

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

Shun Sato

Dept. of Electrical, Electronics, and
Information Engineering
Nagaoka University of Technology
Nagaoka, Japan
s233127@stn.nagaokaut.ac.jp

Hirotaka Kato

Dept. of Science of Technology Innovation
Nagaoka University of Technology
Nagaoka, Japan
s203139@stn.nagaokaut.ac.jp

Kodai Nishikawa

Dept. of Science of Technology Innovation
Nagaoka University of Technology
Nagaoka, Japan
knisikawa@vos.nagaokaut.ac.jp

Hiroki Watanabe

Dept. of Electrical, Electronics, and
Information Engineering
Nagaoka University of Technology
Nagaoka, Japan
hwatanabe@vos.nagaokaut.ac.jp

Jun-ichi Itoh

Dept. of Science of Technology Innovation
Nagaoka University of Technology
Nagaoka, Japan
ito@vos.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 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. Simulation and experimental results verify the effectiveness of the proposed inverter. The proposed method reduces the motor current amplitude by 42.7% in simulation.

Keywords—Boost-type three-phase inverter, Inductor-less, Permanent magnet synchronous motors (PMSMs), space vector modulation (SVM)

I. INTRODUCTION

Recently, electric vehicles (EVs) have rapidly gained popularity, and Permanent Magnet Synchronous Motors (PMSMs) have been widely adopted as traction motors. The use of PMSMs enables higher efficiency and system miniaturization compared with systems using induction motors [1-2]. However, in the high-speed region, PMSMs must adopt field-weakening control due to the increase in the back electromotive force (EMF) caused by magnet flux [3-5], which results in further efficiency degradation. To address this issue, a conventional approach connects a boost chopper to the front stage of the inverter [6-7]. However, the boost chopper requires a large inductor, which increases the overall system volume, weight, and cost. In particular, for EV applications, where installation space is limited and weight reduction is critical, the development of a boost circuit that can operate without large inductors is highly desirable.

As a boost system that does not use an additional inductor, ref. [8] realizes voltage boost operation by connecting a switched-capacitor circuit (SCC), composed of a capacitor, switches, and diodes to the front stage of the inverter. By switching the devices in SCC, the DC-link voltage is obtained as either the supply voltage or the sum of the supply voltage and the capacitor voltage. Ref. [9] integrates the SCC into one phase of the inverter. This integration reduces the number of devices while achieving boost operation. Ref. [10] achieves a

higher output voltage by adopting a multistage SCC structure. However, in these SCC-based circuits, a large current flows through the capacitor. Therefore, they are not suitable for high-power applications. In addition, the number of components in the drive circuit increases and the capacitors must be pre-charged. On the other hand, ref. [11] connects a charge pump circuit in series to the front stage of the inverter. This circuit realizes voltage boost operation by connecting a capacitor, switches, and diodes in series with the DC-power supply voltage. By switching the conducting devices, the DC-link voltage is obtained as either the DC-power supply voltage or the sum of the supply voltage and the capacitor voltage. However, the capacitor must be pre-charged, and only a temporary boost operation is demonstrated. Therefore, continuous motor operation in the high-speed region that requires boost operation is not possible.

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. By switching the additional switches, either the DC-power supply voltage or the capacitor voltage is applied to the DC-link. In addition, a space vector modulation (SVM) method is developed for the proposed circuit 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. The originality of this paper lies in the proposal of a new three-phase inverter topology that achieves continuous voltage boost operation using only a capacitor and two additional switches, without an additional inductor. Unlike conventional boost converters that require bulky inductors, the proposed topology realizes steady-state boost operation with only a small number of additional components.

This paper is organized as follows: First, the proposed inductor-less boost inverter circuit is introduced. Second, a space vector modulation method for the proposed circuit and the capacitor voltage control method are described. Finally, the validity of the proposed circuit is verified through simulation with a PMSM drive system and experimental verification with an IM drive system.

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 switches sw_{dc} and sw_c , respectively. The voltage applied to the inverter is switched between the supply voltage E_{dc} and the capacitor voltage V_c by operating these switches in a complementary manner.

Fig. 2 shows the space vectors in the proposed circuit. In a conventional three-phase inverter, eight space vectors are defined. In contrast, in the proposed circuit, since the DC-link voltage is switched, two sets of eight space vectors with different amplitudes are defined, resulting in a total of 16 voltage vectors. The numbers indicated for each space vector in Fig. 2 represent the states of sw_{dc} , sw_{up} , sw_{vp} , and sw_{wp} from left to right. 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 average vector matches V_{cmd} . To apply the capacitor voltage control described later, V_{cmd} is decomposed into V_{cmd_dc} and V_{cmd_c} , and V_{cmd} is generated through two-step modulations process.

