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Original Paper

Speed control for direct current motor using an AFE rectifier

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Abstract: In this study, the possibility of using an active front-end rectifier to control the speed of a direct current motor is proposed. The proposed method improves the input current, ensuring its waveform is closer to a sine wave than in the existing methods, and reduces the size of capacitors (which are large and expensive). Further, the proposed method exhibits a similar or better performance than the existing methods in terms of speed, torque, input current, and load current control. The rectifier unit's switch is directly controlled to make the input-side current waveform similar to a sine wave, thereby providing high-quality current that includes few harmonics. The PSIM software was used to perform computer simulations for a comparative analysis of the characteristics of the existing methods and proposed method, and the effectiveness of the proposed method was verified.
Keywords: Active front end, Direct current motor, Total harmonic distortion (THD), Input current, Speed control

1. Introduction

Currently, international maritime organizations are strengthening various regulations in the maritime industry to reduce the pollutants emitted by ships. In response to this, various studies are being conducted to reduce atmospheric pollutants, such as nitrogen oxide, sulfur oxide, and carbon dioxide. To resolve this issue, studies are being actively conducted to develop technologies that facilitate driving motors with electricity or from eco-friendly renewable energy, such as generators and fuel cells that use LNG fuel, solar energy, and wind power energy.

When an alternating current (AC) generated by a generator is used in a direct current (DC) or propulsion motor, a process that converts AC to DC is required **[1]**. Existing rectification methods often use the diode front-end (DFE) method using diode elements, which cannot turn on and off, to produce 6-pulse and 12-pulse DC waveforms. However, the input side of the AC power supply includes a high level of harmonics, which deteriorates the power supply quality. The system's efficiency is reduced by a decrease in the power factor, and many ripples occur in the DC output**[2]**. To overcome these issues, a high-capacity passive filter or a phase-shift transformer can be used; however, these cause installation space limitations and increased costs.

Therefore, many studies are currently being conducted on active front-end rectifiers, which actively control AC currents and convert them to DC, instead of DFE rectifiers. This method uses electrical elements that can turn on and off, such as IGBT, GTO, and MOSFET, to control the rectifier to keep the input power supply side current close to a sine wave and reduce the total harmonic distortion (THD)**[3]-[4]**. However, this method increases the switching loss because of the on-off control**[5]**.

This study proposes a speed control method of DC motors using an AFE rectifier, which can control the power factor of the input power supply and improve the input current's waveform as compared to the existing speed control method of DC motors that uses a DFE rectifier.

The response characteristics of the method when step input load torque and speed commands were applied via a computer simulation were confirmed, and a comparative analysis of the existing rectification method and the rectifier proposed in this study was performed.

2. Rectifier Types and Characteristics

2.1 DFE Rectifier

The DFE method consists of a rectifier that converts DC to AC using a diode that cannot control the amount of current. **Figure 1** shows a typical converter that uses a diode bridge.

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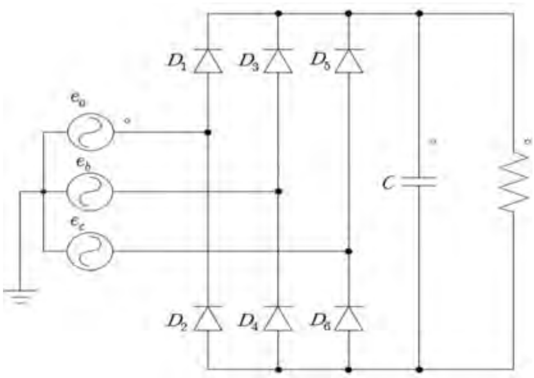


