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Abstract

A linear compressor operated directly by commercial AC electricity (hereinafter "line start linear compressor") was developed in order to reduce the cost by eliminating the expensive controller and to enhance the compatibility with various types of refrigerators. Because of absence of position controller, top dead center (TDC) of the line start linear compressor is influenced by external environments. Parameters of the linear compressor were adjusted to get robust performances against the fluctuations of load and outlet voltage. And new start-up method was investigated to avoid abrupt rising of stroke when the compressor turned on. Results of experiments show the start linear compressor maintains high efficiency and low noise as well as excellent reliabilities even in severe conditions of household refrigerators.

Introduction

The linear compressor is extremely efficient compared to the conventional reciprocation compressors due to low friction loss, simple gas flow path and high efficient linear motor. The piston is directly linked to the moving parts of the linear motor (Fig 1). Instead of a crankshaft that causes much friction losses, the piston is supported by resonant springs to form a free piston system. Refrigerant flows straight through the inside of piston. Rare earth permanent magnets, no end coils, and uniform magnetic flux in stator cores make the linear motor reach up to 95% of efficiency.

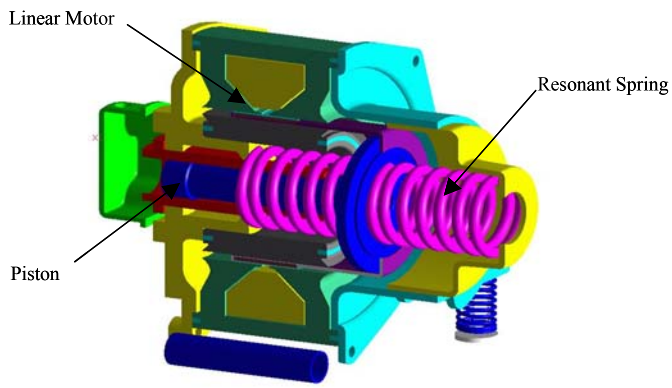


Fig.1 Configuration of linear compressor

The free piston system of the linear compressor required a position controller to maintain the piston at specific top dead centers (TDC) in any conditions, such as load disturbances or voltage fluctuation. The controller also makes it possible for the linear compress to modulate cooling capacity by adjusting the amount of the TDC or stroke in accordance to load conditions of refrigeration cycles. And the controller enables the motor to start softly and quietly.

However, the controllers present problems in economic aspects – cost and compatibility. The position controllers are on the expensive side compared to conventional reciprocating compressors driven by induction motors. Controllers are composed of a microprocessor, precise passive components for detecting voltage and current of the linear motor for calculating the stroke, and power electronic components for manipulating AC voltage applied to the linear motor. And DC power supply is needed for the microprocessor and power electronic elements (Fig. 2). And the linear compressor driven by position controller should be tuned specifically to a refrigeration cycle to get the best performance and to minimize energy consumption by modulating cooling capacity according the condition the refrigerator required.

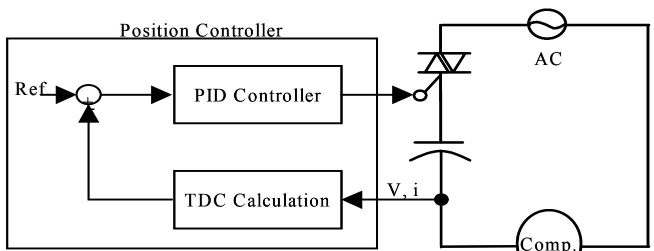


Fig.2 Diagram of the position controller

The linear compressor without a controller was developed to solve these problems. This line start linear compressor runs directly by AC line voltage out of outlets in the houses. Following challenges issue to implement this compressor.

- -Starting method
- -Robust to load and voltage fluctuations
- -Variations of the parameters

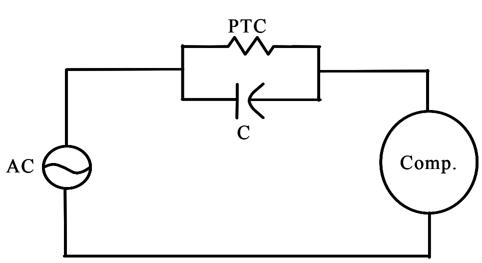
This paper shows the characteristics of the line start linear compressor and the experimental results.

