

Control of Linear Compressor System Using Virtual AC Capacitor

Shin-Hyun Park* and Jong-Woo Choi†

Abstract – Recently, linear compressors of cooling systems such as refrigerators, which have a free piston driven by a linear motor, have attracted much attention because of their high efficiency. For structural reasons, linear compressors applied in refrigerators should use an AC capacitor to ensure stable control. However, AC capacitors are expensive and bulky. In this paper, we propose a new method to realize stable control without a real AC capacitor by implementing a virtual AC capacitor with software. To realize a virtual AC capacitor, a pure integral is calculated. Nonetheless, if an offset current exists, the calculation may diverge to infinity. To solve this problem, a high-pass filter is applied and the compensation for the phase angle and magnitude are realized with a new method. Finally, a virtual AC capacitor enables variable frequency operations. Hence, in case of a lack of voltage, we can compensate by running the linear compressor in high-frequency operations. To improve efficiency, we may optimize the operation frequency. The validity of a virtual AC capacitor has been verified through simulations and experimental results.

Keywords: AC capacitor, Linear compressor, Virtual AC capacitor

1. Introduction

In linear compressors, the piston is directly propelled by a linear actuator and a resonant mechanical spring. Consequently, friction loss is significantly reduced and efficiency is improved. Furthermore, the piston stroke can be easily varied according to the demand. This results in additional energy saving. Therefore, electromagnetic linear compressors have high mechanical efficiency. [1-3]

However, for a stable voltage control of linear compressors, an AC capacitor must be installed to compensate the inductive component of the linear motor. As the installed AC capacitor is designed for a specific frequency, the compressor must operate at that frequency. [4,5]

In this paper, we propose a new concept that implements a virtual AC capacitor with a software algorithm. The virtual capacitor enables stable control of the linear compressor without the disadvantages of a real AC capacitor. Further, we propose a simplified method to compute the pure integral required for the calculation of the virtual AC capacitor. Finally, variable frequency operations are possible with the virtual AC capacitor. Hence, in case of a lack of voltage, we can overcome this problem by a high frequency operation of the linear compressor. To improve efficiency, we may vary the operation frequency. The validity of the virtual AC capacitor has been verified using simulations and experimental results.

2. System models

The performance parameters, such as the efficiency and power factor of the linear compressor in accordance with variations of mechanical and electrical resonance frequencies, are analyzed. The mechanical equation for a linear compressor can be expressed as

$$M\ddot{x} + C\dot{x} + Kx = \alpha i_s, \quad (1)$$

$$\omega_m = \sqrt{\frac{K}{M}} = \sqrt{\frac{K_m + K_{gas}}{M}}, \quad (2)$$

where M , C , and K are the piston mass, damping coefficient, and spring constant, respectively [4]. In (1), x is the piston stroke and is assumed to be a constant for conversions of mechanical to electrical force. The spring constant K is composed of the mechanical spring constant K_m and the gas spring constant K_{gas} . K_m is kept approximately constant and K_{gas} is nonlinearly varied while the compressor passes the discharging-sucking process. The mechanical resonance frequency of the linear compressor is defined as (2), and operation at $\omega = \omega_m$ yields the highest efficiency. [4,5].

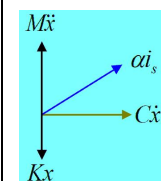
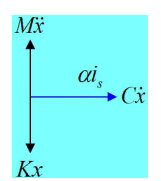
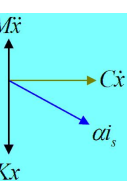
The phase back-EMF $\alpha\dot{x}$ varies depending on the relationship between mechanical resonance frequency and operating frequency. A long stroke means a short clearance distance. In that case, the load and K_{gas} increase. Furthermore, the mechanical resonance frequency changes due to the change in K_{gas} . Thus, the phase difference between the back-EMF and current also changes [5]. The phase diagrams according to the stroke are shown in Table 1.

