Investigation of Optimal Operation Method for Permanent Magnet Synchronous Motor Drive System with 3-level Inverter

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Abstract— **In this paper, an optimal converter drive method for Permanent Magnet Synchronous Motor (PMSM) with a 3-level inverter is discussed in terms of loss minimization. The 3-level inverter can change an operation mode between two modulations namely, PWM and 1'pulse modulation at a decided point. In this paper, we discuss the interchange point for the two modulations subject to the total loss of PMSM drive system in regards to the motor speed. First, the analysis on intersection point between PWM and 1'pulse modulation is demonstrated, and then the results show, that the motor drive system achieves the highest efficiency with PWM before the intersection point. On one hand, implementation of 1'pulse modulation can achieve the highest efficiency.**

Keywords-component; Permanent magnetic synchronous motor, 3-level inverter, PWM drive, 1'pulse modulation

I. INTRODUCTION

Recently, electric vehicles (EV) are actively developed due to the high demand of CO_2 emission reduction from automobile industry. Demanding on the motor drive systems for the EVs are to feature small size, lightweight and high efficiency. The typical motor that applied in EVs is known as Permanent Magnet Synchronous Motor (PMSM) [1]. Then inverter is applied to control the torque in a wide range of variable speed.

The inverter in an EV system is typically driven by two modulations, that is, PWM at low speed region and 1-pulse modulation (square wave modulation) at middle or high speed region [2]. PWM can suppress the torque ripple because the harmonic component is relatively low. On the other hand, implementation of 1-pulse modulation can reduce the switching loss comparing to PWM and increases the fundamental amplitude of the output voltage. Hence, the 1-pulse modulation is often applied to extend the operational region of speed in the motor. In addition, pulse width of the 1-pulse modulation can be varied in a 3-level inverter unlike a 2-level inverter because the 3-level inverter can output zero voltage level. Thus, it can arbitrarily decide the fundamental amplitude of output voltage [3] and it is called as 1'pulse modulation in order to distinguish from the standard 1-pulse modulation that has constant voltage amplitude [4]. Therefore, the interchange point from PWM to 1'pulse modulation can be decided arbitrarily. However, the interchange point needs to be analyzed in consider to achieve the highest efficiency in a drive system.

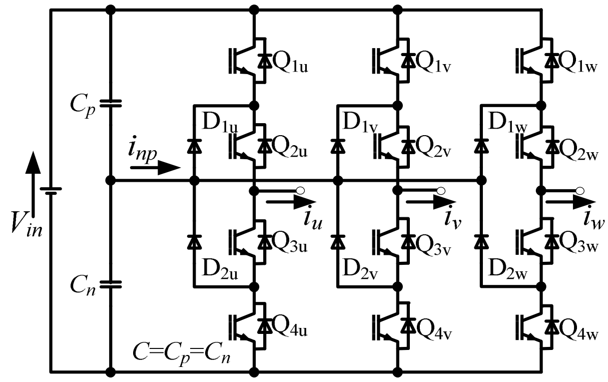


Fig. 1. Circuit topology of neutral point clamped 3-level inverter.

The selection method of the interchange point may include analyzing and comparing the losses for both the PWM and 1'pulse modulation at a same motor speed. At each operation region, the operation method of the smaller loss is selected, which can achieve high efficiency. The study of loss analysis of the 3-level inverter loss or the PMSM loss has been individually reported in Ref. [5-7]. However, the evaluation on losses of the total drive system that is including the 3-level inverter and PMSM has not been reported.

This paper discusses the selection method of the interchange point in terms to achieve minimum loss, by analyzing and comparing the losses for each operation. The total losses of the drive system are subjected to the motor speed and carrier frequency. The total losses are divided into the inverter loss and motor loss. Firstly, we express a quantitative loss calculation method for the inverter. Secondary, a breakdown of losses for the inverter are showed by showing the loss of each element. Thirdly, the loss analysis of PMSM is analyzed by two-dimensional finite element method electromagnetical field analysis (FEM). In addition, the total loss analysis result will clearly demonstrate the relationship between the operation method and total loss. At the end, the neutral-point-clamped 3-level inverter is demonstrated in order to measure the loss of the motor drive system at different carrier frequency for PWM.

