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〈Original Article〉

A study on the speed control of ship propulsion induction motor using improved AFE rectifier

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This paper proposes a possibility of using active front-end rectifier with the SVPWM method for induction motor speed control, which is applicable to small electric propulsion boats. The proposed method can produce a more precise sinusoidal input current waveform and a higher power factor than conventional methods. Its speed, torque, input current, DC voltage, and load current control performance are similar to or better than those of conventional methods. Through computer simulations using the PSIM program, the validity of the proposed method was verified by comparing and analyzing the characteristics of the conventional methods and the proposed method.

Keywords: Active front end, Induction motor, Input current, Speed control

Introduction

In recent years, various environmental regulations have been made stricter to reduce air pollutants emitted from ships. To satisfy the regulations by reducing SOx, NOx, and CO2, many studies have been conducted to date, including regarding electric propulsion ships based on power generators using natural gas or eco-friendly energy sources such as wind, solar, and fuel cells (Kim et al., 2017; Ryu et al., 2015).

The alternating current power generated from a generator needs to be converted to direct current power when the induction motor is used in ship propulsion motors. Conventionally, the diode front end (DFE) method has been used to produce a DC voltage using diode devices such as 6-pulse and 12-pulse rectifiers (Wu, 2006). However, recently, numerous studies have been conducted on the active front end (AFE) rectifier, which actively controls AC power for small- and medium-sized ships (Jeon et al., 2018). The DFE method includes a high level of harmonics on the input power side, which reduces the power quality on the input side, lowers the power factor, reduces the system efficiency, and generates a considerable amount of ripple in the DC stage. To improve this, a phase shift transformer or a large-capacity manual filter can be used, but installation space and cost will increase. As power devices such as IGBT, GTO, and MOSFET, which can be turned on and off, are used for the control of the AFE rectifier, the input current is controlled to produce a sine wave and the total harmonic distortion (THD) is reduced compared with that of the DFE rectifier (Hur et al., 2018; Li et al., 2010). However, switching losses owing to ON-OFF control increase. In the present paper, a space vector pulse-width modulation (SVPWM)-based induction motor speed control method using AFE rectifiers for

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small ship propulsion is proposed. The result shows that this method produces a better input current waveform and a higher power factor than those of the DFE rectifier and the conventional AFE type rectifier, which are used for electric propulsion ships.

Computer simulation is conducted to determine the response characteristics when the load torque command of speed and step inputs are applied, and the characteristics of the proposed rectifier are analyzed and compared with those of conventional rectification methods

Materials and methods

Rectification Method of Electric Propulsion Ships

DFE Rectifier

The DFE method is a rectification technique that converts AC to DC using diodes, which cannot be ON-OFF controlled. Fig. 1 shows a three-phase full-wave rectifier circuit using a typical DFE method.

The rectifier consists of six diodes, and the output current flows if one of the upper diodes (D_1, D_3, D_5) and one of the lower diodes (D_2, D_4, D_6) are turned on. The diode connected to the largest positive (+) voltage among the three AC power supplies is turned on in the upper diodes, and the

other two diodes are reverse biased to remain OFF. On the other hand, the diode connected to the largest negative (-) voltage among the three AC power supplies is turned on in the lower diodes. The three-phase

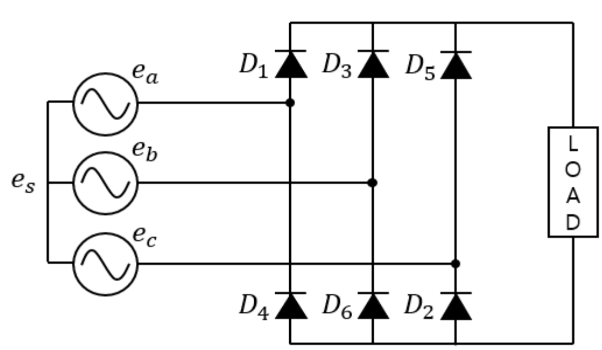


Fig. 1. Three-phase full-wave diode rectifier.

voltages e_a, e_b, e_c can be expressed as follows.

$$e_a = \sqrt{2}Esin(\theta + \frac{\pi}{6}) \quad (1)$$

$$e_b = \sqrt{2}Esin(\theta - \frac{2\pi}{3} + \frac{\pi}{6}) \quad (2)$$

$$e_c = \sqrt{2}Esin(\theta - \frac{4\pi}{3} + \frac{\pi}{6}) \quad (3)$$

As the DC output voltage at the DC link has six pulses that repeat periodically and have the pulse width of and the same size and shape within one period of the power supply voltage, it has an output waveform with six pulses as shown in Fig. 2. Furthermore, a large capacitor is installed to improve the waveform of DC output voltage by smoothing the voltage at the DC link terminal of the rectifier output.

