Neutral Point Supply Scheme for PMSM Drive to Boost DC Voltage

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***Abstract*—Abstract—A novel scheme to supply AC motor drive with a boost function has been proposed. Different from the classic scheme for a three-phase two-level rnverter, the main idea of this so-called Neutral Point Supply (NPS) scheme is to move the power supply to the neutral point of machine. It allows to have the capability of boosting DC-bus voltage without adding semi-conductor components to inverter. The objective of this paper is to make an in-depth study of this scheme through a permanent magnet synchronous machine (PMSM) drive. Firstly, the principle of the NPS scheme is studied. Then the corresponding control strategy is presented. Meanwhile, the RMS phase currents and additional losses in machine are studied respectively. The effectiveness of a NPS scheme for PMSM drive is demonstrated by simulation.**

***Index Terms*—PMSM, boost converter, inverter, neutral point**

I. INTRODUCTION

Thanks to their outstanding features of high power density, high efficiency and excellent dynamic properties, permanent magnet synchronous machines (PMSM) are widely used in the industry and daily life [1] [2]. With the development of electric and electronic technology, frequency conversion technology, AC machines are typically supplied by a three-phase two-level voltage source inverter, as shown in Fig. 1. In this structure, the output capability of inverter depends on the voltage level of DC source. Due to the cost, volume and safety constraints, the voltage level of the DC source is limited. Generally, it is selected to supply an AC voltage a bit larger than the nominal voltage of machine. When a machine operates in a low-speed condition, inverter does not need to be supplied by such a high DC voltage. Indeed, a higher voltage may result in more switching losses. How to adjust the DC voltage of inverter and improve DC voltage utilization are two issues worth of researching.

For the electric propulsion system of electric vehicles (EVs), a DC/DC boost converter is commonly used for transferring the low battery voltage into high voltage [1]. Apparently, the DC/DC boost converter will increase the cost and volume of the whole system. A patent proposed the idea of connecting the power supply to the neutral point of machine [3]. By utilizing the switching operation of the inverter in the zero-voltage vector mode, zero-phase-sequence power is transferred between DC power supply and DC input side of inverter. In this case, the inverter operates as a DC/DC boost converter and the machine's zero-sequence inductance serves as the boost inductor. Therefore, the real DC/DC boost converter is saved possibly. K. Moriya et al introduced a basic Multi-Functional Converter System (MFCS) for HEVs [4]–[6], which is the same concept as [3]. To improve the basic MFCS, the two-type MFCS is proposed as well, the battery connected between the neutral points of two three-phase motors. In this case, the current ripple can be suppressed and it realizes wider input voltage regulation range than that of the basic type [7]. In [8] [9], the authors proposed two types of MFCS with galvanic isolation, which can be used to convert 200-600 V to 14 V or 42 V bidirectionally. The current ripple of MFCS is investigated in [10] [11]. The magnitude of ripple depends on the zero-sequence inductance of machine. In order to increase the zero-sequence inductance and decrease current ripple, the authors proposed the method of optimizing the winding arrangement for a synchronous machine, the experimental results are in good correlation with theoretical predictions. Although all of these literatures aforementioned introduced the idea of suppling DC source from the neutral point of machine like MFCS, but the detailed control scheme is not analyzed. After all, the control of machine and the control of boost converter are simultaneous in MFCS.

In 12, the authors proposed a two-stage boost converter using the neutral point of machine. Based on the basic MFCS, it adds a boost converter between the neutral point of machine and power supply for increasing the boost-up ratio. However, only a six-step operation strategy is applied for machine. In [13], the authors proposed a similar scheme to MFCS, called the Neutral Point Supply (NPS) scheme, which supplies an AC machine by using the neutral point. The NPS scheme has the capacity of enhancing DC-bus voltage for inverter without additional components. By modifying the equation of duty cycle calculation, the Field Oriented Control (FOC) can still be used for controlling machine and the equivalent boost converter can be controlled by open-loop control or close-loop control. The experimental results show the feasibility of a NPS scheme for an induction machine drive. However, the issue of losses caused by the DC current is not yet analyzed.