II. NEUTRAL-POINT-CLAMPED 3-LEVEL INVERTER

Fig.1 shows a circuit diagram of neutral-point-clamped 3-level inverter. There are two topologies in the 3-level inverters: neutral-point-clamped and T-type. In this paper, a neutral-point-clamped type is selected as the interface converter for the PMSM. However the loss analysis method that described in this paper is applicable for the T-type as well.

A neutral-point-clamped 3-level inverter has a higher conduction loss than 2-level inverter because the switching devices are connected in series. On the other hand, the harmonic loss of the motor can be decreased without the need to increase carrier frequency because the output phase voltage is 3 levels.

Fig. 2 shows a relationship between the motor speed and the inverter output voltage. Operating area A is the PWM region and the effect of decreasing of harmonic losses can be evaluated at the 3-level inverter. Area B is the PWM region in 2-level inverter. However, in 3-level inverter, it is the 1'pulse modulation region and the effect of decreasing of the switching loss can be evaluated.

At 1'pulse modulation, the voltage fundamental amplitude is decided by zero-level phase α, and Fourier series expansion of U-phase voltage v_u is expressed in (1). Furthermore, the fundamental amplitude can calculate form the first term of (1). If α = 0, operation method becomes 1-pulse modulation as shown in area C.

$$\begin{aligned} V_u &= \sum_{n=1}^{\infty}\left[\frac{2E_{dc}}{(2n-1)\pi}\cos\{(2n-1)\alpha\}\sin\{(2n-1)\omega t\}\right] \\ &= \frac{2E_{dc}}{\pi}\cos\alpha\sin\omega t + \frac{2E_{dc}}{3\pi}\cos(3\alpha)\sin(3\omega t) \\ &+ \frac{2E_{dc}}{5\pi}\cos(5\alpha)\sin(5\omega t) + \cdots \end{aligned} \tag{1}$$

III. Loss Calculation of 3-level Inverter

A. Loss Calculation of Inverter

In this section, we describe the loss calculation method for inverter [6-9]. The inverter loss P_{inv} is separated into follows: the conduction loss of IGBT P_{con_IGBT}, the conduction loss of diode P_{con_D}, the switching loss of IGBT P_{sw} and the recovery loss of diode P_{rec}, it is expressed in

$$P_{inv} = P_{con\_IGBT} + P_{con\_D} + P_{sw} + P_{rec} \tag{2}.$$

The conduction loss can be calculated by integrating the product of current flowing along elements i_{sw} and the on-voltage v_{on} under the conduction time from θ_1 to θ_2. It is expressed in (3). The on-state voltage v_{on} is proportional to the current flowing along elements i_{sw} and calculated by linear approximation of the on-resistance r_{on} and the voltage drop by PN junction v_0. It is expressed in (4).

$$P_{con} = \frac{1}{2\pi}\int_{\theta_1}^{\theta_2} v_{on} i_{sw} d\theta \tag{3}$$

$$v_{on} = r_{on} i_{sw} + v_0 \tag{4}$$

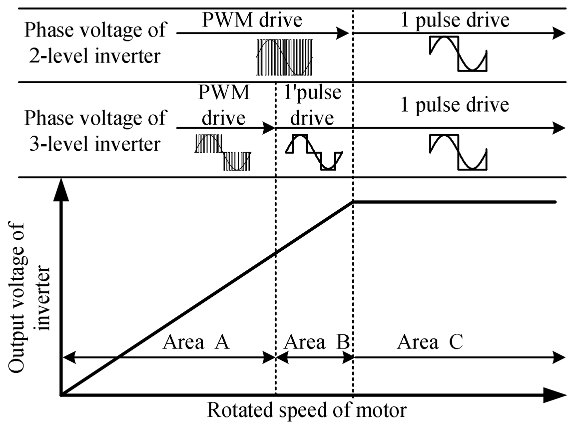


Fig. 2. Comparison of operation method each inverter circuit

TABLE I. PMSM PARAMETERS.