Figure 1: Circuit diagram of a conventional rectifier

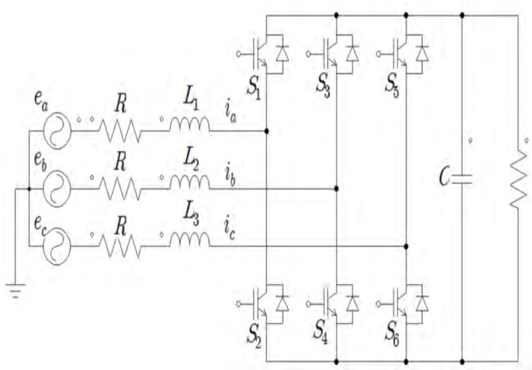


Figure 2: Circuit diagram of an AFE rectifier

This rectifier consists of six diodes, and the output current flows when one of the upper diodes (D_1, D_3, or D_5) and one of the lower diodes (D_2, D_4, or D_6) are turned on at the same time. The diode with the largest amount of voltage in the positive direction among the upper part's 3-phase power supply is turned on, and the remaining two diodes have a reverse-direction bias and are turned off. Simultaneously, the lower part's diode with the largest amount of voltage in the negative direction is turned on and the other two diodes are turned off. The phase voltages e_a, e_b, and e_c at this time are as follows:

$$e_a = \sqrt{2}\,Esin\theta \tag{1}$$

$$e_b = \sqrt{2}\,Esin(\theta - \frac{2\pi}{3}) \tag{2}$$

$$e_c = \sqrt{2}\,Esin(\theta - \frac{4\pi}{3}) \tag{3}$$

To reduce the ripple that occurs during the rectification process, a high-capacity capacitor is installed on the rectifier's output side.

2.2 AFE Rectifier

An AFE rectifier is a power conversion device that controls the amount and phase of the input current. When used together with a switching element, such as IGBT connected in anti-parallel with diodes, it allows current flow in both directions, (from the input unit to DC link unit and vice versa).

The output that goes from the input side to the DC link unit is created via the diodes, and the bidirectional flow from the DC link unit to the input side is controlled using the switching element. The switching element allows a quality current with low THD and high power factor to be supplied by controlling the flow, so that the power supply voltage's waveform and the input current waveform are the same. It is essential to install a line inductor on the input side for the bidirectional energy flow.

Figure 2 shows a 3-phase AFE rectifier. The rectifier consists of six switches in three units. To maintain a fixed DC output voltage during even rapid voltage changes, the power supply's output side is equipped with a capacitor and an inductor for adjusting the amount of rectifier input current during power conversion. At this time, the AC power supply e_a, e_b, and e_c maintain a 3-phase equilibrium.

If the switches in the upper and lower parts are turned on at the same time, dv/dt increases rapidly and causes switch damage. Therefore, a time delay is used during switch operation to control the action of the switches in a mutually complementary way, so that two switches are turned on or off.

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

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

The rectifier's voltage equations are 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, and e_c are the power supply voltages for the a, b, and c phases, respectively. i_a, i_b, and i_c are the phase currents. V_a, V_b, and V_c are the rectifier input voltages.

3. DC Motor Control Using AFE Rectifier

3.1 DC Motor Speed Control Using the Existing DFE Rectifier

This study created a topology for DC motor speed control using an AFE rectifier.

A DFE rectifier that uses a diode bridge was created, as shown in **Figure 3**, for comparison with the proposed AFE rectifier.

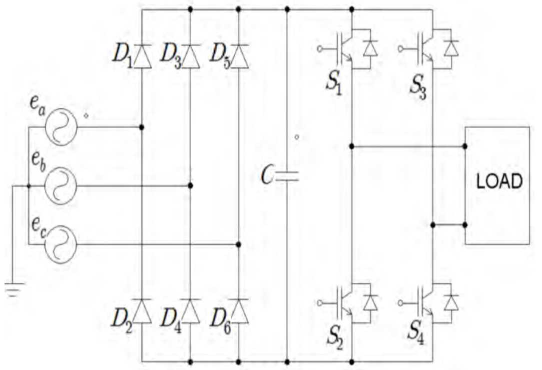


Figure 3: Circuit diagram of a conventional converter

The rectifier with the diode bridge has a capacitor installed in the DC unit to stabilize the DC voltage that is produced. The DC unit's capacitor is equipped with a much larger capacity than a capacitor normally used in an AC unit.