In this paper, the NPS scheme will be studied through a PMSM drive. Its capability of increasing the DC-bus voltage and its flexibility for inverter supply will be discussed. Performances in comparison with a classic scheme will be illustrated by simulation results. Losses caused by the DC current component will be analyzed.

This paper is organized as follows. In Section II, the basic principle of the NPS scheme is presented. In Section III, a corresponding control strategy is developed accordingly. In Section IV, the RMS phase currents and additional losses are analyzed. In Section V, simulation results are provided. The conclusion is finally given in Section VI.

II. Basic Principle of NPS Scheme

Fig.1 shows the classic topology of a three-phase two-level inverter to supply a PMSM, where Uin is the DC voltage source; C is the capacitor of the inverter; N is the neutral point of the PMSM, S1, S2, S3, S4, S5 and S6 are the power electronic switches of the inverter; i_A, i_B and i_C are the phase currents. In this case, the neutral point is not connected. Fig. 2 shows the structure of a NPS scheme, where U_{DC} is the voltage of capacitor C; i_{in} is the input current of neutral point. In Fig. 2, it can be seen that the DC source is directly connected between the neutral point and the negative pole of inverter, and the capacitor is still preserved. Obviously, no additional components have been added and the only modification is the location of the DC source in the NPS structure.

For the NPS structure of a PMSM drive as is shown in Fig. 2, the considered model in *A-B-C* coordinate is:

$$\begin{cases} U_{AN} = Ri_A + L\frac{di_A}{dt} + M\frac{di_B}{dt} + M\frac{di_C}{dt} + e_A \\ U_{BN} = Ri_B + L\frac{di_B}{dt} + M\frac{di_A}{dt} + M\frac{di_C}{dt} + e_B \\ U_{CN} = Ri_C + L\frac{di_C}{dt} + M\frac{di_A}{dt} + M\frac{di_B}{dt} + e_C \\ i_{in} = -(i_A + i_B + i_C) \end{cases} \quad (1)$$

$$\begin{cases} e_A = -\psi_f\omega_e \sin\theta_e \\ e_B = -\psi_f\omega_e \sin\left(\theta_e - \frac{2\pi}{3}\right) \\ e_C = -\psi_f\omega_e \sin\left(\theta_e + \frac{2\pi}{3}\right) \end{cases} \quad (2)$$

where U_{AN}, U_{BN} and U_{CN} are the phase voltages of PMSM; i_A, i_B and i_C are the phase currents; e_A, e_B and e_C are the back-electromotive forces; ψ_f is the permanent magnet flux; θ_e and ω_e are the electrical position and angular velocity of rotor; R, L and M are the resistance, the self-inductance and the mutual inductance of PMSM, respectively.

For the inverter, it is assumed that the switching frequency is high enough to neglect the current ripple. α_A, $\alpha_B$and α_C are defined as the duty cycles corresponding to the upper switches of the inverter, respectively. Moreover, voltage drop in switches is neglected. Thus, in steady state, the average model of the inverter part is expressed as follows:

$$\begin{cases} \alpha_A U_{DC} = U_{AN} + U_{in} \\ \alpha_B U_{DC} = U_{BN} + U_{in} \\ \alpha_C U_{DC} = U_{CN} + U_{in} \end{cases} \quad (3)$$

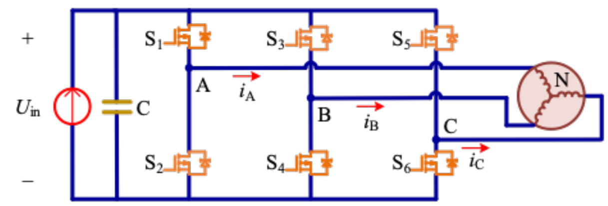

Fig. 1. Classic structure to supply PMSM by a three-phase two-level inverter.