Rating power P_r	3.0 kW
Rating speed N_r	12000 rpm
d-axis inductance L_d	389 μH
q-axis inductance L_q	556 μH
Winding resistance R_a	0.0635 Ω
Back-emf coefficient Φ	0.189 Vs/rad
Armature pairs of poles p	6
Rating Torque T_r	4.0 Nm

The switching loss is proportional to the current flows via elements and the voltage applied to elements. Additionally, the applied voltage to the elements is constant. Therefore, the average switching loss during output cycle is expressed in

$$P_{sw} = E_{dc}\left(e_{on} + e_{off}\right) f_c \frac{1}{2\pi}\int_{\theta_1}^{\theta_2} i_{out} d\theta \tag{5},$$

where, f_c is the carrier frequency, E_{dc} is the DC voltage and i_{out} is the output current. Furthermore, e_{on} is the turn-on energy when the current flowing along elements is 1A and the voltage applied to elements is 1V. The same applies to the turn-off energy e_{off}.

The recovery loss of the freewheeling diode is expressed in (6).

$$P_{rec} = E_{dc} e_{rr} f_c \frac{1}{2\pi}\int_{\alpha}^{\beta} i_{out} d\theta \tag{6},$$

where, e_{rr} is the recovery loss energy.

B. Loss Calculation Results of 3-level Inverter

The loss of the 3-level inverter is calculated based on following condition. The output power is decided from the rated torque and the carrier frequency f_c is 7, 12 and 16 kHz for PWM, respectively. In addition, the modulation strategy for the 3-level converter is applied with unipolar modulation in Ref. [10]. On the other hands, a vector control with $i_d = 0$ for PWM, and V/f control adjoined stabilization control for 1'pulse modulation [11] are applied for the motor. Furthermore, switching devices are applied with IGBT (2MBI100VA-060-50/Fuji electric). Table I shows the parameters of PMSM.

Fig. 3 shows the detail breakdown of the inverter losses. The loss is standardized by the rated motor power. In PWM, the loss at f_c = 7 kHz is the smallest because the switching loss increases in proportional to the carrier frequency. On the other hand, the 1'pulse modulation is shown to have the smallest in all speed range because the switching frequency is the same as the output frequency, i.e. it is the lowest. Thus, the inverter loss at 1'pulse modulation is smaller than that at PWM. In addition, the conduction loss of IGBTs increases and the conduction loss of the diodes decreases with the increasing motor speed. This reasons that the inverter selects the switching pattern which the output time of zero voltage is shortened, i.e. the conduction time of IGBTs (Q1, Q4) increase and the conduction time of clamp diodes decrease, when the output voltage becomes large at high speed.

IV. Loss Analysis of PMSM

A. Development of PMSM Model

The motor loss can be classified: the copper loss by wiring resistance, the iron loss occurring in the core or the magnet and the mechanical loss. In this section, the mechanical loss is ignored because the loss depends only on the motor speed. The motor loss is analyzed by two-dimensional finite element method electromagnetical field analysis (FEM). FEM analyzes the magnetic field occurred in the motor, and then the losses are calculated based on the results. At first, the two-dimensional model of the motor is developed. Next, the analysis is performed by inputting the current waveform which is obtained from the simulation into motor phase.

Table II shows the analysis conditions. The time interval per 1step is decided by considering the effect on the motor loss by the carrier frequency.

B. Loss Analysis Results of PMSM

Fig. 4 shows the breakdown of the motor loss, similar to Fig. 3, the results are standardized by the rated motor power. From the results, the copper loss and the iron loss at the stator are dominant in the motor loss. The loss at 1'pulse modulation shows to be the largest because the harmonic components in the output voltage and current are larger than that of PWM. As the result, the eddy-current occurred in cores and the magnetics becomes higher, and the eddy-current loss is also increase.

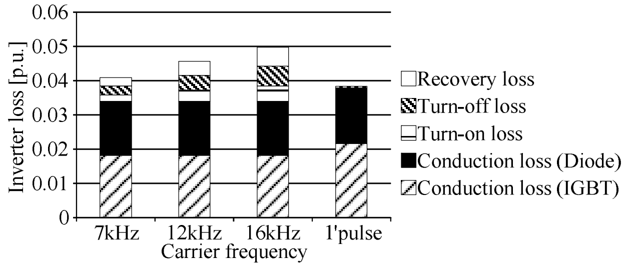
V. Discussions to Minimize Total Loss

From the calculated inverter loss and the analysis of the PMSM loss, the total loss of the drive system can be demonstrated, and next will consider the optimal operation method of 3-level inverter in terms of the minimalize loss.

