Permanent Magnet Synchronous Motor Driven by PWM Inverter with Voltage Booster with Regenerating Capability Augmented by Double-Layer Capacitor

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Keywords: permanent magnet motor, PWM inverter, voltage booster, double-layer capacitor and regeneration

1. System Configuration

An interior permanent magnet (IPM) motor drive system which has regenerating capability augmented by double-layer capacitors is proposed. The configuration of proposed system is demonstrated in Fig. 1. The motor is driven by a PWM inverter with voltage booster. The voltage booster is used to control the dc link voltage in high speed region to improve the system efficiency. Furthermore, the double-layer capacitor as a storage element is combined with the PWM inverter with voltage booster to gain the efficiency for the regenerating operation. In this system, normally, the regenerative power does not return to a battery directly but is stored in the double-layer capacitors for the next motoring action to suppress the excessive regenerative current to battery (see Fig. 2), and the regenerative power returns to the battery when the regenerative energy is larger than a certain value (see Fig. 3). The charging current to the battery is controlled to a constant value to extend the life-time of the battery.

2. Simulated and Experimental Results

The transient and steady state characteristics of the system for 1.5 kW IPM motor are investigated by both simulation and experiment and the results are illustrated in Figs. 2 and 3, respectively. From these figures, one finds the following:
- It is clear that there is good agreement between the simulated and experimental results.
- From behavior of the current to the double-layer capacitor unit \( i_{DL} \), it is also clear that the double-layer capacitor is charged during the decelerating period in Fig. 2. The current from battery \( i_{BT} \) is reduced during the accelerating period due to using of the stored energy.
- From behavior of \( i_{DL}, i_{BT} \) and \( e_{DL} \) in Fig. 3, one finds that the double-layer capacitor unit is charged while the terminal voltage of the double-layer capacitor unit \( e_{DL} \) is less than the limit voltage of \( E_{BT} + 8.0 \text{ V} \). And regeneration to the battery starts when \( e_{DL} \) reaches to the limit voltage. The charging current to the battery is controlled to the value of constant reference \( i_{BT} = -5 \text{ A} \) by the charging current controller and the charging current controller operates correctly in accordance with \( e_{DL} \) and direction of \( i_L \).
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Keywords: permanent magnet motor, PWM inverter, voltage booster, double-layer capacitor and regeneration

1. Introduction

The permanent magnet (PM) motors form an increasingly important class of high performance ac motor drives and are used for not only industrial applications but also electric vehicle and another applications.

There are two main operations of the PM motors over wide speed range. These are performed by 1) the flux weakening operation at high-speed region(1)(2) or 2) a PWM inverter with a dc link voltage control circuit(3)–(5).

The flux weakening operation is more conventional method. However, this operation needs additional current to reduce the magnet flux of motor and the current increases copper loss.

A PWM inverter with a dc link voltage control circuit is another solution. This drive system has several advantages over the drives with flux weakening operation as follows:
- This drive system does not need the current to reduce the magnet flux of the motor. Thus, no additional copper loss by the current is generated.
- If the gating signal 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.
- In spite of variation of the battery voltage, this system can keep the value of a constant dc link voltage in the constant torque region. It makes the motor design much easier in terms of the maximum current of the motor.

The purpose of our research is to improve the efficiency of the PM motor drive system. We use the PWM inverter with dc link voltage control circuit to extend the speed range of the interior permanent magnet (IPM) motor without the flux weakening. We have investigated the stability of the PWM inverter with voltage booster(5) and the characteristics of the drive system(6) and have compared the flux weakening operation with the operation by the PWM inverter with voltage booster analytically(7). The analytical results for both operations demonstrated that the operation by the PWM inverter with voltage booster gave higher efficiency than that given by the flux weakening operation in the constant power region.

To increase the efficiency of the drive system, regenerative energy is also important. In the system of electric vehicles, however, the regenerative energy is consumed by the breaking resistor to extend the life-time of high performance expensive batteries, generally. We paid attention to the double-layer capacitor as a new energy storage element to absorb the regenerative energy. This capacitor has a lot of advantages such as no maintenance, long life-time and quick charge/discharge characteristics with large current, etc. Some papers for applications of the double-layer capacitor have been published. In reference (8), the double-layer capacitor was used for power smoothing and absorbing regenerative energy in elevator applications. In reference (9), the capacitors were attached to the dc link of adjustable-speed drive system through the flyback converter to compensate the dc link voltage drop during short-term power interruptions. We also have proposed a voltage sag compensator...
In this paper, an IPM motor drive system which has regenerating capability augmented by double-layer capacitors is proposed. We combine the double-layer capacitor as a storage element with the PWM inverter with voltage booster to gain the efficiency for the regenerating operation. In the system in reference (8), double-layer capacitors are used to reduce the high power peaks appearing on the power grid. However, the regenerative energy in the system is not returned to the power grid. On the other hand, in our system, the stored regenerative energy in the double-layer capacitors is used for not only the next motoring operation but also charging battery with constant current in accordance with the voltage level of the double-layer capacitors. At first, the system configuration is explained. Next, the transient and steady state characteristics of the system for 1.5 kW IPM motor are investigated by simulation, and the validity of the simulated results is confirmed by the experimental results. Finally, the effectiveness of the system is demonstrated.