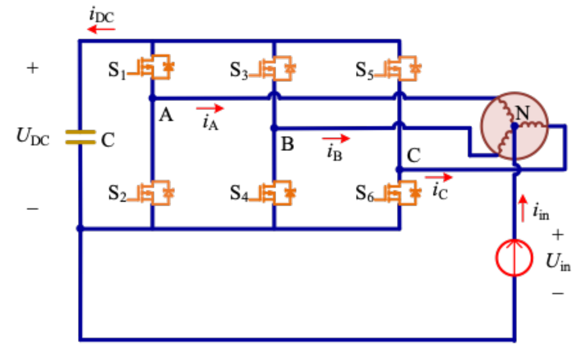

Fig. 2. Classic structure to supply PMSM by a three-phase two-level inverter.

Assuming that the machine is symmetrical and healthy, according to (2), it is obvious that:

$$e_A + e_B + e_C = 0 \quad (4)$$

Combining (1), (3) and (4):

$$(\alpha_A + \alpha_B + \alpha_C)U_{DC} = R(i_A + i_B + i_C) + (L + 2M)\frac{d(i_A + i_B + i_C)}{dt} + 3U_{in} \quad (5)$$

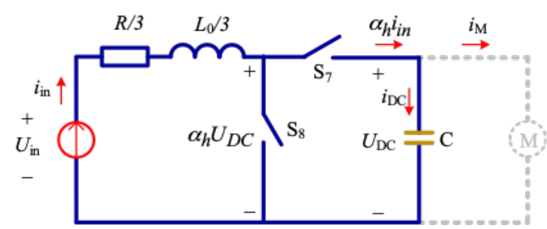

Fig. 3. The equivalent structure of PMSM drive system by using NPS scheme.

With the chosen reference direction of currents shown in Fig. 1 and Fig. 2, the phase currents satisfy the equation of $i_{in} = i_A + i_B + i_C$. $(L + 2M)$ corresponds to the zero-sequence inductance of machine and will be noted L_0. By defining homopolar duty cycle $\alpha_h = (\alpha_A + \alpha_B + \alpha_C)/3$, (5) becomes:

$$\alpha_h U_{DC} = -\frac{R}{3}i_{in} - \frac{L_0}{3}\frac{di_{in}}{dt} + U_{in} \quad (6)$$

Equation (6) corresponds to the average model of a boost converter as shown in Fig. 3. Therefore, the NPS structure of a PMSM drive can also be described as a boost converter supplying an equivalent load (dotted line in Fig. 3) with an equivalent current i_M flowing into the machine. It is worth noting that the resistance of the equivalent boost converter is *R*/3 and the inductance is L_0/3. In addition, the duty cycle of the boost corresponds to the duty cycle of the upper switch

(S7 in Fig. 3). In a traditional boost, it normally corresponds to the duty cycle of the bottom switch (S8 in Fig. 3).

III. Control Scheme

When a machine operates under a low-speed condition, it actually doesn't need such a high DC voltage for inverter. It is evident that higher voltage supplied to inverter leads to higher losses in power electronic devices. Therefore, if the operating condition of machine is varied, it is interesting to adjust the supplied voltage of inverter for decreasing the losses in power electronic devices.

For the classic scheme, the voltage of DC source normally can't change unless by adding a physical DC/DC converter between capacitor and inverter. But that will increase the cost and volume of whole system distinctly.

According to the analysis aforementioned, the NPS scheme has the equivalent structure of a boost converter. So it is possible to use a lower DC source for suppling a same machine. Meanwhile, the voltage of capacitor can be controlled without adding additional component. For decreasing the losses in power electronic device, it is necessary to choose U_{DC} as low as possible but sufficiently high to reach the required voltage for machine. U_{DC} is determined by α_h (according to Fig. 3), so the issue of choosing the best U_{DC} becomes the issue of choosing the best α_h.

The average relation between power supply and capacitor voltage in steady state coming from (6) is:

$$U_{\mathrm{DC}} = \left(U_{\mathrm{in}} - \frac{R}{3} i_{\mathrm{in}}\right) / \alpha_h \tag{7}$$

The duty cycles of the inverter are defined as follows [13]:

$$\begin{cases} \alpha_A = \alpha_h + \frac{U_A^*}{U_{\mathrm{DC}}} \\ \alpha_B = \alpha_h + \frac{U_B^*}{U_{\mathrm{DC}}} \\ \alpha_C = \alpha_h + \frac{U_C^*}{U_{\mathrm{DC}}} \end{cases} \tag{8}$$

U_A^*, U_B^* and U_C^* are the referenced values of the three-phase voltages respectively (i.e. $U_A^* + U_B^* + U_C^* = 0$), which will be generated by controller. Therefore, it satisfies the previous definition of the homopolar duty cycles, $\alpha_h = (\alpha_A + \alpha_A + \alpha_A)/3$. In particular, when $\alpha_h = 0.5$ in (8), it corresponds to the sinusoidal pulse width modulation (SPWM).

