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Research Paper
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Current Control for an AFE Rectifier Using Space Vector PWM

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공간벡터변조방식에 의한 AFE정류기의 전류제어

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Abstract : *Electric propulsion ships are gaining widespread interest in the marine industry owing to extreme air pollution concerns. Consequently, several studies are actively being conducted for improving the power quality. Various methods have been developed that incorporate passive filters, notch filters, and active filters for reducing the harmonic content in the input current of a conventional diode front end rectifier. Among such filters, the active front end (AFE) rectifier is considered as an excellent technology. In this paper, current control for an AFE rectifier employing space vector PWM (Pulse Width Modulation) is proposed. Conventional current control methods for the AFE rectifier, hysteresis, SPWM (Sinusoidal Pulse Width Modulation), and SVPWM (Space Vector Pulse Width Modulation) were simulated by employing the PSIM software tool for analysis and comparisons. The results corroborate that SVPWM has the simplest structure and provides the best performance.*

Key Words : *Hysteresis, SPWM (Sinusoidal Pulse Width Modulation), SVPWM (Space Vector Pulse Width Modulation), Harmonics, Rectifier*

요 약 : 해양산업분야에서는 극심한 대기오염으로 인하여 전기추진선박에 대한 관심이 높아지고 있다. 이로 인해 선내 전력품질의 저하를 개선하기 위한 연구가 활발히 진행되고 있다. 기존 DFE 정류기의 입력전류 고조파 함유량을 완화시키기 위해 수동형필터, 노치필터, 능동형필터 등을 이용한 다양한 방법이 등장하였다. 그 중에서도 능동필터의 일종인 AFE(Active Front End) 정류장치가 우수한 기술로써 평가받고 있다. 본 논문에서는 공간벡터변조에 의한 AFE정류장치의 전류제어방식을 제안하였다. 기존의 히스테리시스 방식, 삼각파 변조방식 및 공간벡터변조방식을 PSIM을 사용해 시뮬레이션을 수행하여 비교, 분석하였고, 그 결과 공간벡터변조방식이 구조가 간단하고 성능이 가장 우수함을 확인하였다.

핵심용어 : 히스테리시스, 삼각파 변조방식, 공간벡터변조방식, 고조파, 정류기

1. Introduction

Recently, the International Maritime Organization (IMO) decided to reduce greenhouse gas emitted from ships by at least 50 percent compared to the total amount of 2008 emissions by 2050 and revised the goal of reducing greenhouse gas by 37 percent compared to the forecast of 2030 under the Framework Act on Low-Carbon, Green Growth. Therefore, measures to reduce emissions from ships are being studied in many ways (Kanellos, 2014), and among them, the development of an electric propulsion system using an electric motor as a propellant is actively underway (McCoy, 2002). In addition, research is being actively conducted to improve the quality of power aboard ships (Doerry and Clayton, 2005; Selarka et al., 2016).

Although rectifiers typically use DFE (Diode Front End) rectifiers with diode elements that cannot be controlled on/off, it is inevitable that the input current will contain many harmonics (Jones and Bose, 1976). A method of increasing the number of pulses by using transformers to improve power quality is also used (Woo, 2006), but there is a disadvantage of increasing the volume of the system and the price rises. On the other hand, the AFE

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(Active Front End) method using an active element is evaluated as an excellent technology as it can improve power quality and reduce system volume at the same time.

The performance, the effect on the distribution system, and the harmonic distortion of the input current depend on the current control method of the AFE rectifier. Generally, hysteresis or SPWM schemes are widely used. Although hysteresis method is easy to implement due to its simple control structure, its disadvantage is that it reduces voltage quality, increases harmonic content of input current, and does not have a constant switching frequency. SPWM (Sinusoidal Pulse Width Modulation) has the advantage of not only good control performance and low harmonic distortion, but also constant switching frequency, but it also has to be compared with reference values by generating triangle wave, which is complicated in the control structure, and it is difficult to get the desired result when noise is inserted in the triangle wave.

