

Inductor-Less Boost Three-Phase Inverter Using Capacitor for Motor Drive Systems

Shun Sato^{1*}, Hirotaka Kato¹, Kodai Nishikawa¹, Hiroki Watanabe¹, Jun-ichi Itoh¹

¹ Nagaoka University of Technology, Nagaoka, Niigata, Japan

*s233127+sato@stn.nagaokaut.ac.jp

Abstract—This paper proposes a boost-type three-phase inverter without a boost inductor for motor drive systems. The proposed circuit achieves boost operation by switching the DC-link voltage between the DC power supply voltage and the boosted capacitor voltage using two additional switches. Furthermore, with the space vector modulation (SVM) method developed for the proposed inverter, the capacitor voltage is maintained at a constant level, enabling continuous boost operation. Hardware-In-the-Loop Simulation (HILS) results verify the effectiveness of the proposed inverter. The proposed method reduces the motor current amplitude by 64.5%.

Keywords—Boost-type three-phase inverter, Inductor-less, Permanent magnet synchronous motors (PMSMs), Space vector modulation (SVM), Hardware-In-the-Loop-Simulation (HILS)

I. INTRODUCTION

Recently, electric vehicles (EVs) have rapidly gained popularity, and permanent magnet synchronous motors (PMSMs) have been widely adopted as traction motors. PMSMs achieve higher efficiency and system miniaturization compared with systems using induction motors. On the other hand, voltage limitation occurs in the high-speed region of PMSM operation. Thus, boosting the DC link voltage is required. To address this issue, a boost chopper is connected to the front end of the inverter [1]. However, the boost chopper requires a large inductor, which increases the overall system volume, weight, and cost. As a boost system without an additional inductor, ref. [2] connects a charge pump circuit using capacitors connected in series to the front end of the inverter. However, it cannot achieve continuous and steady boost operation.

This paper proposes a novel boost-type inverter without a boost inductor for motor drive systems. The proposed circuit is configured by adding only two additional switches and a capacitor to the conventional three-phase inverter. In addition, a space vector modulation (SVM) method is developed to control the capacitor voltage so that it remains constant based on the reference value. As a result, the proposed inverter achieves continuous boost operation in steady state with minimal additional circuit components.

II. PROPOSED BOOST-TYPE THREE-PHASE INVERTER

A. Configuration and modulation method

Fig. 1 shows the configuration of the proposed boost inverter. In the proposed circuit, the supply voltage and the boost capacitor are connected to the DC-link of the inverter through the switches sw_{dc} and sw_c , respectively. The voltage applied to the inverter is switched between the supply voltage E_{dc} and the boosted capacitor voltage V_c by operating these switches in a complementary manner.

Fig. 2 shows the space vectors of the proposed circuit. In a conventional three-phase inverter, eight space vectors are

defined. In contrast, because the proposed circuit switches the DC link voltage, two sets of eight space vectors with different amplitudes are defined, resulting in a total of sixteen. In this paper, the voltage command vector V_{cmd} is modulated using these space vectors. Focusing on the switching state of sw_{dc} , the space vectors used for modulating V_{cmd} are divided into two groups, and the averaged values over one control period are defined as V_{cmd_dc} and V_{cmd_c} . Here, even if V_{cmd_dc} and V_{cmd_c} are individually modulated within the control period, their combined vector matches V_{cmd} . V_{cmd} is decomposed into V_{cmd_dc} and V_{cmd_c} to apply the capacitor voltage control. In addition, V_{cmd} is generated through two-step modulation.

B. Capacitor voltage control method

The boosted capacitor voltage V_c must be maintained to achieve continuous boost operation in steady state using the proposed circuit. Thus, the system is controlled so that the net energy delivered by the capacitor within one control period is zero. In other words, the output power is supplied solely from the E_{dc} side, while the output power from V_c side is kept at zero. The power supplied to the motor from E_{dc} and V_c is determined by the phase relationship between the motor current vector I_{det} and V_{cmd_dc} and V_{cmd_c} as shown in Fig. 2. This condition is satisfied by aligning V_{cmd_dc} with I_{det} and setting V_{cmd_c} orthogonal to I_{det} .

