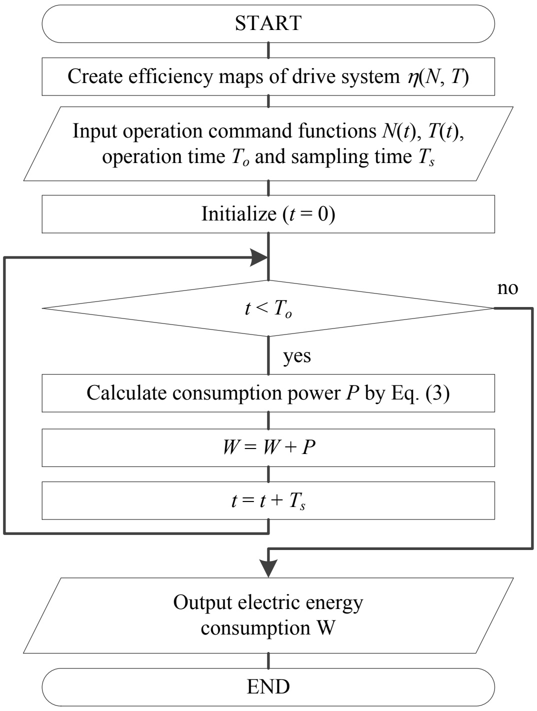


Fig. 2 Calculation flowchart of energy consumption in the PMSM drive system using efficiency map.

level inverter, the switches which are connected to the neutral point of the DC bus always turn off. The IGBTs (2MBI150U2A-060, 600V, 150A, Fuji electric) are applied to the switches. APL-II (Myway) is applied as the DC power supply. The DC link voltage is 180 V. On the other hand, the inverter for the load motor controls the load torque based on the current control. The power consumption is measured by the power meter (WT1800, YOKOGAWA).

Table 1 shows the parameters of the prototype PMSM. The prototype PMSM is designed as the mini model of the EV/HEV. The winding type is the concentrated winding. Therefore, the coil end of the concentrated winding is shorter than that of the distributed winding. However, the distributed winding makes the current waveform become distorted.

B. Energy consumption in EV system

Fig. 4 shows the operation command of the vehicle velocity called JC08 mode. JC08 mode is defined by Ministry of Land, Infrastructure, Transport and Tourism of Japan. It is 20 minutes of the operation command assumed the driving in urban area and highway.

In addition, the running resistance of the vehicle is defined by the air resistance, the rolling resistance, the gradient resistance and the acceleration resistance. The air resistance is proportional to the square of the velocity. The rolling resistance and the gradient resistance do not depend on the velocity. The acceleration resistance is proportional to the acceleration. The velocity is time function because it given by the operation command. Therefore, running resistance is expressed by (4)

$$F_L(t) = K_2\{V(t)\}^2 + K_1\frac{dV(t)}{dt} + K_0 \quad (4),$$

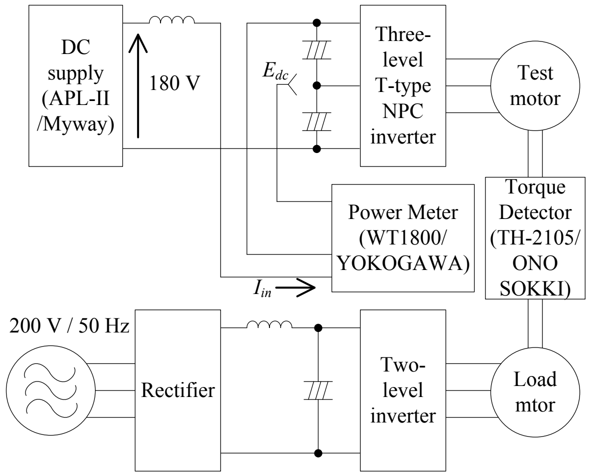


Fig. 3 Configuration of PMSM drive system for energy consumption measurement. The IGBTs (2MBI150U2A-060, 600V, 150A, Fuji electric) are applied to the switches of the three-level inverter. The DC link voltage is 180 V.

Table 1. Parameters of IPMSM.