Implementation of Line Start Linear Compressor

Starting

The stroke of the linear motor rises abruptly large enough to make collisions between mechanical parts the moment it is turned on directly with an outlet voltage. The linear motor is connected with an external capacitor to run at an electrically resonant condition with frequency of the voltage. Therefore, large inrush current occurs when the motor is turned on due to the small starting impedance. And sharp overshoot of the stroke causes collisions, noise, and damages on the mechanical parts. With the position controller, the soft start was possible by letting input voltage increase slowly.

Line start linear compressor uses a PTC to avoid the stroke overshoot. The PTC has characteristics that its resistance increases from the initial value of a dozen ohm to dozens of kilo-ohm as the current flows into it. Connected to the running capacitor with parallel (Fig 3), the PTC prevents the starting current from large inrush by changing the path of current to the inductance of the linear motor (equation 1). When the resistance of PTC goes up, the current begins to flow through the capacitor that results in small impedance by cancellation the inductance out of the capacitance. However, a certain amount of back EMF exits in the motor coil in proportion to initially established start-up stroke (equation 2). This back EMF prevents the inrush current by reducing net amount of voltage applied to the motor.



$$Vac = (Rptc+Rmotor)\ i + L\frac{di}{dt} \qquad \text{------(1)}$$

$$Vac = Rmotor\ i + L\frac{di}{dt} + \frac{1}{C}\int idt + Vemf \qquad \text{--(2)}$$

Fig.3 Starting circuit

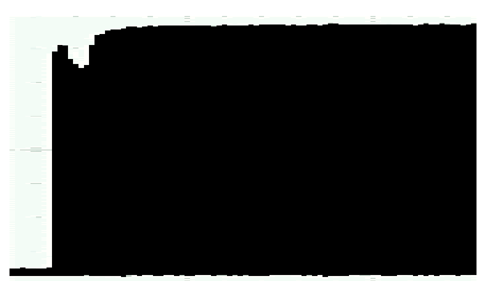


Fig.4 A stroke waveform at start

Load Invariant

Compressors should maintain constant TDC regardless of the amounts of loads in the refrigeration cycles. The loads of the refrigerators depend on the ambient temperatures. Usually the refrigerators guarantee the operations over wide ambient temperatures range of –5℃~ 45℃. And the load is proportional to the ambient temperature. The mid position of the piston in the line start linear compress moves backward and stroke decrease as the load increases, so the TDC becomes large while high cooling capacity is required. In a low ambient temperature, the stroke could be large to output unnecessarily high cooling capacity.

Parameters related to the load disturbance were investigated to get robust performances against the load variations. The linear compressor runs at the mechanically resonant frequency in mass-spring system. The spring effect of compressed refrigerant increases at the high load. Therefore by using more stiff resonant springs and heavier moving mass, the gas spring effect could be reduced. And by setting mechanical resonant frequency lower than that of the controller driven linear compressor, large stroke could be expected even in heavy load conditions because the gas spring effects of the loads help the operating condition approach to the resonance. Experiment results show relatively constant TDC over the wide range of loads (Fig.5).

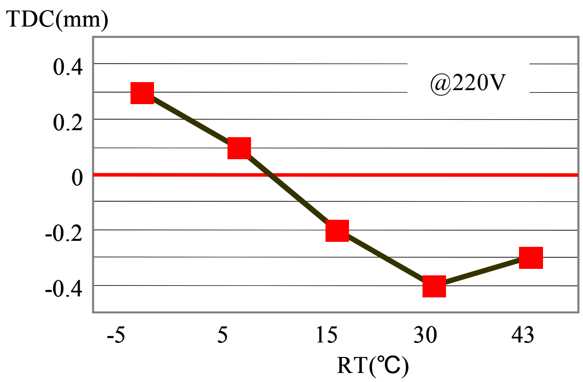
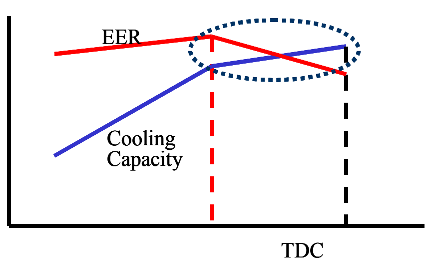


Fig.5 Experimental results over various loads

Robust to Voltage Variation

Voltage levels out of outlets in the houses vary hours by hours and areas by areas according to the conditions of electric power networks. A few percent of the variance from the nominal voltage exist in most areas. The linear motor has the same characteristics with the DC motors. The stroke of the linear motor is proportional to the voltage applied. Therefore, the constant performance could not be anticipated if the stability of voltage or frequency is not managed well in some area.

