A Novel Hybrid Seven-Level Converter for Permanent Magnet Synchronous Motor Driving System Based on Model Predictive Control

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Abstract—A novel hybrid three-phase seven-level converter is proposed in the paper. Each phase consists of a four-level bridge and a two-level H bridge, which contains ten switching devices and a floating capacitor. The circuit structure is introduced and working principle of the converter containing 14 commutation paths is analyzed, which is easy to control the floating capacitor voltage. In order to drive permanent magnet synchronous motor (PMSM) with the proposed converter, model predictive control (MPC) strategy is adopted. The control objectives such as controlling the currents of PMSM and capacitor voltages balancing are included in a cost function with two weight factors, which can control the currents of PMSM and balance the capacitor voltages simultaneously. To validate the proposed control scheme, simulations in two cases are carried out by using Matlab/Simulink software. Finally, the feasibility and efficiency in two cases are verified with the experimental test bench based on RT_LAB.

Index Terms—Capacitor voltages, MPC, PMSM, Seven-Level converter.

I. INTRODUCTION

PMSM has the characteristics of high power density, low loss, small ripple coefficient of torque and fast dynamic response. It has been widely used in electric vehicles, ship propulsion, railway transportation, wind power generation, servo and other fields [1]-[4]. At the high power level, the use of two-level converters is not an appropriate solution. Multilevel converters, with the advantages of low voltage harmonics and low electromagnetic interference, have been widely used to drive PMSM [5]-[6]. In general, multilevel converters are classified into diode-clamped [7], flying capacitor [8] and cascaded multilevel converter topologies [9]. However, as the number of voltage levels increases, the number of switching devices also increases, which will increase the cost, volume and control complexity [10]-[14].

In order to overcome these drawbacks, scholars had proposed a variety of novel seven-level topologies. A topology consisted of a four-level capacitor-clamped bridge and an H-type bridge was presented in [15]. In [16], an IGBT was used to replace two diodes based on [15], which reduced the devices and switching frequency. However, the two topologies were only used in single-phase converters. A novel hybrid seven-level converter consisted with six H-type bridges was proposed in [17]. In [18], a seven-level converter with a three-level NPC bridge and an H-type bridge per phase was studied. Based on [18], the three-level NPC bridge was replaced by three-level T-type bridge in [19]. However, the topology in [19] lacked redundant switching states at the maximum and minimum voltage levels, which makes it difficult to control the floating capacitor voltage.

Based on the existing literature, a new hybrid seven-level converter is proposed in this paper. Each phase consists of a four-level bridge and a two-level H bridge. The structure and working principle of the converter are analyzed and MPC is adopted to drive PMSM with the proposed converter.

II. CIRCUIT STRUCTURE AND WORKING PRINCIPLE

The circuit structure of the seven-level converter for PMSM driving system is shown in Fig. 1. Each phase consists of a four-level bridge and a two-level H bridge, which contains ten switching devices and a floating capacitor. \( S_{x1}, S_{x4}, S_{x5}, S_{x6}, S_{x7} \) and \( S_{x8} \) (\( x \) is A, B or C) are unidirectional blocking devices; \( S_{x2} \) and \( S_{x3} \) are bidirectional blocking devices that usually consisted of two insulated gate bipolar transistors (IGBTs) in reverse series connection. If the voltages of DC bus capacitors \( C_1, C_2 \) and \( C_3 \) are defined as CE and the voltages of floating capacitors \( FC_a, FC_b \) and \( FC_c \) are defined as E, there are 7 different voltages by controlling the switching states of the switching devices. The maximum voltage that \( S_{x1} \) and \( S_{x4} \) can withstand is...
6E, the maximum voltage that $S_{x2}$ and $S_{x3}$ can withstand is 4E and the maximum voltage that $S_{x5}$, $S_{x6}$, $S_{x7}$ and $S_{x8}$ can withstand is E. Therefore, different types of switching devices can be used in the converter to reduce cost and improve efficiency. For instance, if the DC bus voltage is 380V, IGBTs with blocking voltage of 1200V can be selected for $S_{x1}$ and $S_{x4}$, IGBTs with blocking voltage of 600V or 650V can be selected for $S_{x2}$ and $S_{x3}$ and IGBTs with blocking voltage of 150V or 200V can be selected for $S_{x5}$, $S_{x6}$, $S_{x7}$ and $S_{x8}$.