Fig. 3 shows the modulation waveform of the proposed boost inverter. Here, Fig. 3(a) shows the space vectors used for modulation, while Fig. 3(b) shows the corresponding switching pattern. In Fig. 3(a), three space vectors closest to each command vector are selected for the modulation of V_{cmd_dc} and V_{cmd_c} , respectively. As indicated in Fig. 3(b), V_{cmd_dc} is modulated first, followed by V_{cmd_c} . During this process, the inverter-side switches (sw_{up} , sw_{vp} , and sw_{wp}) operate twice within one control period.

B. Capacitor voltage control method

To achieve continuous boost operation in steady state using the proposed circuit, the capacitor voltage V_c must be maintained. 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 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 setting 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} . Under this condition, the modulation constraint for V_{cmd_dc} and V_{cmd_c} is given by

$$\begin{cases} 0 \leq |V_{cmd_dc}| \leq \frac{E_{dc}}{\sqrt{3}} \\ 0 \leq |V_{cmd_c}| \leq \frac{V_c}{\sqrt{3}} \end{cases} \dots\dots\dots (1),$$

$$0 \leq \frac{\sqrt{3}|V_{cmd_dc}|}{E_{dc}} + \frac{\sqrt{3}|V_{cmd_c}|}{V_c} \leq 1 \dots\dots\dots (2).$$

As described earlier, in the proposed circuit, V_{cmd_dc} and V_{cmd_c} are modulated within one control period using time division. Thus, a trade-off relationship exists between their

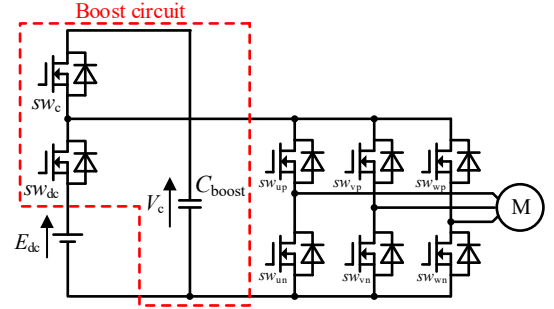


Fig. 1. Proposed boost-type three-phase inverter.

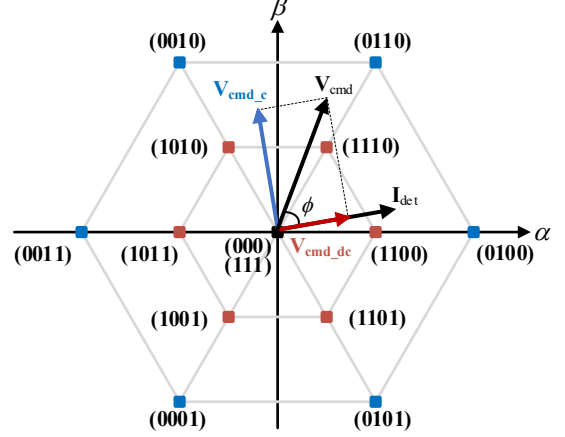
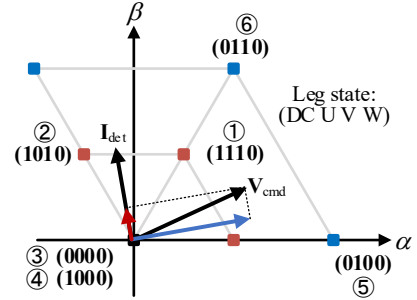
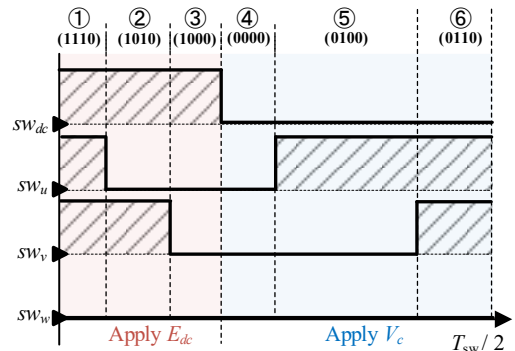


Fig. 2. Defined space vectors in proposed inverter.



(a) Selected space vector in $\alpha\beta$ coordinate.