3.2 DC Motor Speed Control Using the Proposed AFE Rectifier

Figure 4 shows an AFE rectifier composed of a diode and IGBT connected antiparallel to each other, and a rectifier unit. The inverter unit consists of a conventional DC motor speed control topology.

Each IGBT element in the rectifier unit is switched through PWM control. The DC unit is equipped with a 1/50-size small-capacity capacitor instead of a high-capacity capacitor, which was a drawback of the existing method.

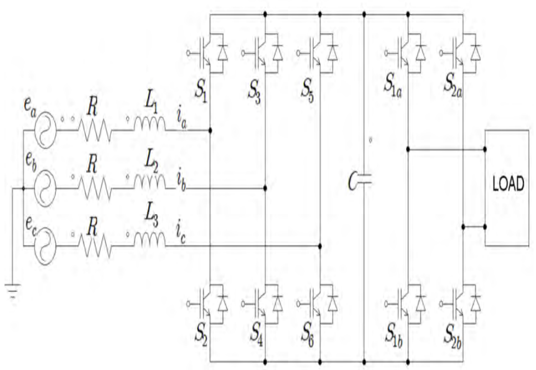


Figure 4: Circuit diagram of the proposed converter

4. Simulation

To verify the effectiveness of the DC motor speed control algorithm that uses an AFE rectifier as proposed in this study, a computer simulation was performed using the PSIM software in the low-speed and high-speed regions.

Table 1: Parameters of the DC motor and system constants used for the computer simulation

Rectified output	2400 W	Armature resistance	0.5 Ω
Rectified voltage	120 V	Stator inductance	20 mH
Rectified current	20 A	Rotor inductance	10 mH
Rectified speed	1750 rpm	Inertia moment	0.4 Kgf·m2
Field Resistance	75 Ω	Sampling period	8 μs

To run the computer simulation, the stage load torque was applied in the low-speed region (300 rpm), and a load proportional to the square of the speed was applied in the high speed region (1500 rpm). **Table 1** presents the parameters and system constants of the DC motor used in the simulation.

4.1 DC Motor Simulation Using DFE Rectifier

Figure 5 shows the PSIM block diagram of a DC motor drive simulation using an existing DFE rectifier. A PI controller was used to control the speed and current.

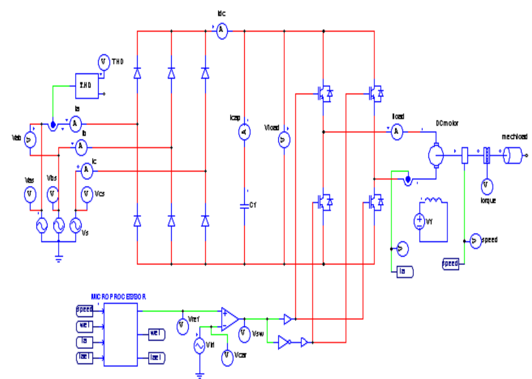
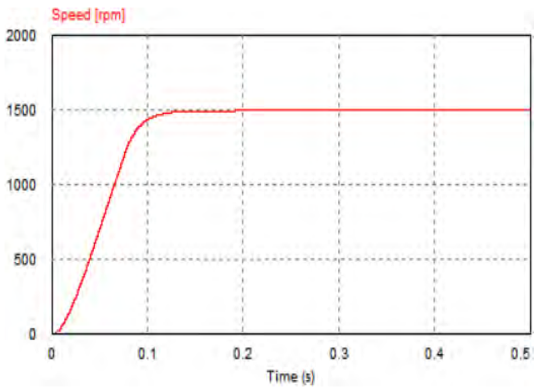