In this paper, the current control method of AFE rectifier by space vector modulation is proposed. The SVPWM (Space Vector Pulse Width Modulation) is complicated to obtain control output. However, you can eliminate the disadvantages of the SPWM by calculating the switching time of each vector in vector space and controlling it on/off (Kim and Sul, 1995).

The software PSIM was used to simulate AFE rectifier by hysteresis, SPWM and SVPWM. Based on the simulation results, the three control methods were compared and analyzed to confirm the validity of the SVPWM proposed in this paper.

2. AFE (Active Front End) Rectifier

AFE rectifier is a rectifier that replace passive element with active element (IGBT, MOSFET module) in a diode rectifier and controls the input current to be a sinusoidal wave that is not distorted by the actuation of a switching device as an intelligent transducer. In addition, the AFE rectifier can control the power factor to 1 as well as minimize the distortion of the waveform of the power source voltage by reducing the harmonics of the power source current. As shown in Fig. 1, AFE rectifier can reduce distortion of power voltage by controlling input current to sine-shaped wave, indicating that they are an appropriate solution to meet the harmonic criteria of IEEE 519-1992 on power supply.

The AFE system has the advantage of lower initial installation costs, while lower costs for cables, filter, compensation equipment and transformers. Also It has the advantage of reducing operating costs due to low reactive power and losses. In addition, AFE rectifier produces an input current waveform close to the sine-shaped wave on the power source, which can control the power factor as well as almost eliminate harmonics. and it can be regenerated to the line supply, compensated when the supply voltage fluctuation, and has good dynamic performance.

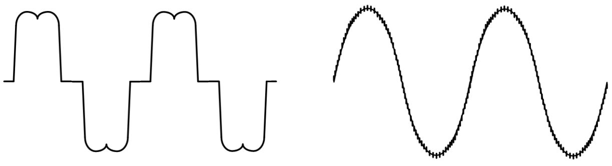

(a) DFE rectifier (b) AFE rectifier

Fig. 1. Current wave forms according to the methods of rectification.

3. Space vector pulse width modulation

In contrast to the individual modulation of a given three-phase command, such as hysteresis and SPWM, the three-phase command voltage is expressed in a single space vector. And thus modulating the three-phase equilibrium voltage is referred to as the "Space Vector PWM, SVPWM" method. The voltage modulated in this way is now the most widely used, with the advantage of decreasing the harmonic content of input current compared to other methods.

In this technique, three-phase voltages should also be expressed as a space vector because command voltages are given as a vector on a complex space. Expressable space vectors have different three phase voltages depending on a total of eight different switching states. Of these eight three-phase voltages, six voltage vectors $V_1 \sim V_6$ are active voltage vectors, all of which are $2V_{dc}/3$ in size and differ in phase. On the other hand, the two voltage vectors V_0 and V_7 are called zero voltage vectors, which are very important because modulation performance varies depending on how this zero voltage vector is used.

When the reference voltage is given as a space vector, the SVPWM uses the above eight voltage vectors. The two effective voltage vectors (V_n, V_{n+1}) and the zero voltage vectors (V_0, V_7) adjacent to the reference voltage vector V^* are generates the same voltage, on average, as the reference voltage vector for a given modulation cycle of T_s, as shown in Fig. 2.

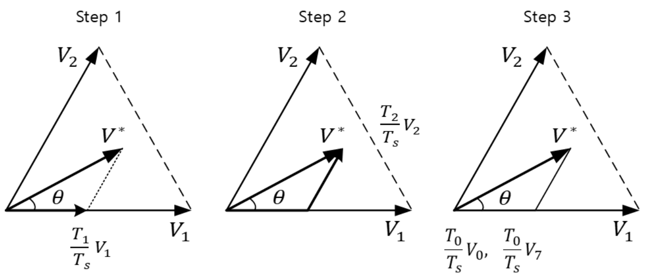


Fig. 2. Process of voltage modulation.

The range of modifiable reference voltage vectors can be illustrated, which, as shown in Fig. 3, is the inner area of the hexagon consisting of six active voltage vectors. You can see that the area where linear modulation of the reference voltage is possible is $V_{dc}/\sqrt{3}$ by the radius of the inner circle, and the maximum size is $2V_{dc}/3$. Voltage utilization rates for various PWM methods are shown in Table 1.