(b) Switching sequence by SVM.

Fig. 3. Modulation scheme in proposed inverter.

magnitudes, which in turn imposes a limitation on the magnitude of the resultant vector V_{cmd} .

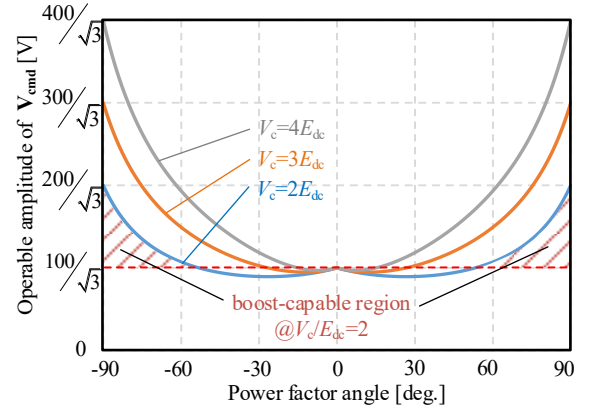
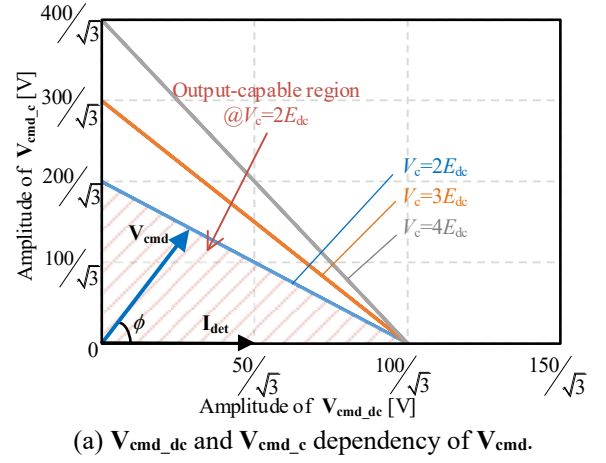
Fig. 4 shows the modulation range of the proposed inverter for cases where $V_c = 2E_{dc}$, $3E_{dc}$, and $4E_{dc}$, respectively. Fig. 4(a) shows the region where $\mathbf{V}_{cmd}$ is achievable, calculated from the amplitudes of $\mathbf{V}_{cmd_dc}$ and $\mathbf{V}_{cmd_c}$ based on (1) and (2). Fig. 4(b) shows the same characteristics with respect to the phase difference between $\mathbf{V}_{cmd}$ and $\mathbf{I}_{det}$. In Fig. 4(a), the three straight lines represent the condition where the middle term of (2) equals one. Voltage command $\mathbf{V}_{cmd}$ is modulated within the shaded area enclosed by these lines and the origin. From Fig. 4(b), it is observed that a higher boost effect is obtained under low-power-factor conditions. This is because, at a low-power-factor, the power supplied from E_{dc} is small, allowing a longer modulation interval to be allocated to $\mathbf{V}_{cmd_c}$ within one control period. On the other hand, as shown in Fig. 4(b), the magnitude of $\mathbf{V}_{cmd}$ becomes smaller than $E_{dc} / \sqrt{3}$ that of a conventional inverter, particularly under high-power-factor conditions. This is because the magnitude of $\mathbf{V}_{cmd}$, which results from the combination of $\mathbf{V}_{cmd_dc}$ and $\mathbf{V}_{cmd_c}$, is determined by the square root of the sum of their squared amplitudes. In the operating region where the proposed circuit cannot produce a higher output voltage than a conventional inverter, sw_{dc} is kept continuously on, and the system operates as a standard three-phase inverter.

Fig. 5 shows the compensation method for the capacitor voltage. Theoretically, the capacitor voltage V_c is maintained at a constant value by setting $\mathbf{V}_{cmd_dc}$ and $\mathbf{V}_{cmd_c}$ as described above. However, in the actual system, voltage drops occur owing to the motor winding resistance and converter losses. Thus, as indicated in Fig. 5(a), even when $\mathbf{V}_{cmd_c}$ is set as intended, the capacitor voltage is not maintained. In order to maintain the desired capacitor voltage, an automatic voltage regulator (AVR) is adopted. The AVR feeds back the detected V_c and treats the capacitor current i_c as the control variable. Since the inverter cannot directly control i_c , a capacitor voltage compensation vector $\mathbf{V}_{cmp}$, shown in Fig. 5(b), is introduced. Voltage command $\mathbf{V}_{cmd}$ is a vector in the same direction as $\mathbf{I}_{det}$. By combining it with $\mathbf{V}_{cmd_c}$ for modulation, the power delivered from the capacitor to the motor is regulated. The relationship between the AVR output i_c and $\mathbf{V}_{cmp}$ is expressed as