In steady state, α_h tends to a constant. At the same time, α_A, α_B and α_C are also restricted between 0 and 1. By considering these limits in (8), it is obvious that [13]:

$$-\alpha_h U_{\mathrm{DC}} \leq U_k^* \leq (1 - \alpha_h) U_{\mathrm{DC}} \quad k \in \{A, B, C\} \tag{9}$$

in which U_k^* represents the referenced value of three-phase voltage.

By substituting (7) into (9), it results in:

$$-\left(U_{\mathrm{in}} - \frac{R}{3} i_{\mathrm{in}}\right) \leq U_k^* \leq \frac{1 - \alpha_h}{\alpha_h} \left(U_{\mathrm{in}} - \frac{R}{3} i_{\mathrm{in}}\right) \tag{10}$$

In (10), when α_h is less than 0.5, the limiting value to generate the sinusoidal wave is the lower one $-(U_{in} - Ri_{in}/3)$. In this case, the maximum achievable output voltage amplitude of the inverter is $(U_{in} - Ri_{in}/3)$. Therefore, the maximum achievable output RMS phase voltage U_{max} is:

$$U_{\max} = \left(\frac{1 - \alpha_h}{\alpha_h}\right) \left(U_{\mathrm{in}} - \frac{R}{3} i_{\mathrm{in}}\right) / \sqrt{2} \tag{11}$$

On the contrary, when α_h is larger than 0.5, the limiting value to generate the sinusoidal wave is the larger one $(1 - \alpha h)(U_{in} i_{in}/3)/\alpha h$. Therefore, the maximum achievable output RMS phase voltage is:

$$U_{\max} = \left(\frac{1 - \alpha_h}{\alpha_h}\right) \left(U_{\mathrm{in}} - \frac{R}{3} i_{\mathrm{in}}\right) / \sqrt{2} \tag{12}$$

By neglecting the voltage drop in resistor R, the value of α_h should be limited between 0.5 and 1. i.e. if α_h is chosen lower than 0.5, the maximum achievable RMS output voltage is fixed to $U_{in}/\sqrt{2}$, but the capacitor voltage is higher than twice U_{in} which will result in more losses in switching devices.

The maximum achievable RMS output voltage in a classic scheme depends on the modulation algorithm. Take the space vector pulse width modulation (SVPWM) as an example, the maximum achievable RMS output voltage is $U_{in}/\sqrt{6} \approx 0.408 U_{in}$. This voltage increases to $U_{in}/\sqrt{2} \approx 0.707 U_{in}$ in the NPS scheme. It is obvious that the NPS scheme has a higher DC voltage utilization than the classic scheme.

According to (12), α_h can be presented as follows:

$$\alpha_h = \frac{U_{\mathrm{in}} - \frac{R}{3} i_{\mathrm{in}}}{U_{\mathrm{in}} - \frac{R}{3} i_{\mathrm{in}} + \sqrt{2} U_{\max}} \tag{13}$$

The FOC controller can still be used in the NPS scheme, with two inner current-loops and one outer speed-loop. The voltages U_d and U_q lead to a new equation (14). The control structure of the NPS scheme is presented in Fig. 4.

$$\alpha_h = \frac{U_{\mathrm{in}} - \frac{R}{3} i_{\mathrm{in}}}{U_{\mathrm{in}} - \frac{R}{3} i_{\mathrm{in}} + \sqrt{U_d^2 + U_q^2}} \tag{14}$$

In Fig. 4, α_h is chosen by (14) and the FOC controller is the same as what in a classic scheme. In this case, the value of α_h is the best one and the capacitor voltage U_{DC} is the most appropriate one. It means that the inverter always operates at the condition of outputting the maximum achievable RMS voltage.