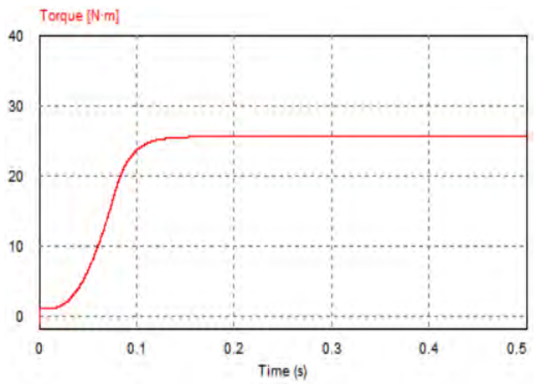
Figure 5: PSIM diagram of a conventional converter

Figure 6 shows a graph of the DC motor's speed response characteristics when speed commands of 0 to 1500 rpm were given. **Figure 6 (a)** shows the change in speed and **Figure 6 (b)** shows the change in load proportional to the square of the speed. **Figure 6 (c)** shows the input unit's phase current waveform, and it includes a lot of harmonics.

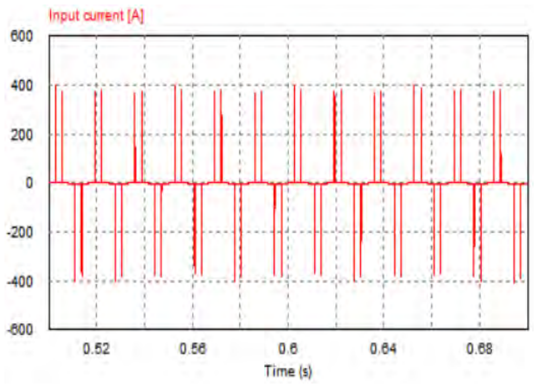
In this case, the measured THD was very high at 743%. **Figure 6 (d)** shows the motor side load current. In a normal state, it was in the range of 27.1–29.3 A with a mean of 28.09 A. **Figure 6 (e)** shows the input unit's voltage and current waveforms.



