Research on predictive current control method of PMSM for continuous switched boost inverter

Liyong Yang, Shuo Han, Shuo Liu and Xiaojuan He

College of Electrical and Control Engineering in North China University of Technology, Beijing 100144, China

hanshuo930204@163.com

Abstract. In this paper, the continuous switched boost inverter (CSBI) is used to improve permanent magnet synchronous motor (PMSM) control performance through predictive control, aiming at the drawback of the traditional PMSM drive system. Between the inverted circuit and the input DC power, a switched boost circuit is added to form a switched boost inverter circuit to achieve higher voltage gain and eliminate the dead band. Meanwhile, the drive system has higher reliability. Moreover, the paper adopts predictive current control (PCC) to control PMSM, comparing with the traditional field oriented control (FOC), PCC has faster dynamic performance and reduces current ripple. Finally, the simulation and experimental results verify the feasibility of the based on the continuous switched boost inverter of predictive current control for PMSM.

1. Introduction

Permanent magnet synchronous motor (PMSM) has high efficiency and power factor comparing with direct current machines and induction machines. It possesses characteristics such as less heat, small, simple structure, large overload current and high reliability. It has been widely used in industrial and agricultural production, industrial automation and information technology field [1]. The traditional drive system modulation usually adopts the space vector pulse width modulation (SVPWM) [2], which can reduce harmonic distortion. Meanwhile, SVPWM technology with the continuous switched boost inverter (CSBI) has good ability to resist electromagnetic interference (EMI) and avoids the distortion of the output waveform [3]. CSBI has high boost capability and shoot-through immunity, it combines the high gain of Z-source inverter (ZSI) [4] and switched boost inverter (SBI) [5] characteristics using a small number of passive components. The CSBI has only one LC filter from the inverter structure. Meanwhile, based on continuous switched boost inverter, establishing the relationship of DC input and alternating current (AC) output analyzes steady state of the inverter.

PMSM control methods are proposed to have good dynamic response performance, such as adaptive PID controller [6], neuro-fuzzy controller [7], direct predictive control (DPC) [8], dead-beat PC [3]. These control schemes have different defects which include fast response, torque ripple, system delay, uncertain parameters and so on. However, predictive current control (PCC) combines advantages of DPC and deadbeat PC, and has been applied successfully in PMSM control.
The cost function is chosen appropriately to force the control process to reach the desired standard for PCC method. It contains the current control squared error, and also adds additional conditions to the controller to satisfy the implementation of several additional criteria. The PCC optimizes the voltage vector and the duty cycle to the cost function which guarantees the global optimum of the selected voltage vector, and obviously improves the steady-state performance of the system.

2. Continuous switched boost inverter

2.1. CSBI topology
CSBI gets high gain and can improve EMI immunity in the boost mode. The inverter combines the advantages of the traditional voltage source inverter (VSI) [5], the SBI and the ZSI. It has the same gain as the ZSI, and possesses the same number of components as the SBI. It doesn't need the dead band of the switch signals, so the output waveform distortion could be avoided [5]. The topology of CSBI with the PMSM as shown in Fig. 1.

![Figure 1. Topology of CSBI](image)

2.2. CSBI operation
The CSBI can provide high voltage gain and can work in two states: shoot-through state and non-shoot-through state. In the shoot-through state, the inductor $L$ is charged by capacitor $C_0$ and input power $U_{dc}$. In the non-shoot-through state, the capacitor $C_0$ is charged by the inductor $L$. The equivalent circuits of the CSBI in the shoot-through and non-shoot-through state are shown in Fig. 2.

![Figure 2. Equivalent circuit of the CSBI: (a) shoot-through state and (b) non-shoot-through state](image)

When the inverter operates in the shoot-through state, the voltage of inductor $L$ and the current of capacitor $C_0$ are given by Fig. 2(a).

$$
\begin{align*}
U_L &= U_{dc} + U_C \\
i_L &= -i_c
\end{align*}
$$

(1)

When the inverter operates in the non-shoot-through state, the voltage of inductor $L$ and the current of capacitor $C_0$ are given by Fig. 2(b).

$$
\begin{align*}
U_L &= U_{dc} - U_C \\
i_c &= i_L - i_{load}
\end{align*}
$$

(2)

where $U_L$ is the voltage of the inductor $L$; $U_{dc}$ is the input source; $U_C$ is the voltage of the capacitor $C_0$; $i_L$ is the current of the inductor $L$; $i_c$ is the current of the capacitor $C_0$; and $i_{load}$ is the output current of the inverter.

When the steady state equilibrium, using the volt-second balance of inductance and the
amp-second balance of capacitor can get the voltage conversion ratio $B$ of the CSBI [9].

$$B = \frac{U_c}{U_d} = \frac{1}{2D - 1}$$  \hspace{1cm} (3)

Where $D$ is the shoot-through duty cycle, and $B$ is the voltage conversion ratio of CSBI. The relationship between voltage conversion ratio and shoot-through duty cycle is shown in Figure 3. Fig. 3 can be seen the $B$ of the system increases with the increase of $D$.