IV. Analysis of RMS Current and Losses

For a NPS scheme, the power flows from the DC source to machine and then passes through inverter to charge capacitor. Thus, an additional DC current component flowing into the coils of the machine will result in additional losses. In order to study the RMS current and the additional losses of a NPS scheme, comparative studies with a classic scheme are carried out. Assuming the fundamental components of phase voltage in the classic scheme are U_A^*, U_B^* and U_C^* and neglecting higher harmonics, according to (3), (7) and (8), for generating the same fundamental components, the phase voltages in a NPS scheme are:

$$\begin{cases} U_{AN} = U_A^* - \frac{R}{3} i_{\mathrm{in}} \\ U_{BN} = U_B^* - \frac{R}{3} i_{\mathrm{in}} \\ U_{CN} = U_C^* - \frac{R}{3} i_{\mathrm{in}} \end{cases} \tag{15}$$

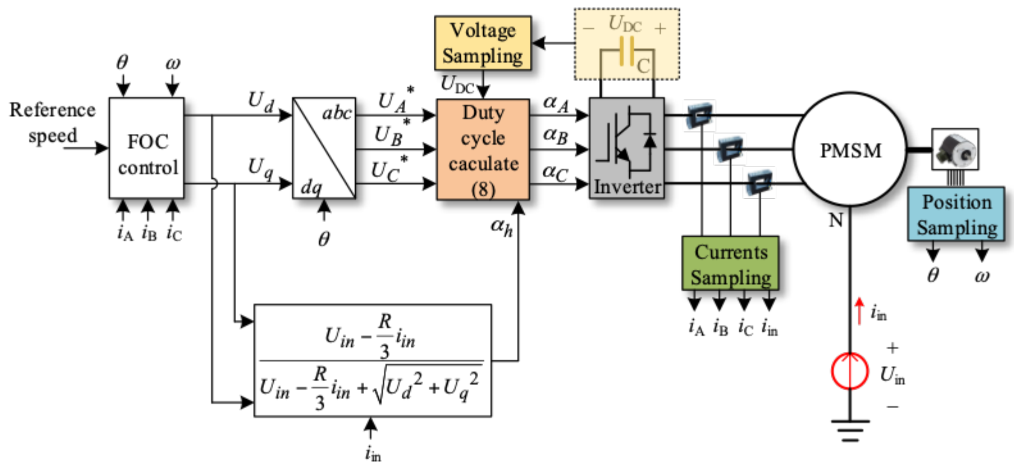

Fig. 4. The control structure of the NPS scheme.

Obviously, the phase voltages of a NPS scheme have an additional DC component $(Ri_{\text{in}}/3)$. Therefore, the additional DC voltage will generate an additional DC current $i_{\text{in}}/3$ which leads to additional losses in machine.

Defining the RMS phase current of a classic scheme is I, thus the value in a NPS case is presented as follows:

$$I_1 = \sqrt{I^2 + \left(\frac{i_{\text{in}}}{3}\right)^2} \tag{16}$$

Equation (16) shows the RMS phase current of a NPS scheme including two parts, one is from the AC component which generates the rotating magnetic field and electromagnetic torque for the machine, the other is from the DC component which charges the capacitor as a boost current. Assuming the hysteresis loss and eddy-current loss are the same in the two schemes, defining the power P only generated by the AC component and whole power P_1 generated by the total current, with the control method proposed in section III, P and P_1 are therefore formulated as follows:

$$\begin{cases} P_1 = \frac{i_{11}^2 R}{3} + 3U_{\max} I \cos\phi = U_{\text{in}} i_{\text{in}} \\ P = 3U_{\max} I \cos\phi \end{cases} \tag{17}$$

in which $\cos\phi$ is the power factor of the machine. It is obvious that a larger i_{in} leads to more additional losses in the machine.