Maximum power	3 kW
Maximum torque	4 Nm
Base speed	7200 r/min
Maximum speed	12000 r/min
Rated current	16.9 Arms
Armature pairs of poles	6
d-axis inductance	0.389 mH
q-axis inductance	0.556 mH
Winding resistance	0.0635 Ω
Back-EMF coefficient	0.0182 Vs/rad

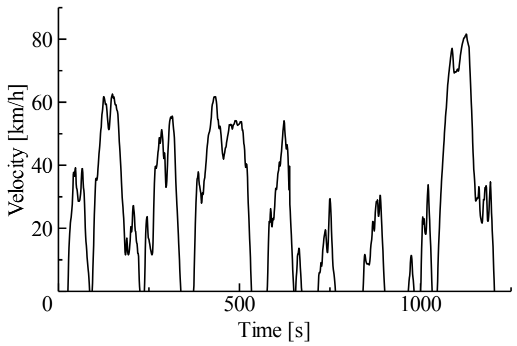


Fig. 4 Operation command of speed (JC08 mode). It is 20 minutes of the operation command assumed the driving in urban area and highway

where,

$$K_2 = \frac{1}{2}\rho C_d A \quad (5),$$

$$K_1 = M + M_i \quad (6),$$

$$K_0 = Mg(\mu\cos\theta + \sin\theta) \quad (7),$$

V is the velocity, ρ is the density of air, C_d is the air resistance coefficient, A is the projected area of the vehicle, μ is the rolling resistance coefficient, M is the mass of the vehicle, M_i is the equivalent inertia weight of the rotating part in the drive mechanism, g is the gravitational acceleration and θ is the gradient angle.

When the calculation of the energy efficiency is applied, the running resistance F_L is converted to the load torque of PMSM T_L. The velocity V is also converted to the speed of PMSM N. The running resistance and the velocity are expressed by (8), (9).

$$F_L = \alpha T_L \quad (8),$$

$$V = \beta N \quad (9),$$

where, α and β are the proportional constant. Therefore, the load torque applied in (3) is expressed by (10).

$$T_L(n) = \frac{\beta^2}{\alpha} K_2 \{N(n)\}^2 + \frac{\beta}{\alpha} K_1 \frac{N(n) - N(n-1)}{T_s} + \frac{1}{\alpha} K_0 \quad (10)$$

As the condition of the energy consumption measurement, JC08 mode is applied to the speed command. JC08 is defined by the velocity of the vehicle. Hence, it is converted to the speed of PMSM. In this case, the speed is assumed to 12000 r/min at 160 km/h. The load torque command is obtained by (10). However, the prototype PMSM is smaller than the actual PMSM for EV/HEV. Thus, the torque command is decided by the actual vehicle parameters which are scaled down based on the parameters of the prototype PMSM. Note that the acceleration resistance is ignored because the equivalent inertia weight of the rotating part in the actual drive mechanism is not clear. In addition, it assumes that the effect of the load torque by the acceleration resistance is negligibly small. Furthermore, JC08 is assumed as the driving in urban area and highway. Therefore, the load torque is decided to be approximately 15% of the maximum torque at 0 r/min and half of the maximum torque at the maximum speed. The load torque command is expressed by (11).

$$T_L(n) = 8.544 \times 10^{-9} \times \{N(n)\}^2 + 0.58 \quad (11)$$

Fig. 5 shows the measurement result of energy consumption of the PMSM drive system for the EV system by each inverter topology. When the energy consumption is measured, the system is warmed up in order to avoid the variation in the mechanical loss or the copper loss which is dependent on the temperature. It is confirmed that the winding temperature is maintained nearly constant. In addition, the carrier frequency is 4 kHz. From Fig. 5, the average energy consumption by the two-level inverter and by the three-level inverter are 70.8 Wh and 68.2 Wh, respectively. Therefore, the energy consumption decreases by 3.67% when the three-level inverter is applied. This is caused by the reduction of the switching loss and the harmonic loss. However, the switch which is connected to the neutral point of the DC bus consists of two IGBTs connected anti-serially. Thus, the conduction loss of the three-level inverter is larger than

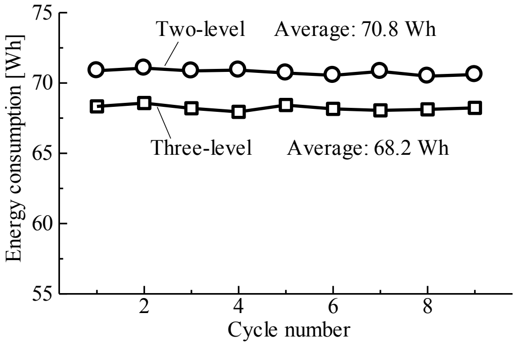


Fig. 5 Energy consumption of PMSM drive system for EV system by each inverter topology. The energy consumption decreases by 3.67% when the three-level inverter is applied.

that of the two-level inverter because the number of switches through which the current flows is three per one phase. When the RB-IGBT applies to the switch which is connected to the neutral point of the DC bus, the energy consumption by three-level is expected to further decrease.

