Power Loss Reduction and Optimum Modulation Index of PWM Inverter with Voltage Booster for Permanent Magnet Synchronous Motor Drive

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Abstract

The power loss in the voltage booster of a pulse-width-modulated (PWM) inverter with voltage booster for a surface permanent magnet (SPM) motor drive system and the modulation index of PWM inverter are investigated by a computer simulation. For the power loss, it is shown that the copper loss in DC reactor dominates the loss in the voltage booster and the reduction of the resistance of DC reactor makes the voltage booster unstable. Moreover, the stable region is examined for various values of the proportional gain of a DC link voltage regulator and the resistance of DC reactor. The stable region for small values of the resistance is enlarged by feedforward compensation. And the reduction of the loss in the voltage booster is realized. Finally, in the steady state, the PWM inverter without pulse dropping is realized. The variable parameter which provides the DC link voltage with voltage margin is introduced. We name this parameter voltage margin factor. And the value of the parameter at which the PWM inverter has no pulse dropping in both the steady and transient states is investigated.

Key words: Permanent magnet synchronous motor, PWM inverter, Voltage booster, Power loss reduction

1 Introduction

With appearance of high-performance rare-earth magnets, permanent magnet (PM) synchronous motors have higher efficiency and became more compact recently. Therefore, the

are performed by 1) the flux weakening operation in high speed region[1], [2], or 2) using a pulse-width-modulated (PWM) inverter with a DC link voltage control circuit such as a voltage booster[3], [4].

In general, surface permanent magnet (SPM) motors have higher efficiency than interior permanent magnet (IPM) motors. However, the SPM motors are unsuitable for the flux weakening operation because of their small inductance. Therefore, a PWM inverter with a DC link voltage control circuit is one of the suitable selections for SPM motor drives. This selection has several advantages over the IPM motor drives with the flux weakening operation. These advantages are as follows:

- This system does not need the current to reduce the magnet flux of the motor. Thus, no copper loss by the current is generated.
- Even if gating is suddenly removed from the inverter switches during high speed operation, the amplitude of the line-to-line back-emf generated by the spinning PM rotor magnets is kept under the DC link voltage. Therefore, this system has no probability of serious faults expected for the IPM motor drive with the flux weakening operation[5].

Because of the above reasons, if the loss in the DC link voltage control circuit is reduced, the PWM inverter with the DC link voltage control circuit can offer a high efficient and safe drive system for PM motors. In several papers, the PM motor driven by the PWM inverter with a voltage booster was discussed. In [3], the efficiency of the drive system was improved by a discussed.

In this paper, the power loss in the voltage booster of the SPM motor drive system and the modulation index of PWM inverter are investigated by a computer simulation. It is shown that the copper loss in the DC reactor dominates the loss in the voltage booster. And also it is indicated that the reduction of the resistance of the reactor makes the voltage booster unstable. To clarify the stability of the voltage booster, the stable region is examined for various values of the proportional gain of a DC link voltage regulator, K_{pv}, and the resistance of the DC reactor, R_{chop}. The stable region for small values of R_{chop} is enlarged by a feedforward compensation[6]. As a result, the reduction of the loss in DC reactor is realized. Next, we introduce a variable parameter K_{edc} which provides voltage margin for the DC link voltage required by the current regulators. We name this parameter the voltage margin factor. And the K_{edc} value at which the PWM inverter has no pulse dropping in both the steady and transient states is investigated.

2 Circuit scheme

The circuit and block diagram of the PWM inverter with the voltage booster is shown in Fig.1. This system consists of a conventional PWM inverter and a voltage booster which can control the DC link voltage. This system operates as a conventional PWM inverter when the DC link voltage reference $e_{dc}{}^*$ is less than the battery voltage E_{BT} and operates as a PWM inverter with variable DC link voltage when $e_{dc}{}^*$ is greater than E_{BT}.