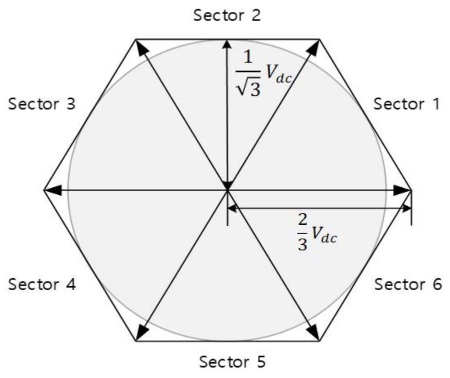


Fig. 3. Controlled voltage areas in SVPWM.

Table 1. Voltage utilization by modulation technique

	Max. fundamental line-to-line voltage	Utilization rate of voltage
6-step	$\frac{2}{\pi}V_{dc}$	100 %
SPWM	$\frac{V_{dc}}{2}$	78.5 %
SVPWM	$\frac{V_{dc}}{\sqrt{3}}$	90.7 %

On average, regardless of the order in which the active and zero voltage vectors are applied within the voltage modulation cycle, the average output voltage can be obtained equally. However, the voltage modulation performance, i.e. harmonics characteristics, switching frequencies, and voltage utilization, depends on the order in which they are applied. The symmetrical SVPWM, which places the active voltage vector in the center of the modulation cycle, reduces the size of the current ripple, thus achieving better harmonic characteristics.

4. Simulation

4.1 Composition of rectifier

In this paper, to find out what the performance and harmonic characteristics of AFE rectifier are like according to current control method, simulations were performed using software PSIM program for three control methods: hysteresis, SPWM and SVPWM.

Fig. 4 is the schematic diagram of the AFE rectification system, Table 2 is the system parameters used for simulation.

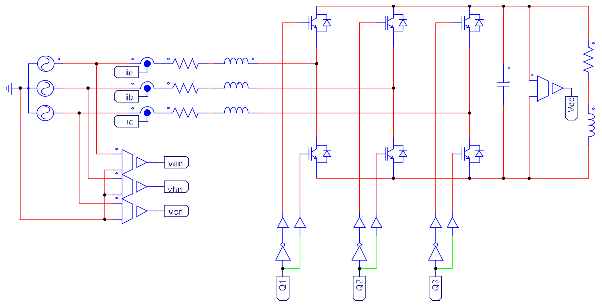


Fig. 4. Schematic diagram for AFE rectifier system.

Table 2. System parameters in AFE rectifier system

Parameter	Value
Power	50[V], 60[Hz]
Cable resistance	0.1[Ω]
Boost inductor	2.5[mH]
Capacitance	2[mF]
Load	25[Ω], 5[mH]
Switching Frequency	10[kHz]

4.2 Hysteresis

The hysteresis control measures the reference value and the actual value of the current and switches on/off control using the error and hysteresis band.

Fig. 5 represents a waveform of steady-state DC link output voltage with hysteresis method, and Fig. 6 represents a phase voltage and input current waveform. The output voltage contained a lot of ripples and the power factor was 0.99.

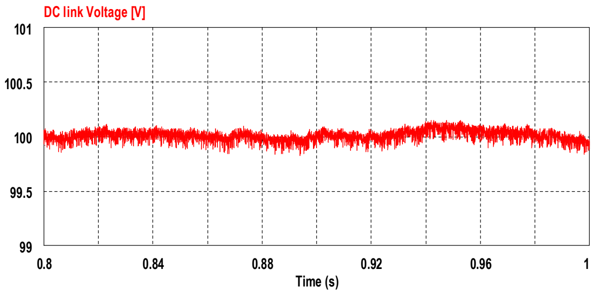


Fig. 5. DC link Voltage (Hysteresis control).