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Table 1. Phase diagrams according to piston stroke

State	Low stroke	-	High stroke
M, K	$\omega > \sqrt{\frac{K}{M}}$	$\omega = \sqrt{\frac{K}{M}}$	$\omega < \sqrt{\frac{K}{M}}$
Phasor diagram			

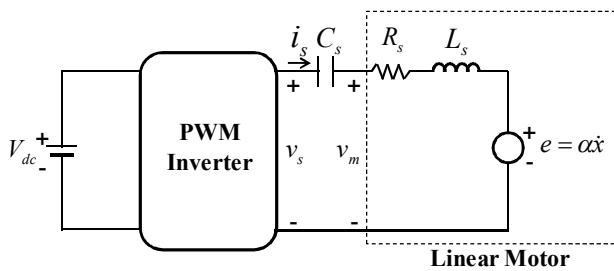


Fig. 1. Single-phase PWM inverter feeding a linear motor

Fig. 1 shows a single-phase PWM inverter equipped with an AC capacitor to drive a linear compressor.

According to Fig. 1, the PWM output-voltage v_s and motor-input-voltage v_m equations can be written as

$$v_s = L_s \frac{di_s}{dt} + R_s i_s + \frac{1}{C_s} \int i_s dt + \alpha \dot{x}, \quad (3)$$

$$v_m = v_s - \frac{1}{C_s} \int i_s dt = L_s \frac{di_s}{dt} + R_s i_s + \alpha \dot{x} \quad (4)$$

Fig. 2 shows a simplified structure of a linear compressor to explain the TDC and the clearance distance. TDC refers to the top dead center position of the piston when the discharge valve is located. The distance between the TDC and the piston is called the clearance distance.

As the force applied to the linear motor increases, the stroke increases and the clearance distance decreases.

