Novel phase-locked loop-based resonant frequency tracking control for linear reciprocating compressor

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Abstract

The paper presents a novel phase-locked loop (PLL)-based resonant frequency tracking method for linear compressors with oscillatory motions. The proposed method achieves the phase-locked control between two signals by using PLL, which includes a multiplier, and a low-pass filter to obtain the phase signal difference. Consequently, based on the phase signal difference, the electrical frequency of the power supply can be adjusted through a PI (proportional-derivative) regulator such that the phase signal difference converges to 90° and the linear compressor works under the resonant frequency conditions. The analytical expression of the resonant frequency condition is proposed for the linear compressor. Then, the detailed design and procedure of the proposed method are presented. The designed method and the resonant frequency characteristics are verified by using the simulation experiment. The simulated results demonstrate that the proposed algorithm has faster response speed and higher convergence accuracy to step load change in comparison with the other commonly used algorithms.

Keywords: linear compressor; resonant frequency tracking; phase-locked loop; low-pass filter; PI regulator

1. INTRODUCTION

Unlike the conventional rotary compressor that employs a crankshaft as the intermediate mechanism for converting the rotary motions from an induction motor to linear reciprocating motions to drive a compressor pump [1], the linear reciprocating compressor utilizes a linear reciprocating motor and resonant springs to directly drive the compressor piston and therefore has relatively high overall efficiency due to the elimination of the inherently frictional loss caused by the crankshaft mechanism in conventional rotary compressors [2]. The efficiency improvement of 10–20% has been demonstrated in linear compressors as compared with conventional rotary compressors [3]. The linear reciprocating compressor also offers significant advantages over its conventional counterpart including compact structure, higher controllability, lower vibration and noise and simpler modulation means. Therefore, the direct-drive linear compressor has attracted much attention recently and has been employed in household refrigeration appliances, thermoacoustic, vasculature and Stirling regenerative cryogenic systems as a key component to save energy and reduce CO₂ emission [4].

The linear compressor operates most efficiently and requires the minimal electromagnetic force when its oscillation frequency equals the resonance frequency [5, 6]. Since the resonant frequency of the linear compressor is not only related to the mechanical spring elastic coefficient and the total mass of the actuator but also varies with the load, it is possible to make the linear compressor motor work under the resonant conditions by tracking the resonant frequency of the motor current. Therefore, the main goal of the linear compressor control is focused on how to track its resonant frequency of the linear compressor to achieve the efficient operations. The resonant frequency tracking approaches are thus very important in ensuring the highly efficient and reliable operations of the linear compressor under various working conditions.
conditions. There have been several different kinds of resonant frequency tracking techniques developed for the linear compressors during recent years. A method of average value of stroke-current product (ASCP) for regulating the resonant frequencies of the linear compressor with a pulse-width modulation inverter was investigated in [7]. In [8], a system-level controller was proposed to simultaneously achieve the stroke control and the resonance tracking by using nonlinear observers for gaining necessary information. The emphasis of the method was on the power factor and efficiency regulations based on the control of the average value of the product of the piston position and motor current. In [9], a model reference adaptive system-based resonant frequency tracking control algorithm was proposed, in which the system resonant frequency was directly calculated through the parameter adaptive rate. The effectiveness of the algorithm was verified by using simulation results. In [10], a learning feed-forward current controller consisting of a feedback proportional-integral controller and a feed-forward B-spline neural network was proposed for resonant frequency tracking of linear compressors. The steady state and transient performances of the controller were verified by using extensive simulation and experiment results. In [11], a resonant frequency tracking control strategy was proposed for a linear compressor to make the system resonant frequency vary with the force of gas compression. In [12], an adaptive resonant current controller was designed to allow the compressor to track the mechanical resonance frequency and simultaneously control the motor force. The controller was verified by simulation results. In [13], a phasor algorithm was proposed to calculate the natural frequency of the linear compressor. The calculated natural frequencies were verified by the tested motor efficiency. In [14, 15], a novel resonant frequency estimation method that calculates the phase difference between a supplied voltage and a mover position was proposed; the method calculates the phase difference by using the arctangent of a Fourier coefficient, which controls the drive frequency to keep the phase difference at 90°. The method was verified by experiment.