Next, the calculation results of the energy consumption are compared with the measurement results because the proposed calculation method is evaluated. Note that the efficiency map of the prototype drive system is necessary. Therefore, the efficiency map is made by the measuring efficiency of the prototype drive system.

Fig. 6 shows the efficiency map of the prototype system when each inverter drives the prototype PMSM. The maximum efficiency is 83.7% (5400 r/min, 1.09 Nm) with the two-level inverter and 87.5% (5400 r/min, 1.08 Nm) with the three-level inverter.

Table 2 shows the calculation result based on Fig. 2 of the energy consumption. The error ratio between the calculation results and the measurement results is less than 5% in the system applied the both inverter topologies.

C. *Energy consumption in flywheel energy storage system*

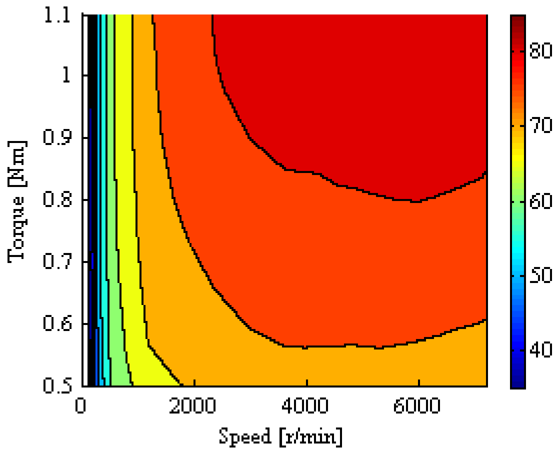
The flywheel energy storage system (FESS) is applied to the power leveling system because it is long life time due to no chemical structure.

Fig. 7 shows the operation command of the FESS for power fluctuation compensation control [8]. In the FESS, when PMSM is operated as a generator during deceleration, kinetic energy is converted into the electrical energy. On the other hand, during acceleration, the electrical energy is stored as kinetic energy, which is working as a motor.

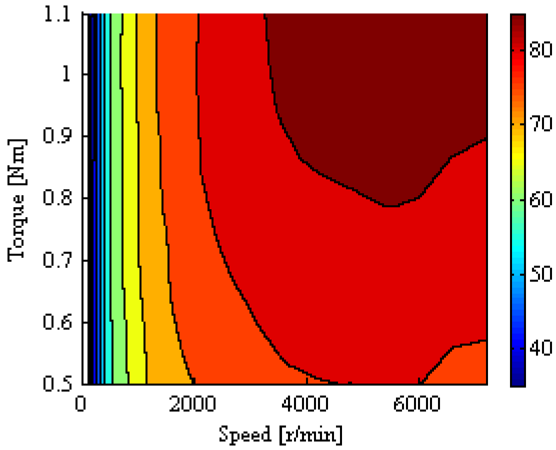
In addition, the output torque of the PMSM is decided by the inertia of the flywheel and the acceleration. Therefore, the load torque command is expressed by (12).

$$T_L(n) = (J_f - J_m)\frac{N(n) - N(n-1)}{T_s} \quad (12),$$

where, J_f is the inertia of the flywheel and J_m is the inertia of the PMSM.



(a) With two-level inverter. The maximum efficiency is 83.7% (5400 r/min, 1.09 Nm)



(b) With three-level inverter. The maximum efficiency is 87.5% (5400 r/min, 1.08 Nm).

Fig. 6 Efficiency map of PMSM drive system.

Table 2 Calculation result of energy consumption of the PMSM drive system for the HEV system by each inverter topology.

Inverter topology	Calc.	Meas.	Error ratio
Two-level	68.4 Wh	70.8 Wh	3.39%
Three-level	65.2 Wh	68.2 Wh	4.40%

Fig. 8 shows the measurement result of energy consumption of the PMSM drive system for the FESS by each inverter topology. The average energy consumption by the two-level inverter and by the three-level inverter are 67.4 Wh and 57.8 Wh, respectively. Therefore, the energy consumption decreases by 14.3% when the three-level inverter is applied.

Table 3 shows the calculation result of energy consumption of the PMSM drive system for the FESS by each inverter topology. The error ratio between the calculation results and the measurement results is less than 5% in the system applied the both inverter topologies. Therefore, the validity of the proposed calculation method is confirmed.

