[Oh, 3(7): July 2016]
DOI-10.5281/zenodo.56983

ISSN 2348 – 8034
Impact Factor- 4.022

GLOBAL JOURNAL OF ENGINEERING SCIENCE AND RESEARCHES

PERFORMANCE ANALYSIS OF SENSORLESS STROKE CONTROL SYSTEM USING DIFFERENT FILTERS FOR LINEAR COMPRESSORS

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ABSTRACT

In order to control the cooling capability of a refrigerator or an air conditioner in which linear compressors are applied, the piston stroke and current should be controlled instantaneously. Generally, the piston frequency is fixed as 60Hz and the piston stroke is adjusted. In this paper, performance analysis of instantaneous piston stroke in a single phase PWM inverter has been done for four different types of filters. These filters are used to calculate and control the maximum values of the estimated piston stroke and current instantaneously and to analyze the dynamic characteristics of the stroke control in a linear compressor system. Some simulation studies have been done to verify the feasibility of our control algorithms.

Keywords- linear compressor, piston stroke, PWM inverter, filter

I. INTRODUCTION

The developed countries like U.S., EU, and Japan have some kind of energy regulation programs to decrease energy consumption of the electric home appliance. In a house, a refrigerator consumes about 30% of the total electric energy and the compressor which circulates refrigerant through the refrigeration system consumes most of electric energy in a refrigerator. So, energy efficient compressors are essential for saving of household electric energy. Over the past several decades, a series of linear compressors have been developed for various applications in order to meet the need for efficient compressors [1-7].

Because all the driving forces in a linear compressor act along the linear line of motion, there is no sideways thrust on the piston. The compressor of this type substantially reduces sliding bearing loads. Thus, no need for the conversion mechanism and no sideways thrust make a linear compressor more efficient than a reciprocating compressor. In addition, the sudden peak noises which are generated as a reciprocating compressor is turned on and off can be eliminated in a linear compressor by virtue of the soft start-stop operation [7]. These advantages of a linear compressor over a reciprocating one have encouraged refrigerator manufacturers to develop linear compressors for various applications.

In this paper, performance analysis of instantaneous piston stroke in a single phase PWM inverter has been done for four different types of filters. These filters are used to calculate and control the maximum values of the estimated piston stroke and current instantaneously and to analyze the dynamic characteristics of the stroke control in a linear compressor system. Some simulation studies have been done to verify the feasibility of our control algorithms.

II. STROKE AND CURRENT CONTROL FOR LINEAR COMPRESSORS

Fig.1 shows the structure of a linear compressor developed for refrigerators. The conventional reciprocating compressor uses a crank mechanism in order to change rotational motion of motors into linear motion. Accordingly, the reciprocating compressor can be operated safe by the crank mechanism, even though it makes the reciprocating compressor less efficient. On the other hand, the moving parts of a linear compressor are not constrained by a crank mechanism. So, the closed loop control system for the accurate control of piston position is necessary.

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Figure:

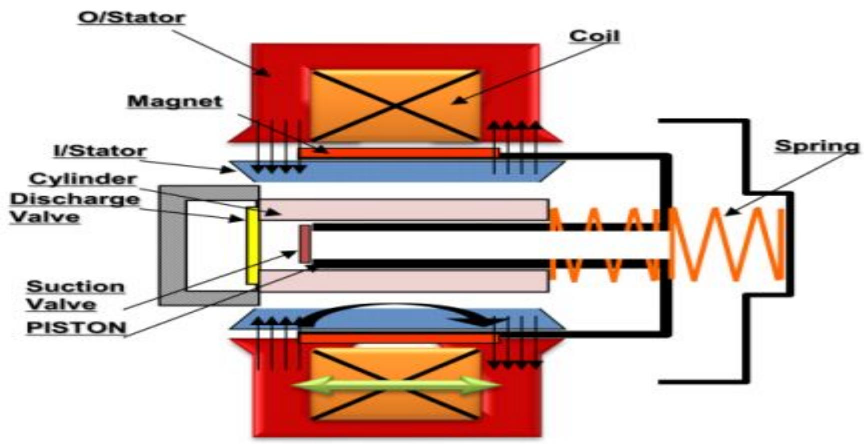

Fig.1.Structure of a linear compressor

Fig.2 shows the operating principle of a linear compressor. When alternating current is applied at the coil in the electric and magnetic field, the piston is moved to from the left to right direction according to the direction of the current. With increasing the alternating current, the magnetic field is increased with the counterclockwise direction and the magnetic field pushes the electromagnet attached to the piston to the left side. With the current reduced to zero, the electro-magnet is reached to the most left side, and if the current flows to the clockwise direction, it moves to the right side. The electromagnet is reached to the most right side if the current is reached to zero again. This cycle will be repeated during each period time of the frequency applied for the compressor. Therefore, the control of the amplitude of piston stroke and current accurately and instantaneously is an important thing to improve the efficiency of a linear compressor.

We will now estimate the piston position indirectly. The equivalent electrical circuit of linear motors can be modeled. From the circuit model, we can get the linear differential eq.(1). The thrust force can be expressed in eq.(2).

$$\alpha \frac{dx(t)}{dt} + L_e \frac{di(t)}{dt} + R_e i(t) = V(t) \quad (1)$$

$$F_e(t) = \alpha i(t) \quad (2)$$

Figure:

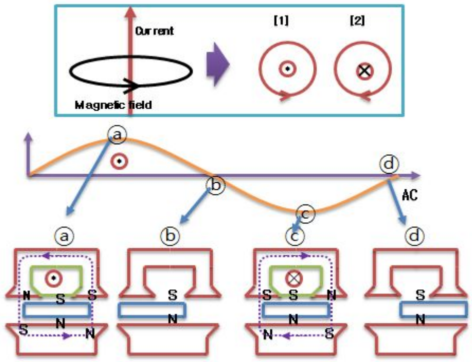

Fig. 2 Operating principle of a linear motor

Since the magnetic flux density varies depending on the piston position, the force constant and the effective inductance are functions of the piston position. The effective resistance is assumed to be constant because its variance, being negligible, is ignored. is the applied voltage to the linear motor, is the current flowing through the winding coil, and is the piston position. The mechanical equation of motion can be described as:

$$M\frac{d^2x(t)}{dt^2}+C\frac{dx(t)}{dt}+Kx(t)=\alpha i(t)-A_p\Delta P(t) \tag{3}$$

where M, C, and K denote the equivalent mass, viscous damping coefficient, and spring constant, respectively. A_p is the cross-sectional area of the piston, $\Delta P(t)$ is the pressure difference between the compressor chamber and the back surface of the piston. Taking the Laplace transform of the above eqs. (1–3) yields:

$$X(s)=G(s)V(s)+W(s)\Delta P(s) \tag{4}$$

$$G(s)=\frac{\alpha}{ML_eS^3+(MR_e+CL_e)S^2+(CR_e+\alpha^2+L_eK)S+R_eK} \tag{5}$$

$$W(s)=\frac{(L_eS+R_e)A_p}{ML_eS^3+(MR_e+CL_e)S^2+(CR_e+\alpha^2+L_eK)S+R_eK} \tag{6}$$

A closed-loop linear compressor control system needs piston position information. In order to measure the piston position, an inductive position sensor, in which the inductor is a small stationary coil wound on a ferrite coil, can be used. However, this position sensor is more expensive than a current or voltage sensor. It is also hard to install a position sensor in a linear compressor. Hence, it is more desirable to estimate the piston position indirectly.