Fortunately, the linear compressor has a range where relatively constant cooling capacity kept over the various strokes or TDC (Fig. 6). An adequate selection of a motor coil turns can compensate the variation of TDC caused by voltage variances. The experimental results show the line start linear compressor are still sensitive to the amount of the voltage compared to other types of compressors (Fig.7). However the drop-in test in a refrigerator confirmed the variations of cooling capacity from the voltage tolerances makes little difference in the refrigeration performances. Only duty ratio of the compressor working is changed according to the capacities. Multiple coils of the linear motor can provide solutions over wider ranges of voltage variance.



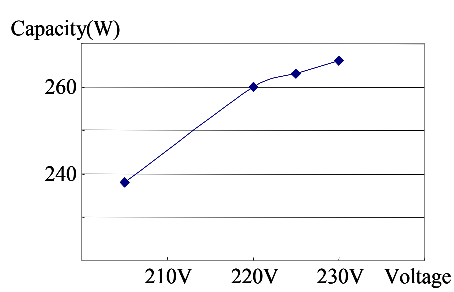


Fig 6 Cooling capacity vs. TDC Fig.7 Test results of cooling capacity over voltages

Effects of Parameter Variances

The performances of the line start linear compressor are sensitive to the variances of the parameters of the linear motor and mechanical system. Especially the motor constant influences the stroke. A bigger one than target value of the motor constant results in a less stroke, vise versa. The motor constant is closely related to the properties of permanent magnets; residual flux density and the dimensions. It is hard to provide precise qualities of these properties in the mass production processes of the permanent magnets.

Statistic analysis has been done with data out of years-long experiences in manufacturing of the linear compressors in LG. The standard deviation of TDC came out to 0.07mm. This means about 68.2% among products have the target TDC value within the variance of 0.07mm. Except three or four among a million of productions are within the variance 0.42mm. The variances could reduce much less by applying quality control methods at the manufacturing lines.

Experimental Results

Realties of environments were considered when designing the actual line start linear compressor. Three coils were installed in the linear motor in order to provide the uniform performances over up to±15% of variance from the nominal voltage (Fig. 8). Total coils of three are used when the high voltages applied, two coils when around nominal voltage and only one coil at the low voltages. The coils are selected during the operation when the outlet voltage comes to lie on the corresponding regions (Fig. 9). Hysteresis function was engaged at each boundary of voltage regions to prevent chatters of relays when the voltage happens to change near the boundaries. In addition to PTC, a reactor was also put in order to guarantee safer start-up at any voltages under any load conditions by providing a larger margin of TDC at starting.

The cost of drive was reduced significantly by replacing the complicate power electronic circuits by relays. The line start drive is used for switching the relays by the condition of line voltage detected by a microprocessor and the cost was reduced by 43% compared to the conventional position controller (Fig. 10). . The cost of the compressor body was not changed because no new parts or components were added on the existing compressor.