2. System Configuration

Fig. 1 shows the configuration of the proposed system. This system consists of a conventional PWM inverter, a voltage booster which can control the dc link voltage and double-layer capacitor unit to store regenerative energy temporarily. The IPM motor is 1.5 kW and has six poles. 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 $E_{BT}$.

The double-layer capacitor unit and the charging current controller are located between the voltage booster and the battery. For the motoring operation, the energy needed by the motor is supplied by the battery through the diode $D_7$. For the temporary regenerating operation, the regenerative energy is stored in the double-layer capacitor unit and is used for the next motoring operation. For the long time regenerating operation, the regenerative energy charges the battery with a constant current when the terminal voltage of the double-layer capacitor unit exceeds a limit voltage. The charging current to the battery is controlled by a hysteresis controller.

The nominal values of parameters of a double-layer capacitor are 2.3 V and 6000 F. We made two capacitor banks. Each bank consists of 50-series-connected capacitors. The two banks were connected in parallel and a double-layer capacitor unit was made. We assumed the equivalent circuit for the capacitor unit as illustrated in Fig. 2 and decided the equivalent capacitance $C_{DL}$ and the equivalent internal resistance $R_{eq}$.
where \( P\) is the pole number, \( \phi \) is the flux of field, \( L_d \) and \( L_q \) are the \( d\)- and \( q\)-axes inductance. Solving (1) for \( i_q \), the following equation is obtained.

\[
i_q = \frac{2}{P} \frac{T}{\phi + (L_d - L_q)i_d}
\]

This equation expresses a hyperbola for a certain torque in the \( i_d-i_q \) plane. For the maximum torque per ampere operation, we choose the operating point on the hyperbola which is the nearest to the origin of the \( i_d-i_q \) plane. The trajectory for the maximum torque per ampere operating point is plotted in Fig. 3. The trajectory in the third quadrant is for the regenerating operation. We used an approximation for the trajectory with the following equation.

\[
i_q^* = -Ki_q^{2.5}
\]

The value of \( K \) was decided as 0.01456 by the least-square method. Using this \( i_q^* \) can make the motor current minimum even if the motor is in the regenerating operation.

The dc link voltage reference \( e_{dc} \) is calculated from \( v_{id} \) and \( v_{iq} \) to make the stator current control possible. The parameter \( K_{edc} \) is used to avoid partial saturation for the PWM voltage. When \( e_{dc} \) becomes higher than battery voltage \( E_{BT} \), the voltage booster begins to operate to increase the dc link voltage \( e_{dc} \). And \( e_{dc} \) is controlled to the value which is enough to control the motor currents. The feedforward of the reactor current \( i_q^\star \) is used to stabilize the voltage booster.

The charging current to battery is controlled in accordance with the terminal voltage of double-layer capacitor unit \( e_{DL} \) and the direction of the reactor current \( i_q \). The details will be described in the next chapter.

The values of the parameters used for the proposed system for regenerating operation was described in the next chapter.

### 3. Regenerating Operation

In the proposed system, normally, the regenerative power does not return to a battery directly but is stored in the double-layer capacitor unit for the next motoring action to suppress the excessive regenerative current to battery (Mode I). And the regenerative power returns to the battery when the regenerative energy is larger than a certain value (Mode II). The charging current to battery is controlled to a constant value to extend the life-time of the battery.

We decided the condition to switch between Mode I and Mode II as the following:

1. If \((E_{BT} + 8 \text{ V}) < e_{DL} \), then the controller begins charging battery. (Mode I \rightarrow Mode II)
2. If \((E_{BT} + 2 \text{ V}) > e_{DL} \), then the controller stops charging battery. (Mode II \rightarrow Mode I)

\( E_{BT} \) is the battery voltage and the value was 100 V, and \( e_{DL} \) is the terminal voltage of electric double-layer capacitor unit. If the terminal voltage increases from 102 V to 106 V, the stored energy in the electric double-layer capacitor unit increases as follows.

\[
\frac{1}{2} 	imes 207 \times (106^2 - 102^2) = 86112 \text{ J}
\]

This energy corresponds to the regenerative power of 1.5 kW for one minute. Practically, there are a lot of factors which affects to \( E_{BT} \) and \( e_{DL} \) such as voltage drop in switching devices, change of voltage across the internal resistance for current direction, etc. Taking these factors into account, the hysteresis band for switching between Mode I and Mode II was chosen as 6 V (from 102 V to 108 V). The voltage of 2 V is voltage margin.