However, most of the conventional resonant frequency tracking methods depend on the steady state characteristics of the linear compressor. The existing resonant frequency tracking methods also mainly depend on the phase signal differences of the motor currents and piston position and demand the phase signal measurement of the motor currents and piston position individually. Since these phase signal measurements need at least half electrical period, the power supply frequency needs to be adjusted every half electrical period, which will slow down the response of the resonant frequency tracking. It is obvious that the current resonant frequency tracking methods suffer from the disadvantages of low response, complex operation and low anti-disturbance ability. The phase-locked loop (PLL) technology is usually used in phase synchronization and extraction, etc., and is widely used in power generation subsystem grid-connection [16, 17], motor control sliding mode observer angle calculation, etc. [18, 19].

In this paper, a novel PLL-based resonant frequency tracking control for linear reciprocating compressor is presented. By adopting a multiplier, low-pass filter and a PI regulator, the proposed PLL control method can be used to effectively and quickly track the resonant frequency and improve the system efficiency of the linear compressor under variable loading conditions. The operational principle, design and implementation procedure of the proposed method are detailed, and the performance of the proposed method is demonstrated by extensive simulation experiments in comparison with other commonly used algorithms.

The main contributions and innovations are as follows:

1. The proposed resonant frequency tracking method does not require complex phase measurements and phase difference calculation, or the complex coordinate transformation, and can be easily implemented with high response speed.

2. The proposed method can also achieve the tracking frequency control that is consistent with the current sampling frequency, which greatly improves the dynamic performance of the resonant frequency tracking response of the linear compressor under variable loading conditions.

3. The proposed method can track the resonant frequency quickly and effectively, thus improving the system efficiency of the linear compressor under various loading conditions. Therefore, due to the significant advantages, the proposed method is deemed to be appropriate for the proposed compressor applications.

2. THE RESONANT FREQUENCY CONDITION

In order to derive the resonant frequency condition, the efficiency mathematical model of the linear reciprocating compressor system is conducted and analyzed. The linear compressor system reaches the maximum efficiency when operating frequency equals to the resonant frequency. Therefore, the resonant frequency tracking needs to be maintained in order to optimize the motor efficiency.

2.1. Modeling of the linear reciprocating compressor system [6]

The model of the linear reciprocating compressor system can be represented as Figure 1. According to Newton’s second law, the dynamic equation of the mechanical system of the linear compressor can be obtained as shown in Equation (1), where
\( m \) is the total mass of the actuator and \( F_l \) is the load force. During the movement of the compressor, the working medium of compression is refrigeration gas, which is a typical nonlinear gas force.

\[
m \frac{d^2x}{dt^2} + c_mv + k_sx + F_l = F_e = k_Fi
\]  

According to the equivalent circuit diagram in Figure 2, the voltage equation of the electromagnetic system is

\[
u(t) = R_ei(t) + L_0 \frac{di(t)}{dt} + k_Fv
\]  

A linearized model of gas spring is usually employed to model the nonlinear gas force as shown in Equation (3), where \( k_g \) is the equivalent spring elasticity coefficient of the gas force and \( c_g \) is the equivalent damping coefficient of the gas force.

When the linear oscillating actuator drives the compressor load, and the gas pressure increases, the gas-force equivalent spring stiffness coefficient and gas-force equivalent damping coefficient will increase accordingly.

\[
F_g = k_gx + c_gv
\]  

The linearized mathematical model of the electromechanical system when the linear oscillating actuator is loaded with a compressor can be obtained as

\[
\begin{cases}
  m \frac{d^2x}{dt^2} + C \frac{dx}{dt} + Kx = k_Fi \\
  u = R_ei + L_0 \frac{di}{dt} + k_Fi
\end{cases}
\]  

The pneumatic force is equivalent to the elastic force and damping force, which are superimposed into the actual elastic force and damping force as the following:

\[
\begin{cases}
  C = c_m + c_g \\
  K = k_s + k_g
\end{cases}
\]  

Where \( K \) is the equivalent spring stiffness coefficient, \( C \) is the equivalent damping coefficient, under the non-load condition, \( c_g = k_g = 0 \).

2.2. Analysis of the system efficiency [9]

When the voltage source is designed as input, the voltage vector equation can be expressed as

\[
\dot{U} = \dot{I} \left( R_e + jX_e \right) + \dot{E} = \dot{I}Z_e + k_F \dot{V}
\]  

According to the expression mode of velocity impedance, we obtain

\[
\dot{V} = \frac{\dot{F}_e}{Z_m} = \frac{k_F \dot{I}}{Z_m}
\]  

Furthermore, the equivalent circuit of the linear oscillating actuator with mechanical load is shown in Figure 3.