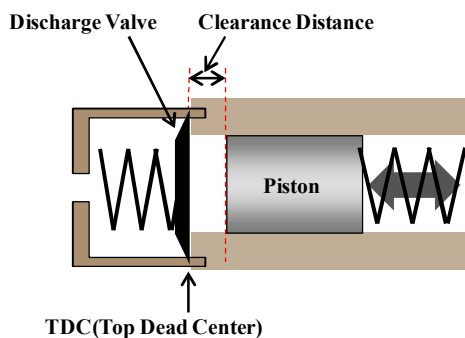


Fig. 2. Simplified structure of a linear compressor

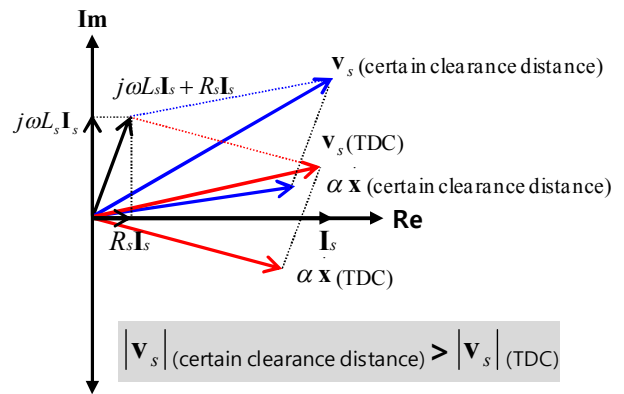


Fig. 3. Phasor diagram without AC Capacitor

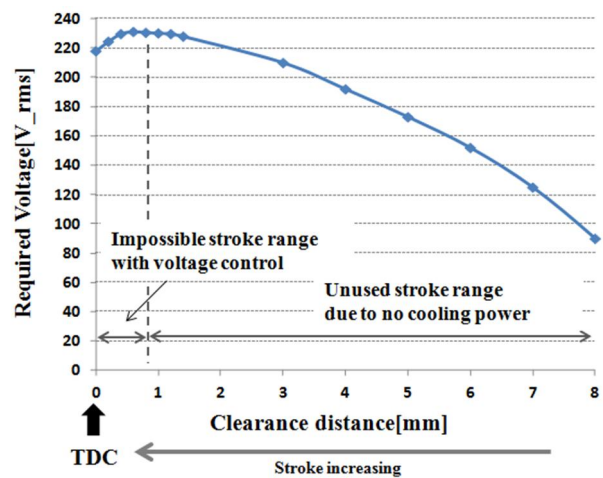


Fig. 4. Required voltage without AC capacitor

Without the AC capacitor, the motor voltage equation can be expressed as

$$v_s = L_s \frac{di_s}{dt} + R_s i_s + \alpha \dot{x}. \quad (5)$$

Without the AC capacitor, the required voltage decreases as the stroke increases. The magnitude of the back-EMF increases while moving from $\alpha \dot{x}$ (certain clearance distance) to $\alpha \dot{x}$ (TDC), as shown in the phasor diagram of Fig. 3. However, the required v_s decreases due to the phase difference between the back-EMF and current.

As shown in Fig. 4, when the voltage is enhanced to enhance the stroke, the required voltage decreases after a certain clearance distance. Therefore, a certain stroke range exists where the voltage control is not applicable.

If the AC capacitor C_s is designed to compensate for the influence of the linear motor's inductance L_s in (3), the $L_s \frac{di_s}{dt}$ term can be removed and the voltage equation can be rewritten as

$$v_s = R_s i_s + \alpha \dot{x}. \quad (6)$$

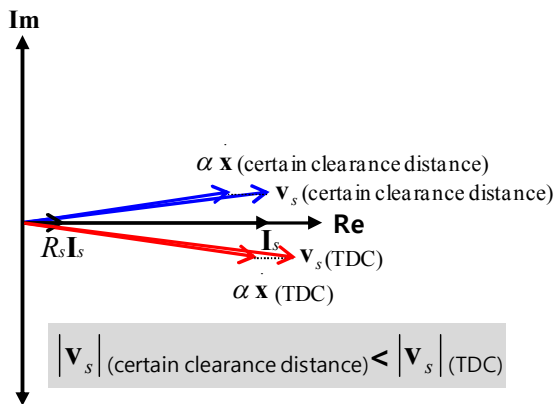


Fig. 5. Phasor diagram with AC capacitor

The phasor diagram for this case is shown in Fig. 5. The voltage v_s increases with an increase of the back-EMF while moving from $\alpha\hat{x}$ (certain clearance distance) to $\alpha\hat{x}$ (TDC). This is the main difference between Fig. 3 (without AC capacitor) and Fig. 5 (with AC capacitor).

With an AC capacitor, the required voltage v_s is proportional to the back-EMF $\alpha\hat{x}$, as shown in Fig. 5. Hence, controlling the stroke is possible using voltage control.

3. Virtual AC Capacitor

In this paper, we propose a new method that can perform stroke control by using a virtual AC capacitor for voltage control.

As shown in Fig. 6, the AC Capacitor voltage v_c is calculated by integrating the phase current obtained by the current sensor. The final output voltage v_m of the controller, shown in (4), is obtained by subtracting v_c from v_s . This way, the voltage across the motor can have the same values as in the case of a system with a real AC capacitor. Therefore, it is possible to control the stroke even without a real AC capacitor by simple calculations of v_c .

3.1 Integration implementation

For the v_c calculation, a pure integration of the phase current is necessary. However, if an offset-current

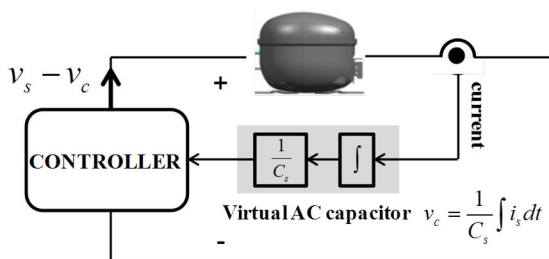


Fig. 6. Control block diagram of virtual AC capacitor

component is present, it will accumulate, as shown in Fig. 7(b). To eliminate the effect of an offset component, a high-pass filter (HPF) is used in the study.