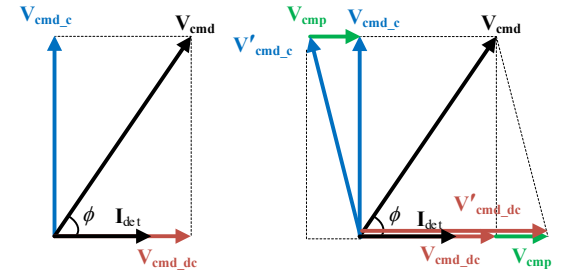
$$\mathbf{V}_{cmp} = \frac{2}{3} \frac{V_c \mathbf{I}_{det}}{|\mathbf{I}_{det}|^2} i_c \dots\dots\dots (3).$$

By using (3), the control output of the AVR is converted into the voltage command for inverter modulation. Here, the compensating vector that cancels $\mathbf{V}_{cmp}$ is added to $\mathbf{V}_{cmd_dc}$. This prevents the amplitude and phase of the inverter output voltage $\mathbf{V}_{cmd}$ from being influenced by the introduction of $\mathbf{V}_{cmp}$. As a result, the capacitor voltage is maintained at a constant value, allowing control toward the desired voltage during operation. A small capacitor can be used, since the voltage ripple generated across the capacitor contains only the switching-frequency component. This allows for a more compact system configuration.

Fig. 6 shows the overall control block diagram of PMSM drive system using proposed boost circuit. The FOC(field-oriented-control) block controls the d- and q-axis currents and generates the voltage command vector $\mathbf{V}_{cmd}$, and the modulation and V_c control block generates switching patterns from $\mathbf{V}_{cmd}$ and controls the boost capacitor voltage. First, the inverter voltage command vector $\mathbf{V}_{cmd}$ is generated from the torque command and the d-axis current command in the FOC



(b) Power factor dependency of $\mathbf{V}_{cmd}$.
Fig. 4. Boost-operable region in proposed inverter.



(a) Without compensation. (b) With compensation.
Fig. 5. Capacitor voltage compensation method.

block. Next, voltage command $\mathbf{V}_{cmd}$ is decomposed into $\mathbf{V}_{cmd_dc}$ and $\mathbf{V}_{cmd_c}$ using $\mathbf{I}_{det}$. Then, the capacitor current command i_c^* calculated by the AVR is converted into $\mathbf{V}_{cmp}$ based on (3), and then both $\mathbf{V}_{cmd_c}$ and $\mathbf{V}_{cmd_dc}$ are compensated. Finally, switching pulses are generated by the SVM method using the compensated vectors $\mathbf{V}'_{cmd_dc}$ and $\mathbf{V}'_{cmd_c}$. As shown in Fig. 3, in the SVM process, $\mathbf{V}_{cmd_dc}$ is modulated first, followed by $\mathbf{V}_{cmd_c}$.

III. TEST RESULTS

Table 1 shows the simulation conditions 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 value of E_{dc} is determined based on the back electromotive force at the no-load base