With (12) and (17):

$$\frac{P}{P_1} = \frac{1}{2} + \sqrt{\frac{1}{4} - \frac{RIU_{\max}\cos\phi}{U_{\text{in}}^2}} \tag{18}$$

Equation (18) shows the ratio between P and P_1. A higher ratio means less additional losses in machine. For (18), if U_{in} is determined, it is obvious that the lower I, lower $U_{\max}$ and lower $\cos\phi$ lead to less addition losses in machine. Therefore it seems that the NPS scheme is more suitable for low-power condition, such as a low-speed high-torque condition.

For a given machine drive, it is easy to evaluate this ratio. The parameters of the studied PMSM drive system are given in Table I. The DC source is fixed to 400 V in the classic scheme. For the NPS scheme, 60% of this value (240 V) is enough to generate the maximum achievable RMS voltage based on these analysis of the maximum achievable RMS output voltage aforementioned in Section III.

TABLE I
PARAMETERS OF THE PMSM DRIVE

Parameter	Value	Parameter	Value
Rated power	1.6(kW)	Inverter DC voltage	3(V)
Number of pole pairs	3	Rated current	4.42(A)
Stator resistance	2.06 (Ω)	Rated torque	$7.64(\text{N}\cdot m)$
d-axis inductance	9.15(mH)	Power factor	0.91
q-axis inductance	9.15(mH)	Efficiency	0.9
0-axis inductance	3(mH)	Rated speed	2000(rpm)

Selecting $U_{\text{in}=240V}$ and considering the worst condition of $\cos\phi = 1$, (19) becomes:

$$\frac{P}{P_1} = \frac{1}{2} + \sqrt{\frac{1}{4} - 2.06\frac{IU_{\max}}{240^2}} \tag{19}$$

The radio with respect to I and U_{in} is illustrated in Fig. 5. When the machine is operating in rated condition, the ratio P/P_1 is larger than 0.97, which means the additional losses caused by DC current is small. If the machine operates in lower-power condition, the ratio will be better. For example, when the machine is working in a low-power condition (RMS phase voltage is 10 V and RMS phase current is 4.42 A), the ratio P/P_1 is 0.998 and the proportion of additional losses caused by DC current component in the machine is only 0.002.

Obviously, with the advantage of only using a DC source whose voltage is 60% of the value in a classic scheme, the disadvantage of the additional losses of the NPS scheme remains reasonable. In additional, when the operating condition of machine is varied, the NPS scheme can decrease these losses in switching devices compared with the classic scheme by adjusting capacitor voltage.

V. SIMULATION RESULTS

In order to verify the effectiveness of a NPS scheme applied in PMSM drive, a simulation model (average model) is

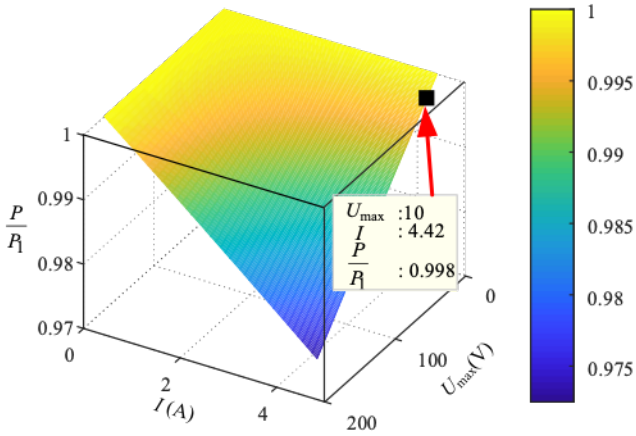

Fig. 5. The ratio between P and P_1.

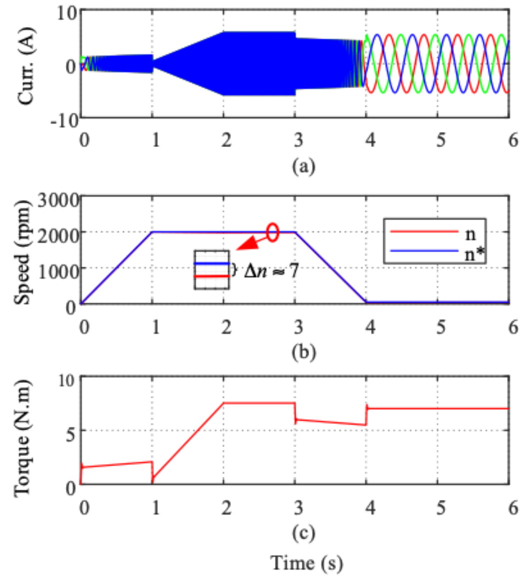

Fig. 6. Simulation results of the classic scheme: (a) phase currents, (b) speed, and (c) torque.