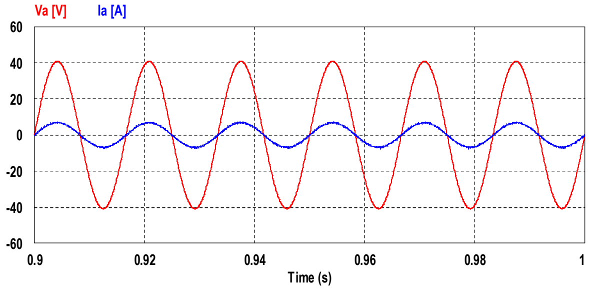
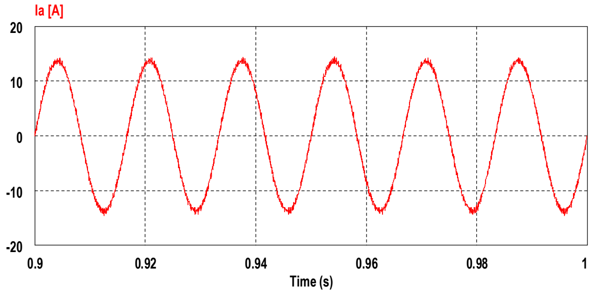
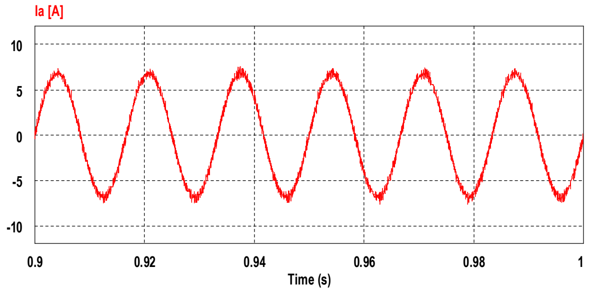


Fig. 6. Source voltage and current (Hysteresis control).

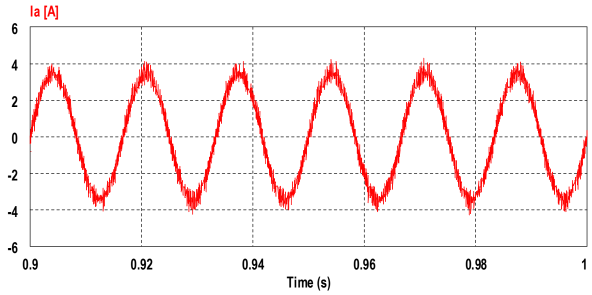
Fig. 7 is the input current waveform on the power source with varying load resistance. The total harmonic distortion (THD) of the current was the same as 11.7% in each case.



(a) Input current (with Load: 12.5[Ω])



(b) Input current (with Load: 25[Ω])



(c) Input current (with Load: 50[Ω])

Fig. 7. Responses of current (Hysteresis control).

4.3 Sinusoidal PWM (SPWM)

The Sinusoidal PWM method is on/off controlled by comparing the reference value with the triangular carrier wave. The frequency of the triangular carrier wave used in the simulations is 10 [kHz].

Fig. 8 shows the DC link output voltage of the SPWM. It can be found that the ripple has decreased significantly compared to the hysteresis control method. Fig. 9 shows the waveform of the power source voltage and input current. The power factor was 0.99, similar to hysteresis.

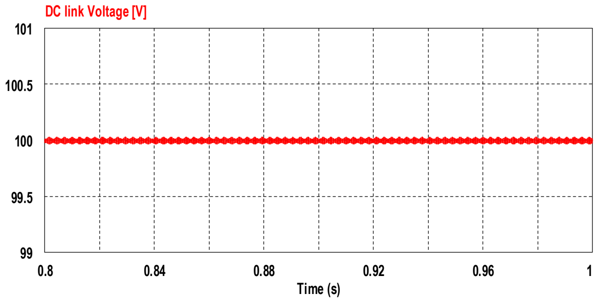


Fig. 8. DC link Voltage (SPWM).