### 4. Simulated and Experimental Results

4.1 Temporary Regenerating Operation

Simulation of the proposed system for regenerating operation was performed. The values of the parameters used for the...
Table 1. Values of parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent magnet synchronous motor</td>
<td></td>
</tr>
<tr>
<td>Rated output power</td>
<td></td>
</tr>
<tr>
<td>Rated rotational speed</td>
<td>1750 rpm</td>
</tr>
<tr>
<td>Rated torque</td>
<td>8.18 Nm</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>170V 1.5kW</td>
</tr>
<tr>
<td>Rated current</td>
<td>6.1 A</td>
</tr>
<tr>
<td>Pole number</td>
<td>6</td>
</tr>
<tr>
<td>Armature resistance</td>
<td>$R$ 0.775 Ω</td>
</tr>
<tr>
<td>d-axis inductance</td>
<td>$L_d$ 5.71 mH</td>
</tr>
<tr>
<td>q-axis inductance</td>
<td>$L_q$ 9.94 mH</td>
</tr>
<tr>
<td>Flux of field</td>
<td>$\Phi$ 0.2848 Wb</td>
</tr>
<tr>
<td>Voltage booster and PWM inverter</td>
<td></td>
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<tr>
<td>Battery voltage</td>
<td>$E_{BT}$ 100 V</td>
</tr>
<tr>
<td>DC link capacitor</td>
<td>$C_{dc}$ 1000 µF</td>
</tr>
<tr>
<td>Inductance of DC reactor</td>
<td>$L_{chop}$ 3 mH</td>
</tr>
<tr>
<td>Resistance of DC reactor</td>
<td>$R_{chop}$ 0.1 Ω</td>
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Controller

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling period</td>
<td>$T_s$ 125 µs</td>
</tr>
<tr>
<td>Proportional gain of speed regulator</td>
<td>$K_p_s$ 0.4</td>
</tr>
<tr>
<td>Integral time constant of speed regulator</td>
<td>$\tau_s$ 25.0 s</td>
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<tr>
<td>Proportional gain of current regulator</td>
<td>$K_p_i$ 20.0</td>
</tr>
<tr>
<td>d-axis integral time constant of current regulator</td>
<td>$\tau_d = L_d/R$ 2.8 ms</td>
</tr>
<tr>
<td>q-axis integral time constant of current regulator</td>
<td>$\tau_q = L_q/R$ 4.0 ms</td>
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<tr>
<td>Proportional gain of DC link voltage regulator</td>
<td>$K_p_v$ 0.001</td>
</tr>
<tr>
<td>Integral time constant of DC link voltage regulator</td>
<td>$\tau_v$ 10.0 s</td>
</tr>
<tr>
<td>Feedforward gain for DC reactor current</td>
<td>$K_{dc}$ 0.02</td>
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<tr>
<td>Constant for DC link voltage margin</td>
<td>$K_{edc}$ 1.2</td>
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<tr>
<td>Switching frequency of PWM inverter</td>
<td>$f_{sw,_inverter}$ 4 kHz</td>
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<tr>
<td>Switching frequency of voltage booster</td>
<td>$f_{sw,_chop}$ 8 kHz</td>
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</table>

Double-layer capacitor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent capacitance</td>
<td>$C_{DL}$ 207 F</td>
</tr>
<tr>
<td>Equivalent internal resistance</td>
<td>$R_{DL}$ 0.06 Ω</td>
</tr>
</tbody>
</table>

Simulation are listed in Table 1. At first, we investigated the temporary regenerating operation. The acceleration and deceleration for high inertia load were simulated and the results are shown in Fig. 4(a). The experimental results corresponding to the simulated results are also shown in Fig. 4(b). The inertia of moment was 0.058 kg-m$^2$ (tested IPM motor: 0.004 kg-m$^2$, load IPM motor: 0.044 kg-m$^2$ and couplings: 0.01 kg-m$^2$) and the acceleration and deceleration were performed between 100 r/min to 1800 r/min. The averaging regenerative power is nearly 500 W during the decelerating period. For the terminal voltage of the double-layer capacitor unit e$_{DL}$, the voltage booster operates for the speed between 500 r/min to 1800 r/min. In addition, D/A converter output signal was used for the experimental e$_{DL}$ because e$_{DL}$ had a lot of small ac components on a large dc component. For the change of experimental e$_{DL}$, the ac coupling of the digital oscilloscope was also tried but it was not available because e$_{DL}$ had some very low-frequency components.