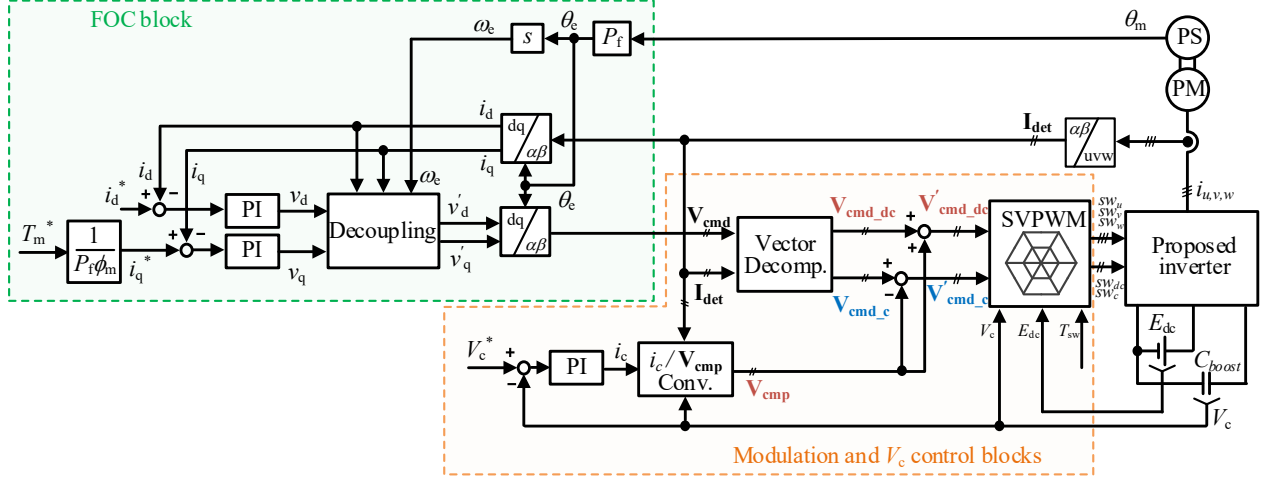


Fig. 6 Control block diagram for PMSM drive system using proposed boost inverter.

speed of the PMSM. The capacitance of the boost capacitor is determined as 100 μF so that the voltage ripple caused by the switching component remained below 2%. The voltage controller bandwidth f_{AVR} is determined as 50Hz to be lower than that of the motor current controller in the FOC block. The PMSM is operated in the high-speed region where flux-weakening control is required because the proposed circuit achieves boost operation under low power factor conditions.

Table 2 shows the experimental conditions for IM drive. Although the target application is PMSM drive systems, an IM drive system was used in the experiment to verify the basic boost operation and transition performance of the proposed inverter. The IM is driven by V/f control that operates in open loop. The supply voltage E_{dc} is set to 150 V, and the reference value of the capacitor voltage V_c is set to 300 V. The IM was operated under no-load conditions to evaluate the boost operation in a low power-factor region. In the experimental setup, the capacitor is charged and discharged during the transition between non-boost and boost operation.

A. Simulation results for PMSM

Fig. 7 shows the simulated operating waveforms under different motor speed conditions. In the line-to-line voltage waveform, the gray trace represents the actual output voltage, while the black trace indicates the fundamental component. In the waveform of the capacitor voltage, the gray line represents the reference value, the black line indicates the measured response. In the waveform of the torque, the gray line represents the command value, the black line indicates the measured response. Fig. 7 shows the simulated waveforms under the following conditions: (a) motor rotational speed $\omega_m=1.0\text{p.u.}$, (b) $\omega_m=1.5\text{p.u.}$, and (c) $\omega_m=2.0\text{p.u.}$. The torque command T_m^* is set to 0.1p.u.. As shown in Fig. 7, the motor torque matched the command value. In addition, under the conditions of (b) and (c), the line-to-line voltage exceeds E_{dc} . Furthermore, under the conditions of (b) and (c), the capacitor voltage V_c matches the command value. This means that the proposed circuit achieves continuous boost operation under low power factor conditions.

Fig. 8 shows the responses of capacitor voltage V_c and the line-to-line voltage, motor current when the torque command

Table 1. Simulation configuration.

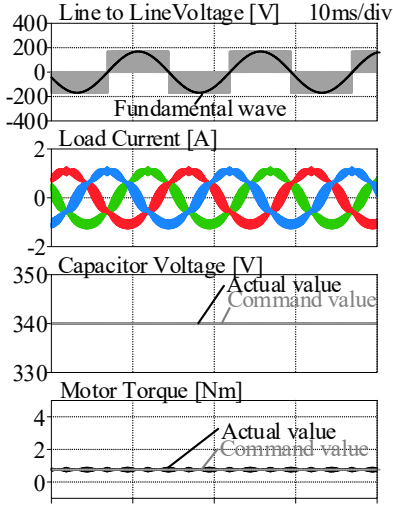
Parameter	Value
Input voltage E_{dc}	170 V
Capacitor voltage command V_c^*	340 V
Control period T_{sw}	100 μs
Boost capacitor C_{boost}	100 μF
Bandwidth of AVR f_{AVR}	50 Hz
Bandwidth of ACR f_{ACR}	600Hz
Motor rated speed ω_h	2000 r/min
Rated Torque T_n	3.8 Nm
Poles peris P_f	2
Motor winding resistance R	0.1 Ω
Motor Inductance L_m	3.78 mH
Linked magnetic flux ϕ_m	0.233Wb

Table 2. Experimental configuration.