In addition, as the 5th, 7th, 11th, 13th, 17th and 19th order harmonics are included in the input current, the THD is approximately 25 [%] to 30 [%], which seriously

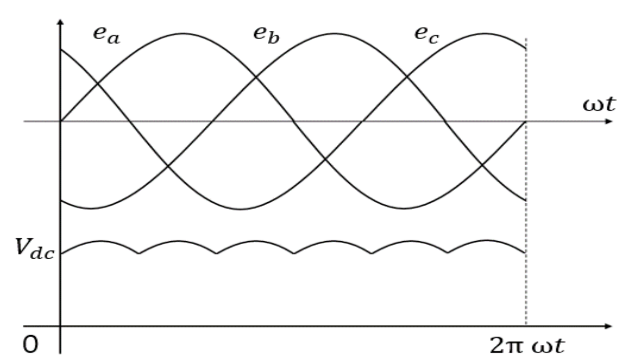


Fig. 2. Voltage output of DC link for three-phase full-wave diode rectifier.

Table 1. Voltage distortion limits

Bus voltage E at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$E \le$ 1.0 kV	5.0	8.0
1.0kV $< E \le$ 69 kV	3.0	5.0
69kV $< E \le$ 161 kV	1.5	2.5
161kV $< E$	1.0	1.5

degrades the quality of the entire power system. Furthermore, it is significantly out of the range determined by the standard range of the IEEE Std 519-2014 standard, which specifies the THD factor shown in Table 1.

DFE Rectification Technique using Phase Shift Transformer

A phase shift transformer is a device installed to remove power system harmonics generated from the switching of a power converter for voltage and frequency conversion in an electric propulsion ship. If an AC signal is rectified by the secondary and tertiary wirings of the phase shift transformer, a DC output waveform with multiple pulses can be obtained at the DC link. Therefore, the DC waveform will be improved. In electric propulsion ships, multiple phase shift transformers and DFE rectifiers are used to produce a DC output waveform with 12 pulses, 18 pulses, and 24 pulses. However, a phase shift transformer takes too much space in a ship engine room where space is limited, and the initial cost increases owing to the installation of multiple transformers and rectifiers.

In the 12-pulse rectification method, the phase difference of between the secondary and tertiary windings of the phase shift transformer improves the DC output waveform at the DC link and the THD at the power output node. Moreover, the 18-pulse and 24-pulse rectification methods improve the rectification effect through the phase difference of transformer wiring.

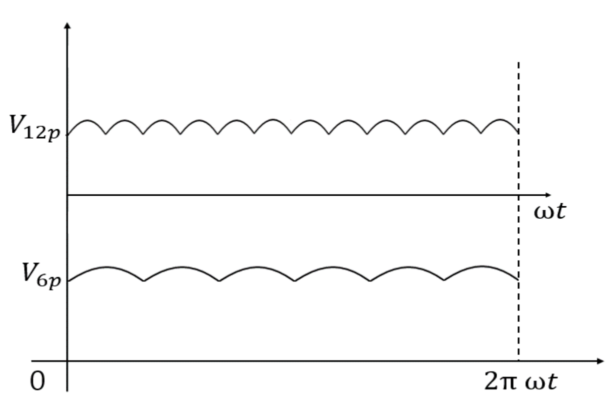


Fig. 3. Comparison of output voltages of 6-pulse

Fig. 3 shows the results of comparing the DC link stage DC output waveforms of the 6-pulse and 12-pulse rectification methods. It can be observed that the 12-pulse rectification method shows a relatively smooth signal compared with the 6-pulse rectification method, because the DC output voltage has 12 pulses per cycle. However, although the DC output waveform at the DC link stage and the THD at the power output node can be improved by introducing the multi-pulse rectification method with phase shift transformers, 6- and 12-pulse rectification methods do not satisfy IEEE Std. 519-2014 requirements. Therefore, high-level rectification methods, such as 18-pulse or 24-pulse rectification methods, should be used. However, even if an 18-pulse or 24-pulse rectification method is designed, the design of a zigzag transformer, which is normally used in the high-level rectification method, is complicated, and thus, errors may occur. Furthermore, the 5th, 7th, 11th and 13th harmonics are not eliminated. In addition, the internal configuration of the zigzag transformer is more complicated and bulky than that of a phase shift transformer for a 12-pulse rectification method.

AFE Rectification Method

The AFE rectifier is a power converter that controls the magnitude and phase of the rectifier input current. In other words, by using a switching element such as IGBT connected in parallel with the diode, current can flow in both directions between the input stage and the direct link stage (i.e., bidirectional).

The flow from the input to the DC link node occurs through the diode, and the reverse flow from the DC link node to the input is controlled using a switching element. In the control, the switching element is controlled to produce a power supply voltage waveform that is the same waveform as the input current waveform, and thus, it is possible to supply high-quality power with low THD and high power factor. Installation of a line inductor at the input is essential for bidirectional energy flow.