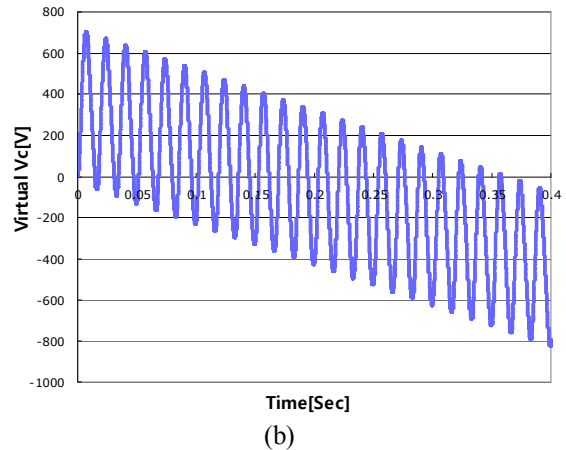
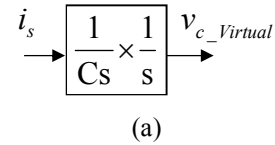


Fig. 7. (a) Block diagram of a virtual v_c calculation; (b) Virtual v_c waveform with offset component.

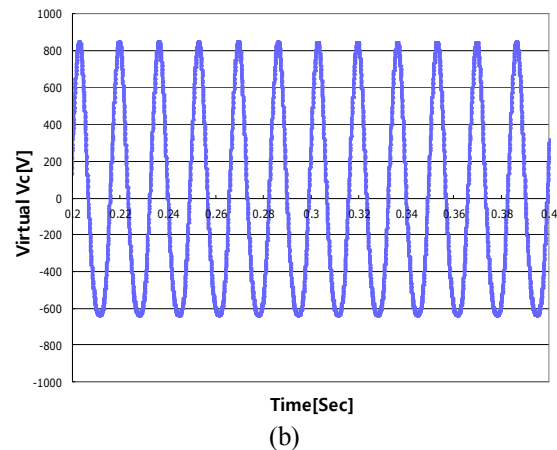
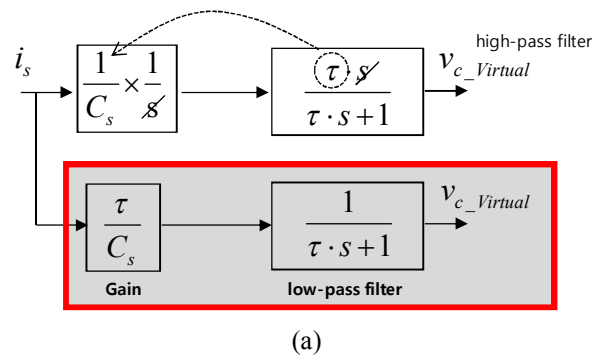


Fig. 8. (a) Block diagram for elimination of an offset Component; (b) Virtual v_c waveform with HPF

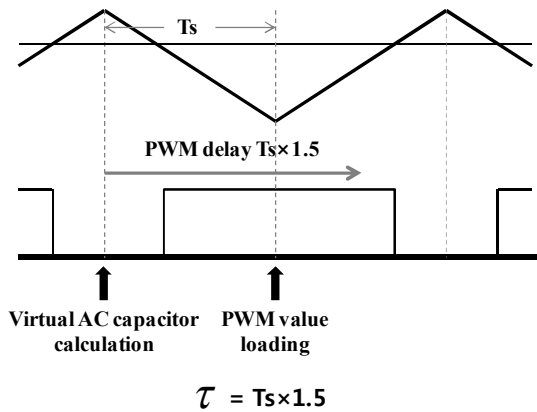


Fig. 9. Phase angle compensation

3.2 Compensation of phase angle and magnitude

Using an HPF to perform an integral calculation for a virtual v_c calculation and eliminating the effect of an offset component is equal to applying a gain and a low-pass filter (LPF), as shown in Fig. 8 (a).