Linear compressor is usually supported by a single-phase inverter, such that the motor current and voltage are single-phase AC quantities. The mathematical model of the system is written in phasor form as Equation (8), where \( \omega \) is the system frequency.

\[
\begin{cases}
  \dot{U} = R_e \dot{I} + j \omega L_0 \dot{I} + k_F \dot{V} \\
  - m \omega^2 \ddot{X} + j \omega C \ddot{X} + K \ddot{X} = k_F \dot{I}
\end{cases}
\]  

The voltage–current relationship is

\[
\dot{U} = \left( R_e + j \omega L_0 \right) \dot{I} + \frac{k_F^2 C}{C + (m \omega - K/\omega)} \dot{I}
\]  

The input power is

\[
P_i = \text{Re} \left( \dot{U} \dot{I}^* \right) = \left[ R_e + \frac{k_F^2 C}{C^2 + (m \omega - K/\omega)^2} \right] |\dot{I}|^2
\]  

The output power is

\[
P_o = \text{Re} \left( \dot{F}_g \dot{V}^* \right) = \text{Re} \left[ (c_g \dot{V} + k_g \ddot{X}) \dot{V}^* \right] = c_g \dot{V} \dot{V}^*
\]  

We have

\[
P_o = \frac{k_F^2 c_g}{C^2 + (m \omega - K/\omega)^2} |\dot{I}|^2
\]
Then, the efficiency is

\[ \eta = \frac{P_o}{P_i} = \frac{k_F^2}{k_g^2 C + R_e \left( C^2 + (m \omega - K / \omega)^2 \right)} \]  

(13)

From Equation (11), it can be seen that the system reaches maximum efficiency condition when the operating frequency equals to \( \sqrt{K/m} \), which is the resonant frequency. Moreover, the resonance frequency will vary with the equivalent spring elasticity coefficient \( k_g \), which is contained in \( K \). Therefore, the resonant frequency tracking control must be implemented to reach maximum efficiency condition. Furthermore, under resonance condition, the phase angle difference between piston position and motor current can be derived as

\[ \dot{\chi} = \frac{k_F}{(K - m \omega^2)} + j \omega C \]  

(14)

\[ \theta_{x-i} = - \arctan \left( \frac{\omega C}{K - m \omega^2} \right) \]  

(15)

It can be seen from Equation (15) that when system reaches resonant condition, the phase angle difference between piston position and motor current will equal 90°.

3. THE RESONANT FREQUENCY TRACKING CONTROL

The section presents the design of the proposed resonant frequency tracking method used in the linear compressor regulation. The operational principle, the design and the implementation procedure of the proposed method are detailed.

3.1. The proposed control method

Based on the principle of PLL, an error signal related to the phase difference between the piston position and motor current is constructed, and the power supply frequency is adjusted through the closed loop control to make the error signal equal to zero in order to realize the resonant frequency tracking control, while the phase difference is equal to 90°. As shown in Figure 4, the proposed novel resonant frequency tracking method is introduced in the linear compressor system to track the resonant frequency such that the line compressor (LC) works efficiently. The LC can be regulated by using an inverter driven by four channel PWM (pulse-width modulation) signals, which are generated by the SPWM (sinusoidal pulse-width modulation) algorithm.

The principle and structure of the resonant frequency tracking method are illustrated in Figure 5. As shown in the figure, the method mainly comprises a multiplier, a low-pass filter, a PI regulator and an adder. After the piston position signal and motor current signal pass through the multiplier and low-pass filter, the error signal of the PLL is generated as the input, and the power supply frequency is regulated by adjusting the power supply frequency to reach the resonant condition. Then, the input error signal of the PLL will converge to zero. The proposed method can be used directly on-line and in real-time to minimize the resonant frequency tracking error under all conditions.

The working principle of the proposed method is described as follows.

As shown in Figure 5, the instantaneous signal values of the motor current \( i \) and the piston position \( x \) are measured, respectively, then the product \( i \cdot x \) of the signal values of the motor current \( i \) and piston position \( x \) are obtained through a multiplier. Consequently, the phase signal difference (\( \Delta \phi \)) of the product can be obtained by passing the product signal through a low-pass filter.