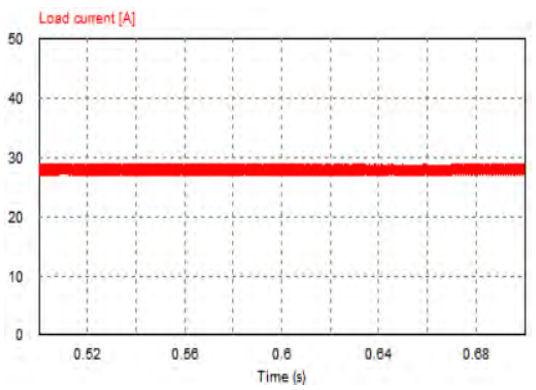
(a) Speed



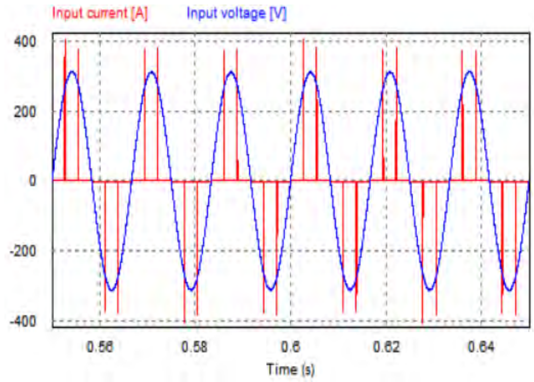
(b) Torque



(c) Input current



(d) Load current

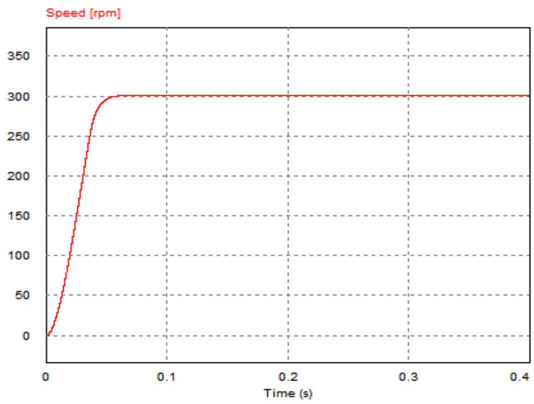


(e) Phase voltage and current

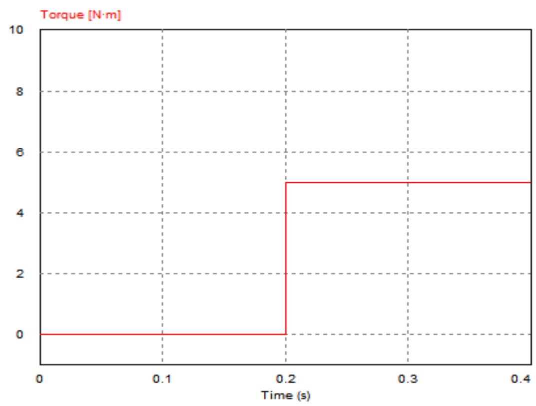
Figure 6: Simulation responses for step change of speed setting (0→1,500 [rpm])

Figure 7 shows graphs of the response when a load torque of 5 N·m was applied during a normal operation at 300 rpm.

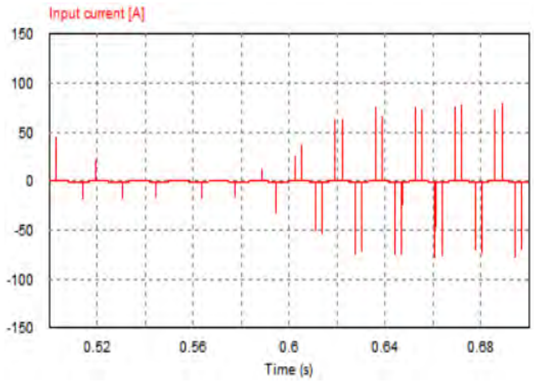
Figure 7 (a) shows the changes in the motor's speed and **Figure 7 (b)** shows the changes in torque before and after the load torque was applied.



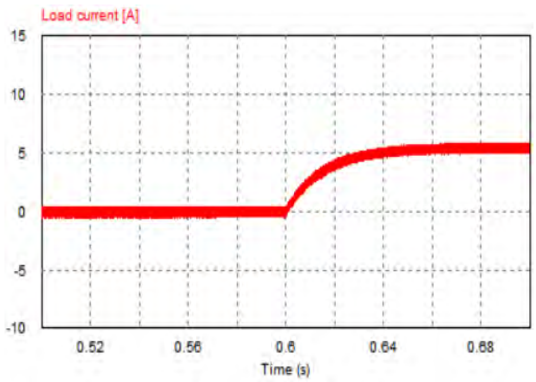
(a) Speed



(b) Torque



(c) Input current



(d) Load current

Figure 7: Simulation responses for step change of load torque (300 [rpm], 5 [N·m])

Figure 7 (c) shows the changes in the input unit's phase current before and after applying the load torque, and the input unit current's THD was 689% in the normal state. This means that too many harmonics were included in the input unit current. **Figure 7 (d)** shows the motor load current before and after the load torque was applied. In the normal state, it was in the range of 4.43–6.21 A and had a mean of 5.22 A.

4.2 DC Motor Simulation Using AFE Rectifier

Figure 8 shows the PSIM block diagram of a DC motor simulation using an AFE rectifier, as proposed in this study. The same PI controller was used as the existing DFE rectifier to control the speed and current, and sine pulse width modulation was used to control the voltage.