If an HPF is used, the filtered output signal leads the input signal and the magnitude of the filtered output is smaller than the original input. In this paper, we propose a simple method to compensate the phase angle and magnitude without complicated calculations, as shown in Fig. 9.

If the current-sampling point is at the top of a triangle wave, we calculate the voltage of the virtual AC capacitor at that time. Further, the PWM data are applied during the following sampling period. The PWM delay measures 1.5 times the sampling period ($T_s \times 1.5$). If we choose the time constant of the HPF (τ) to be $T_s \times 1.5$, the leading time of the HPF can be naturally compensated for by the PWM delay time. Finally, to compensate the magnitude, the filtered output is multiplied by $\frac{\sqrt{1+(\tau\omega)^2}}{\tau\omega}$.

3.3 Field-weakening control of linear compressor

With an AC capacitor the voltage component of $j\omega L_s I_s$ can be removed, which results in the same phasor diagram as in Fig. 5. If a virtual AC capacitor is implemented without a real AC capacitor, the voltage component $j\omega L_s I_s$ exists.

Therefore, the required voltage for the same stroke is larger than with an actual AC capacitor. As speed increases, the required voltage also increases. In the case of a virtual AC capacitor the required voltage of the inverter output reaches its maximum before the required voltage of an actual AC capacitor.

To compensate the lack of voltage, we propose a field-weakening control of the linear compressor. Linear compressors have a high phase difference between the current and back-EMF when the operating frequency is

higher than the mechanical resonance frequency, as shown in Fig. 10. If the operating frequency is enhanced, the required voltage is reduced. Hence, a field-weakening control is possible by changing the operation frequency, as shown on Fig. 10.

In the case of an actual AC capacitor, the capacitance is selected considering the motor inductance and only one operating frequency. Therefore, when the operation frequency varies, the capacitance of the AC capacitor does not fit to the new operating frequency. Thus, a stable stroke

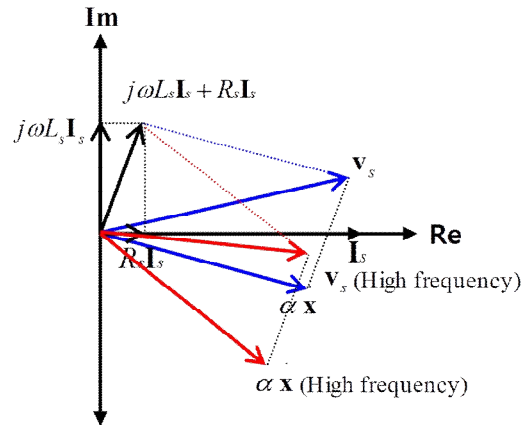


Fig. 10. Phase diagram of operation with high frequency

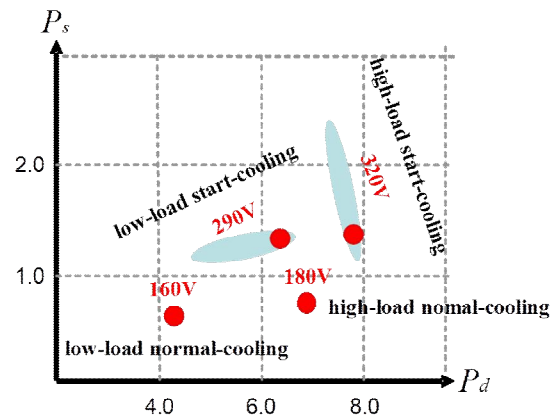


Fig. 11. Required voltage for linear compressor P_d , P_s (P_d : Discharge pressure, P_s : Suction pressure)

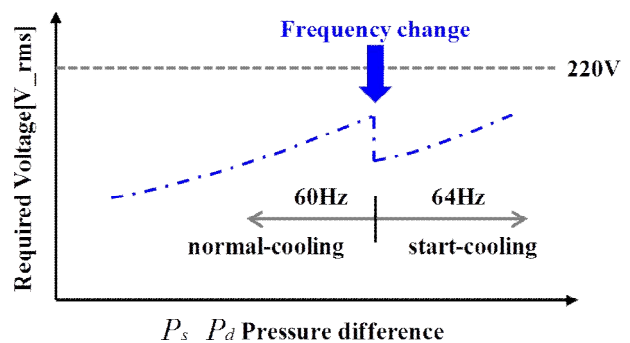


Fig. 12. Required voltage by frequency change

control cannot be performed.

