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Restart Test Design For Inverter Compressors

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ABSTRACT

When a short power cut or electricity failure occurs on an electric supply system, which the household refrigerator is connected to, the suction and discharge pressures of the system become unbalanced, and the compressor exposes to higher loads than rated conditions. If the power recovers very quickly before the pressures get balanced, the compressor may not overcome the load and fails to start up. If the inverter control of the compressor has Class B protection software instead of mechanical overload protector; the inverter software forms a fault signal, cuts the energy through the compressor and waits for a while that provides pressure balancing before the next compressor start up trial.

Provided that the compressor starts up, or the inverter control cuts energy by a fault signal, the compressor periodically tries running in an infinite loop. This situation prevents compressor running and cooling of the refrigerator. In order to prevent this, the inverter board and the control software should be controlled at every load condition if it works properly or not.

Generally, a standard restart test is done to refrigerators by cutting the electricity off and energizing after a few seconds in order to check if the compressor starts up or a fault signal occurs. This test only checks one load condition and every different suction-discharge pressure value after power cut cannot be simulated that can occur in the field. Simulation of all loads on the refrigerator is a hard situation because providing variable suction-discharge pressure values on the refrigerator system is impossible and waiting for pressure balancing takes a long time for every load condition.

For this paper; a compressor restart test is studied without a refrigerator and an array of suction-discharge pressures that can occur against the compressor is determined in case of a short power off-on situation in order to check all load conditions of the refrigerator. The test is carried out by compressor- electronic control pairs on a cooling system simulator. The compressor test results are verified by testing the same compressors on the refrigerator.

1. INTRODUCTION

Refrigerator cooling cycle occurs by the heat transfer performed by the refrigerant. The refrigerant absorbs the heat from the cooling area and transmits to the environment. In this period, the compressor is in charge of compressing the refrigerant via its piston and increasing its pressure. Figure 1 shows the refrigerator cooling cycle and flow direction of the refrigerant with numbers ‘1’ to ‘4’. Summation of the cooling process is given below in order, with the numbers in Figure 1:

- 1-2 Compression of the refrigerant from low to high pressure .
- 2-3 Concentration of the refrigerating fluid by heat transfer at condenser .
- 3-4 Expansion and pressure decreasing at capillary tube.
- 4-1 Vaporization of the refrigerant at evaporator, by heat transition from the cooled area to the refrigerant.

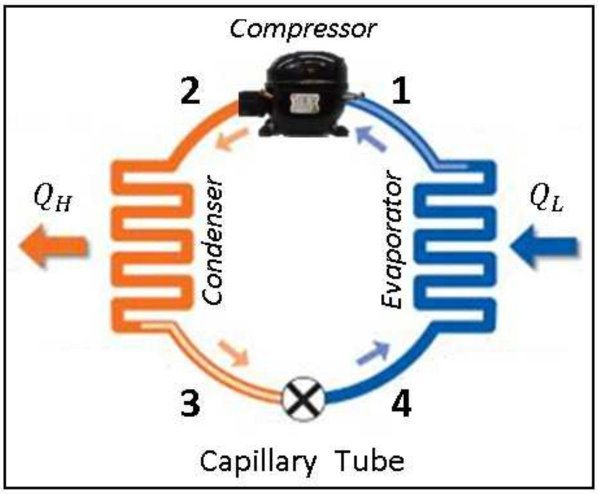

Figure 1: Refrigerator Cooling Cycle

'1' indicates suction port, '2' indicates dicharge port of the compressor. As Kim *et al.* (2009a) briefly described the start and restart operations of the reciprocating compressor, the start-up usually occurs when a pressure difference between suction and discharge port is nearly zero. In order to restart the compressor after it stops running, a temporary pause of starting is required until the pressure of the suction and the discharge port goes to an equilibrium state since the presence of the pressure difference between the suction and the discharge port acts as an excessive load to the motor for driving the compressor.

2. THE RELATIONSHIP BETWEEN RESTART OF INVERTER COMPRESSOR AND CLASS B SOFTWARE

An overload protector opens its contacts by sensing high current and/or temperature. The contacts close again in definite time at the protector's datasheet. While choosing an overload protector for an Inverter Compressor, closing time of the contacts should be long enough to balance suction and discharge pressures.