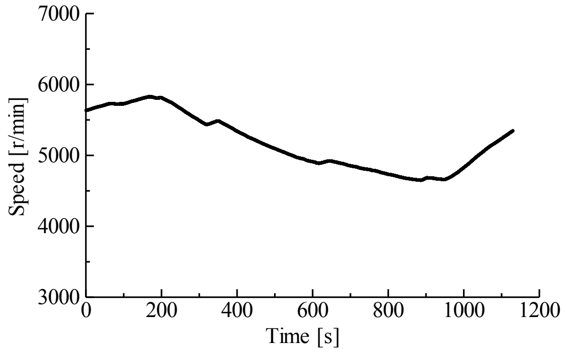


Fig. 7 Operation command of FESS for power fluctuation compensation control.

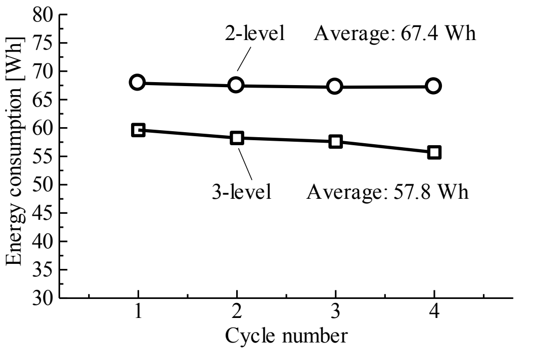


Fig. 8 Energy consumption of the PMSM drive system for the FESS by each inverter topology. The energy consumption decreases by 14.3% when the three-level inverter is applied.

Table 3 Calculation result of energy consumption of the PMSM drive system for the FESS by each inverter topology.

Inverter topology	Calc.	Meas.	Error ratio
Two-level	66.0 Wh	67.4 Wh	2.16%
Three-level	59.6 Wh	57.8 Wh	3.06%

V. Evaluation of Three-level Inverter in Actual HEV

In this section, the energy consumption of the actual HEV drive system is evaluated. In particular, the energy consumption of the system with the three-level inverter is compared with that with the two-level inverter. In addition, the operation condition when the three-level inverter reduces the energy consumption more effectively is considered. However, the detailed specifications of the actual HEV drive system are not clear. Therefore, the specifications are inferred by literatures.

From [9], the parameters of the inverter assume that the input voltage is 650 V and the maximum output current is 141 A. From these parameters, the IGBT (6MBI300V-120-50, 1200 V, 300 A, Fuji electric) is applied to the switching device. In addition, two IGBTs connected anti-serially is applied to the switch which is connected to the neutral point of the DC bus in the three-level inverter. Moreover, the carrier frequency is 5 kHz in the both inverters. Then, the inverter efficiency map is obtained by the circuit simulator (PLECS Blockset, Plexim) based on the above conditions. Note that the trend of the loss analysis results in the circuit simulator almost agrees with that of the measurement results in [10].

The efficiency map of PMSM driven by the two-level inverter (carrier frequency: 5 kHz) is drawn. In this section, the efficiency map of PMSM driven by the three-level inverter is also necessary. Therefore, it is obtained by the scaling efficiency map of the PMSM driven by the two-level inverter.

The copper loss of PMSM does not depend on the inverter topologies because it is dominated by the fundamental component [5]. In addition, the difference of the harmonic iron loss in the magnetic steel sheet by the inverter topology is slight because the magnetic steel sheet is the structure which is difficult for the eddy current to flow. Therefore, the different component of the loss by the inverter topology is the eddy current loss in the permanent magnet. The eddy current loss in the permanent magnet is relatively small when PMSM is driven by the sinusoidal voltage. Thus, this loss can be considered to be independent from the fundamental frequency. In other words, the eddy current loss in the permanent magnet is dominated by the harmonic component. Although the characteristic of harmonic component at each modulation index is different between the two-level inverter and the three-level inverter, the change of the eddy current loss in the permanent magnet by the inverter current phase or the inverter current amplitude is small in the distributed winding PMSM [2][11]. Hence, the eddy current loss in the permanent magnet does not depend on the modulation index of the inverter. For these reasons, this loss is independent of the speed or torque of the PMSM. Therefore, the PMSM loss decreases by constant when the PMSM is driven the three-level inverter. From the loss analysis results of PMSM by the finite element method, the average eddy current losses by applying the two-level inverter and by applying the three-level inverter are 299 W and 144 W, respectively [5]. In this time, the PMSM loss applying the three-level inverter is smaller 155 W than applying the two-level inverter.

Fig. 9 shows the efficiency map of the HEV drive system applying each inverter. When the three-level inverter is applied, the high efficiency region around 95% enlarges.