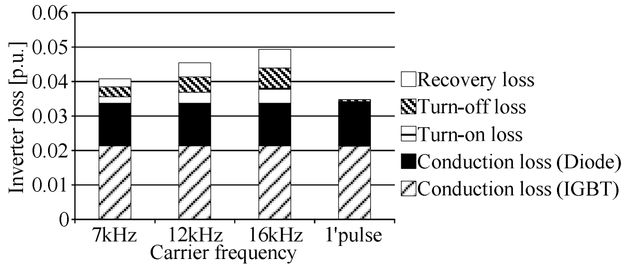
The total loss of the motor drive system P_{loss} is expressed in

$$P_{loss} = P_{sw} + P_{rec} + P_{con} + P_{Cu} + P_{Fe} + P_{mec} \quad (7),$$

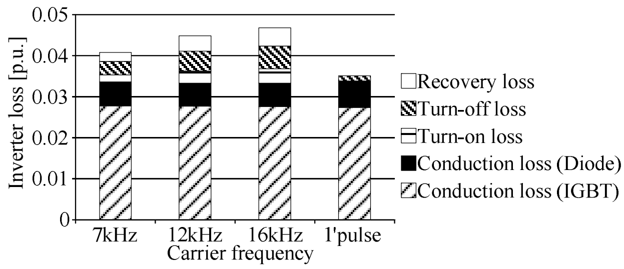
where P_{con} is the conduction loss, P_{Cu} is the copper loss, P_{Fe} is the iron loss and P_{mec} is the mechanical loss. Here, 1'pulse modulation can reduce the switching and recovery loss than PWM drive.



(a) Speed is 0.1 p.u. at PWM and 0.2 p.u. at 1'pulse modulation.



(b) Speed is 0.3 p.u..



(c) Speed is 0.5 p.u..

Fig. 3. Inverter loss analysis results for each operation condition.

TABLE II. PMSM PARAMETERS OF FEM.

Core (rotor, stator)	35H300/Nippon Steel
Magnet	NMX-41SH/Hitachi Metals
Coil turns per phase	11 Turns
Number of elements	48,953
Number of contact points	26,683
Time interval per 1step	8.33e-6
Calculation time	8 hours
Computer	Xeon X5450 3.0GHz

In order to be higher efficiency than PWM drive compared with the 1'pulse modulation, the equation (8) should be respected.

$$P_{sw\_PWM} + P_{rec\_PWM} > \Delta P_{con} + \Delta P_{Cu} + \Delta P_{Fe} \quad (8),$$

where, P_{sw_PWM} and P_{rec_PWM} are the switching loss and the recovery loss, respectively, ΔP_{con}, ΔP_{Cu} and ΔP_{Fe} are the difference between PWM drive and 1'pulse modulation of the conduction loss, the cupper loss and the iron loss, respectively. The mechanical loss P_{mec} is ignored because the loss at PWM drive equals to that at 1'pulse modulation in order to depend only on a motor speed. In addition, the switching loss P_{sw} and the recovery loss P_{rec} at 1'pulse modulation are ignored because these are vanishingly lower than that at PWM drive.

Furthermore, it assumes that the current harmonic component at PWM drive is vanishingly smaller than that at 1'pulse modulation. In addition, the difference between PWM drive and 1'pulse modulation of the iron loss ΔP_{Fe} is formulated by the analysis result of the FEM. Under these conditions, the equation (8) is expressed in (9).

$$P_{sw\_PWM} + P_{rec\_PWM} > \frac{I_n}{I_{out\_PWM}} P_{con\_PWM} + 3R_a I_n^{\ 2} + ae^{-b\omega} \quad (9),$$

where, I_{out_PWM} is the RMS of the current at PWM, I_n is the harmonic component of the current at 1'pulse modulation, a and b are constant value, ω is the electrical angular frequency. In addition, I_n is expressed in (10) [12].

$$I_n = \sum_{n=1} \left(\frac{\frac{2E_{dc}}{(2n+1)\pi} \cos\{(2n+1)\alpha\}}{\omega\sqrt{L_d^{\ 2} + L_q^{\ 2}}} \right) \quad (10)$$

If the equation (9) is respected, the total loss at 1'pulse modulation is lower than that at PWM drive. Therefore, in this case, the use of 3-level inverter can achieve higher efficiency drive than the use of 2-level inverter. In other words, if the equation (9) is not respected, the total loss at 1'pulse modulation is higher than that at PWM drive. The use of a 3-level inverter is not benefit and a 2-level inverter has a cost advantage with that kind of system.