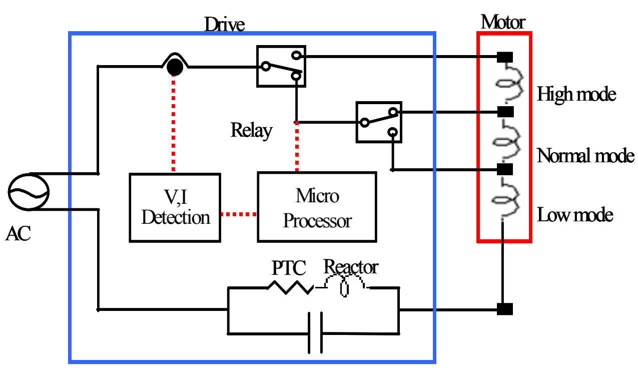


Fig.8 Schematic diagram of line start drive

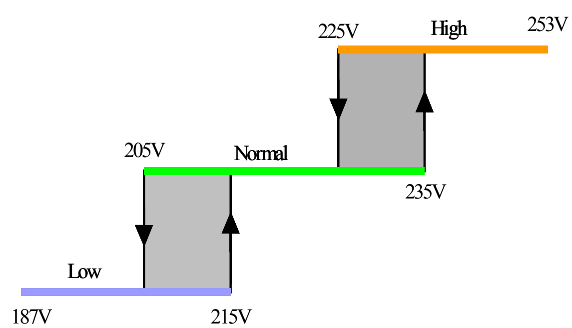


Fig.9 Voltage regions of each mode

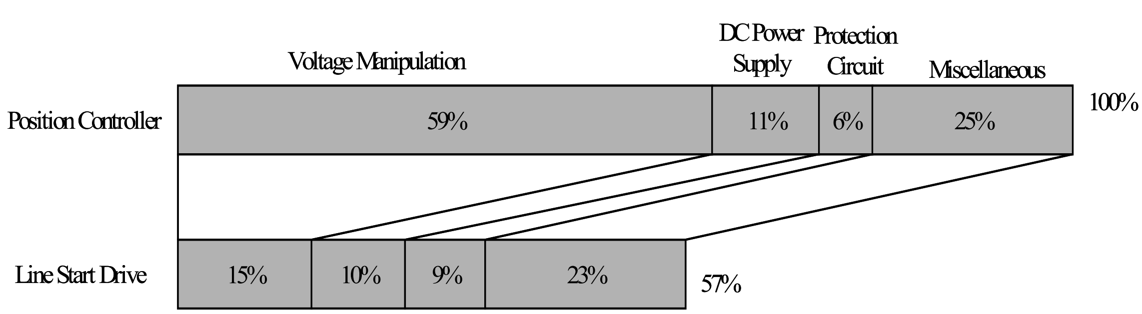


Fig.10 Comparison of the cost between the Position controller and Line Start Drive

Following experiments of the line start linear compressor were carried with the R600a refrigerant at 220V/60Hz. A 24cuft side by side type of refrigerator made in LG Electronics was used for drop-in tests

Efficiency

The line start linear compressor is more efficient in principle than one with a controller. Due to the absence of the controller loss, and harmonic losses caused by the discontinuous current, the measured efficiency of the line start linear compressor increased by 2.5% compared to the existing linear compressor.

Fig. 11 shows the test results of cooling capacity and EER at each voltage range. (Evaporator temperature: -26℃, Condenser Temperature : 38℃, Ambient Temperature : 32.2℃) Note that EER increases as the capacity becomes low at normal and high mode operations. It means that modulation of cooling capacity could be available through further research on these characteristics.

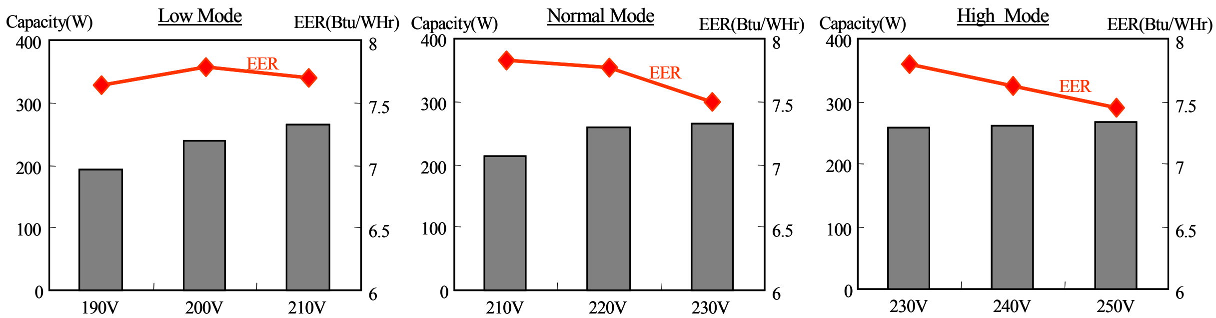


Fig.11 Test results of EER over various voltage ranges

Noise

The noise tests of the line start linear compressor with various voltages were carried out to examine the effect of various strokes (Fig 12). The drop-in tests shows less than 1 dB change only at the back of the refrigerator when operated within the normal voltage range (Fig 13). Noise at the back of the refrigerator also changes the moment relays are switched. 2dB of noise level change occurred in the worst case, such as changing voltage abruptly form minimum to maximum, which rarely occurs in actual environments (Fig 14).