Rearranging eq. (1), one obtains

$$\frac{dx(t)}{dt}=\frac{1}{\alpha}\left(V(t)-L_e\frac{di(t)}{dt}-R_ei(t)\right) \tag{7}$$

The estimated value of the piston can be obtained by integrating Eq. (7):

$$\begin{aligned}\hat{x}(t)&=\int_0^t\left(\frac{dx}{d\tau}\right)d\tau\\&=\frac{1}{\alpha}\int_0^t[V(\tau)-R_ei(\tau)]d\tau-\frac{L_e}{\alpha}i(t)\end{aligned} \tag{8}$$

In general, the stroke is defined as the distance between the top and bottom piston positions during one cycle of operation (i.e., the peak value of piston position). Therefore, the estimated stroke can be easily calculated using the estimated piston position. Let a 90^{o} phase time delay filter be defined as

ISSN 2348 – 8034
Impact Factor- 4.022

$$H_d(s) = \frac{\omega-\beta s}{\omega+\beta s}, \quad \beta = 1, \quad |H_d(s)| = 1, \tag{9}$$

$$\angle H_d(j\omega) = -\frac{\pi}{4} - \frac{\pi}{4} = -\frac{\pi}{2} \tag{10}$$

The 90° phase time delay filter $H_d(s)$ of eq. (9) is also called as the 1st order all pass filter.

Next, we can consider another filter called as the 1st order low-pass filter :

$$H_{1-low}(s) = \frac{\omega}{\omega+s} \tag{11}$$

As a third filter, we consider the 2nd order all pass filter as

$$H_{2-all}(s) = \frac{s^2-2\zeta\omega_n s+\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}, \quad \zeta = 1 \tag{12}$$

Finally, the 2nd order low-pass filter is considered as

$$H_{2-low}(s) = \frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}, \quad \zeta = \frac{1}{\sqrt{2}} \tag{13}$$

,

$$\hat{x}(t) = x_m \sin \omega t \tag{14}$$

then the output of these filters would be

$$\hat{x}_d(t) = x_m \sin \omega t \tag{15}$$

We can obtain the estimated maximum value of the piston stroke as

$$\hat{x}_\mathrm{m} = \sqrt{\hat{x}^2(t) + \hat{x}_d^2(t)} \tag{16}$$

Fig.3 shows the block diagram of the closed-loop sensorless stroke control system for a linear compressor. The applied voltage $V(s)$ and the motor current $i(s)$ can be measured from a single PWM inverter. The inner proportional–integral (PI) current controller is aimed to control the current loop.

Fig.3 shows the block diagram of the closed-loop sensorless stroke control system for a linear compressor. The applied voltage and the motor current can be measured from a single PWM inverter. The inner proportional–integral (PI) current controller is aimed to control the current loop.

Figure:

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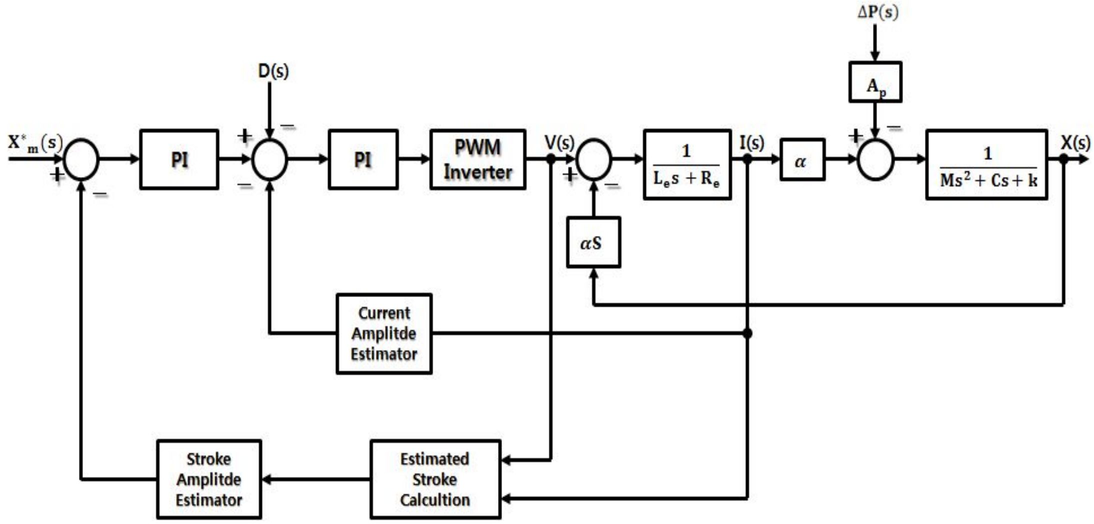


Fig. 3 Block diagram of the sensorless stroke control system.