In the controller, the DC link voltage reference $e_{dc}{}^*$ is calculated by the following equation.

$$e_{dc}{}^*=K_{edc}\sqrt{2}\sqrt{v_{sd}^2+v_{sq}^2} \qquad (1)$$

where v_{sd} and v_{sq} are the output signals from the current PI regulators. The voltage margin factor K_{edc} ($\geq$1.0) is used to avoid the pulse dropping in the PWM inverter. In the steady state, K_{edc} is related to the modulation index m in the PWM inverter by the equation $K_{edc} = 1\ /\ m$ while the voltage booster operates. For K_{edc}=1, the voltage reference $e_{dc}{}^*$ is just equal to the kept. The margin factor K_{edc} is investigated in the section 4.

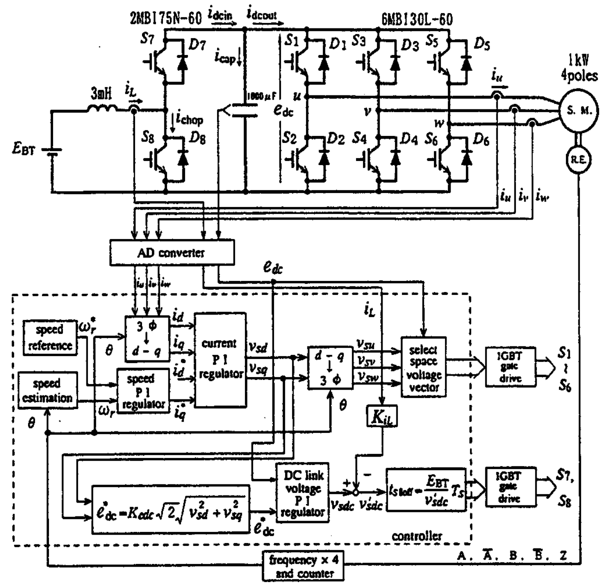


Fig.1. Circuit and block diagram of PWM inverter with voltage booster

The feedforward compensation of the DC reactor current i_L, which is discussed in the section 3, is used to stabilize the operation of the voltage booster. The values of the parameters of the PM motor, the voltage booster, the PWM inverter and the controller are listed in Table 1.

3 Power loss reduction in voltage booster

3.1 Power loss in voltage booster

When the battery voltage E_{BT} and the ripple of the reactor current, $\Delta\ i_L$ are constant, the relation between the inductance of the reactor, L, and the switching frequency of the voltage booster, f, can be written as the following form:

$$L=\frac{k_L}{f} \qquad (2)$$

where $k_L=\dfrac{E_{BT}}{\Delta i}\left(1-\dfrac{E_{BT}}{e_{dc}}\right)$

Also the relation between the inductance L and

$$P_L = R i_L^{\,2} = k_R \sqrt{\frac{k_L}{f}}\, i_L^{\,2} \qquad (4)$$

Fig. 2 shows the loss in DC reactor, P_L, the loss in switches, P_{sw}, and the total loss in the voltage booster, $P_{chop} = P_L + P_{sw}$, as a function of the switching frequency of the voltage booster, f. The loss in switches, P_{sw}, includes the conduction loss in the diode and the IGBT, the turn-on and turn-off loss in the IGBT and the recovery loss in the diode. To calculate the loss P_{sw}, we used the data book offered by the manufacturer[7]. The losses P_{chop}, P_L and P_{sw} were calculated with the following condition:
i_L = 9A, Δi_L = 0.8A (5% of the rated motor current), e_{dc} = 102V, 4000rpm, IGBT 2MBI75N-60.
The points A and B were calculated for the real reactors we have. From Fig. 2, one finds the following:
- For the air-core reactor, the P_{chop} - f curve shows the minimum value (P_{chop} = 80.1W) at f = 25.5kHz (L_{chop} = 0.85mH, R_{chop} = 0.59Ω). And for the iron-core reactor, the curve shows the minimum value (P_{chop} = 23.8W) at f = 5.3kHz (L_{chop} = 4.06mH, R_{chop} = 0.12Ω).