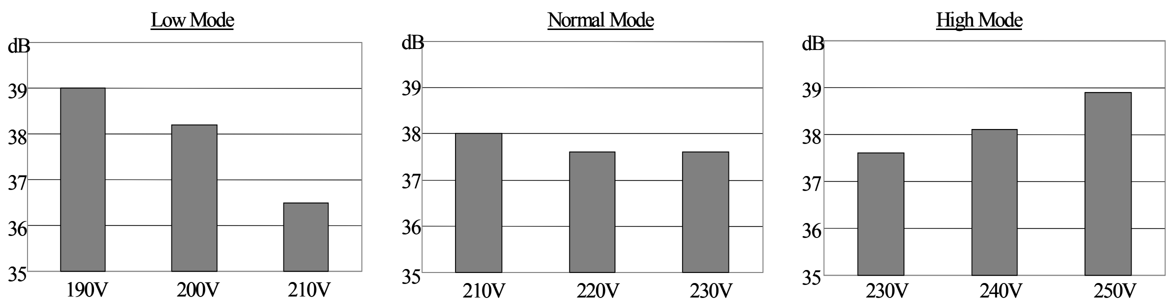
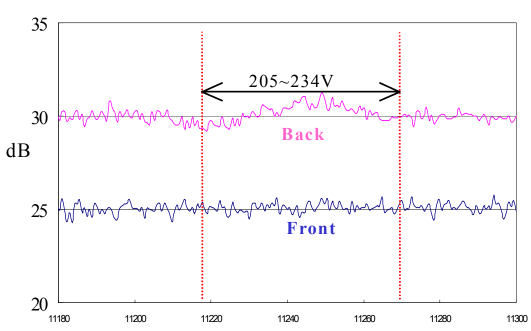


Fig.12 Noise test results of compressor



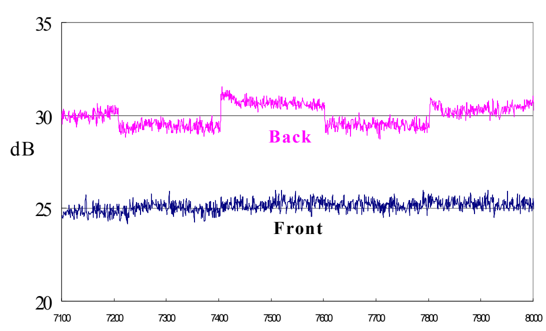


Fig.13. Refrigerator noise change by voltages Fig.14 Refrigerator noise by switching relay

Reliability

In addition to standard reliability tests, another two tests should be carried due to the unique characteristics of the line start linear compressor. The line start linear compressor has wider distributions of TDC over full range of voltage tolerances and load variations (Fig 15). First, the line start linear compressor could run with a large TDC when operated at overload and low voltages applied (Bottom right area in Fig. 15). The refrigerator at this condition could fail to reach target temperatures due to the lack of cooling capacity. On the contrary, the piston hits the discharge valve and protrudes from the cylinder head when operated at low loads and high voltages (Top left area in Fig.15). This may cause the damages on the discharge valve and other mechanical parts.