In this study, however, the operating frequency can be changed by implementing a virtual AC capacitor via software.

Fig. 11 shows the required voltage according to the discharge pressure P_d and suction pressure P_s without any AC capacitor in a refrigerator with a linear compressor. When the refrigerator operates for the first time, it will be overloaded in the transient state and the required voltage exceeds the maximum voltage (220 V). During normal steady-state operation, it is possible to lower the voltage below the commercial power of 220 V.

Therefore, if the operating frequency varies according to the load, as shown in Fig. 12, the lack of voltage can be compensated.

4. Simulation Results

The proposed virtual AC capacitor method was verified using MATLAB Simulink. Fig. 13 shows the simulated result without AC capacitors. Fig. 14 shows the simulated result of a system with an implemented virtual AC

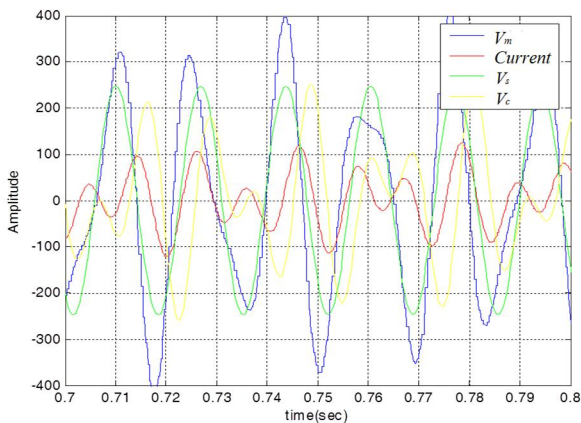


Fig. 13. Simulation results without AC capacitor

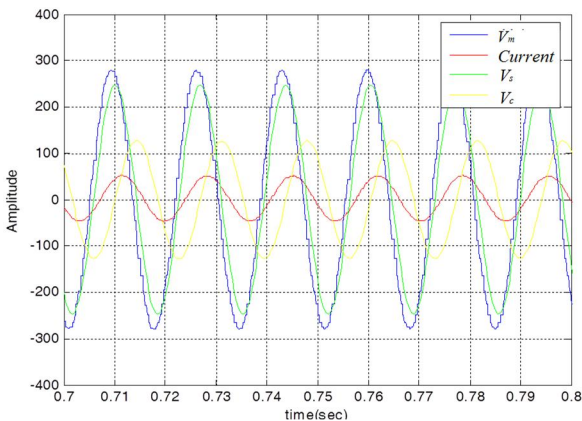


Fig. 14. Simulation result without AC capacitor using a virtual AC capacitor

capacitor under the same conditions. In the simulations, the change in K_{gas} according to the stroke was considered. The data obtained by the experimental results is stored in a MATLAB m-file and applied during simulations. v_c is calculated by integrating and high-pass-filtering the measured current, and the final output voltage $v_m = v_s - v_c$ is applied to the linear compressor model.

It can be confirmed from the simulation results that a stable stroke control cannot be performed without any AC capacitor, as shown in Fig. 13. Even though a constant voltage reference v_s is applied, the stroke is not stabilized, the back-EMF and current are oscillating, and both the current and the capacitor voltage are unstable.

As a result of the application of a virtual AC capacitor under the same conditions, it can be confirmed that the operation is stable, as shown in Fig. 14.