The low-pass filtering is performed on the product signal \( i \cdot x \) to obtain the error signal \( \Delta e_\phi \) as Equation (16), where \( \Delta \phi \) is the phase difference signal.

\[ \Delta e_\phi = 2 \times \text{LPF} (i \cdot x) \propto \sin \Delta \phi \]  

(16)

As shown in Equation (16), the error signal \( \Delta e_\phi \) is proportional to the sinusoidal value of the phase difference, which can be described as Equation (17), where \( \varphi_x \) is the phase of the piston position signal and \( \varphi_i \) is the phase of the current signal.

\[ \Delta \phi = \frac{\pi}{2} + \varphi_x - \varphi_i \]  

(17)
Then, as illustrated in Figure 4, based on the phase signal difference, the electrical frequency of the power supply can be adjusted through the PI regulator, that is, the SPWM (sinusoidal pulse-width modulation) frequency of the motor power supply can be adjusted until the steady-state tracking error signal is zero. Consequently, the power supply frequency of the linear compressor will be equal to its resonant frequency and the linear compressor works under the resonant conditions.

The working principle of the above method can be analyzed as follows:

The motor current and the piston position signals can be described as

\[ i = i_m \sin (om + \varphi_i) \]  \hspace{1cm} (18)
\[ x = x_m \sin (om + \varphi_x) \]  \hspace{1cm} (19)

where \( \omega \) is the power supply frequency (rad/s), \( i_m \) is the amplitude of a sinusoidal current waveform and \( x_m \) is the amplitude of a sinusoidal piston position waveform.

Therefore, the product \( i \cdot x \) can be described as

\[ i \cdot x = i_m \sin (om + \varphi_i) \cdot x_m \sin (om + \varphi_x) \]
\[ = \frac{1}{2}i_m x_m \left[ \cos (2om + \varphi_i + \varphi_x) - \cos (\varphi_i - \varphi_x) \right] \]  \hspace{1cm} (20)

Moreover, the error signal \( \Delta e_\varphi \) can be calculated as

\[ \Delta e_\varphi = 2LPF (i \cdot x) = i_m x_m \cos (\varphi_i - \varphi_x) \]
\[ = i_m x_m \sin \left( \frac{\pi}{2} + \varphi_x - \varphi_i \right) = k \sin (\Delta \varphi) \]  \hspace{1cm} (21)

where \( k \) is the product of the amplitude of piston position signal waveform and that of the current signal waveform and \( LPF \) represents a digital low-pass filter, which can filter out the \( 2\omega \) signal component of the frequency \( i_m x_m \sin (2om + \varphi_i + \varphi_x) \).

When the phase error \( \Delta \varphi = \frac{\pi}{2} + \varphi_x - \varphi_i \) is zero, that is, \( \Delta e_\varphi = 0 \), the phase difference between the motor current and piston position will be 90° (equal to \( \pi/2 \) in rad) and then the linear compressor reaches the resonant state. Hence, the resonant frequency tracking regulation of the linear compressor can be achieved by regulating the error signal to zero, i.e. \( \Delta e_\varphi = 0 \).

The above low-pass filter \( LPF \) is a first-order filter with variable cut-off frequency, and the cut-off frequency varies with the actual power supply frequency \( \omega \) of the linear compressor, \( \omega_c = \omega / M \) where \( M = 1.0 \sim 10 \). By using the low-pass filter with variable cut-off frequency, the high frequency (2\( \omega \)) component in the product signal \( i \cdot x \) that is independent of the error signal \( \Delta e_\varphi \) will be better filtered out.

The PI regulator adjusts the power supply frequency such that \( \Delta e_\varphi = 0 \). The regulator utilizes an incremental adjustment mode, that is, \( \omega(k) = \omega(k - 1) + PI(\Delta e_\varphi) \), where \( \omega(k - 1) \) is the power supply angular frequency of the previous control period and the initial value is the intermediate value within the operating frequency range of the linear compressor, that is, \( \omega(0) = \omega_{\text{max}} / 2 \).
In addition, by keeping the voltage amplitude $U_m$ of the linear compressor power supply unchanged, the voltage phase angle $\theta_e$ can be obtained by the integration of the power supply frequency $\omega$ with respect to time. Then, according to the power supply voltage amplitude $U_m$ and voltage phase angle $\theta_e$, the four channel PWM signals can be produced through the SPWM algorithm and can be used to control the inverter. Then, the single-phase AC inverter output can be generated to drive the linear compressor.