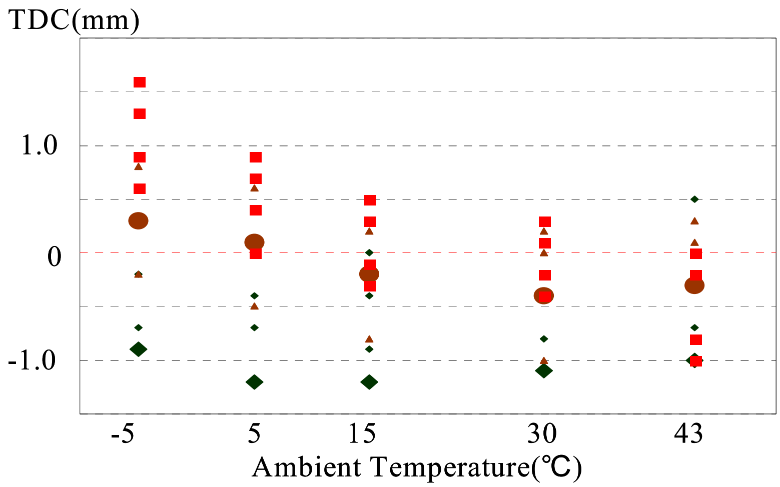


Fig.15 Distribution of TDC over full range of voltages and ambient temperature

Fig.16 shows the results of a pull down test of the refrigerator at 43℃ of ambient temperature with low voltages. The line start liner compressor was proved to satisfy the most severe load condition in the refrigerators.

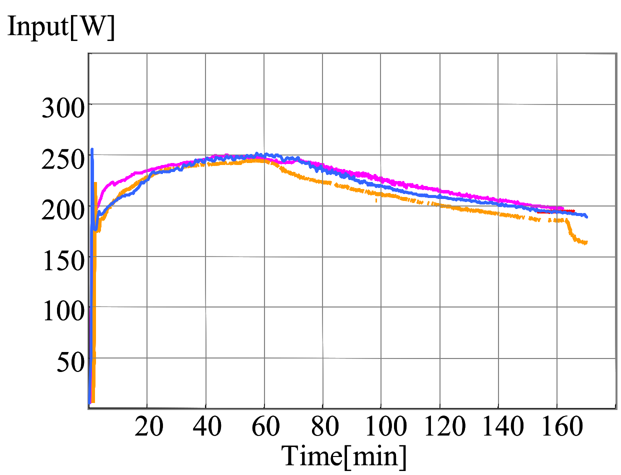


Fig.16 Pull down test at 43℃of ambient temperature

Acceleration tests were carried out to examine the effects of excessive strokes. The refrigerators were operated at –5℃ of ambient temperature with a high voltage. The position of the pistons was measured to protrude by about 2mm from the cylinder head. The compressors were let to run continuously for 2 weeks equivalent to 20 years operating in the field. No damages on the valves or other mechanical parts were found after the tests.

Conclusion

A line start linear compressor that operates directly by commercial electricity was implemented on the purpose to reduce cost by eliminating the position controller. Replacing the expensive controller by a PTC and simple relay circuit, significant cost reduction was achieved even providing better efficiency as well as providing soft starting with the outlet voltage. Parameters were investigated to perform robustly against the fluctuations of the load and voltage applied. Experiments results verified the linear compressor employable in the refrigerators. From the similarities to RSCR-type reciprocating compressors, the line start linear compressor presents excellent compatibility with various types of refrigerators.

Reference

1. H. K. Lee, G.Y. Song, J.S. Park, E.P. Hong, W.H. Jung, K.B. Park, "Development of the Linear Compressor ", Proceedings International Compressor Conference, 2000, Purdue University, West Lafayette, Indiana, USA
2. G.Y. Song, H.K. Lee, J.Y Yoo, J. K. Park, Y. H. Sung, "Development of the Linear Compressor for a Household Refrigerator", Appliance Manufacturer Conference & Expo, 2000,Cincinnati, USA
3. H-K Lee, J-T Heo, G-Y Song, K-B Park, S-Y Hyeon, Y-H Jeon, "Loss Analysis of Linear Compressor", International Conference on Compressors, I Mech E, 9-12 September, 2001, City University, London, UK
4. K.B Park, E.P. Hong, H.K. Lee, "Development of a Linear Motor ", Proceedings International Compressor Engineering Conference, 2002, Purdue University, West Lafayette, Indiana, USA
5. J.W. Kim, J-T Heo, J.D. Kim, S.Y. Hyeon, Y-H Jeon, "Linear Compressor for Natural Refrigerant", International Conference on Compressors, I Mech E, 7-10 September, 2003, City University, London, UK
6. K.B. Heo, H.K. Lee, C.W. Lee, M.K. Hwang, J.Y. Yoo, Y.H. Jeon, "Control of Linear Compressor", International Conference on Compressors, I Mech E, 7-10 September, 2003, City University, London, UK