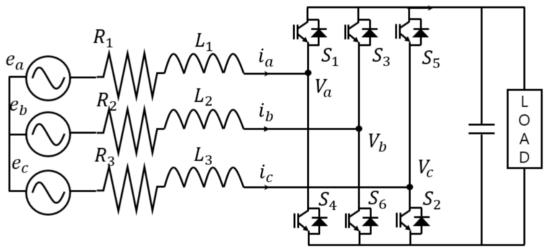


Fig. 4. Circuit diagram of AFE rectifier.

Fig. 4 shows a three-phase AFE rectifier. The rectifier consists of six switches in three stages, one capacitor is installed at the power output node to maintain a constant DC output voltage under sudden voltage fluctuations, and one load is installed at the power output to adjust the amplitude of the rectifier input current during power conversion. During the rectification, the AC voltage supplies, e_a, e_b, e_c maintain three-phase equilibrium.

If the upper and lower switches are turned on simultaneously, dv/dt increases rapidly, causing damage to the switch. Therefore, a delay is introduced in the operation of the switch to provide complimentary motion control for the two switches to turn on and off.

$$e_a + e_b + e_c = 0 \tag{4}$$

$$i_a + i_b + i_c = 0 \tag{5}$$

The voltage equation of the rectifier is as follows.

$$e_a = Ri_a + L\frac{di_a}{dt} + V_a \tag{6}$$

$$e_b = Ri_b + L\frac{di_b}{dt} + V_b \tag{7}$$

$$e_c = Ri_c + L\frac{di_c}{dt} + V_c \tag{8}$$

where e_a, e_b, e_c are phase a, b, and c power supply voltages, respectively, i_a, i_b, i_c are phase a, b, and c currents, respectively, and V_a, V_b, V_c are phase a, b, and c input voltages, respectively.

Comparison of Harmonics in Conventional Rectification Techniques

Conventional electric propulsion system rectifiers include the DFE rectifier and the AFE rectifier. The DFE rectifier can be classified into 6-pulse, 12-pulse, 18-pulse, and 24-pulse rectification methods depending on the DC output waveform. Using a three-phase full-wave rectifier circuit, which is the most typical type, 6 pulses having a pulse width of 60° and the same size and shape can be produced, and thus, a 6-pulse DC output waveform can be obtained. However, the THD on the power output node will increase from 25 [%] to 27 [%], and a large capacitor must be installed at the DC link stage to improve the DC output waveform.

To improve the THD generated from a 6-pulse rectification method at the high power output and the output waveform at the DC link stage, a phase shift transformer is installed before the rectifier so that 12-pulse, 18-pulse, and 24-pulse DC output waveforms can be obtained. When the phase shift transformer is installed, it is possible to improve the output waveform and reduce the THD at the power output node by adjusting the phase shift angle. However, owing to the limited space in a ship and the large volume of the phase shift transformer, the volume of the overall system becomes large, the price increases, and the design of the phase shift transformer becomes complicated as the output waveform approaches a DC waveform.

As the AFE rectifier method can control the rectifier, the DC output waveform at the DC link stage can be improved and its amplitude can be maintained at a constant value. In addition, the THD on the power output node is approximately 3 [%] to 5 [%], which is the lowest among the conventional rectification methods.

Table 2 shows the result of comparing the THDs at the power output node in the conventional rectification technique. As 6-pulse and 12-pulse rectification methods based on the DFE rectification method do not satisfy

Table 2. Comparison of Total harmonic distortion by rectifier type

Rectifier Type	Total Harmonic Distortion (THD)
6 Pulse	25 ~ 27%
12 Pulse	8 ~ 11%
18 Pulse	4 ~ 5%
24 Pulse	2 ~ 3%
AFE	3 ~ 5%

the requirements of IEEE Std. 519-2014, an 18-pulse or 24-pulse rectification method should be used, which causes several problems owing to the installation of phase shift transformers. Furthermore, although the conventional AFE rectifier is capable of active rectifier control to satisfy the required level of THD, as the zero-crossing technique is used to determine the phase angle of the power supply voltage, it is impossible to measure the exact phase angle when distortion is introduced to the power supply voltage. Consequently, the control of the rectifier becomes unstable with shunting, resulting in an error in the rectifying operation.

Proposed AFE Rectifier

Conventional AFE rectifiers have used hysteresis current control techniques, which have been widely used in small systems because of their excellent transient response and simple operation. However, hysteresis controllers are analog controllers, and their use is limited because the switching frequency is not constant.

To address this problem, in this paper, an electric propulsion motor speed control algorithm using an AFE rectifier is proposed to control the current by applying a SVPWM technique. All conventional pulse-width modulation techniques have been used to modulate each of the three-phase command voltages individually. In contrast, the SVPWM method is a technique of modulating the three-phase command voltages as a space vector in a complex space. When the voltage is modulated by this technique and applied to a motor, the harmonics in the current and torque are less than those in other techniques (Kim, 2016).