Figure 9 shows a graph of the DC motor's speed response characteristics when speed commands from 0 to 1500 rpm were applied. **Figure 9 (a)** shows the changes in the motor's speed. The stable control results were similar to those of the existing method. **Figure 9 (b)** shows the changes in load proportional to the square of the speed. The load was similar to that of the existing method in transient states. **Figure 9 (c)** shows the input unit phase current. The THD was 3.51%, and the waveform was similar to a sine wave, unlike the existing method. **Figure 9 (d)** shows the motor load current. In a normal state, it was in the range of 27.4–29.1 A with a mean of 28.4 A. **Figure 9 (e)** shows the input unit's voltage and current wave forms. The power factor was 0.86.

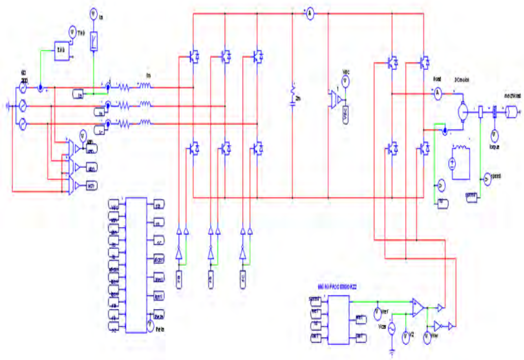
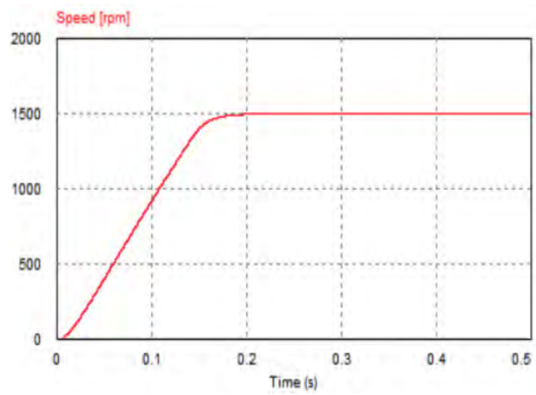
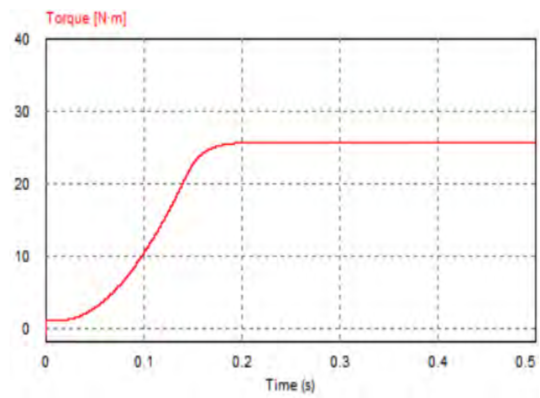


Figure 8: PSIM diagram for the proposed AFE converter topology

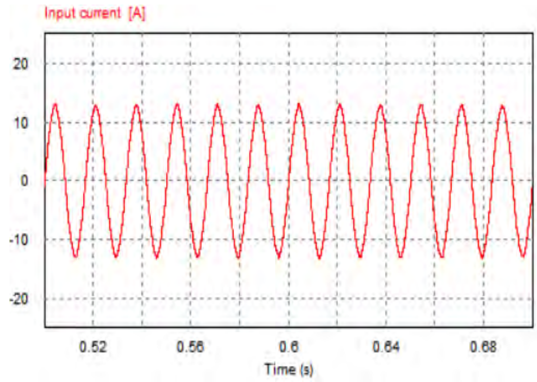
Figure 10 shows graphs of the response when a load torque of 5 N·m was applied during a normal operation at 300 rpm. **Figure 10 (a)** shows the changes in the motor speed. The stable control results in transient states were similar to the existing method. **Figure 10 (b)** shows the change in torque before and after the load torque was applied.