5. Experimental Results

Fig. 15 shows the block diagram of the hardware configuration and experimental set. A current-regulated

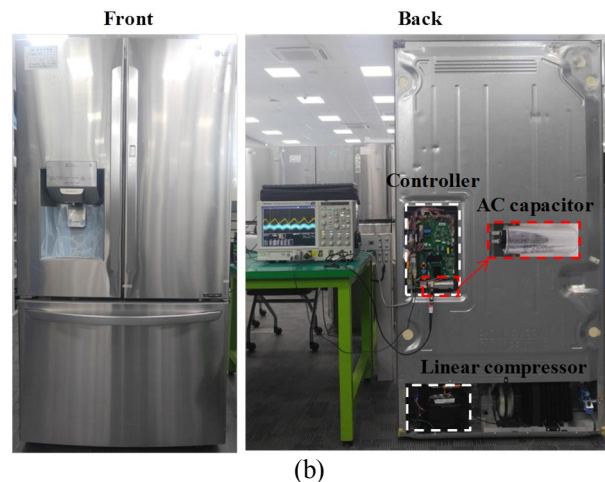
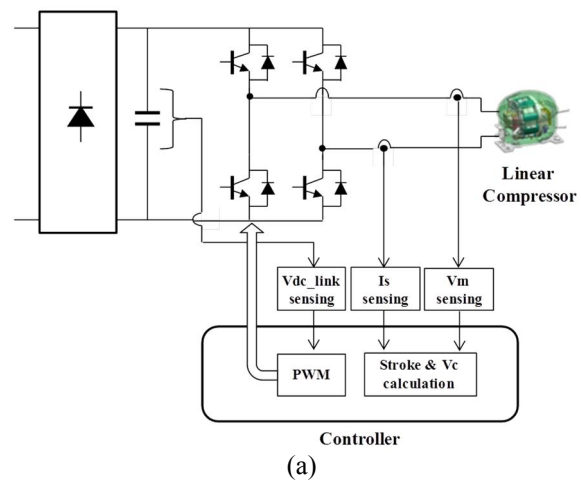


Fig. 15. (a) Block diagram of the hardware configuration; (b) Experimental set

Table 2. Parameters of a linear motor and controller

Linear Compressor		Controller	
L	530 mH	Operation Frequency	60/64 Hz
R	9.2 Ω	Switching Frequency	2.5 kHz
α	90	MICOM	Toshiba TMPM374FWUG
Mass	690 g	Inverter module	Sanken SIM6822M670
K_m	37000 N/m		

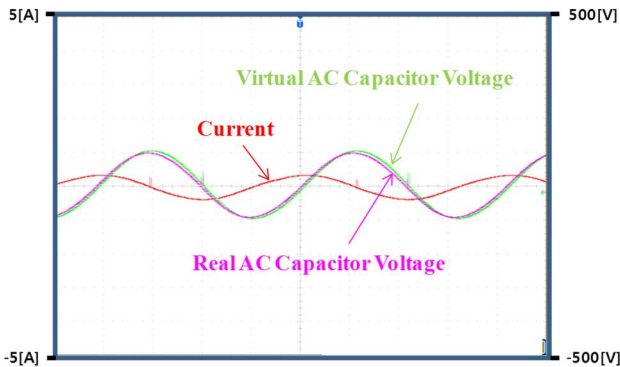


Fig. 16. Current, real AC capacitor voltage and virtual AC capacitor voltage

power FET, single-phase voltage-fed inverter, and linear compressor for the refrigerator were used for the experimental study. The input voltage and current of the linear motor are sensed by an isolation device. The amplifier is used for stroke calculations and the voltage of the DC-link capacitor is sensed for the PWM signal.

The parameters of a linear motor and controller are shown in Table 2.

Fig. 16 are waveforms that tested at no load condition to only compare real AC capacitor and virtual AC capacitor. The calculation results of the virtual AC capacitor voltage are almost equal to the real AC capacitor voltages, as shown in Fig. 16.