Figure 3. Relationship between voltage conversion ratio and shoot-through duty ratio

3. PMSM model and control strategy

PCC [6] aims to improve the response speed and steady-state error of PMSM, and the PCC replaces the PI controller to use current control in the FOC. Similar to other predictive control methods, the PCC based on the motor model in the switching period to get the desired current, the feedback of the desired currents are $i_{dk}$ and $i_{qk}$, the value of rotor speed $\omega$ from coder and the value of the $d$-$q$ currents. Fig.4 shows the diagram of the PCC algorithm using a PI controller as a speed control loop. This paper uses $i_{*d}=0$ control method.

3.1 Discrete model of PMSM

In the PCC algorithm [6], the control variables are stator currents. In order to predict the stator currents of given switching states, the differential equation model needs to transform to discrete time model based on the dynamic model of the motor. In this way, the next state of $d$-$q$ currents is predicted by the current value of the $d$-$q$ currents, the measured electrical angle and the input $d$-$q$ voltages.

When the sampling period is very short, the surface mounted PMSM ($L=L_d=L_q$) is created a discrete time model by Taylor series expansion [6].

$$i_{*d}(k+1) = (1 - \frac{RT}{L_d})i_{*d}(k) + \frac{1}{L_d}\omega(k)l_{*q}(k),$$

$$i_{*q}(k+1) = (1 - \frac{RT}{L_q})i_{*q}(k) + \frac{1}{L_q}\omega(k)l_{*d}(k).$$

(4)

3.2 Predictive Current Control Method

The design of the controller involves the calculation of the reference voltage that should be implemented in the current time step, so as to ensure that the current will follow the reference voltage in the next step. This goal is to get the minimum value of the difference between the predicted currents $i_{dk+1}$, $i_{qk+1}$ and the reference values $i_{*d}$, $i_{*q}$. 

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Figure 4. Block diagram of the PCC algorithm
The cost function selects the voltage vector that minimizes between the predicted current and given current. It contains the current control squared error, and adds additional conditions to the controller to satisfy the implementation of several additional criteria. The value of predictive current can be given by the discrete model (4) of PMSM, a cost function [7] is calculated as follows:

\[
g(\hat{u}_{k}^*, u_{k}) = i_{ak}, (i_{qk} - i_{qk})^2
\]

The cost function includes \(u_{dk}^*\) and \(u_{qk}^*\), it must ensure that achieve the minimum value in each step. Through (4), the predictive currents \(i_{dk+1}, i_{qk+1}\) can be expressed the reference voltage \(u_{dk}^*, u_{qk}^*\), and measured currents \(i_{dk}, i_{qk}\), and speed value \(\omega_{s}\), respectively. The cost function is rewritten as,

\[
g(u_k) = u_k^T \lambda^2 u_k + \mu_k u_k
\]

The parameters of this cost function are defined as:

\[
u_k = \begin{bmatrix} u_{dk} \\ u_{qk} \end{bmatrix}, \\
\lambda = \frac{T_s}{L_{sh}}, \\
\mu_1 = 2\lambda(i_{zh} - \frac{RT_i}{L_{sh}} i_{zh} + \omega_n T_i i_{qz-1}), \\
\mu_2 = 2\lambda(-\omega_n T_i i_{zh} + i_{qo} + \frac{RT_i}{L_{so}} i_{qo} - \omega_n T_i \psi_t)
\]

The diagonal-constant matrix \(\mu_k\) of \(\hat{g}\) is time variable, because they depend on the feedback currents \(i_{zh}, i_{qo}\) and rotor speed \(\omega_n\). Moreover, \(\mu_2\) depends on the output of the speed control loop orthogonal reference current \(i_{qo}\). Therefore, the optimization process takes place at each time step and produces a variable voltage reference signal.

Because of the safety and reliability of the motor, an additional constraint is required that the current amplitude does not exceed a certain maximum value. The technical specifications of the motor select the maximum current as the maximum transient permissible current. The maximum current constraint needs a certain limit; that is,

\[
\begin{cases}
i_{zh} < i_{MAX} \\
i_{qo} < i_{MAX}
\end{cases}
\]

Substitute (4) into (7) to obtain the optimal voltage value for the controller,

\[
u_{k} = \frac{1}{\lambda}(i_{ux} - i_{z} + \frac{RT_i}{L_{so}} i_{z} - \omega_n T_i i_{q}) \\
u_{k}' = \frac{1}{\lambda}(i_{ux} + \omega_n T_i i_{z} - i_{q} + \frac{RT_i}{L_{so}} i_{q} + \omega_n \psi_t)
\]