If the inverter compressor has Class B Protection, a time delay should occur on the motor control software in order to provide enough time for pressure balancing before energizing compressor. Kim *et al.* (2009b) mentioned that, the temporary waiting time for restarting is generally fixed to 5 minutes in a commercial refrigerator so that the compressor may start its operation before the pressure between the suction and the discharge port reaches a balanced state.
At Class B protection, motor control software has "Safety Related" functions that can detect abnormal and/or unsafety conditions to cut power and protect both the compressor and the control board. Some of these Class B functions are:

- Locked rotor fault
- Running Overload
- Loss of Phase
- Short circuit or open circuit failures of related electronic components.

By sensing any abnormal or unsafe condition, the software turns off the electronic control board in order to stop the compressor running. After waiting for the defined waiting time (in minutes), the electronic control board turns on and try to run the compressor again. This waiting and trial cycle repeats for a determined number of times until the compressor properly starts up. If the compressor still cannot start-up, the inverter board completely turns off without any other trials. If the power outage and recovery occur from the mains, the suction and discharge pressures may not have enough time to get balanced and the compressor may be exposed to an excessive load. In this case, either the compressor should start-up and run or Locked Rotor Alarm should occur by Class B software in order to start the waiting and trial cycle for restart. If start-up or locked Rotor Alarm do not occur, an infinite loop of trial of motor control software is in question which prevents cooling until unplugging the refrigerator and plugging again.

Class B Software is not only more reliable but also more complicated. That's why, it should be tested carefully because while it provides protection, it can cause functional problems of the compressor or inverter board in any missing working condition.

Kim *et al.* (2008) verified the effectiveness of a starting method using the reciprocating compressor load change system. A simplified refrigeration system is used to provide 10 pressure differences between suction and discharge ports of the compressor and starting current waveforms in order to check the starting method.
Kim *et al.* (2009c) also tested another improved starting method by using a similar test bed in order to adjust some specific suction and discharge pressure differences.

3. CURRENT START-UP AND RESTART TESTS APPLIED TO COMPRESSORS AND REFRIGERATORS

3.1 Restart Test of Refrigerators

Generally, a refrigerator is tested by cutting the electricity off and energizing after some seconds in order to check if the compressor starts up or a fault alarm occurs on the inverter board. But only one certain time gap between power cut and re-energizing refrigerator is applied at Restart Test in order to determine if the compressor properly starts up or how long or how many trials does it take for the compressor to start up at one condition.

But in real life, because the time interval between power outage and recovery is countless, the compressor load during restart is not clear. Since power recovery can be either in 1 second or 10 seconds or in minutes after outage; the suction-discharge pressures can be at any level during restart. But this test checks only one load condition that occurs after 10 seconds and cannot simulate other possibilities of the pressure difference between suction and discharge outlets during restart, which may occur on site.

3.2 Start-up and Stall Tests of Single Compressors

The test system shown in Figure 2, is used for starting or stall testing of a single compressor. In order to simulate the cooling cycle of a refrigerator during start-up or stall conditions. After fixing the compressor, R600a refrigerant is pumped into the system. The valves and manometers at both suction and discharge port provides adjusting the pressures.

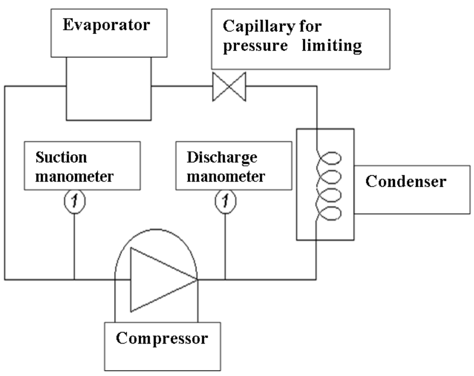

Figure 2: Compressor Start Up ans Stall Test System

Unlike start-up test, the compressor stall test is done by setting unequal pressures at suction and discharge ports. Discharge pressure levels that the compressor can reach and cannot reach can be seen at stall curves. If the stall curve of the compressor is below the stall curve of a refrigerator, the compressor is not compatible for that refrigeration system. The compressor should have enough shaft power to overcome the refrigerator load particularly at Pull Down point of the refrigerator at minimum working voltage and maximum working temperature. Stall curves of 2 different compressors and a refrigerator is seen at Figure 3, which shows that the 2 compressors can work properly on that refrigerator at the suction-discharge pressures indicated in the graph.