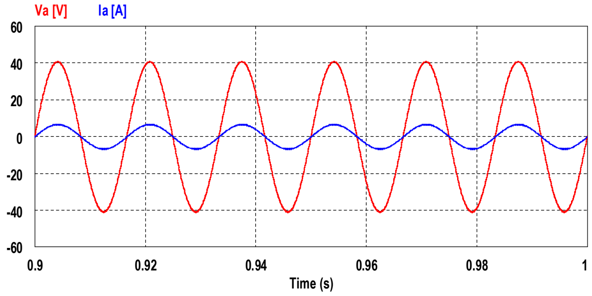
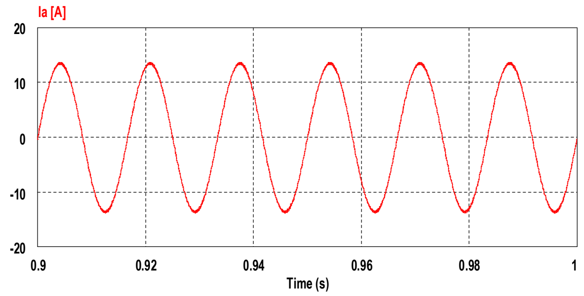
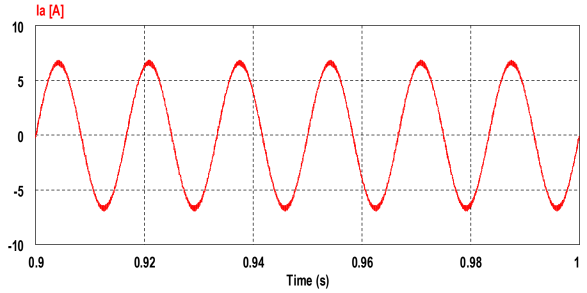


Fig. 9. Source voltage and current (SPWM).

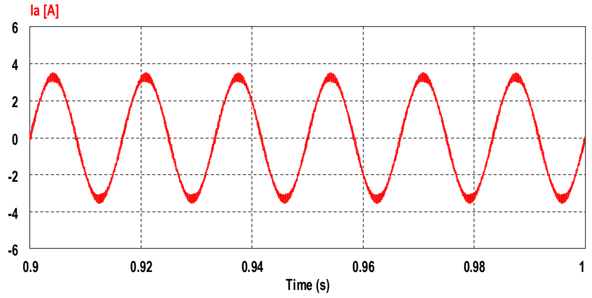
Fig. 10 is the input current waveform on the power source at steady state with various load resistance. The total harmonic distortion of current was 0.97 %, 1.95 % and 3.93 %, respectively, a significant decrease compared to the hysteresis method.



(a) Input current (with Load: 12.5[Ω])



(b) Input current (with Load: 25[Ω])



(c) Input current (with Load: 50[Ω])

Fig. 10. Response of current (SPWM).

4.4 Space Vector PWM (SVPWM)

Use three-phase/two-phase transformation to separate variables from each other and control them. Then, after switching to a three-phase variable using two-phase/three-phase transformation, the reference voltage is sent to the counter to provide the output pulse for each phase at the specified moment. A symmetrical modulation was used to reduce the ripple of input current. Fig. 11 shows steady-state DC output voltage of the space vector PWM scheme. It shows the output characteristics of a constant voltage with few ripple. Fig. 12 is a waveform of power source voltage and input current. The power factor was 0.99.

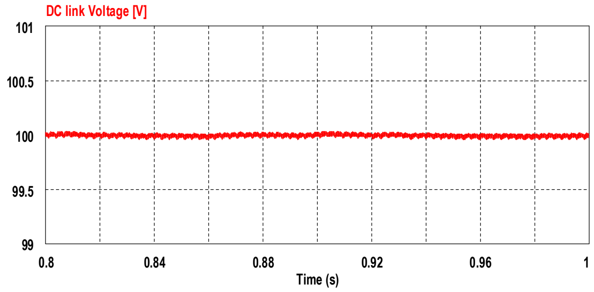


Fig. 11. DC link Voltage (SVPWM).