developed by using MATLAB/Simulink platform. Parameters of the PMSM are given in TABLE I. The performance of a NPS scheme is studied and the comparison with a classic scheme will be discussed. The DC source in a classic scheme is 400 V and that in a NPS scheme is 240 V. The same FOC controller is used in both schemes. In addition, the homopolar duty cycle α_h of the equivalent boost is chosen by (14). For the simulation, the referenced speed increases from 0 to 2000 rpm during to 0-1s, and then it remains at 2000 rpm from 1 to 3 s. After that, it decreases from 2000 to 50 rpm between 3 and 4 s. Finally, it remains at 50 rpm after 4 s. The load is added from 0 to 7 $\text{N} \cdot m$ during to 1-2 s, and then it remains at 7 $\text{N} \cdot m$ after 2 s.

The simulation results of the classic scheme are presented in Fig. 6, n is the real speed and n* is the referenced one. The results of phase currents, speed and electromagnetic torque are illustrated in Fig. 6(a), (b) and (c). In Fig. 6(b), it can be seen that the real speed tracks the referenced one accurately, the error $\Delta n \approx 7$ rpm.

Fig. 8 shows the detailed comparison between the NPS scheme and the classic scheme when the machine is working in the nominal condition. In the figure, i_{A1} is the current of phase A by using the NPS scheme; i_{A2} is the current of phase A by using the classic scheme; I_0 is the mean value of i_{A1} and its absolute value equals to i_{in}. It can be seen that i_{in} is about 7.1 A, I_0 is -2.36 A, U_{DC} is 430 V and α_h is 0.54. According to (17), the additional losses caused by DC current is 34.6 W in the NPS scheme. Compared with the rated power (1.6 kW), the additional losses are tiny. The ratio between the additional losses and rated power is nearly 0.022.

Fig. 9 shows the comparison between the NPS scheme and the classic scheme when the machine is operating in low-speed (50 rpm) high-torque (7 N) condition. In the figure, it can be seen that i_{in} is about 0.6 A and I_0 is - 0.2 A. Additional losses in the machine are 0.25 W. U_{DC} is 256 V and α_h is 0.94. It is worth noting that, in this case, the voltage of capacitor is lower than that in the classic scheme. If considering the impedance of the inverter, a lower capacitor voltage leads to lower losses in inverter. i.e. when a machine operates in low-speed but high-

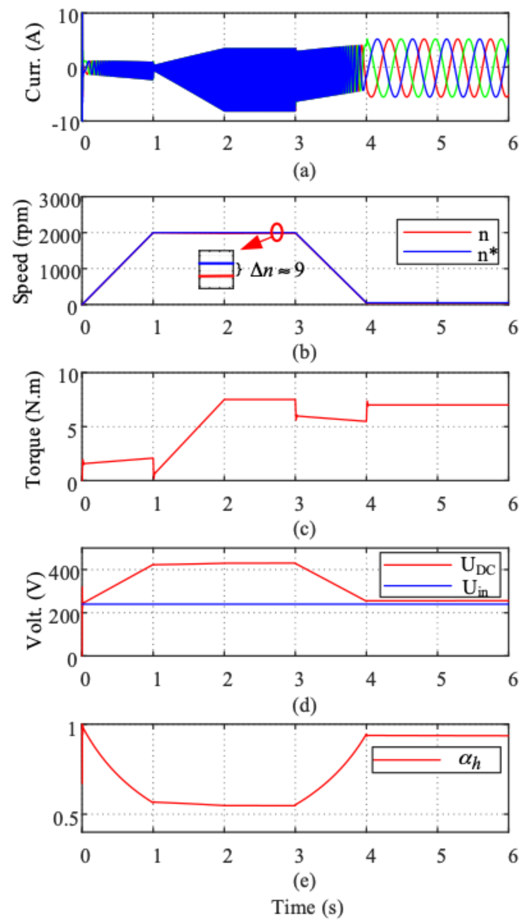

Fig. 7. Simulation results of NPS scheme: (a) phase currents, (b) speed, (c) torque, (d) capacitor voltage, and (e) homopolar duty cycle.