The waveform without the real AC capacitor and feedback of the virtual AC capacitor is shown in Fig. 17. This result was tested in normal-cooling of refrigerator at ambient temperature 25°C. As shown in the simulation result in Fig. 13, this experimental result shows that the current is oscillating and its stability is very poor.

The waveform with an AC capacitor is shown in Fig. 18. This result was tested in normal-cooling of refrigerator at ambient temperature 25°C same as Fig. 17. The current shape is different from the no load condition in Fig. 16 because the load of linear compressor is different when discharging and sucking. In the case of a real AC capacitor, it can be confirmed that the current is not oscillating and the control is stable.

The waveform without a real AC capacitor and with a feedback virtual AC capacitor is shown in Fig. 19. This

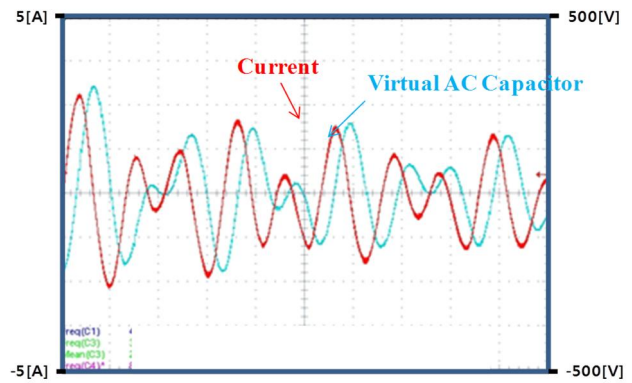


Fig. 17. Without real AC capacitor and feedback of virtual AC capacitor

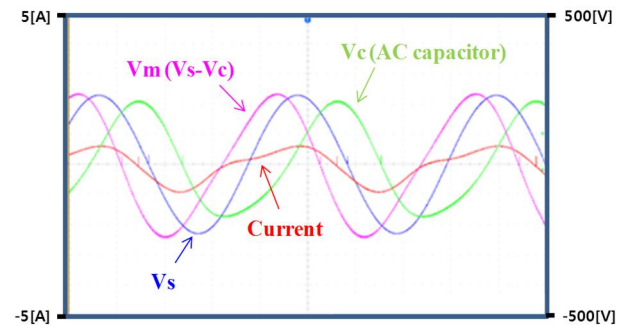


Fig. 18. Voltages and current with real AC capacitor

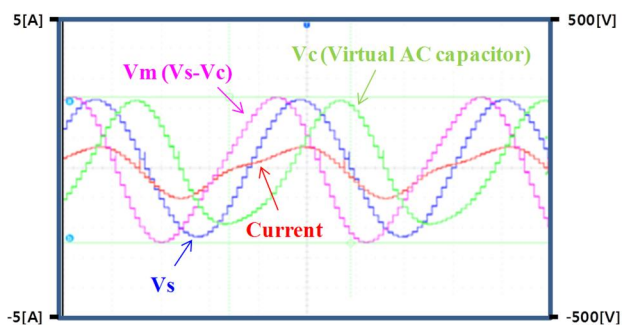


Fig. 19. Voltages and current with virtual AC capacitor

result was tested at same condition as Fig. 18. The waveforms are almost equal to those in the case of a real AC capacitor. Thus, the system is very stable.

6. Conclusion

In this paper, we proposed a new control method using a virtual AC capacitor. Its functionality has been verified through simulations and experiments. Further, the latter confirmed that a stable stroke control is possible even without a real AC capacitor by controlling only the voltage. The offset problem that occurred during the integral calculation required for AC capacitor voltage calculation

was eliminated by using the gain and a low-pass filter. We have proposed and verified a simple method to compensate for phase angle and magnitude without complicated calculations. By using a virtual AC capacitor, it is possible to remove the large and expensive AC capacitor. The integration of the latter enables a control of the compressor's operating frequency. Hence, field-weakening control is possible. Additional benefits of changing the operating frequency are the uncomplicated design of the linear compressor and the efficiency improvement. Therefore, we can easily avoid mechanical resonance of components and operate at maximum efficiency.

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