By using the Newton's iterative optimal algorithm, the system can run the optimization process, and the \(r+1\) iteration function is expressed by the function of the \(r\)th iteration result [6], that is,

\[
u_{k+1} = u_{k} - \gamma(u_{k} + \frac{1}{2\lambda^2} \mu_k^2)
\]

The coefficient \(\gamma (0<\gamma<1)\) of the Newton’s method is introduced to modify. It can reduce the step size to prevent potential numerical instability, divergence, and overshooting.
**Table 1.** Parameter of the used PMSM

| Parameter                  | Value         |
|----------------------------|---------------|
| Rated Voltage $U_n$        | 160V          |
| Rated Current $I_n$        | 5.5A          |
| Rated Speed $\omega_n$     | 1200r/min     |
| Inductance $L$             | 17mH          |
| Per Phase Winding Resistance $R$ | 1.3Ω        |
| Torque Constant $k_m$      | 1.23Nm/A      |
| Number of Pole Pairs $n_p$ | 3             |
| Inertia $J$                | 0.00087kg·m²  |

**Table 2.** Parameters of the control system

| Parameter                  | Value         |
|----------------------------|---------------|
| Switching frequency $f_s$  | 5kHz          |
| Sample time $T_c$          | 0.2μs         |
| Boost circuit inductance $L$ | 2mH          |
| DC bus capacitor bank $C_0$ | 560μF        |
| Optimization step coefficient $\gamma$ | 0.7          |

4. **Simulation results**

In this part, Fig. 5 shows the relationship between the input voltage $U_{dc}$ and the bus voltage $U_c$. Then, the PCC algorithm in SVPWM was carried out using a PMSM. Nominal parameters are given in Table 1, and the performance of the PCC scheme has been analyzed by simulation. Table 2 shows the parameters of the Control System, and the shoot-through duty cycle is $D=0.2$ in this simulation.

4.1. **The input voltage and the bus voltage simulation results of CSBI**

![Figure 5. The input voltage and the bus voltage](image)

In Fig.5, the input voltage $U_{dc}$ is 60V, according to (3) gets the bus voltage $U_c$ after boost circuit. The steady state after external load, the bus voltage is 100V satisfying the equation (3).
4.2. PMSM simulation results

Figure 6. Simulation results: (a) stator current waveform and (b) rotor speed waveform

The motor starts at no-load. Then, a step of external load is 0.2 N·m and a constant speed is about 150r/min that are applied at about t=0.5s and then removed at t=1s. Finally, a step of external load is 0.5 N·m and a constant speed is about 250r/min that are applied at about t=1s and then removed at t=1.5s.

In Fig.6(a), after external load, the waveform of the stator current could recover quickly. In Fig.6(b), under the SVPWM, the PCC peak time is 0.0023s, the maximum speed overshoot is 8%, and the transient time is 0.0049s.

The performance of the PCC has been analyzed by simulation results as shown in the Table 3.

Table 3. Simulation Results for PCC.

|                      | PCC  |
|----------------------|------|
| Speed peak time      | 0.0023s |
| Speed transient time | 0.0049s |
| Speed overshoot      | 8%   |
| Speed steady-state error | 0     |

5. Experimental results

The experimental setup basically consisted of a PMSM with a control board implemented in stm32f407ZGT6 and EMP570T100C5. Then, it verifies the relationship between the input voltage $U_{dc}$ and the bus voltage $U_c$. The PMSM and the control system parameters are the same as Table 1 and Table 2, and the shoot-through duty cycle is $D=0.3$ in this experiment.

5.1. The input voltage and the bus voltage experimental results of CSBI

Figure 7. The input voltage and the bus voltage (2s/div)

In Fig.7, the input voltage $U_{dc}$ is 36V, according to the equation (3) gets the bus voltage $U_c$ after boost circuit. The bus voltage is 92.5V satisfying the equation (3) after the steady state.
5.2. PCC experimental result
In this part, the motor starts at no-load. Then, a constant speed is 50r/min, and a constant speed changes 200r/min a few minutes later.

![Rotor speed experimental results](image)

**Figure 8.** Rotor speed experimental results (1s/div)

Fig. 8 shows the rotor speed experimental results of a speed controller with the PCC method. The speed rising time is 0.8s. Meanwhile, the PCC method has not overshoot and steady-state error. The PCC algorithm possesses preferable response speed.

6. Conclusion
This paper designs a kind of PCC of PMSM for the CSBI, it combines and improves the CSBI, SVPWM method and PCC algorithm. The PMSM drive system can obtain the continuous input current from DC power source, and avoid the output waveform distortion. When the input voltage fluctuation, the voltage of the capacitor remains the same. It can be seen from the simulation and experimental results that the same results can be obtained by using the PCC method based on the CSBI. Meanwhile, the control system also acquired excellently steady control effect.

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