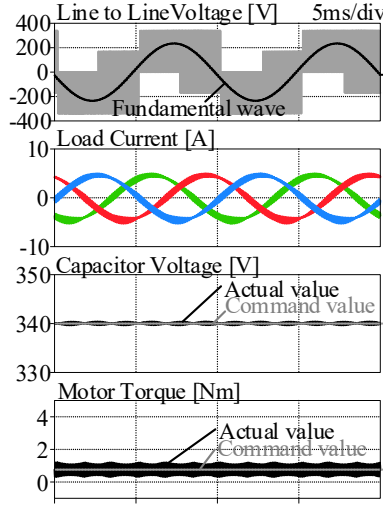
Parameter	Value
Input voltage E_{dc}	150 V
Capacitor voltage command V_c^*	300 V
Control period T_{sw}	100 μs
Boost capacitor C_{boost}	200 μF
Bandwidth of AVR f_{AVR}	50 Hz
Motor rated speed ω_h	1500 r/min
Rated power P_n	3.7kW
Poles pairs P_f	2
Rated voltage V_n	200 V
Rated current I_n	15 A

is changed in a step. The torque command T_m^* is stepped from 1.0p.u. to 0.0p.u.. The motor rotational speed is set to 2.0p.u.. In the waveform of the capacitor voltage, the gray line represents the reference value, the black line indicates the measured response. In the line-to-line voltage waveform, the gray trace represents the actual output voltage, while the black trace denotes its fundamental component. As shown in Fig. 8, the amplitude of the motor current decreases as the torque decreases. In contrast, the amplitude of the line-to-line voltage increases as the torque decreases. This is because the proposed circuit provides a large boost ratio under low-torque operation. These results mean that the proposed circuit achieves a reduction in motor current amplitude under low-torque and high-speed conditions.

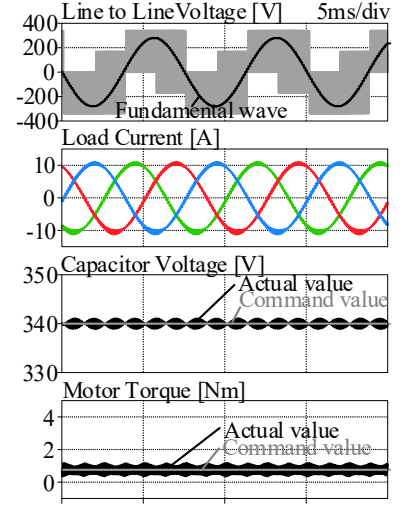
Fig. 9 shows the responses of capacitor voltage V_c and the line-to-line voltage, motor current when switching between boost operation and non-boost operation. The torque command T_m^* is set to 0.2p.u.. The motor rotational speed is



(a) $\omega_m=1.0\text{p.u.}$



(b) $\omega_m=1.5\text{p.u.}$



(c) $\omega_m=2.0\text{p.u.}$

Fig. 7. Boost operation waveforms.

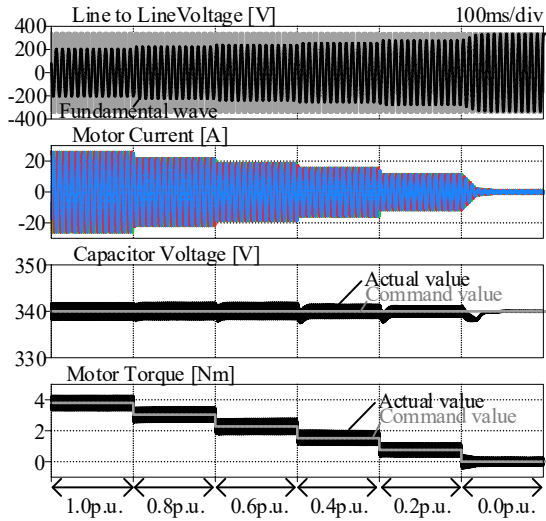


Fig. 8 Operating waveform at different torque condition.