3.2. The implementation procedure

The proposed resonant frequency tracking method can be implemented in the LC system. In order to ensure that the LC operates under the resonant frequency condition over a wide range, a detailed implementation procedure is required.

Therefore, the implementation procedure of the proposed method can be described as follows:

(a) Collect the instantaneous signal value of the stator current $i$ of the linear compressor by using a current sampling chip. Collect the instantaneous signal value of the piston position $x$ by using a resistance type position sensor.

(b) Obtain the product ($i \cdot x$) through a multiplier.

(c) Consequently, the phase signal difference ($\Delta e_\phi$) of the product can be obtained by passing the product signal through a low-pass filter.

$$\Delta e_\phi = 2\text{LPF} (i \cdot x) \quad (23)$$

The transfer function of the digital low-pass filter can be described as

$$\Delta e_\phi = 2\text{LPF} (i \cdot x) \quad (24)$$
where the cut-off frequency $\omega_c = \omega / M$ and the value of $M$ can be selected within the range of 1.0 $\sim$ 10.

(d) Then, use a PI regulator to adjust the power supply frequency such that the error signal $\Delta\phi$ converges to zero. The detailed procedure is as follows: when $\Delta\phi > 0$, increase the power supply frequency; when $\Delta\phi < 0$, reduce the power supply frequency; when $\Delta\phi = 0$, keep the power frequency unchanged, that is, the current frequency is the resonant frequency.

By using the incremental PI regulator, namely, the output of PI regulator is added to the power supply frequency of the previous control state to obtain the current power supply frequency that needs to be applied, namely,

$$\omega(k) = \omega(k-1) + PI(\Delta\phi)$$  \hspace{1cm} (25)

(e) Keep the voltage amplitude $U_m$ of the compressor power supply unchanged; obtain the voltage phase angle $\theta_e$ through the integration of power supply angular frequency $\omega$ with respect to time. Then, according to the voltage phase angle $\theta_e$ and the voltage amplitude $U_m$, generate the four channel PWM signals through the SPWM algorithm for controlling the inverter such that the single-phase AC electrical output from the inverter can be produced to drive the linear compressor. The calculation formula can be designed as

$$\theta_e(k) = \theta_e(k-1) + \omega(k) \cdot T_s$$  \hspace{1cm} (26)

where $T_s$ is the control period, which is equal to the current sampling period.

4. RESULTS AND DISCUSSIONS

The performance of the proposed control method is verified through simulation experiments and comparisons with the commonly used algorithms. A linear compressor control system based on the ASCP [7] algorithm is also constructed in Simulink to demonstrate the advantages of the proposed algorithm.

4.1. Control system and startup performance

A linear oscillating actuator control system with the proposed method is constructed in Matlab/Simulink as shown in Figure 6.

The motor parameters in simulation are given as follows:

- $R_e = 18 \ \Omega$, $L_0 = 0.59 \ H$, $k_F = 47.08 \ N/A$, $m = 0.93 \ kg$, $c_g = 20 \ N.s/m$ and $k_g = 30 \ kN/m$, i.e. the system resonant frequency is equal to 28.59 Hz. At startup, the target amplitude is set to 5 mm, and the system startup frequency is equal to 23.34 Hz.

The PI controller parameters are as follows: $k_p = 20$, $k_i = 300$ for
stroke controller; $k_p = 1$, $k_i = 30$ for frequency controller, $M = 6$ for the low-pass filter. In addition, the original piston position signal is amplified by 1000 times to improve the control accuracy.

As shown in Figure 7, the dotted lines represent the actual system resonant frequency of 28.59 Hz, and the ±1% settling time of the estimated system resonant frequency is 0.384 s, which demonstrates that the proposed method has the advantages of fast convergence speed and acceptable accuracy.

Figure 8 shows the response curve of piston position and motor current during startup process. Under PLL control strategy, the operating frequency quickly converges to the real system resonant frequency, and the spike current only appears at the startup instant. As shown in Figure 8, under the adjustment of the closed-loop stroke controller, the stroke value quickly reaches the target value with a small overshoot. Figure 9 illustrates that the steady-state phase angle difference between piston position and motor current is equal to 90°, which verifies the accuracy of the proposed PLL-based resonance frequency tracking control at startup.

4.2. Response to step load change
A sudden discharge pressure increase of the compressor causes a step load change. Several literatures indicate that the discharge pressure increase of linear compressors causes an increase of $k_g$ and $C_g$. Therefore, the system equivalent spring coefficient $K$ increases, which increases the system resonance frequency.