In the proposed method, the phase voltage vector of the three-phase command voltage rotates counterclockwise in the complex space or d–q axis coordinate system as shown in Fig. 5. In the SVPWM method, the command voltage, which is provided as the voltage vector, is generated by using an inverter and eight voltage vectors. The command voltage for a constant modulation period T_s using two effective voltage vectors (V_n, V_{n+1}) and zero voltage vectors (V_0, V_7) adjacent to the command voltage vector V^* produces an average voltage equal to the vector.

The process of synthesizing the voltage consists of three steps, as shown in Fig. 6, and this process repeats for every voltage modulation period T_s. First, it is assumed that the magnitude and phase of the command voltage vector V^* are constant during the modulation period. In the first step, a vector V^* of two effective voltage vectors adjacent to the command voltage vector V_1 is applied for T_1 hours. Subsequently, the other adjacent vector V_2 is applied for T_2 hours to match the phase and magnitude with V^*, which can produce the

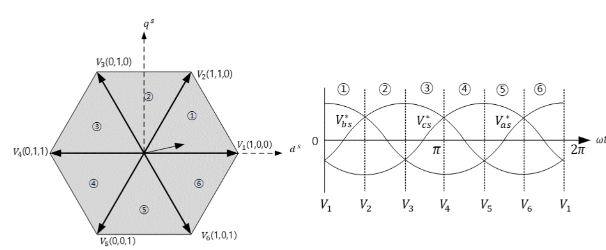


Fig. 5. Movement of the reference voltage vector

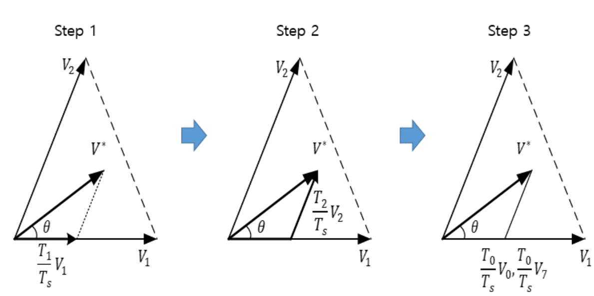


Fig. 6. Process of voltage modulation.

same voltage as V^*. Finally, if the sum of T_1 and T_2 of the two vectors is less than the voltage modulation period T_s, a zero voltage vector V_0 or V_7 is applied for the remaining time T_0 so that no more voltage is applied.

The zero voltage vectors required for this modulation process and the application times T_0, T_1, T_2 of the two effective voltage vectors are as follows.

$$\int_0^{T_s} V^* dt = \int_0^{T_1} V_n\, dt + \int_{T_1}^{T_1+T_2} V_{n+1}\, dt + \int_{T_1+T_2}^{T_s} V_{0,7}\, dt \qquad (9)$$

Assuming that the command voltage vector V^* and the DC input voltage V_{dc} are constant during the voltage modulation period T_s, equation (9) can be simplified to the following

$$V^* \cdot T_s = V_n \cdot T_1 + V_{n+1} \cdot T_2 \qquad (10)$$

When the command voltage vector V^* is located in sector ①$(0 \le \theta \le 60^\circ)$, the two complex axis component equations are expressed as follows.

$$\begin{cases} T_s \cdot |V^*| \cdot \cos\theta = T_1 \cdot \left(\frac{2}{3} V_{dc}\right) + T_2 \cdot \left(\frac{2}{3} V_{dc}\right)\cos 60^\circ \\ T_s \cdot |V^*| \cdot \sin\theta = T_2 \cdot \left(\frac{2}{3} V_{dc}\right)\sin 60^\circ \end{cases} \qquad (11)$$

where $|V^*|$ and θ are the magnitude and phase of the voltage vector, respectively. Using this equation, the application time of the effective voltage vector and the zero voltage vector can be calculated as follows.

$$T_1 = T_s \cdot a \cdot \frac{\sin(60^\circ - \theta)}{\sin 60^\circ} \qquad (12)$$

$$T_2 = T_s \cdot a \cdot \frac{\sin\theta}{\sin 60^\circ} \qquad (13)$$

$$T_0 = T_s - (T_1 + T_2) \qquad (14)$$

where $a = |V^*| / (\frac{2}{3} V_{dc})$이다.

The application time of the effective voltage vector and the zero voltage vector in the remaining sectors is also the same.

In the SVPWM technique, the sum of the application times of the valid voltage vectors should not be greater than the modulation period T_s. In other words $T_1 + T_2 \le T_s$. The magnitude of the command voltage that satisfies this condition can be obtained as follows.

$$T_1 + T_2 \le T_s \rightarrow V^* \le \frac{V_{dc}}{\sqrt{3}} \frac{1}{\sin(60^\circ + \theta)} \qquad (15)$$

The range of modulated command voltage vectors can be defined by using equation (15) and is shown in Fig. 7 where it is a hexagonal inner sector of six effective voltage vectors. The minimum and maximum amplitudes of the command voltage are $V_{dc}/\sqrt{3}$ and $2V_{dc}/3$, respectively.