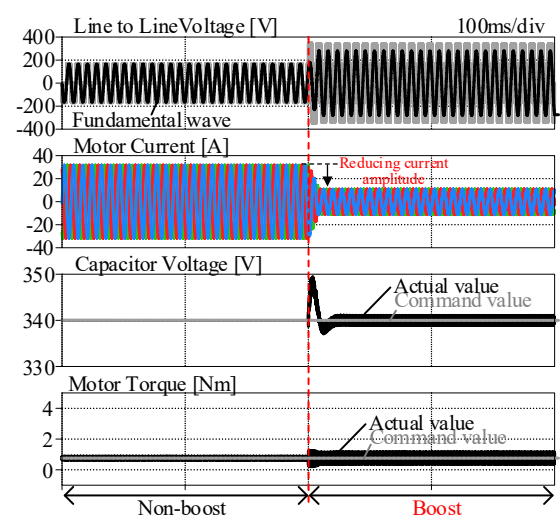


Fig. 9 Switching waveform between boost operation and non-boost operation.

set to 2.0p.u.. In the waveform of the capacitor voltage, the gray line represents the reference value, the black line indicates the measured response. In the line-to-line voltage waveform, the gray trace represents the actual output voltage, while the black trace denotes its fundamental component. As shown in Fig. 9, the motor current amplitude during boost operation is 42.7% lower than during non-boost operations. 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.

B. Experimental Results for an IM

Fig. 10 shows the waveforms of the line-to-line voltage, the motor current and the capacitor voltage during steady-state operation of the IM. The amplitude of V_{cmd} is set to $210/\sqrt{3}$ V. The motor speed is set to 1.0p.u.. As shown in Fig. 10,

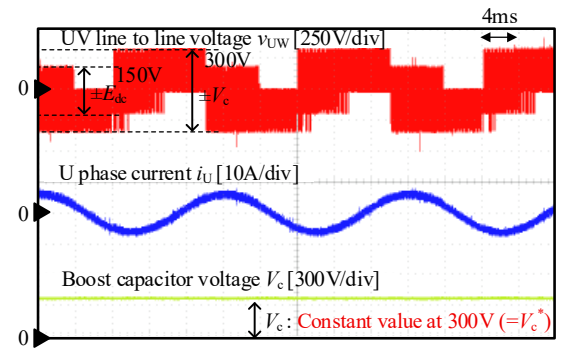


Fig. 10 Waveforms during steady-state operation

the amplitude of line-to-line voltage exceeds E_{dc} . In addition, the capacitor voltage is maintained at a constant value and shows stable operation. These results mean that stable motor operation is achieved during boost operation.

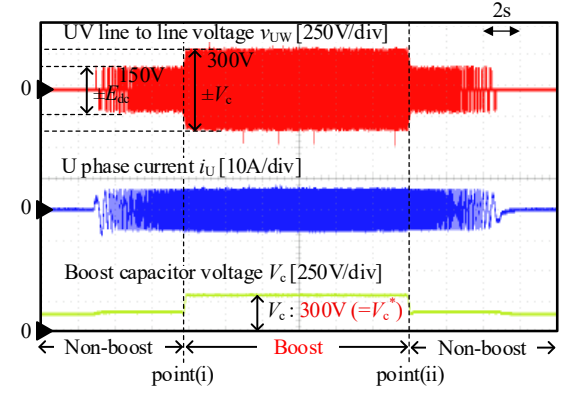
Fig. 11 shows the waveform of the line-to-line voltage, the motor current, and the capacitor voltage during acceleration and deceleration operation of the IM. Fig. 11(a) shows the overall behavior during acceleration and deceleration operation. Fig. 11(b) and (c) show enlarged waveforms during the transition between boost and non-boost operation at points (i) and (ii). The final amplitude of V_{cmd} is set to $210/\sqrt{3}$ V. As shown in Fig. 11(b) and (c), the motor current is not distorted, and its amplitude remains constant before and after the transition between boost and non-boost operation in the enlarged waveforms. In addition, the capacitor voltage during boost operation is maintained at 300 V and shows stable operation. These results mean that stable motor operation is achieved during boost operation. They also mean that the transition between boost operation and non-boost operation is performed seamlessly.

IV. CONCLUSION

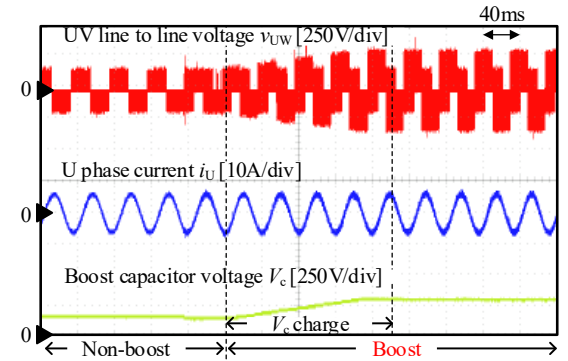
This paper proposes a boost-type inverter without a boost inductor for motor drive systems. In the proposed circuit configuration, the boost capacitor is connected in parallel with the DC-power supply voltage through switching devices. The DC-link voltage is increased by alternating the switch states. In addition, by maintaining the capacitor voltage constantly using an automatic voltage regulator (AVR), continuous boost operation in steady state was achieved. The validity of the proposed boost-type inverter and its space vector modulation (SVM) method have been verified through simulation and experimental verification. The simulation results show that the proposed method reduces the motor current amplitude by 42.7% in simulation. In addition, the experimental results show that stable motor operation is achieved. In future work, the effect of boost operation on reducing the motor current amplitude will be verified using an experimental prototype.