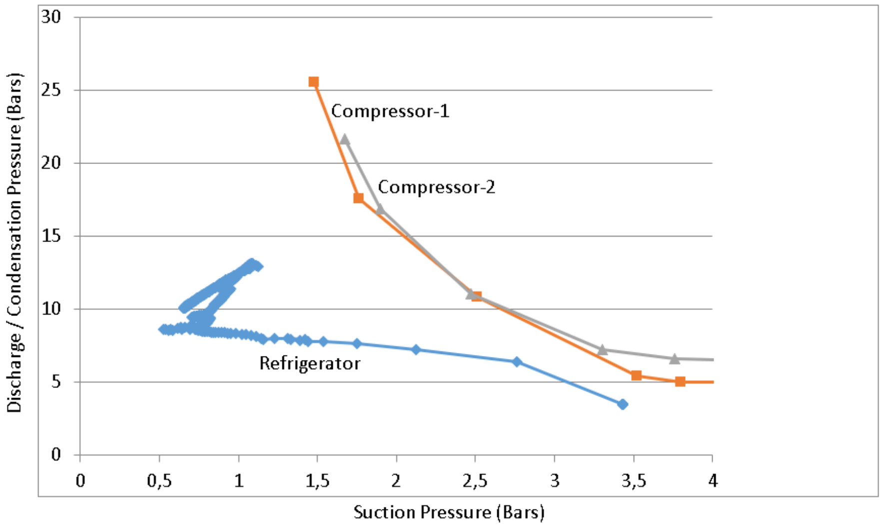

Figure 3: Comparison of Compressor and Refrigerator Stall Curves

3.3 The Reason Why a Restart Test is Necessary For Inverter Compressors

It is not possible to apply Stall Test to inverter compressors used by Class B protection, because the safety functions prevent the compressor to reach high suction pressures. The compressor start-up test only checks the compressor load at rated equilibrium pressure. Refrigerator Restart Test is the best way to simulate power off-on condition. But, simulation of all possible restart loads on a refrigerator is a hard situation because adjusting different suction-discharge pressure values on the same refrigerator system is not possible and waiting for pressure balancing takes a long time for every restart checking by power off – on. As Andrade and Negrao (2013a) explained, the experimental tests in order to check the performance of household refrigeration systems are expensive and time-demanding, e.g., a single start-up experiment can take more than 12 h to be performed. Guzella and Gomez (2017), Hermes and Melo (2018), Andrade and Negrao (2013b) studied on numerical simulations of household refrigerators during start up and cycling operations. Even if their results were close to actual measurements, discrepancies exist at some conditions. These models are useful for preliminary examinations but still needs to be verified by tests.

However, it is easy to test the start and restart compatibility of a single compressor and inverter board pairs without refrigerator. Therefore, a new test need arised to check if inverter compressors with Class B protection will start-up properly or not at any load when the refrigerator restarts.

4. STUDIES FOR TEST DESIGN AND DETERMINATION OF TEST METHOD

Every time a refrigerator runs and stops, rebalancing values of pressures at suction and discharge ports change. The balanced pressures of a newly produced and packaged refrigerator is different from that of a refrigerator that has been operated for a long time. Or balanced pressures of refrigerators with different capacities or designs are not the same even if they worked and stopped at the same condition. That’s why, there are too many suction-discharge pressure pairs at refrigerator restart after a power outage and back on case. However, the number of possible pressure pairs are limited by the refrigerator design.

The first task of the test design is to determine the test conditions by covering all possible loads, and to determine the boundary of suction and discharge pressure. Thereby; cooling, start – up, pull down and restart test results of current household refrigerator series are examined and all possible suction – discharge pressure pairs are listed within the limits of the cooling system design. Since the compressor loads during start-up are critical; not only the unbalanced pressure pairs that occur after a sudden power off-on case is determined, but also the balanced pressure pairs are listed. While suction pressure levels are obtained within 0.5 – 5.0 Bars, discharge pressure levels are obtained within 2.0 to 8.0 Bars. 38 pressure pairs are determined as testing condition.