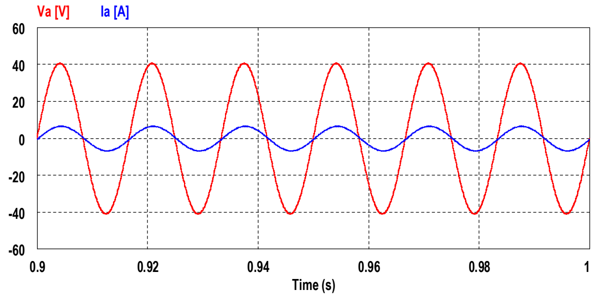
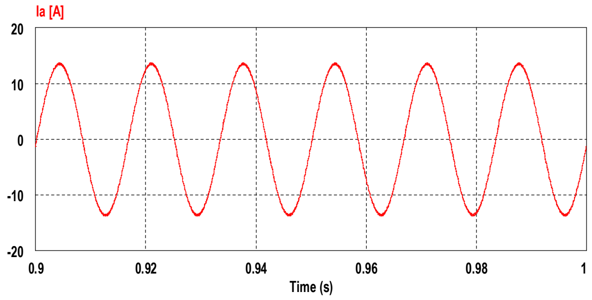
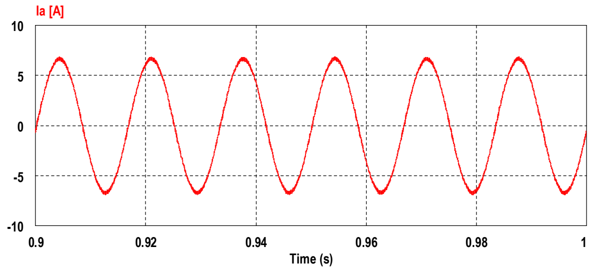


Fig. 12. Source voltage and current (SVPWM).

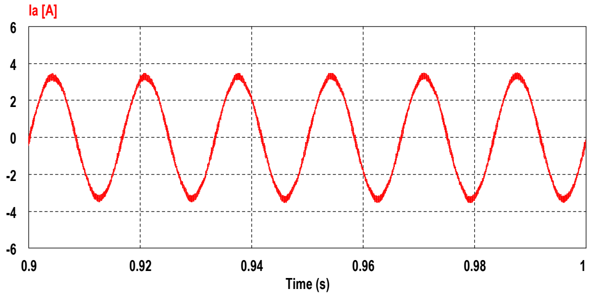
Fig. 13 is a power source voltage and input current waveform at steady state with varying load resistance. The total harmonic distortion of current was 0.91 %, 1.8 % and 3.57 %, respectively, slightly improved compared to the SPWM method.



(a) Input current (with Load: 12.5[Ω])



(b) Input current (with Load: 25[Ω])



(c) Input current (with Load: 50[Ω])

Fig. 13. Response of current (SVPWM).

5. Conclusions

This paper proposed a new current control method of AFE rectification system, which is being applied to the power conversion system for improving power quality. In the past, hysteresis control which is simple to control and easy to implement or SPWM control is commonly used. Hysteresis control, however, has the disadvantage of not only varying switching frequencies according to band width, but also unstable output voltage and high harmonic content in input current. In addition, the SPWM method has a constant switching frequency and reduces the harmonic component of input current, but it requires a hardware supply of triangular wave and may not provide smooth control when noise is generated.

On the other hand, for the space vector PWM scheme proposed in this paper does not require the addition of hardware, a disadvantage of triangular wave modulation, so the control structure is simple, such as hysteresis control.

To demonstrate the effectiveness of the proposed method, simulations were performed under the same conditions for each method. As a result, the SVPWM system was able to verify that the output voltage characteristics were more stable and that the input current's THD was significantly reduced compared to hysteresis control. This method also showed similar or slightly superior performance in terms of DC output characteristics and input current THD, compared to SPWM. The output characteristics and input current harmonic characteristics of the three current control methods differed, but the power factor was all controlled close to 1.

Therefore, it is believed that in the future, the current control method proposed in this paper by space vector PWM can be applied widely in areas where improvement of power quality, such as ships, is essential.

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