Table.1. Values of parameters.

Permanent magnet synchronous motor		
Rated output power		1kW
Rated rotational speed		2500rpm
Rated torque		3.92Nm
Rated voltage		100V
Rated current		16A
Pole number	P	4
Armature resistance	R	0.09Ω
d-axis inductance	L_d	0.25mH
q-axis inductance	L_q	0.36mH
Flux of field	ϕ	0.0785Wb
Voltage booster and PWM inverter		
Battery voltage	E_{BT}	80V
DC link capacitor	C_{dc}	1000μF
Inductance of DC reactor	L_{chop}	3mH
Resistance of DC reactor	R_{chop}	0.1Ω
Controller		
Sampling period	T_s	250μs
Proportional gain of speed regulator	$K_{p\omega}$	1.0
Integral time constant of speed regulator	τ_ω	2.0s
Proportional gain of current regulator	K_{pi}	0.6
d-axis integral time constant of current regulator	$\tau_{id}=L_d/R$	2.8ms
q-axis integral time constant of	$\tau_{iq}=L_q/R$	4.0ms

- The loss in DC reactor, P_L, dominates the loss in the voltage booster, P_{chop}.
- The iron-core reactor with low resistance decreases the loss in the voltage booster by a factor of 3 (from 80.1W to 23.8W).

3.2 Stability of voltage booster

To solve the simultaneous deferential equations for the system in Fig. 1, we used the FORTRAN language. At first, an air-core reactor (L_{chop} = 3mH, R_{chop} = 1.1Ω) was used as the DC reactor and the voltage booster was stable. Next, the reactor was exchanged to an iron-core reactor (L_{chop} = 3mH, R_{chop} = 0.1Ω) to reduce the copper loss in the reactor. In this case, however, the voltage booster indicated unstable behavior.

The stable region of the voltage booster was examined for various values of the proportional gain of DC link voltage regulator, K_{pv}, and the resistance of the DC reactor, R_{chop}. In our system, the voltage reference e_{dc}^* is decided by the output signals of the current PI regulators. In this section, however, the reference e_{dc}^* was fixed at 120V (e_{dc}^* / E_{BT} = 1.5) to simplify. And

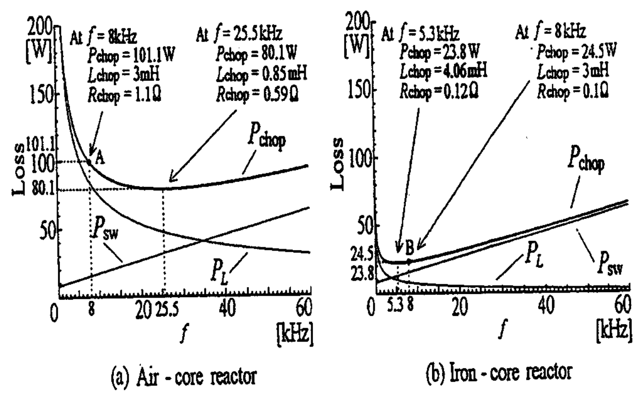
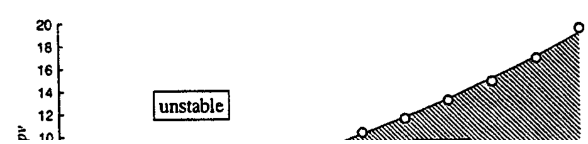


Fig.2. Losses in voltage booster (4000rpm, e_{dc}^* = e_{dc} = 102V, i_L = 9A, Δi_L = 0.8A (5% of the rated motor current))



80% of the rated power was selected for the load of motor. Fig.3 represents the stable and unstable regions. In this figure, the open circles stand for the stable points and the cross stands for the unstable point. The open circle A in Fig.3 indicates the operating point for R_{chop} = 1.1 Ω (corresponding to the point A in Fig.2(a)) and the cross B indicates the operating point for R_{chop} = 0.1 Ω (corresponding to the point B in Fig.2(b)). The computed waveforms of various parts for the two operating points A and B are shown in Fig.4. From Fig.3 and 4, it is clear that the operating point B is in the unstable region.