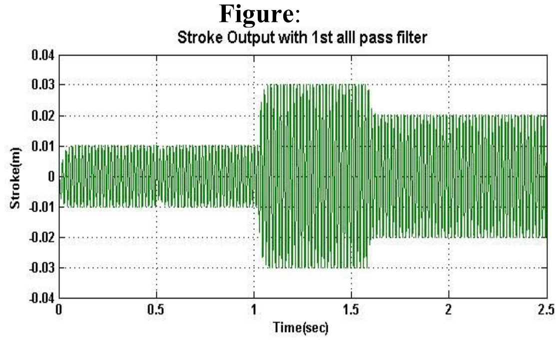
III. SIMULATION STUDIES

For the simulation studies to analyze the performance of four different types of filters, a 2.2 kW linear motor is chosen as shown in Table 1. The set-point value of the stroke varies from 0.01m to 0.03m for analyzing the dynamic characteristics. The running frequency is set to be 60 Hz.

Table 1. Linear motor specifications

Rated output power	2.2 kW
Rated voltage	220 V_{rms}
Rated current	7 A_{rms}
Rated stroke	0.02m
Resonant frequency	60 Hz
	2.5 Ω
	55 N/A
	0.12 H

Figure:



(a) response of linear motor position

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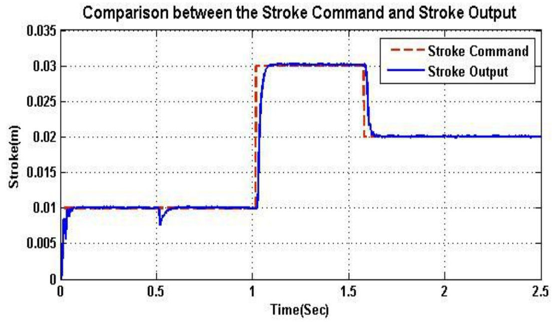
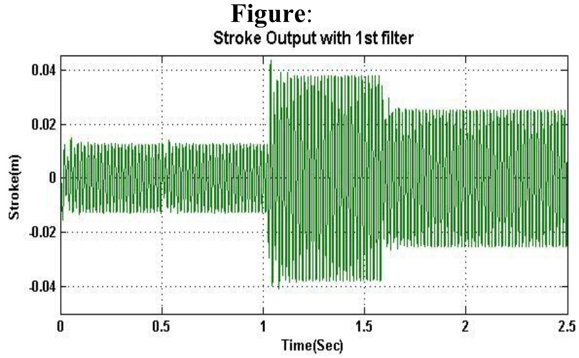


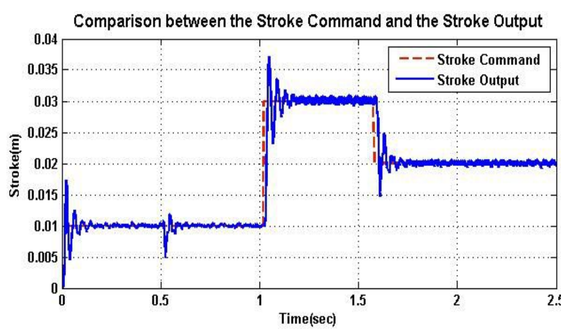
(b) stroke command and stroke response

Fig. 4 Responses for case of the 1st order all pass filter

Figure:



(a) response of linear motor position



(b) stroke command and stroke response

Fig. 5 Responses for case of the 1st order low pass filter

Figure:

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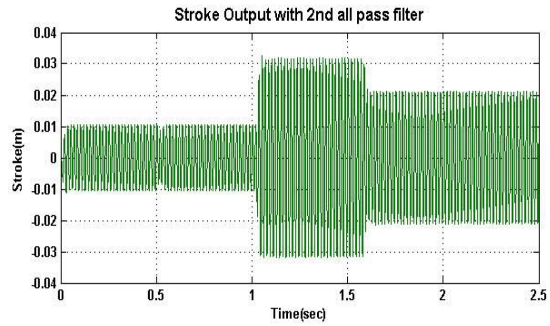
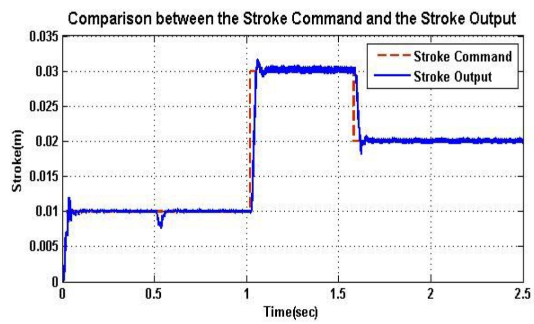


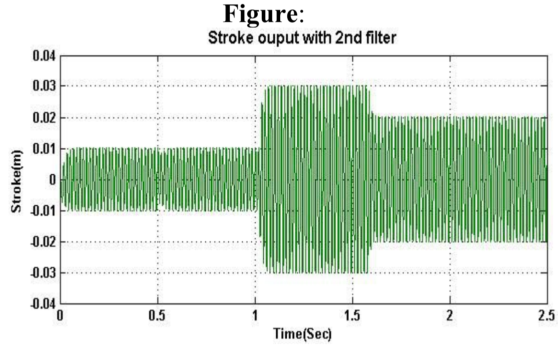
(a) response of linear motor position



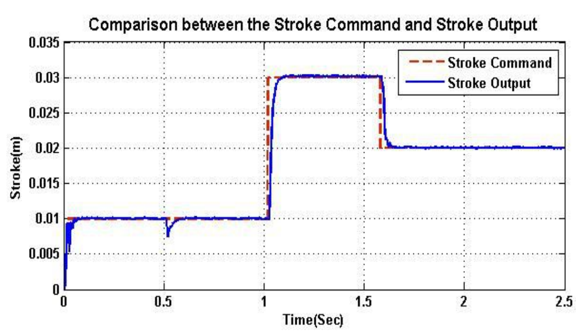
(b) stroke command and stroke response

Fig. 6 Responses for case of the 2nd order all pass filter

Figure:



(a) response of linear motor position



(b) stroke command and stroke response

Fig. 7 Responses for case of the 2nd order low pass filter

At first, the stroke command was set to be 0.01m. At t = 0.5sec, the external load torque of 0.2p.u. was applied. At t = 1sec, the stroke command was changed to 0.03m. Finally, at t=1.6sec, it was changed to 0.02m. Fig. 4 shows the responses of motor position and stroke for case of the 1st order all pass filter. Because some filters are needed to estimate stroke out of motor position, various filters such as all pass or low pass are used to compare their dynamic performances. Fig. 5 shows the responses of motor position and stroke for case of the 1st order low pass filter. Fig. 6 and Fig. 7 show the responses for case of the 2nd order filters. Through some simulation studies, we found that the proposed filters were very useful for stroke control of sensorless linear compressor system.

IV. CONCLUSION

The performance analysis of instantaneous piston stroke in a single phase PWM inverter has been done for four different types of filters. These filters are used to calculate and control the maximum values of the estimated piston stroke and current instantaneously and to analyze the dynamic characteristics of the stroke control in a linear compressor system. Through some simulation studies, we found that the proposed filters were very useful for stroke control of sensorless linear compressor system.

V. ACKNOWLEDGEMENTS

This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education, Science and Technology(No.2011-0023587)

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