Fig. 3 shows the capacitor voltage compensation method. In the actual system, voltage drops due to the motor and converter losses. Thus, as indicated in Fig. 3(a), even when

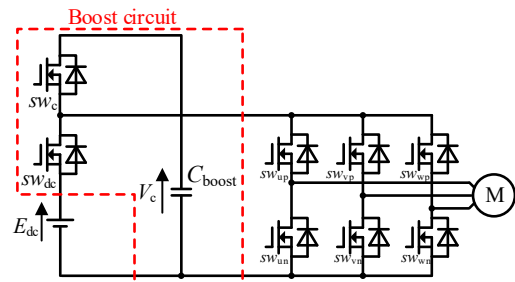


Fig. 1. Proposed inductor-less boost-type three-phase inverter.

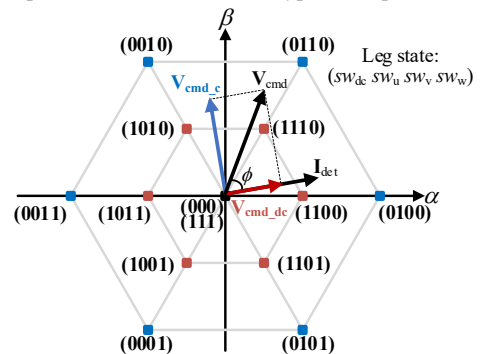


Fig. 2. Defined space vectors in proposed circuit.

V_{cmd_c} is set as intended, V_c is not maintained. In order to maintain the desired capacitor voltage, an automatic voltage regulator (AVR) is adopted. Since the inverter cannot directly control the capacitor current i_c , which is used as the control variable of the AVR, a capacitor voltage compensation vector V_{cmp} , shown in Fig. 3(b), is introduced. The voltage command V_{cmp} is a vector in the same direction as I_{det} . By combining it with V_{cmd_c} for modulation, the power delivered from the capacitor to the motor is regulated. The relationship between the AVR output i_c and V_{cmp} is expressed as

$$V_{cmp} = \frac{2}{3} \frac{V_c I_{det}}{|I_{det}|^2} i_c \quad (1).$$

The introduction of V_{cmp} changes the amplitude and phase of V_{cmd} . A vector that cancels V_{cmp} is added to V_{cmd_dc} to prevent this effect.

Fig. 4 shows the overall control block diagram. First, V_{cmd} is separated into V_{cmd_dc} and V_{cmd_c} using I_{det} . Next, i_c^* calculated by the AVR is converted into V_{cmp} , and V_{cmd_c} and V_{cmd_dc} are compensated. Finally, switching pulses are generated by space vector modulation (SVM) based on the compensated V'_{cmd_dc} and V'_{cmd_c} .

III. HILS EVALUATION FOR PMSM

Table 1 shows the conditions in the HILS environment for PMSM drive. The supply voltage E_{dc} is set to 170 V, and the capacitor voltage V_c is set to 340 V. The capacitance of the boost capacitor is determined to be 100 μ F so that the voltage ripple caused by the switching component remains below 2%. The PMSM is operated in the high-speed region where flux-weakening control is required. This is because the proposed circuit achieves boost operation under low-power-factor conditions.