Fig. 1. The circuit structure of seven-level converter for PMSM driving system.

There are 14 commutation paths in the proposed converter, as shown in Fig. 2 and Table. I. In the Table. I, $V_{FCx}$ is the floating capacitor voltage. $I_x$ is the phase current and the positive direction of $I_x$ is shown in Fig. 1. “↑”, “↓” and “¬” represent increase, decrease and no change of $V_{FCx}$, respectively. $V_x$ is the output voltage.
As can be seen from Table I, when the output voltage is 6E, 4E, 2E or 0, Ix doesn’t flow through CFx, and the voltage of CFx will be not changing. When the output voltage is 5E, 3E or E, Ix flows through CFx and the direction of Ix determines whether CFx is charged or discharged. Therefore, it’s easy to control the voltage of CFx.

III. MODEL PREDICTIVE CONTROL

The scheme of the seven-level converter for PMSM driving system based on MPC is shown in Fig. 3.

The variables in Fig. 3 are as follows:

1) reference speed of PMSM $\omega^*$ and measured speed of PMSM $\omega$;
2) reference DC bus capacitor voltage $V_{DC}^*$ and reference floating capacitor voltage $V_{FC}^*$;
3) measured DC bus capacitor voltage $V_{DC}$ ($V_{DC1}$, $V_{DC2}$, $V_{DC3}$) and measured floating capacitor voltage $V_{FC}$ ($V_{FC1}$, $V_{FC2}$, $V_{FC3}$);
4) $d$-axis reference current $i_d^*$ and $q$-axis reference current $i_q^*$;
5) measured current in static frame $i_a$, $i_b$, $i_c$ and current in rotated frame $i_d$, $i_q$;
6) electrical angle $\theta$, DC power supply $U_{dc}$ and switching states $S_k$ ($X$ is $A, B$ or $C$).

$\omega$ and $\theta$ are measured by speed detector and position detector, respectively. $i_q^*$ is obtained by inputting $\omega^*$ and $\omega$ to proportional-integral (PI) speed controller and $i_d^*$ is set to zero. $V_{DC}^*$ is set to 2E and $V_{FC}^*$ is set to E. The currents in static
frame (abc) can be converted to the currents in rotated frame (dq) using

\[
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix} = T_{abc \rightarrow dq} \begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
\]

(1)

where \( T_{abc \rightarrow dq} = \begin{bmatrix} \cos \theta & \cos(\theta - 2/3\pi) & \cos(\theta + 2/3\pi) \\ -\sin \theta & -\sin(\theta - 2/3\pi) & -\sin(\theta + 2/3\pi) \end{bmatrix} \) is the transformation matrix. Finally, MPC strategy is adopted with the variables to control the PMSM.

Similarly, the mathematical model of PMSM in static frame (abc) can be converted to rotated frame (dq) as follows

\[
\begin{bmatrix}
u_d \\
u_q
\end{bmatrix} = \begin{bmatrix}
R_d i_d + \frac{d\psi_d}{dt} - \omega \psi_q \\
R_q i_q + \frac{d\psi_q}{dt} + \omega \psi_d
\end{bmatrix} = T_{abc \rightarrow dq} \begin{bmatrix}
u_a \\
u_b \\
u_c
\end{bmatrix}
\]

(2)

where \( u_d, u_q, i_d \) and \( i_q \) are dq-axis voltages and dq-axis currents, respectively. \( \psi_d \) and \( \psi_q \) are dq-axis fluxes, respectively. \( u_a, u_b \) and \( u_c \) are abc-axis voltages. \( R \) is resistance and \( \omega \) is the speed of PMSM.