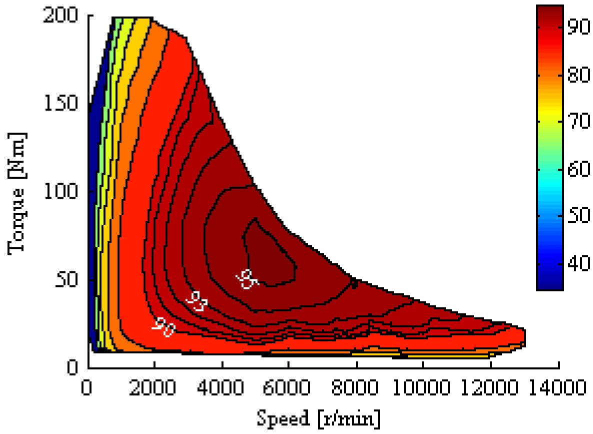
Then, the energy consumption is calculated when the PMSM is operated based on JC08 mode. The two patterns of the load torque command are given because the change of the energy consumption is also evaluated by the load torque. Therefore the 0% gradient and 10% gradient are assumed. The load torque commands are obtained in the same way as (11). These at the 0% gradient and 10% gradient are expressed by (13) and (14), respectively.

$$T_0(n) = 1.389 \times 10^{-7} \times \{N(n)\}^2 + 10 \tag{13}$$

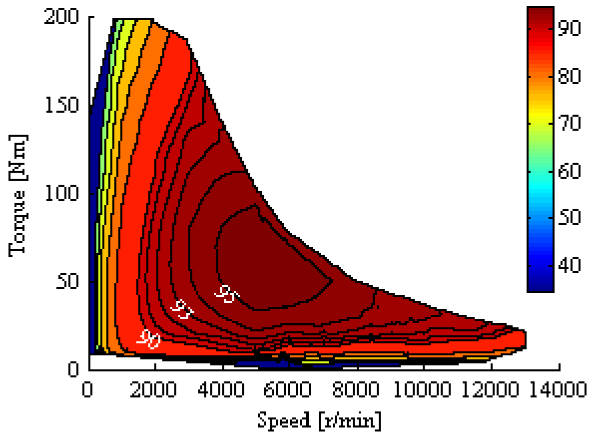
$$T_{10}(n) = 1.389 \times 10^{-7} \times \{N(n)\}^2 + 40 \tag{14}$$

Fig. 10 shows the calculation results of the energy consumption when the HEV drive systems are driven based on JC08 mode. The energy consumption is normalized by the energy consumption using the two-level inverter. In 0% gradient, the energy consumption applying the three-level inverter is smaller 2.2% than applying the two-level inverter. On the other hand, in 10% gradient, the decreasing ratio of the energy consumption is 1.0% by applying the three-level inverter.

current. Consequently, the ratio of the conduction loss increases as the current becomes large. The conduction loss of the three-level inverter is same as that of two-level inverter in principle. In addition, the copper loss is proportional to the square of the current. Thus, the ratio of the copper loss also increases as the current becomes large. Hence, the effect of the decreasing energy consumption by the three-level inverter grows weak as the load torque becomes large.



(a) With two-level inverter.



(b) With three-level inverter.

Fig. 9 Efficiency map of PMSM drive system with each inverter topology for HEV.

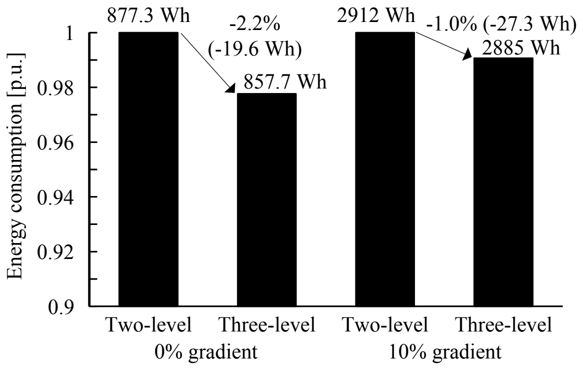


Fig. 10 Energy consumption of PMSM drive system for HEV by JC08 mode.

Therefore, it is clarified that when the three-level inverter is employed, the decreasing ratio of the energy consumption compared with the two-level inverter in the light load region is higher than that in the heavy load region. In order to increase the output torque, the current in the inverter and the PMSM had to be increased. The switching loss is proportional to the current and the conduction loss is proportional to the square of the

VI. CONCLUSION

In this paper, the calculation method of the energy consumption based on the efficiency map is proposed. It is confirmed that the error ratio between the calculation result and the measurement result of the energy consumption is less than 5%. In addition, the energy consumption of the PMSM drive system for HEV is calculated by the proposed method. As a result, it is clarified that when the three-level inverter is employed, the energy consumption decrease ratio compared with the two-level inverter in the light load region is higher than that in the heavy load region.

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