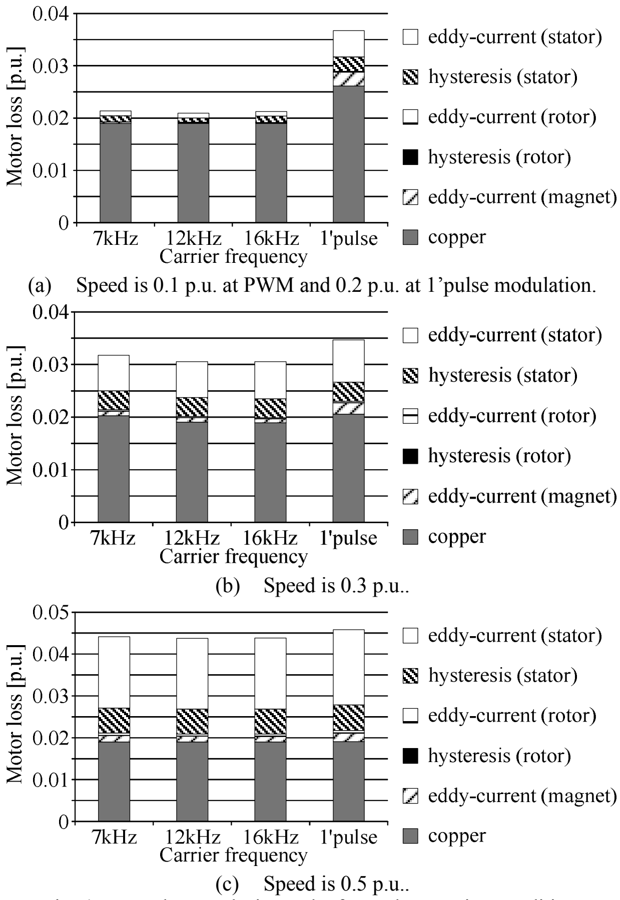
Fig. 5 shows relationship between the motor speed and the total loss, and the optimal interchange point of the operation method. For the speed region under 0.3 p.u., the PWM drive (fc = 7 kHz) shows to achieve the smallest loss. On the other hand, at the speed region over 0.3 p.u., 1'pulse modulation shows to achieve the smallest loss because the rate of the inverter loss in total loss is higher. In this region, the equation (9) is respected. Thus, the high efficiency can be achieved by interchange the operation method at 0.3 p.u. speed in this case.

VI. EVALUATION BY EXPERIMENTATION

The drive system of PMSM was implemented to compare the total loss with the implementation of spoken operation method. In this section, the total loss that measured by the system is showed.

Fig. 6 shows a configuration of the developed drive system. The power consumption of the inverter is measured by the power meter (WT1800/YOKOGAWA). The measured power points for the inverter are between the DC bus capacitor and the output of inverter. In addition, the torque meter is put between the test motor and the load motor. The operation conditions are output torque T = 2.0 Nm and carrier frequency f_c = 10, 12 and 16 kHz for PWM. The motor control method uses a vector control with i_d = 0 and applied a balance control because voltage of two DC capacitors should be equalized [13]. Furthermore, switching devices are selected with IGBT (2MBI50P-140/Fuji electric) in order to confirm that the validity of (9). Besides, the tested motor is the same as table II.

The loss of the motor is separated as follows. Firstly, the motor loss is the difference between the output power of the inverter and the shaft power of the motor. The copper loss is calculated by the winding resistance and the RMS of the motor current. The mechanical loss is calculated by the torque at no-load running. Finally, the iron loss is the value which the copper loss and the mechanical loss are excepted in the motor loss.



(a) Speed is 0.1 p.u. at PWM and 0.2 p.u. at 1'pulse modulation.

(b) Speed is 0.3 p.u..

(c) Speed is 0.5 p.u..