A. Steady state operation

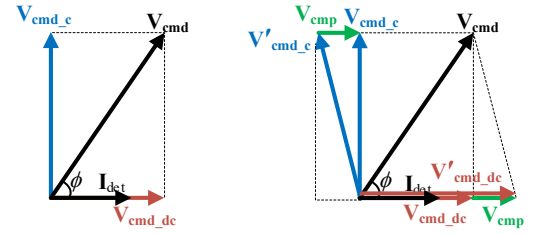
Fig. 5 shows the waveforms of the motor mechanical angle, capacitor voltage V_c , line-to-line voltage, and motor current under constant torque and speed conditions. The motor torque command is set to 0.2p.u.. The motor rotational speed is set to 2.0p.u.. As shown in Fig.5, the line-to-line voltage exceeds E_{dc} . In addition, the capacitor voltage V_c matches the command value. This means that the proposed circuit achieves continuous boost operation in the high-speed region and low-power-factor conditions.

B. Current reduction effect by boost operation

Fig. 6 shows the responses of the capacitor voltage V_c , line-to-line voltage, and motor current when switching between boost operation and non-boost operation. The torque command is set to 0.2p.u.. The motor rotational speed is set to 2.0p.u.. As shown in Fig. 6, the motor current amplitude during boost operation is 64.5% lower than during non-boost operation. This is because the required d-axis current decreases due to the boost operation. This result means that the proposed circuit achieves a reduction in motor copper loss during boost operation compared with non-boost operation.

REFERENCES

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(a) Without compensation. (b) With compensation.
Fig. 3. Capacitor voltage compensation method.

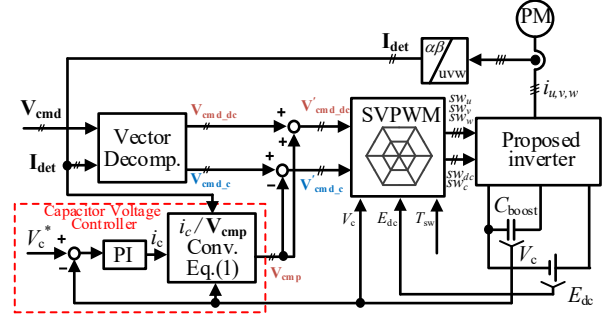


Fig. 4. Control block diagram of proposed inverter.

Table 1. HILS evaluation configuration.

Parameter	Value
Input voltage E_{dc}	170 V
Capacitor voltage command V_c^*	340 V
Control period T_{sw}	100 μ s
Boost capacitor C_{boost}	100 μ F
Bandwidth of AVR f_{AVR}	50 Hz
Motor rated speed ω_n	2000 r/min
Rated torque T_n	3.8 Nm
Poles pairs P_f	2
Motor winding resistance R	0.1 Ω
Motor Inductance L_m	3.78 mH
Linked magnetic flux ϕ_n	0.233Wb

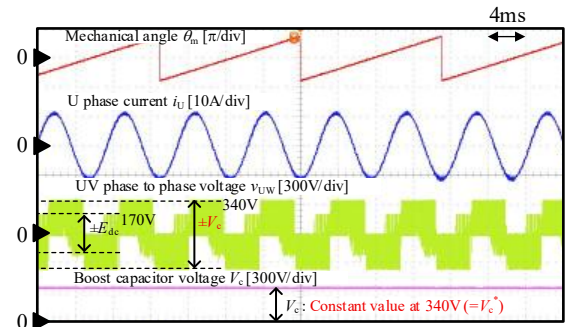


Fig. 5. Boost operation waveform.

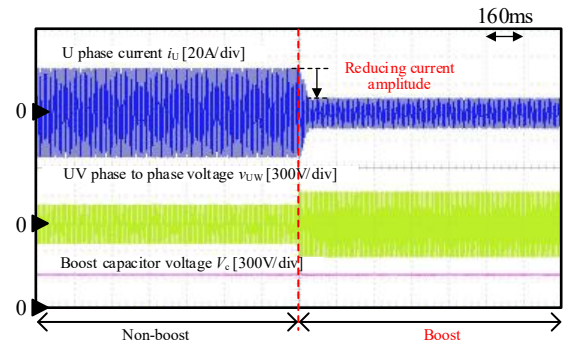


Fig. 6. Switching waveform between boost operation and non-boost operation.