\[
\begin{align*}
\psi_d &= L_d i_d + \psi_f \\
\psi_q &= L_q i_q
\end{align*}
\]

(3)

where \( L_d \) and \( L_q \) are the dq-axis inductances, respectively. \( \psi_f \) is the permanent magnet flux. (3) is substituted into (2) and the voltages in rotated frame (dq) are given as follows

\[
\begin{bmatrix}
u_d \\
u_q
\end{bmatrix} = \begin{bmatrix}
R_d i_d + L_d \frac{d\psi_q}{dt} - \omega L_q i_q \\
R_q i_q + L_q \frac{d\psi_q}{dt} + \omega L_r i_d + \omega \psi_f
\end{bmatrix}
\]

(4)

where the coupling relationship between dq-axis voltages is showed in dotted-line section. The d-axis voltage is not only controlled by d-axis current, but also affected by q-axis current. The q-axis voltage can be analyzed similarly. Therefore, a decoupling method is adopted in this paper to make the system easier to be controlled.

The decoupled dq-axis voltages are as follows

\[
\begin{align*}
u_d &= R_d i_d + L_d \frac{d\psi_q}{dt} - \omega L_q i_q \\
u_q &= R_q i_q + L_q \frac{d\psi_q}{dt} + \omega L_d i_d + \omega \psi_f
\end{align*}
\]

(5)

Therefore, the change rate of currents in rotated frame (dq) can be expressed as follows

\[
\begin{align*}
\frac{d i_d}{dt} &= \frac{1}{L_d} u_d - \frac{R_d}{L_d} i_d \\
\frac{d i_q}{dt} &= \frac{1}{L_q} u_q - \frac{R_q}{L_q} i_q - \omega \psi_f
\end{align*}
\]

(6)

The discrete-time model can be obtained from (6) for one-step horizon time \( (k+1) \), as demonstrated below:

\[
\begin{align*}
i_d(k+1) &= \frac{T_s}{L_d} u_d(k) + (1 - \frac{T_s}{L_d}) i_d(k) \\
i_q(k+1) &= \frac{T_s}{L_q} u_q(k) + (1 - \frac{T_s}{L_q}) i_q(k) - \frac{T_s}{L_q} \omega \psi_f
\end{align*}
\]

(7)

where \( i(k) \) is the current measured in \( k \) state, \( i(k+1) \) is the predicted current in \( (k+1) \) state, \( u(k) \) is the voltage in \( k \) state and \( T_s \) is the switching period of the system.

The control objectives such as controlling the currents of PMSM and capacitor voltages balancing are included in a cost function as follows

\[
g = [i_d^* - i_d(k+1)]^2 + [i_q^* - i_q(k+1)]^2 + A(V_{dc'} - V_{dc})^2 + A(V_{dc'} - V_{dc})^2
\]

(8)

where and \( B \) are weight factors for the DC bus capacitor voltage balancing and floating capacitor voltage balancing, respectively.

The controller uses all the switching states of seven-level converter for the prediction and evaluates them using (8). The switching state, which minimizes the cost function, is then chosen and applied at the next sampling interval. To sum up, the following procedure should be used:

1) Sample \( V_{dc}, V_{fc}, i_d(k), i_q(k), u_d(k), u_q(k) \)
2) Obtain \( i_d^*(k) \) by inputting \( \omega^* \) and \( \omega(k) \) to PI speed controller.
3) Estimate \( i_d(k) \) and \( i_q(k) \) from \( i_d(k), i_q(k) \) and \( i_d(k) \) using (1).
4) Estimate \( u_d(k) \) and \( u_q(k) \) from \( u_d(k) \), \( u_q(k) \) and \( u_q(k) \) using (2).
5) Decouple \( u_d(k) \) and \( u_q(k) \), as shown in (4) and (5).
6) Extrapolate \( i_d(k) \) and \( i_q(k) \) to \( i_d(k+1) \) and \( i_q(k+1) \) using (7).
7) Select the switching state which minimizes (8).