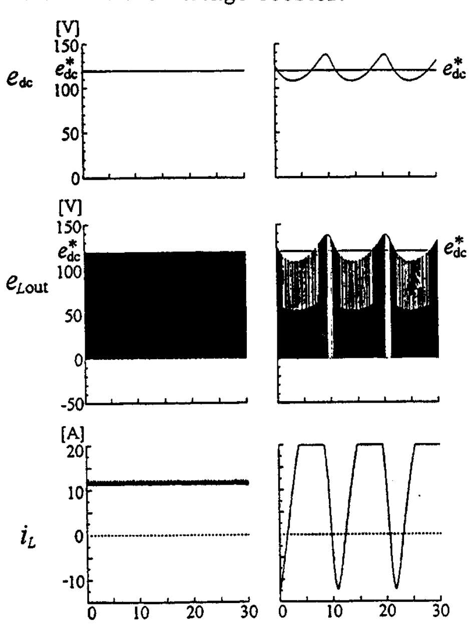
3.3 Feedforward compensation

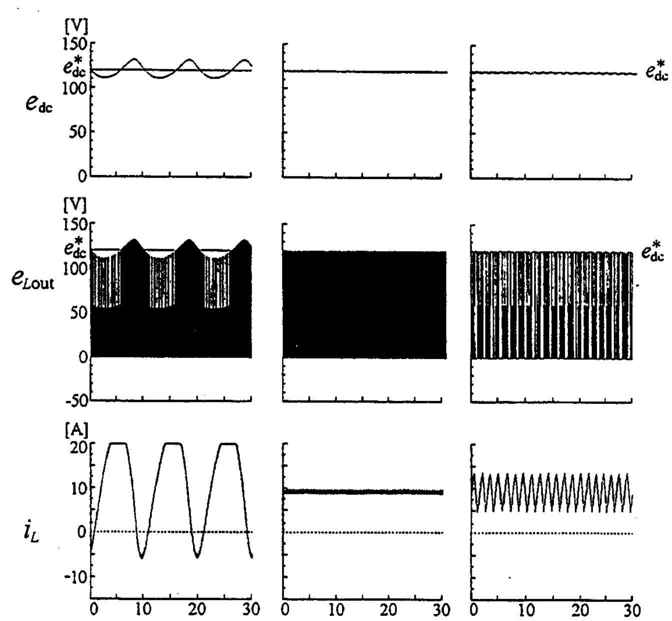
We introduce the feedforward compensation of the reactor current i_L to stabilize the voltage booster[6].

To demonstrate the effects of the feedforward compensation, the computed waveforms of various parts for the operating point corresponding to B in Fig.2 and 3 are shown in Fig.5. Fig.5(a), (b) and (c) show the undercompensated, just compensated and overcompensated waveforms, respectively. The appropriate selection of the feedforward gain K_{iL} can stabilize the voltage booster.

4 Choice of parameter *Kedc*

In this section, the K_{edc} value at which the PWM inverter has no pulse dropping in both the steady and transient states is investigated. The calculated waveforms of various parts in the steady state are indicated in Fig.6(a). In this figure, we chose 1 as the value of K_{edc}, which means that the value of the modulation index m is equal to 1, because high value of the modulation index is desirable to reduce the core loss in motors. However, the parts in the ellipses in Fig.6(a) are partially distorted because of the effect of the saturation, that is, the pulse dropping of the inverter output voltage. Fig.7 illustrates the saturation of the inverter output voltage. Fig.7(b) shows the vector diagram of the permanent magnet synchronous motor corresponding to the time C in Fig.6(a). The vectors $pL_d i_d$ and $pL_q i_q$ show that the margin of v_d is enough but that of v_q is not enough. Consequently, the ripple of i_d is large and that of i_q is small in Fig.6(a). To avoid the pulse dropping, various values of the voltage margin factor K_{edc} were investigated for both the steady and transient states. For the steady state, the current waveform distortion was observed for various values of K_{edc}, speed and load. For