Fig. 4. Motor loss analysis results for each operation condition.

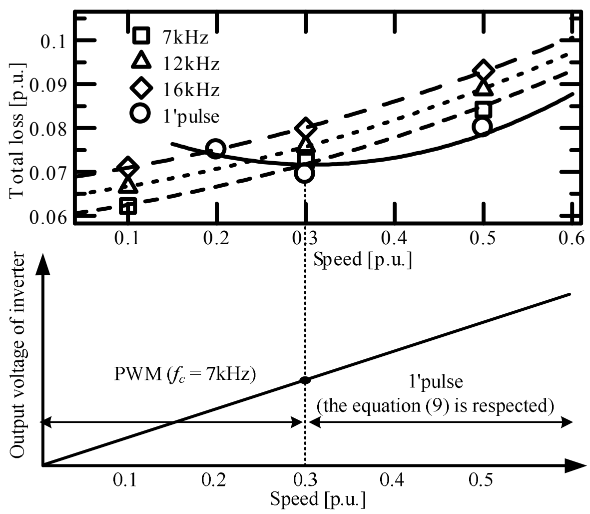


Fig. 5. The total loss of a PMSM drive system and switching point of operation method.

Fig. 7 shows U-V line-to-line voltage and U phase current waveforms of the 3-level inverter at carrier frequency f_c = 16 kHz. From Fig. 7, it is noted that the current waveform is distorted because the PMSM is a concentrated windings and back electromotive force of the motor contains harmonic component. In addition, the reason includes that the inductance of the motor is smaller than typically PMSMs.

Fig. 8 shows measurement results of the drive system loss. The rate of the mechanical loss and the iron loss increases with the increasing motor speed, because a mechanical loss and an iron loss are proportional to motor frequency, i.e. the speed and motor voltage, respectively. Therefore, when a PMSM is turned at high speed, it is effective to use a magnetic material which an iron loss decreases due to decrease the total loss.

Fig. 9 shows analysis results of the inverter loss using simulation. From Fig. 8 and Fig. 9, the measurement result is basically consistent with analysis results. The inverter loss is dominated by the conduction loss. This reason is that the output current is larger than that of a 2-level inverter. In addition, the conduction loss is not depends on the carrier frequency because the harmonic components in the current are decreased by the 3-level inverter. Furthermore, the loss at f_c = 10 kHz is the smallest, because the switching frequency is the lowest.

Fig. 10 shows the analysis results of the motor loss using FEM and compare between the analysis results and the measurement results. As the result, the eddy-current loss of stator dominates more than half of the motor loss at 0.5 p.u. speed because the eddy-current loss increases in proportional to the motor frequency. In addition, the loss of f_c = 12 kHz is the smallest at 0.3 p.u. speed. The reason is that the copper loss by the harmonic components of the current is smaller than that of f_c = 10 kHz. Furthermore, the amplitude of magnetic flux density is decreased by carrier frequency but the frequency of that increases, therefore, the motor loss is the smaller than that of f_c = 16 kHz.

Fig. 11 shows the total loss of developed PMSM drive system based on measurement results. The loss at 10 kHz is the smallest because the rate of the inverter loss is larger than that of the motor loss. The rate of the motor loss in the total loss is low because the harmonic components of the voltage and the current decrease as the 3-level inverter. Therefore, it is desirable that carrier frequency is lowered as much as possible with that kind of system. However, if the carrier frequency has a profound effect on the motor loss, it is contemplated that the optimal carrier frequency is changed by motor speed.

VII. CONCLUSION

In this paper, the loss minimized operation method of a 3-level inverter was considered in order to achieve a high efficiency motor drive system. As the result, it can be obtained that the total loss decreases when the operation method is interchanged at the point where the curve of PWM loss intersects with 1'pulse modulation. In addition, if the rate of the inverter loss is lower, the use of a 3-level inverter is not benefit and a 2-level inverter has a cost advantage with that kind of system. Furthermore, the motor drive system by a neutral-point-clamped 3-level inverter was tested and the losses of the system were measured and compared with analysis results at each carrier frequency. As the result, when a rate of a motor loss in total loss is lower, it is high efficiency that a carrier frequency is lower. In the future work, the 3-level inverter will be operated with 1'pulse modulation and the loss will be compared at PWM and 1'pulse modulation. Furthermore, calculation of a motor loss will be simplified.