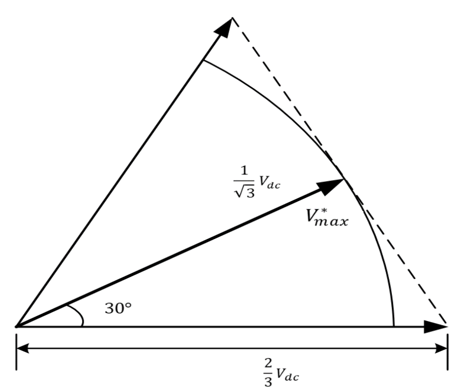


Fig. 7. Controlled voltage areas in SVPWM.

Results and discussion

Simulation

To prove the effectiveness of the induction motor speed control algorithm using the AFE rectifier, computer simulations were performed using the PSIM (Ver. 11.3) program in the high- and low-speed range.

Computer simulations were performed by applying a load proportional to the square of the speed in the high-speed range (1,500 [rpm]) and applying a step load

Table 3. Parameters of induction motor and system constants used for computer simulation

Rated output	3 [HP]	R_r	1.56 [Ω]
Rated voltage	220 [V]	L_s	180 [mH]
Rated current	9 [A]	L_r	180 [mH]
Rated speed	1735 [rpm]	L_m	176 [mH]
Poles	4	J (Moment of inertia)	0.1 [Kg·m2]
R_s	2.0 [Ω]	Sampling cycle	10 [μs]

torque in the low-speed range (300 [rpm]). Table 3 shows the parameters and system constants of the induction motor used in the simulation.

Fig. 8 shows the PSIM block diagram of the induction motor driving simulation using an AFE rectifier.

In the induction motor using the conventional converter, hysteresis controller was used to control the voltage and induction motor speed and current of the converter.

In the induction motor using the proposed converter, a proportional–integral controller is used to control the converter voltage of the SVPWM technique, and a hysteresis controller is used to control the speed and current of the induction motor.

Induction motor of high speed range

Fig.9 & Fig. 10 shows the speed response characteristics of the induction motor when a speed command is applied from 0 [rpm] to 1,500 [rpm].

Comparing Fig. 9 (a) and Fig. 10 (a), and Fig. 9 (b) and Fig. 10 (b) when the speed command is changed from 0 [rpm] to 1,500 [rpm], which is the high-speed range, the transient-state analysis showed that the proposed induction motor control method using the AFE rectifier and the conventional induction motor control method are both stable in speed control and torque control.

Comparing Fig. 9 (c) and Fig. 10 (c), and Fig. 9 (d) and Fig. 10 (d), it was observed that the THD of the input current waveform in the conventional induction motor control method is 3.4 [%], whereas that of the input current waveform of the proposed method is 2.54 [%], which confirms that the proposed method improves the quality of the input current.

Comparing Fig. 9 (d) and Fig. 10 (d), it was observed that the DC voltage is controlled well in both the improved AFE rectification method and the conventional

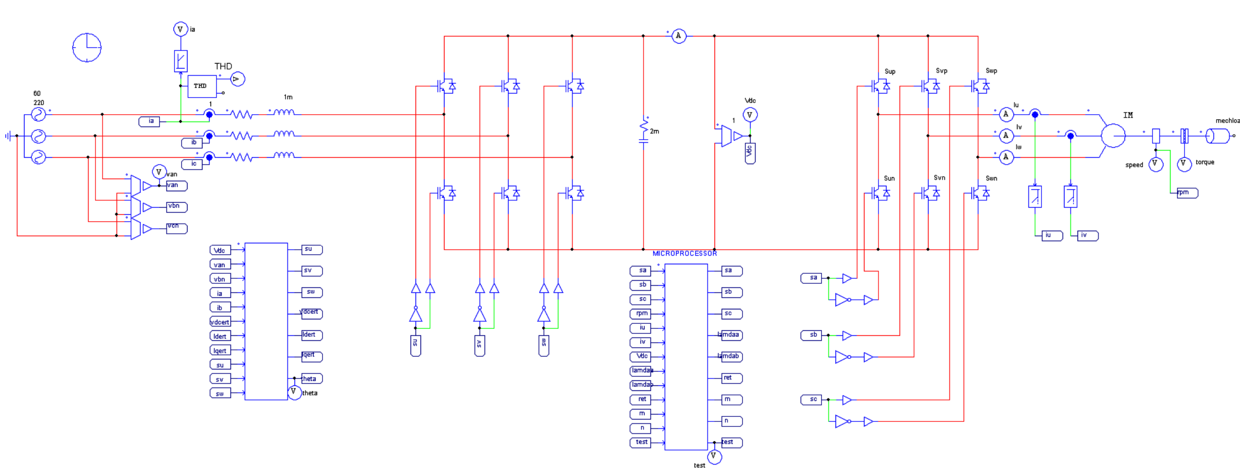
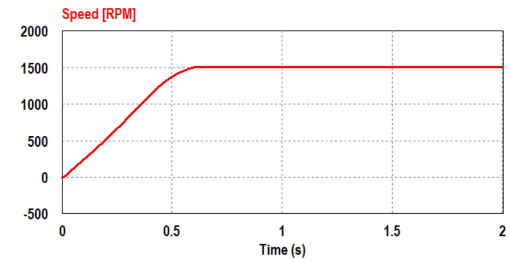
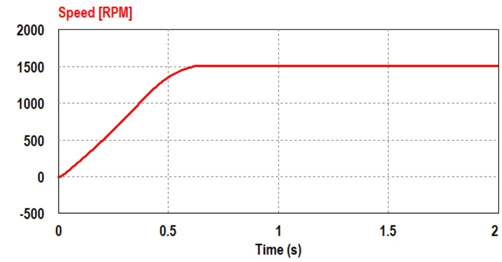