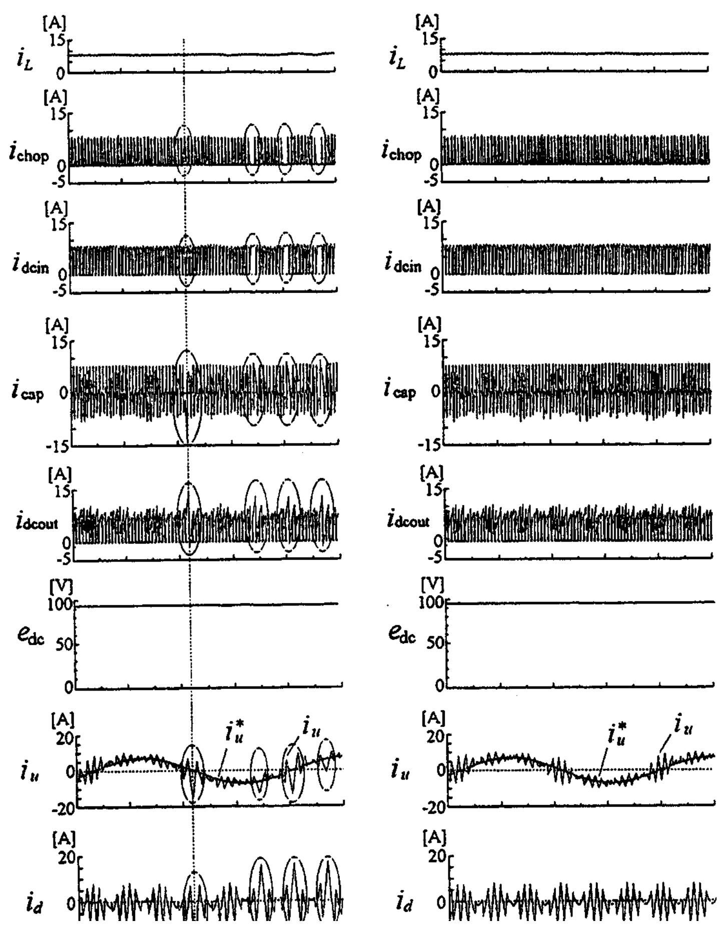


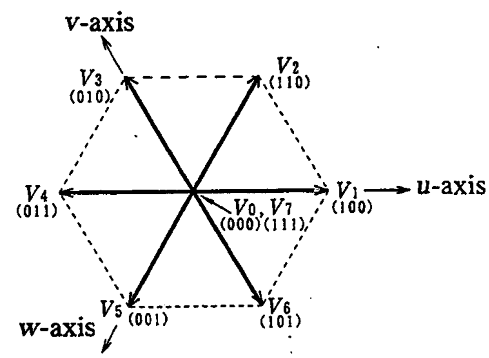


transient state, the q-axis current reference i_q^* was changed from the value corresponding to no load to the value corresponding to 50% load at each speed and the current waveform distortion was observed for various values of K_{edc} and speed. As the result, we found that the pulse dropping disappears for the value of K_{edc} above 1.02 in the steady state and above 1.1 in the transient state, respectively. For example, the steady state waveforms for K_{edc} = 1.02 are demonstrated in Fig.6(b). And the transient state waveforms for K_{edc} = 1.0, 1.05 and 1.1 are shown in Fig.8. We choose 1.1 as the value of K_{edc} at which the PWM inverter has no pulse dropping. In other wards, our system operates as a conventional PWM inverter with the value of m between 0 and 0.91 when e_{dc}^* is less than E_{BT} and operates as a PWM inverter with fixed value of m (0.91) and variable DC link voltage when e_{dc}^* is greater than E_{BT}.