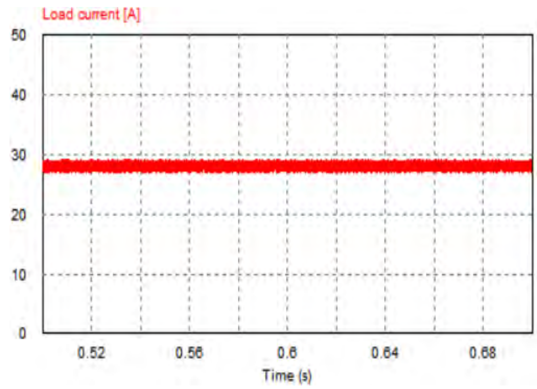
(a) Speed



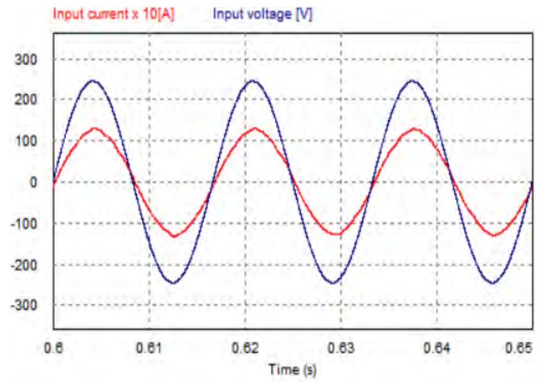
(b) Torque



(c) Input current



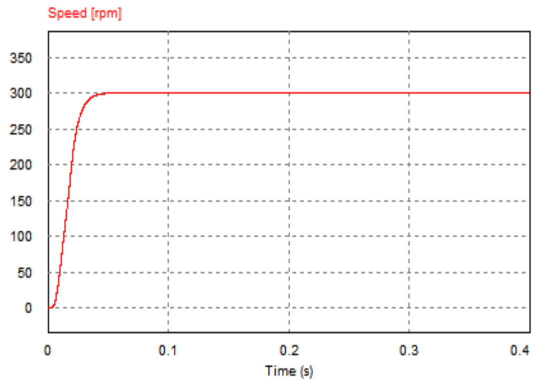
(d) Load current



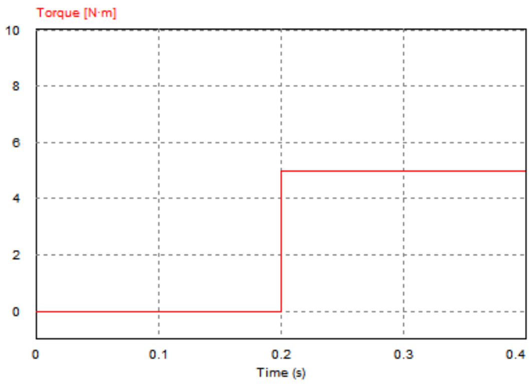
(e) Phase voltage and current

Figure 9: Simulation responses for step change of speed setting (0→1,500 [rpm])

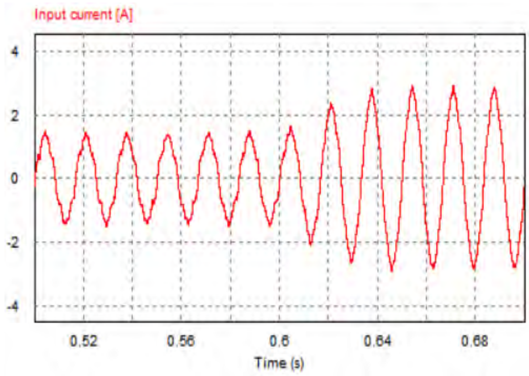
Figure 10 (c) shows the changes in the input unit phase current before and after load torque was applied. After the load became stable, the input unit current showed a form that was closer to a sine wave, unlike that in the existing method. The THD was 5.84%. Furthermore, the change in the amount of current because of the load torque was smaller than that in the existing method. **Figure 10 (d)** shows the motor load current before and after the load torque was applied. After the load became stable, it showed a flow within a range of 4.43-6.51 A with a mean of 5.24 A. Even in the transient states, it achieved stable control similar to the existing method.