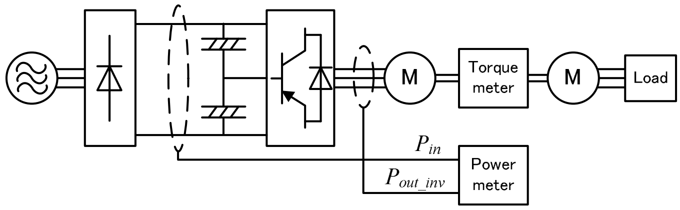


Fig. 6. Configuration of the developed drive system.

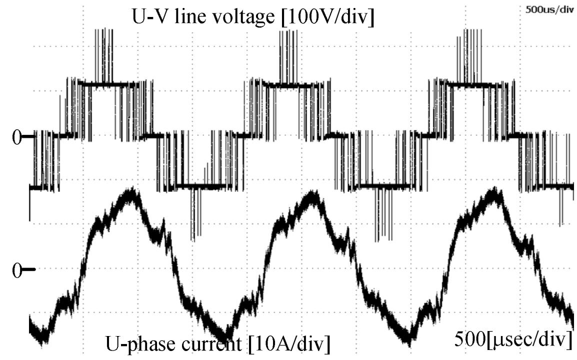
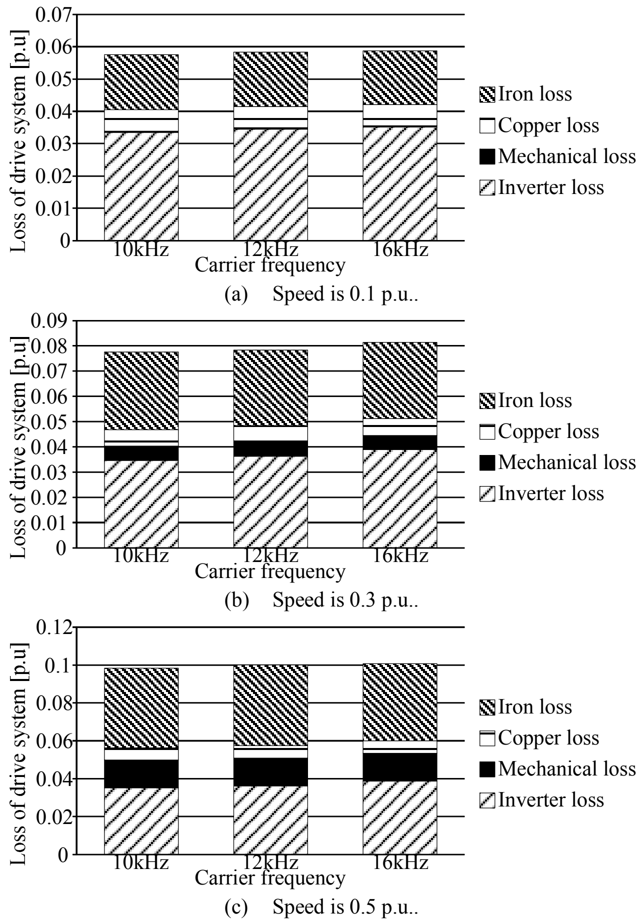
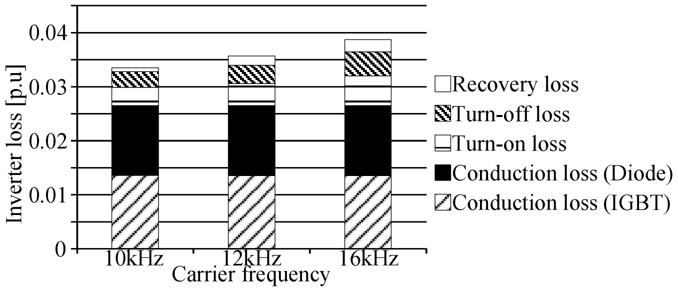


Fig. 7. U-V line-to-line voltage and U phase current waveform of using the 3-level inverter at carrier frequency f_c = 16 kHz.