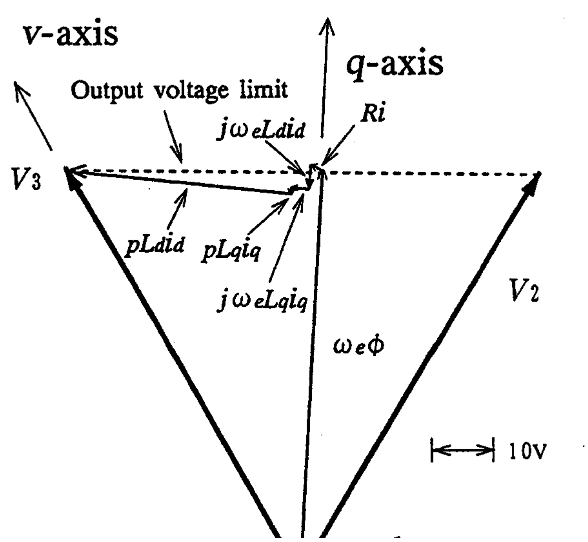
5 Conclusions

The power loss in a voltage booster of a PWM inverter with voltage booster was investigated by a computer simulation. The stable region of the voltage booster was examined and was enlarged by a feedforward compensation. As a result, the reduction of the loss in DC reactor was realized. Furthermore, the modulation index of PWM inverter was investigated and the PWM inverter without pulse dropping in both the steady and transient states was realized by the appropriate selection of the voltage margin factor K_{edc}.





(a) Voltage vectors



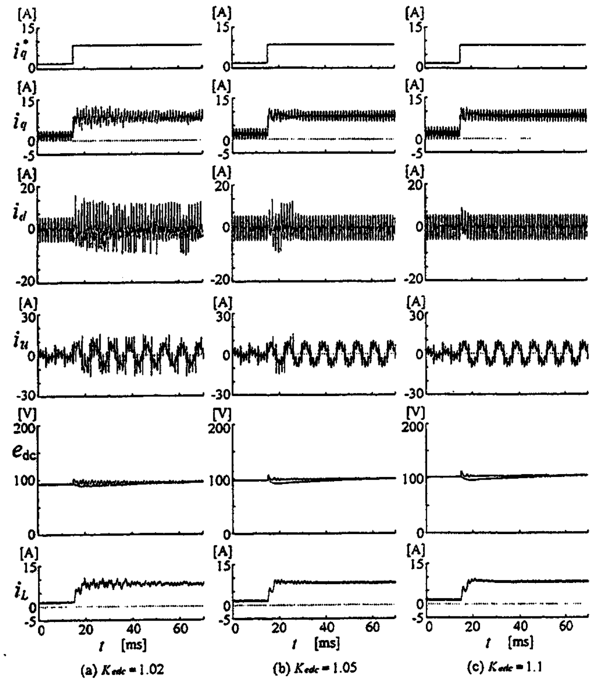


Fig.8. Transient state waveforms of voltage booster and PM motor for step change of q-axis current reference i_q* ($Kpv = 5.0$, $K_{iL} = 5.0$, 4000rpm)

We conclude from the results the following.

1) The copper loss in DC reactor dominates the loss in the voltage booster.
2) Both the increase in the proportional gain of DC link voltage regulator and the decrease in resistance of DC reactor drive the voltage booster into the unstable region.
3) The feedforward compensation of DC reactor current contributes to stabilize the voltage booster. By the feedforward compensation, we could use a DC reactor with low resistance and the loss in the voltage booster was reduced from 80.1W to 23.8W.
4) The value of the modulation index m (1.0) caused the pulse dropping and the motor current distortion. However, the pulse dropping and the current distortion disappeared for the value of the voltage margin factor K_{edc} above 1.02 in the steady state and above 1.1 in the transient state, respectively. The selected value of K_{edc} (1.1) realized the PWM inverter without pulse dropping in both the steady and transient states and the modulation index m was the constant 0.91 in the steady state.

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