torque condition, such as in the case of EVs, the advantage of the NPS scheme is more significant since it can not only

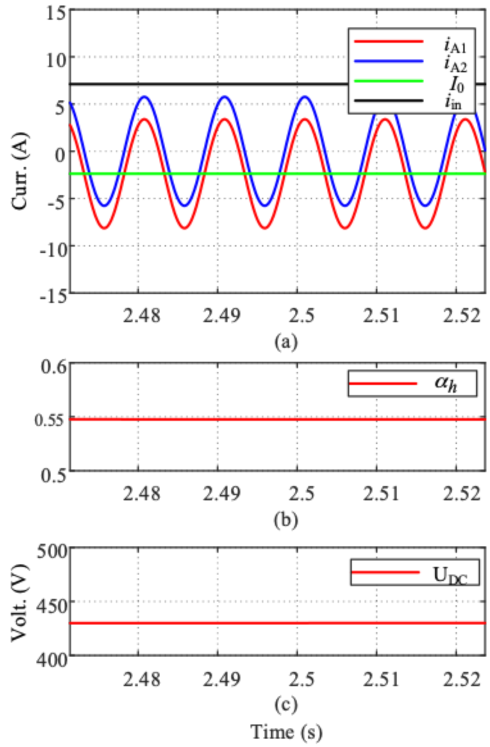

Fig. 8. Comparison between NPS scheme and classic scheme in the rated condition: (a) phase A current, the mean current of phase A and input current, (b) homopolar duty cycle, and (c) capacitor voltage.

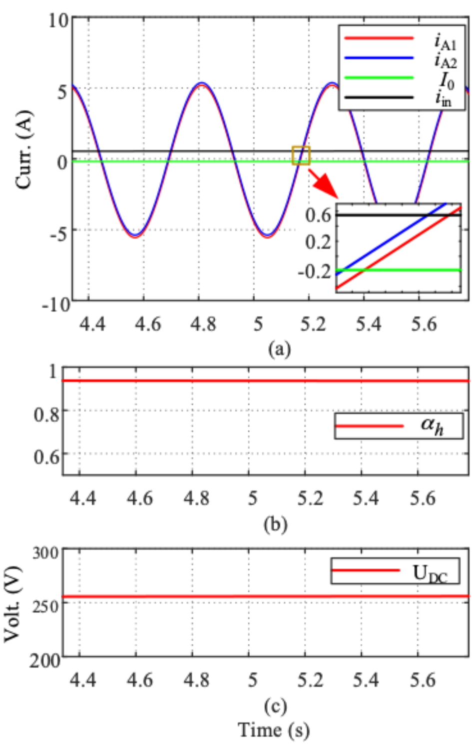

Fig. 9. Comparison between NPS scheme and classic scheme in a low-speed high-torque condition: (a) phase A current, the mean current of phase A and input current, (b) homopolar duty cycle, and (c) capacitor voltage.

boost the voltage for battery packs without an additional boost converter but also reduce the switching losses by controlling the capacitor voltage.

VI. Conclusion

A NPS scheme to supply a PMSM with a boost function was studied. It has the capability to operate machine by using a lower DC source compared with a classic scheme. Meanwhile, it is easy to implement the NPS scheme by only shifting the DC source to the neutral point of machine from the classic structure of a three-phase two-level inverter. The effectiveness of the NPS scheme is verified by simulation and a comparison analysis between the NPS scheme and the classic one is studied. According to the results, it can be seen that by using the NPS scheme, a 240 V DC source supplies a same PMSM showing almost a same performance compared with a 400 V DC source required in a classic scheme. The additional losses are only 34.6 W when the machine operates in nominal condition (1.6 kW) and the losses will be lower under a low-power condition (such as the low-speed high-torque condition).

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