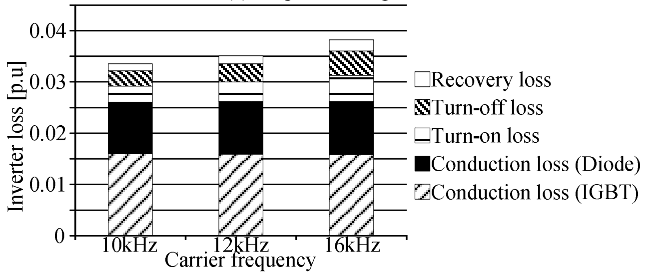


(c) Speed is 0.5 p.u..

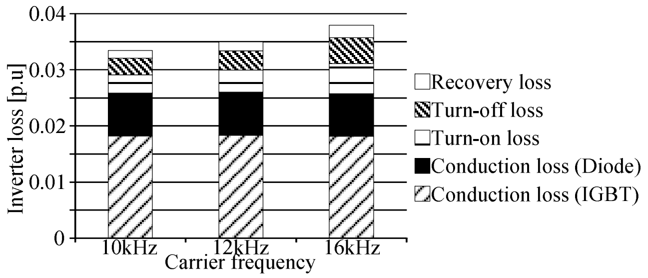
Fig. 8. Loss measurement results of developed PMSM drive system.



(a) Speed is 0.1 p.u..

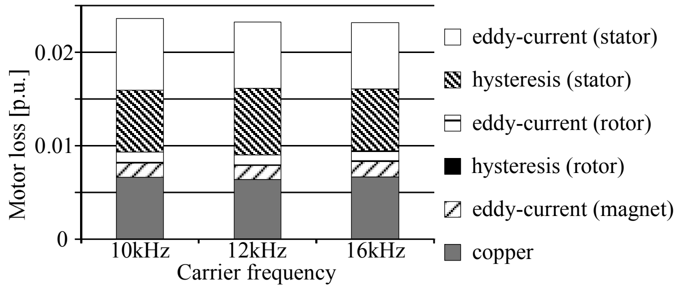


(b) Speed is 0.3 p.u..

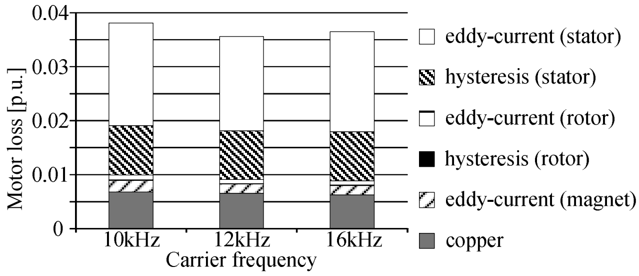


(c) Speed is 0.5 p.u..

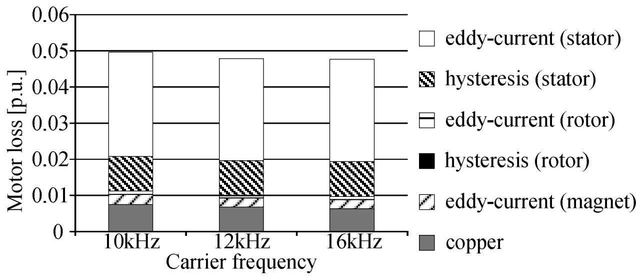
Fig. 9. Analysis result of the inverter loss using simulation.



(a) Speed is 0.1 p.u..



(b) Speed is 0.3 p.u..



(c) Speed is 0.5 p.u..

Fig. 10. Analysis result of the motor loss using FEM.

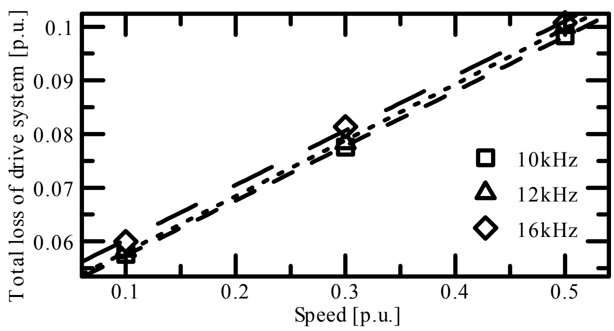


Fig. 11. The total loss of developed PMSM drive system based on measurement results.

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