REFERENCE

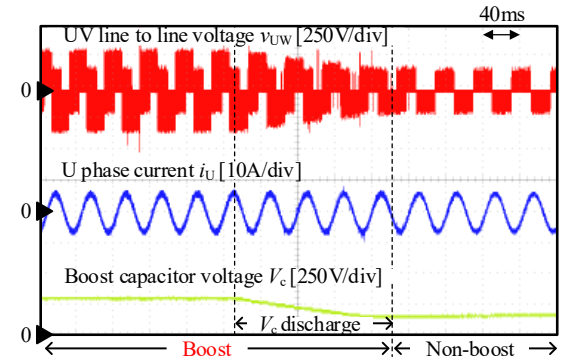
- [1] J. O. Estima and A. J. Marques Cardoso, "Efficiency Analysis of Drive Train Topologies Applied to Electric/Hybrid Vehicles," in *IEEE Transactions on Vehicular Technology*, vol. 61, no. 3, pp. 1021-1031, March 2012.
- [2] Y. Hu, S. Zhu and C. Liu, "Magnet Eddy-Current Loss Analysis of Interior PM Machines for Electric Vehicle Application," in *IEEE Transactions on Magnetics*, vol. 53, no. 11, pp. 1-4, Nov. 2017.
- [3] T. M. Jahns, "Flux-weakening regime operation of an interior permanent-magnet synchronous motor drive", *IEEE Trans. Ind. Appl.*, vol. IA-23, no. 4, pp. 681-689, Jul. 1987.
- [4] S. Morimoto, M. Sanada and Y. Takeda, "Wide-speed operation of interior permanent magnet synchronous motors with high-performance current regulator", *IEEE Trans. Ind. Appl.*, vol. 30, no. 4, pp. 920-926, Jul./Aug. 1994.
- [5] R. Schiferl and T. A. Lipo, "Power capability of salient pole permanent magnet synchronous motors in variable speed drive applications", *IEEE Trans. Ind. Appl.*, vol. 26, no. 1, pp. 115-123, Jan./Feb. 1990.
- [6] P. Garcia, L. M. Fernandez, C. A. Garcia and F. Jurado, "Energy management system of fuel-cell-battery hybrid tramway", *IEEE Trans. Ind. Electron.*, vol. 57, no. 12, pp. 4013-4023, Dec. 2010.
- [7] J. Cao and A. Emadi, "A new battery/ultracapacitor hybrid energy storage system for electric hybrid and plug-in hybrid electric vehicles", *IEEE Trans. Power Electron.*, vol. 27, no. 1, pp. 122-132, Jan. 2012.
- [8] A. Hota, M. M. Qasim, J. L. Kirtley and V. Agarwal, "Novel Switched Capacitor Boost Inverter Configuration for Three-Phase Induction



(a) Overall waveform.



(b) Enlarged waveforms at point (i).



(c) Enlarged waveforms at point (ii).

Fig. 11 Waveforms during acceleration and deceleration.

Motor Driven Home Appliances," in *IEEE Transactions on Industry Applications*, vol. 57, no. 2, pp. 1450-1458, March-April 2021.

- [9] A. Hota and V. Agarwal, "A Novel Leg-Integrated Switched Capacitor Inverter Topology for Three-Phase Induction Motor Drives," in *IEEE Transactions on Industrial Electronics*, vol. 71, no. 5, pp. 4353-4360, May 2024.
- [10] A. Hota and V. Agarwal, "Novel Switched Capacitor Quadruple-Boost Inverter Configuration for 3 ϕ Induction Motor Drive," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 5, pp. 6093-6100, Oct. 2022.
- [11] H. Matsumoto and Y. Nebu, "A Boost Driver With an Improved Charge-Pump Circuit," in *IEEE Transactions on Industrial Electronics*, vol. 61, no. 7, pp. 3178-3191, July 2014.