Figure 10 shows that the estimated resonance frequency converges from initial value of 28.59 Hz to the target value of 30.88 Hz in 0.126 s, which verified that the proposed PLL-based resonance frequency tracking control has fast response speed and high convergence accuracy to step load change.

Figure 11 shows that under the adjustment of the stroke closed-loop controller, the stroke amplitude reaches the target value after about 0.3 s, and there is no spike in the current response. Figure 12 illustrates that the steady-state phase angle difference between piston position and current is still equal to 90°, which also verifies the accuracy of the proposed PLL-based resonance frequency tracking control at step load change.
4.3. Comparison with ASCP algorithms

Figure 13 shows the structure diagram of ASCP-based linear compressor control system; furthermore, the motor parameters, operating conditions and the control parameters of the stroke controller are the same as Section 4.1.

Figure 14 illustrates that at startup process, the PLL algorithm achieves ±1% error with a settle time of 0.384 s, while ASCP algorithm achieves ±1% error with a settle time of 0.531 s. The PLL algorithm has much faster convergence speed compared with the ASCP algorithm at startup process and decrease the setting time by about 27.7%.

Figure 15 shows that at step load change condition, the PLL algorithm achieves ±1% error with a settle time of 0.126 s, while ASCP algorithm achieves ±1% error with a settle time of 0.339 s. The PLL algorithm has much faster convergence speed compared with the ASCP algorithm at step load change condition and decrease the setting time by about 62.8%.

5. DISCUSSIONS

The slow convergence of the ASCP algorithm is due to using the ASCP value as a reference for frequency adjustment. A large ASCP value causes an increase of frequency adjustment rate, while a small ASCP value causes a reduction of frequency adjustment rate. However, the ASCP value is not only related to the phase angle difference between piston position and motor current but also related to the product of stroke and peak motor current.

At startup process, the ASCP value is very small due to that the stroke and motor current have not reached their steady state. Therefore, a lower frequency adjustment rate is adopted, which causes the ASCP algorithm to converge slowly. At step load change condition, the calculation of ASCP value requires the integration calculation in the oscillating period corresponding to the supply voltage frequency, while the sudden change in supply frequency causes the hysteresis and oscillation in the calculated ASCP value, which will lead to a decrease in the dynamic performance of resonant frequency tracking.

In the proposed PLL algorithm, by constructing the product signal of current and displacement, and performing low-pass filtering of the signal with variable cut-off frequency, a real-time error signal proportional to the phase angle difference of \( i-x \) is obtained. The refresh frequency of the real-time error signal is proportional to the current sampling frequency, which is much higher than the system oscillation frequency and can continuously reflect the phase angle difference between the piston position signal and motor current signal when the working conditions change. The voltage phase is adjusted by the PLL control to realize the resonant frequency tracking control. When the real-time error signal converges to zero, the resonant frequency tracking control is realized. Therefore, the proposed PLL algorithm has a much faster dynamic response compared with the ASCP algorithm.

6. CONCLUSION

In this paper, a novel PLL-based resonant frequency tracking method has been proposed for the linear compressor.

(1) The resonant frequency condition was derived by analyzing the efficiency model of linear reciprocating compressor system.

(2) The method proposed in this paper only needs the measurements of the instantaneous signal values of the motor current and the piston position.

(3) In the proposed method, a multiplier and a low-pass filter are used to obtain the phase signal difference, and then a PI regulator is used to make the phase signal difference converge to 90°. Therefore, the resonant frequency tracking and the high-efficiency resonant working conditions of the linear compressor can be achieved effectively.

(4) The detailed resonant frequency condition is analyzed and then the detailed design procedure of the proposed method is presented.

(5) The designed method and the resonant frequency characteristics of the proposed control method are verified by using the simulation experiment and comparisons with the other commonly used algorithms. The results indicate that the PLL algorithm achieves ±1% error with a regulation time of 0.126 s, while ASCP algorithm achieves ±1% error with a regulation time of 0.339 s.

The proposed method has been only verified by simulation, but there are no experimental results. In the future, the proposed method should be verified by experimental results, which will promote the industrial application of novel resonant frequency tracking control of the linear compressor.

7. CONFLICT OF INTEREST

To the best of our knowledge, the named authors have no conflict of interest, financial or otherwise.

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