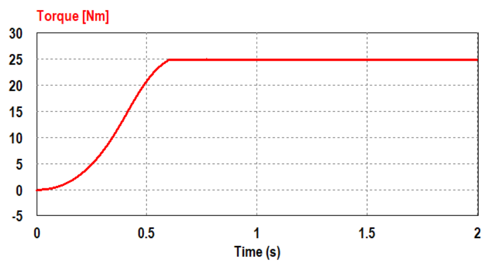
Fig. 8. PSIM diagram of electric propulsion system.



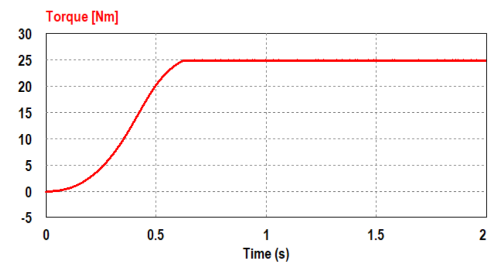
(a) Speed



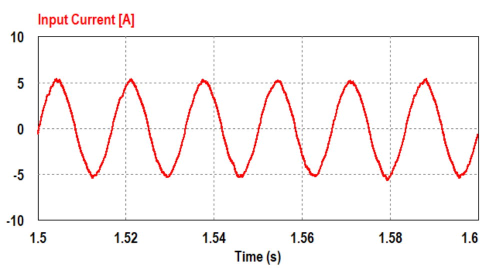
(a) Speed



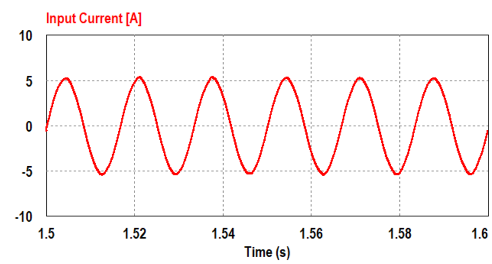
(b) Torque



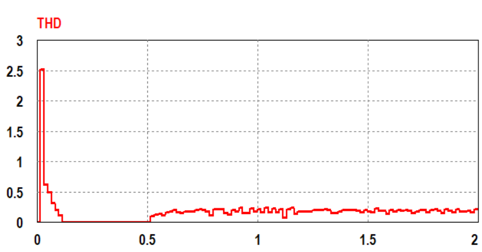
(b) Torque



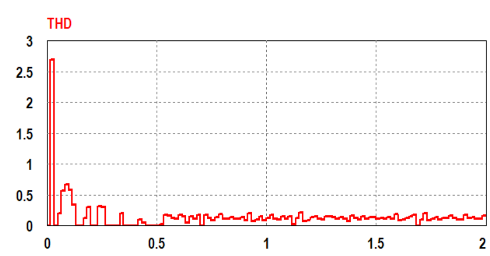
(c) Input current



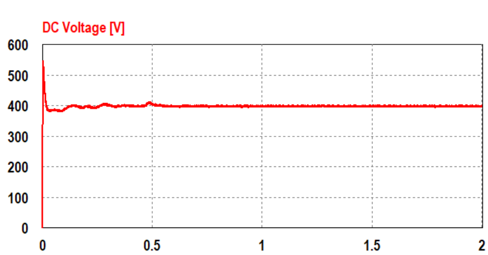
(c) Input current



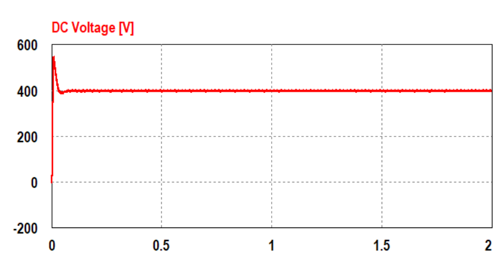
(d) THD



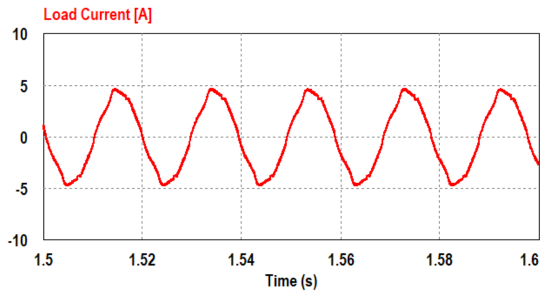
(d) THD



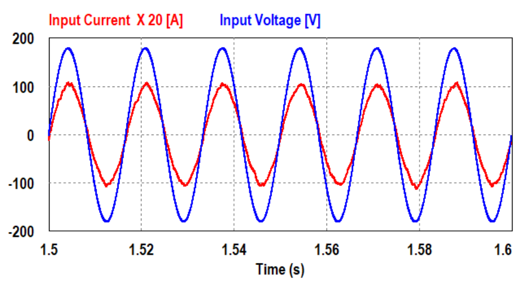
(e) DC Voltage



(e) DC Voltage

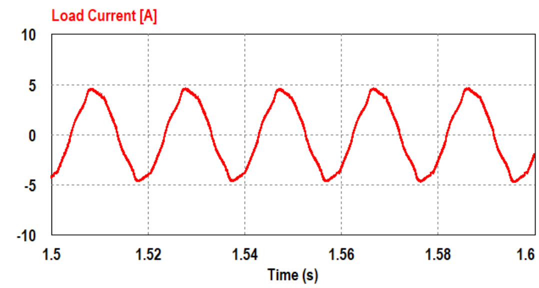


(f) Load current

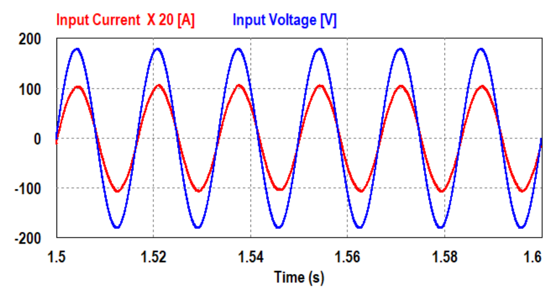


(g) Phase voltage and current

Fig. 9. Simulation responses for the step change of speed setting of conventional converter (0→1,500 [rpm]).



(f) Load current



(g) Phase voltage and current

Fig. 10. Simulation responses for the step change of speed setting of proposed converter (0→1,500 [rpm]).

method.

Comparing Fig. 9 (e) and Fig. 10 (e), it was observed that the maximum amplitudes of the load currents in the conventional method and the proposed AFE method are approximately 4.9 [A] and 4.85 [A], respectively, and thus are very similar to each other. In the transient state, it was observed that the current is stably controlled in the proposed method as well as in the conventional method.

Comparing Fig. 9 (f) and Fig. 10 (f), it was observed that the power factor of the conventional method is 0.96, whereas that of the proposed method is 0.99. Therefore, the power factor was slightly improved.

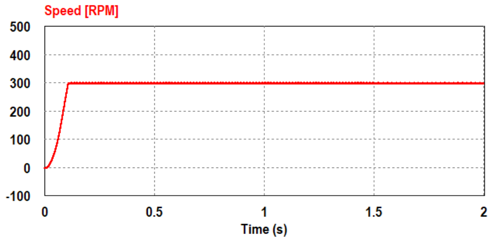
Induction motor of low speed range

Fig. 11 & Fig. 12 shows the response when the load torque of 10 [N·m] is applied during steady-state operation at 300 [rpm].

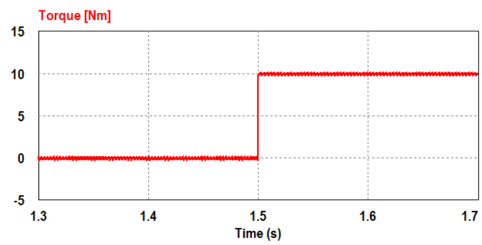
Comparing Fig. 11 (a) and Fig. 12 (a), and Fig. 11 (b) and Fig. 12 (b), when the speed command was changed from 0 [rpm] to 300 [rpm], which is the low-speed range, it was observed that the speed and torque are stably controlled during the transient state in the proposed method as well as in the conventional method.

Comparing Fig. 11 (c) and Fig. 12 (c), both methods produce a very precise sine wave and have excellent quality of the input current. In Fig. 11 (d) and Fig. 12 (d), it is confirmed that the proposed converter has better DC voltage control than the conventional converter.