It is also possible to design and establish a separate test system specifically to specifically check the restart compatibility of compressor- electronic control pair by simulating the working characteristics of the refrigeration system. In order to use the current source, the semi-anechoic Ccmpressor noise test chamber is used to adjust all 38 test conditions. The picture of the test chamber is shown in Figure 4.

Figure 4: Compressor Noise Testing Room

5. TESTS CONDUCTED AND THEIR RESULTS

At least 15 pcs of compressors were tested under the defined pressure pairs, and the test results were recorded on the Test format shown at Table 1.

Table 1: Compressor Restart Test Format

Explanation	Pressure Pair (Bars)		Compressor/inverter responses after inverter is energized at defined suction-discharge pressures		
	Suction Pressure	Discharge Pressure	No Start-Up, No Locked Rotor Alarm Occured (Infinite Loop)	Locked Rotor Alarm occured	Compressor Start-Up and run
Balanced Pressures	a	a			X
	b	b			X
	c	c			X
Un-Balanced Pressures	Min	Min		X	
	.	.			X
	.	.		X	
	.	.	X		
	Max	Max		X	

By evaluating and analyzing the relation between test results and pressure differences between suction and discharge ports, some test conditions that provide the same compressor load and have the same test results are removed. So that, number of test conditions are minimised in order to accelerate the test.

At first, temperature is also evaluated in order to simulate the compressor load for the compressor restart test. When the compressor is heated, the phase currents of the compressor motor change under each load. But since all possible pressure pairs are listed as a test condition, heating the compressors removed from test conditions.

The test is applied to compressors with different designs, cooling capacities, motors and inverters. In order to check the repeatability of the test, at least 3 compressors with the same properties are tested and 15 test results are compared.

Figure 5 shows two different examples of negative test results. At any suction-discharge pressure pairs of the test; if the compressor fails to start up, or if its inverter software does not issue a locked rotor alarm to cut off the energy passing through the compressor, it means that the test has failed. The compressor of motor, inverter hardware and/or software should be checked and revised until there will be no marking at "No Start No Locked Rotor" column shown at Figure 5.

Compressor Model: G, Inverter HW: H, Inverter SW: K

Compressor Suction Pressure (Bar)	Compressor Discharge Pressure (Bar)	No Start No Locked Rotor Alarm	Locked Rotor Alarm	Start Up
2,0	2,0			X
...	...			X
3,5	3,5			X
...	4,0			X
....	4,8	X		
...	3,5			X
0,5	4,5			X
...	....		X	
...	...		X	
...	5,0	X		
1,2	....			
1,2	8			
....	....	X		
...	5,2	X		
1,7	6,5		X	
....	5,5	X		
...	...	X		
2,2	7,2	X		
2,8	....	X		
....	...	X		
...	...	X		
3,3	...			X
3,6	4,5			X
3,7	...	X		
4,0	4,5			X
....	....		X	
4,0	6,3		X	

Compressor Model: J, Inverter HW: K, Inverter SW: L

Compressor Suction Pressure (Bar)	Compressor Discharge Pressure (Bar)	No Start No Locked Rotor Alarm	Locked Rotor Alarm	Start Up
2,0	2,0			X
...	...			X
3,5	3,5			X
...	4,0			X
....	4,8			X
...	3,5			X
0,5	4,5			X
...	....			X
...	...			X
...	5,0			X
1,2	....		X	
1,2	8	X		
....	....		X	
...	5,2		X	
1,7	6,5	X		
....	5,5		X	
...	...	X		
2,2	7,2		X	
2,8	....		X	
....	...	X		
...	...		X	
3,3	...		X	
3,6	4,5			X
3,7	...		X	
4,0	4,5			X
....	....			X
4,0	6,3		X	

Figure 5: Examples of Negative Test Results done to different Compressor, Inverter HW and SW Combinations

"No Start No Locked Rotor" columns are completely empty at Figure 6, which means the test results are positive. So the combination of compressor motor, inverter hardware and software can be reliably tested on refrigerator cabinets.