### IV. SIMULATION AND EXPERIMENT

#### A. Simulation Results

To validate the proposed control scheme, simulations are carried out by using Matlab/Simulink software with the parameters as indicated in Table. II and Table. III. DC\(_1\), DC\(_2\) and DC\(_3\) are DC bus capacitors, FC\(_a\), FC\(_b\) and FC\(_c\) are floating capacitors. The weight factors are selected as A=0.5 and B=0.1.

| TABLE II SIMULATION PARAMETERS OF CONVERTER |
|---------------------------------------------|
| Parameters                  | Values |
| DC bus voltage              | 600V   |
| DC bus capacitor            | 2000 uF|
| floating capacitor          | 1000 uF|
| switching frequency         | 20kHz  |
| initial voltage of DC\(_1\) | 250V   |
| initial voltage of DC\(_2\) | 200V   |
| initial voltage of DC\(_3\) | 150V   |
| initial voltage of FC\(_a\) | 120V   |
| initial voltage of FC\(_b\) | 100V   |
| initial voltage of FC\(_c\) | 80V    |
The simulation results are shown in Fig. 4. The speed of PMSM is shown in Fig. 4(a), where it reaches the rated value of 1000r/min at 0.015s. A step change in the speed of PMSM from 1000 to 1500r/min (0.118s) is applied at 0.1s. The $q$-axis reference current $i_q^*$ and measured current $i_q$ are shown in Fig. 4(b), where the $q$-axis current tracks to its reference very well during the transient and steady-state condition. The waveforms of line voltage $U_{ab}$ and phase current $I_a$ are smooth and harmonics are low, as depicted in Fig. 4(c). As demonstrated in Fig. 4(d) and Fig. 4(e), perfect balancing of the DC bus capacitor voltage and floating capacitor voltage have been achieved. In addition, the common-mode voltage showed in Fig. 4(f) is mainly between $\pm 1/3U_{dc}$, which reduced the electromagnetic interference. Thus, the proposed control scheme is feasible.

### B. Experimental Results

In order to verify the performance, an experimental test bench based on RT_LAB has been developed, as shown in Fig. 5. The converter was controlled by a DSP (TMS320F28335) and a FPGA (EP4CE22F17C8N). The main parameters are as follows: DC bus voltage is 300V; DC bus capacitor is 2000 uF; floating capacitor is 1000uF; switching frequency is 20 kHz. The parameters of the motor are the same as those in simulation and weight factors are selected as $A=0.6$ and $B=0.3$.

Fig. 5. RT-LAB experimental platform.

To fully demonstrate the feasibility and validity, two cases are considered. In the first case, the speed of PMSM is maintained at 1000r/min and the load torque steps from 5 to
where the speed of PMSM can be calculated ($f$ is the switching frequency and $P$ is the current frequency). The period of current $T$ can be obtained from Fig. 6(a) and $P = 1/T$. We can see that the speed of PMSM reaches the rated value of 1000 r/min. As shown in Fig. 6(a), the line voltage and phase current reach steady rapidly after a short period of distortion. The DC bus capacitor voltage and the floating capacitor voltage are balanced but the ripple of DC bus capacitor voltage gets larger due to the increase of torque, as demonstrated in Fig. 6(b) and Fig. 6(c). In Fig. 6(d), the common-mode voltage of the motor is mainly between $\pm 1/3U_{dc}$, therefore the electromagnetic interference of the motor is low.

Fig. 6. Experimental results at constant speed.

Fig. 7. Experimental results at constant torque.

V. CONCLUSION

In this paper, a novel hybrid seven-level converter is proposed. The circuit structure and working principle of the converter are analyzed. In order to drive PMSM with the proposed converter, MPC is adopted to control the current of PMSM and balance the capacitor voltages. The simulation results and experimental results reveal that the PMSM run smoothly. The harmonics of line voltage and phase current are low and capacitor voltages are balanced. The common-mode voltage is mainly between $\pm 1/3U_{dc}$. Therefore, the feasibility and validity of the hybrid seven-level converter for PMSM driving system based on MPC are verified.

REFERENCES

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