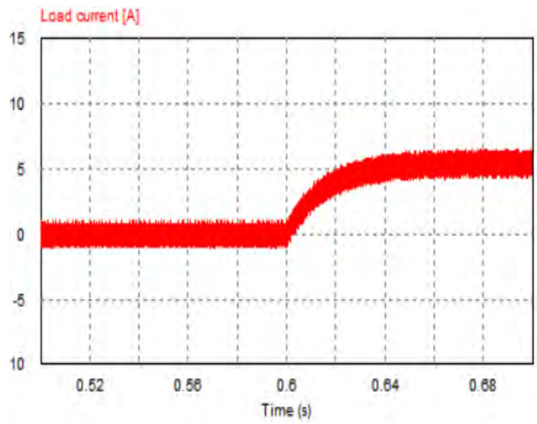
(a) Speed



(b) Torque



(c) Input current



(d) Load current

Figure 10: Simulation responses for step change of the load torque (300 [rpm], 5 [N·m])

4.3 Simulation Review

By comparing **Figure 6 (a)** and **Figure 9 (a)** as well as **Figure 6 (b)** and **Figure 9 (b)**, it can be seen that when speed commands from 0 rpm to a high-speed region of 1500 rpm were used, the DC motor control method that used an AFE rectifier (as proposed in this study) and the DC motor control method that used the existing DFE method were able to control the speed and torque in a similar stable manner during the transient state intervals.

When **Figure 6 (c)** and **Figure 9 (c)** are compared, it can be seen that the existing method's input unit current waveform had a THD of 743% and included too many harmonics to be compared to a sine wave. The input unit current waveform of the proposed method had a THD of 3.41% and was similar to a sine wave. It was confirmed that the input current was significantly improved.

When **Figure 6 (d)** and **Figure 9 (d)** are compared, it can be seen that the mean values of the load currents during a normal state in the existing DFE method and the proposed AFE method were not very different at 28.09 and 28.04 A, respectively. Even in the transient state intervals, the proposed method controlled the current in a stable manner, similar to the existing method.

By comparing **Figure 7 (a)** and **Figure 10 (a)** as well as **Figure 7 (b)** and **Figure 10 (b)**, it can be seen that when speed commands from 0 rpm to a low-speed region of 300 rpm were used, the proposed AFE method controlled the speed and torque in a stable manner during the transient states, similar to the DFE method.

When **Figure 7 (c)** and **Figure 10 (c)** are compared, it can be seen that the existing method's input unit current waveform contained a large number of harmonics with a TDH of 689%. The input unit current waveform of the proposed method shown in **Figure 10 (c)** has a waveform similar to a sine wave with a THD of 5.84%, thereby highlighting that the input current quality was improved.

When **Figure 7 (d)** and **Figure 10 (d)** are compared, it can be seen that the mean values of the load currents during a normal state after the load torque was applied in the existing method and the proposed method were not very different at 5.22 and 5.24 A, respectively. Even in transient intervals, the proposed method was able to perform stable control, similar to the existing method.

When **Figure 6 (e)** and **Figure 9 (e)** are compared, it can be seen that the proposed method made a great improvement so that the power factor was 0.86.

5. Conclusions

In this study, computer simulations were performed using the PSIM software to verify the performance of a DC motor speed control method using an AFE rectifier, and the results are as follows:

1) The AFE rectification method proposed in this study exhibited a performance similar to that achieved using the existing DFE rectification method in terms of speed control, torque control, and load current control.
2) The AFE rectifier provided high-quality current that included few harmonics by controlling the rectification unit's switch to make the input-side current waveform similar to a sine wave, and it improved the input unit power factor.
3) The DC unit capacitor in the AFE rectifier was 1/50th the size of the capacitor in the DFE rectifier, thereby reducing the capacitor volume and cost.

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