From Fig. 4, one finds the following:

- It is clear from this figure that there is good agreement between the simulated and experimental results except some noises in the experimental results.
- From behavior of the current to the double-layer capacitor unit i$_{DL}$, it is also clear that the double-layer capacitor is charged during the decelerating period. The current from battery $i_{BT}$ is reduced during the accelerating period due to using of the stored energy.
- The d-axis current i$_d$ changes so as to perform the maximum torque per ampere operation in accordance with the q-axis current i$_q$.
- In the experimental results, the terminal voltage of the double-layer capacitor unit e$_{DL}$ changes smaller than that in the simulated results.

4.2 Long Time Regenerating Operation

We investigated the long time regenerating operation. Steady state regenerating operations were simulated and the simulated results are represented in Figs. 5(a) and 7(a). The enlarged waveforms corresponding to A in Fig. 5(a) and C in Fig. 7(a) are illustrated in Figs. 6(a) and 8(a), respectively. The regenerative power was produced by a 15 kW IPM motor with inverter control in the experimental system. The battery current
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Fig. 5. Characteristics for steady state regenerating operation (average regenerative power is 200 W)

(a) Simulated results  (b) Experimental results

reference was set to $i_{BT}^* = -5$ A (charging operation) and $E_{BT}$ was 100 V. The simulated results in Figs. 5(a) and 7(a) are for two values of the regenerative power of 200 W and 700 W, respectively. The regenerative power of 200 W was chosen so that the absolute value of reactor current $i_L$ might be less than the absolute value of battery current $i_{BT}$ and 700 W was chosen so that the absolute value of $i_L$ might be greater than the absolute value of $i_{BT}$.

Experimental results corresponding to Figs. 5(a), 6(a), 7(a) and 8(a) are shown in Figs. 5(b), 6(b), 7(b) and 8(b), respectively. The same value of hysteresis band was set for both simulation and experiment to control the charging current to the battery $i_{BT}$. For the experiment, however, effective hysteresis band became wider than that for the simulation because of the delay of comparator device. As a result, the experimental $i_{BT}$ and $i_{DL}$ included less high frequency components than the simulated results. In addition, the experimental $e_{DL}$ also included less high frequency components than the simulated results because D/A converter output signal from DSP system was used for the experimental $e_{DL}$.

From Figs. 5–8, one finds the following:

- There is good agreement between the simulated and experimental results.
- From behavior of $i_{DL}$, $i_{BT}$ and $e_{DL}$, it is clear that the double-layer capacitor unit is charged while the terminal voltage of the double-layer capacitor unit $e_{DL}$ is less than the limit voltage of $E_{BT} + 8.0$ V in Fig. 5 and 7.

Regeneration to the battery starts when $e_{DL}$ reaches to the limit voltage. The direction of $i_{DL}$ is switched from positive (charge) to negative (discharge) for the regenerative power of 200 W in Fig. 5(a) and (b). On the other hand, the direction of $i_{DL}$ does not change for the regenerative power of 700 W in Fig. 7(a) and (b).

- The charging current to the battery is controlled to the value of constant reference $i_{BT}^* = -5$ A by the charging current controller and the charging current controller operates correctly in accordance with $e_{DL}$ and direction of $i_L$.

- From the enlarged waveforms of $e_{DL}$ in Fig. 6(b), the variation of $e_{DL}$ is coursed because of the variation of $i_L$ in the experimental system and the variations of $e_{DL}$ and $i_L$ become seriously for large $i_L$ in Fig. 8(b).

- In comparison Figs. 5 and 6 with Figs. 7 and 8, it is clear that the d-axis current $i_d$ changes properly in accordance with the change of the q-axis current $i_q$ so that the maximum torque per ampere operation may be accomplished.

5. Conclusion

An IPM motor drive system which has regenerating capability augmented by double-layer capacitors was proposed. The double-layer capacitor as a storage element was combined with the PWM inverter with voltage booster to gain the efficiency for the regenerating operation. Normally, the...
regenerative power does not return to a battery directly but is stored in the double-layer capacitors for the next motoring action to suppress the excessive regenerative current to battery, and the regenerative power returns to the battery when the regenerative energy is larger than a certain value. The charging current to the battery is controlled to a constant value to extend the life-time of the battery. The transient and steady state characteristics of the system for 1.5 kW IPM motor were investigated by both simulation and experiment, and the effectiveness of the system was demonstrated by the simulated and experimental results.

We conclude from the results the following.
- The validity of the simulated results was confirmed by comparing the simulated results with that obtained from the experimental.
- The fact that for two modes of the regenerating operation the system works properly, is confirmed by both simulation and experiment.

The proposed system can recovery the regenerative energy effectively and would be able to contribute for the extension of the life-time of the battery.

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