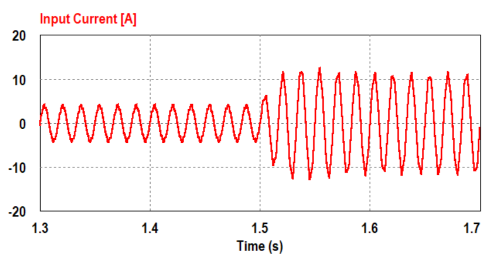
Comparing Fig. 11 (e) and Fig. 12 (e), it was observed that the maximum amplitudes of the load currents in the steady state after load torque was applied in the conventional method and the proposed AFE method are approximately 13.2 [A] and 12.9 [A], respectively, and



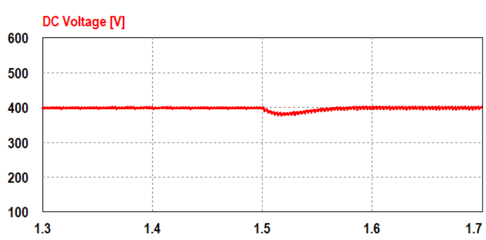
(a) Speed



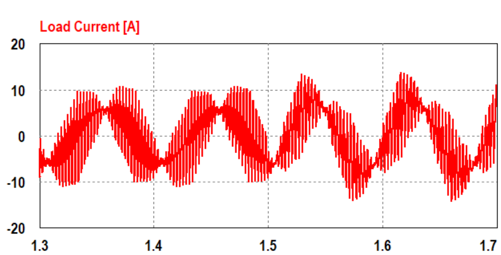
(b) Torque



(c) Input current

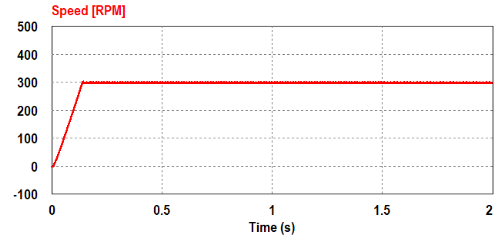


(d) DC Voltage

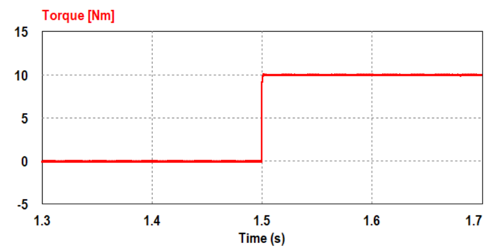


(e) Load current

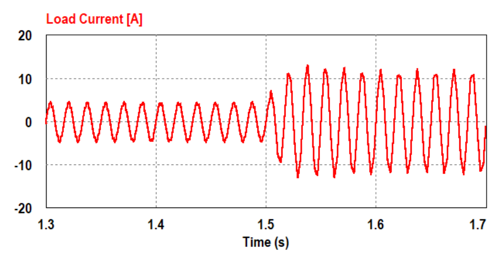
Fig. 11. Simulation responses for the step change of load torque of conventional converter (300 [rpm], 10 [N·m]).



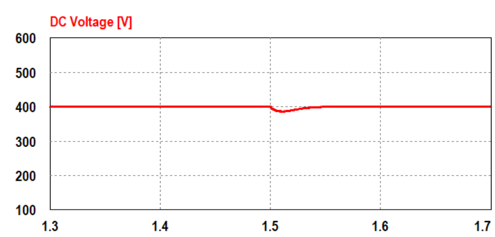
(a) Speed



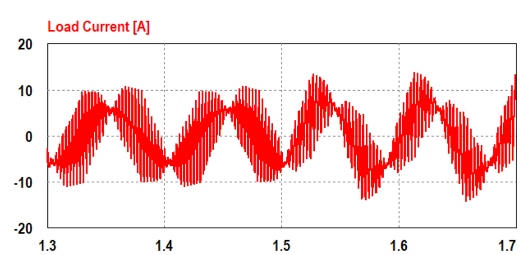
(b) Torque



(c) Input current



(d) DC Voltage



(e) Load current

Fig. 12. Simulation responses for the step change of load torque of proposed converter (300 [rpm], 10 [N·m]).

thus are very similar to each other. In the transient state, it was observed that the current is stably controlled in the proposed method as well as in the conventional method.

Conclusion

To verify the speed control performance of the electric propulsion motor using the improved AFE rectifier, a computer simulation using the PSIM program was performed, and the results are as follows.

1. The proposed AFE rectification method shows better performance than the hysteresis based AFE rectification method in terms of speed control, torque control and load current control.
2. Through the improved AFE rectifier, the input current waveform became a more precise sine wave, thus providing better-quality current with fewer harmonics (0.86%) and improving the input power factor (3%).
3. It was confirmed of the oscillation of the DC voltage waveform in the conventional rectifier is 3.9 [V], whereas that of the DC voltage waveform of the improved AFE rectifier is 1.2 [V].

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