Compressor Model: A, Inverter HW: B, Inverter SW: C

Compressor Suction Pressure (Bar)	Compressor Discharge Pressure (Bar)	No Start No Locked Rotor Alarm	Locked Rotor Alarm	Start Up
2,0	2,0			X
...	...			X
3,5	3,5			X
...	4,0			X
....	4,8		X	
...	3,5			X
0,5	4,5			X
...	....			X
...	...			X
...	5,0			X
1,2	....			X
1,2	8		X	
....	....			X
...	5,2			X
1,7	6,5		X	
....	5,5			X
...	...		X	
2,2	7,2		X	
2,8	....			X
....	...		X	
...	...		X	
3,3	...		X	
3,6	4,5			X
3,7	...		X	
4,0	4,5			X
....	....			X
4,0	6,3		X	

Compressor Model: D, Inverter HW: E, Inverter SW: F

Compressor Suction Pressure (Bar)	Compressor Discharge Pressure (Bar)	No Start No Locked Rotor Alarm	Locked Rotor Alarm	Start Up
2,0	2,0			X
...	...			X
3,5	3,5			X
...	4,0			X
....	4,8			X
...	3,5			X
0,5	4,5			X
...	....			X
...	...			X
...	5,0			X
1,2	....			X
1,2	8			X
....	....			X
...	5,2			X
1,7	6,5		X	
....	5,5		X	
...	...		X	
2,2	7,2		X	
2,8	....		X	
....	...		X	
...	...		X	
3,3	...		X	
3,6	4,5			X
3,7	...		X	
4,0	4,5			X
....	....			X
4,0	6,3		X	

Figure 6: Examples of Positive Test Results done to different Compressor, Inverter HW and SW Combinations

Lee *et al*. (2008) monitored the starting current waveforms of the BLDC Motor used in the reciprocating compressor of household appliances by providing a pressure differences between the suction and the discharge port of the compressor, thereby optimized the motor control software to improve the starting. At this study, motor phase currents are also monitored by osciloscope during start-up, locked rotor and neither start-up nor locked rotor (infinite loop of start-up trial and fail). The differences between phase current waves of three different cases are shown in Figure 7, 8 and 9.

At start-up condition, the phase current fluctuates for a while until start up is done. After the start-up is done, the current flows around a stable level to make the compressor run, as shown in Figure 7.

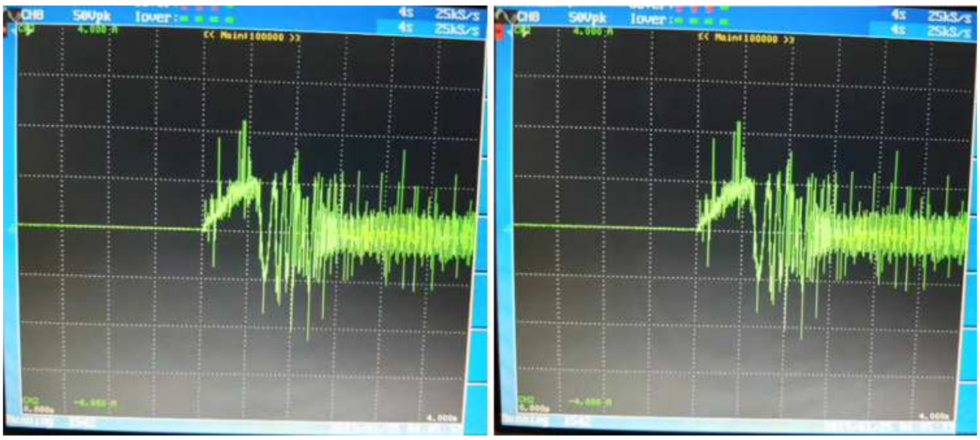

Figure 7: Oscilloscope Views of Motor Phase Current During Compressor Restart Test
Start up and Run Condition

At locked rotor condition, the software creates a false alarm, cuts off the energy through the compressor and calculates the time to wait for the next trial. That’s why, after locked rotor detection, the phase current directly goes to zero value as shown in Figure 8.

Figure 8: Oscilloscope Views of Motor Phase Current During Compressor Restart Test
Locked Rotor Condition

In the case of neither start-up nor locked rotor condition (That is, the test fails), the phase current distortion continues because the compressor cannot overcome the load for start-up as shown in Figure 9. In addition, the amplitude and duration of the current have not reached the locked-rotor current limit, so the motor control software cannot provide locked-rotor alarm. In this case, the motor control software continuously energizes the compressor without waiting of pressure balancing, and an infinite loop occurs which prevents cooling process.

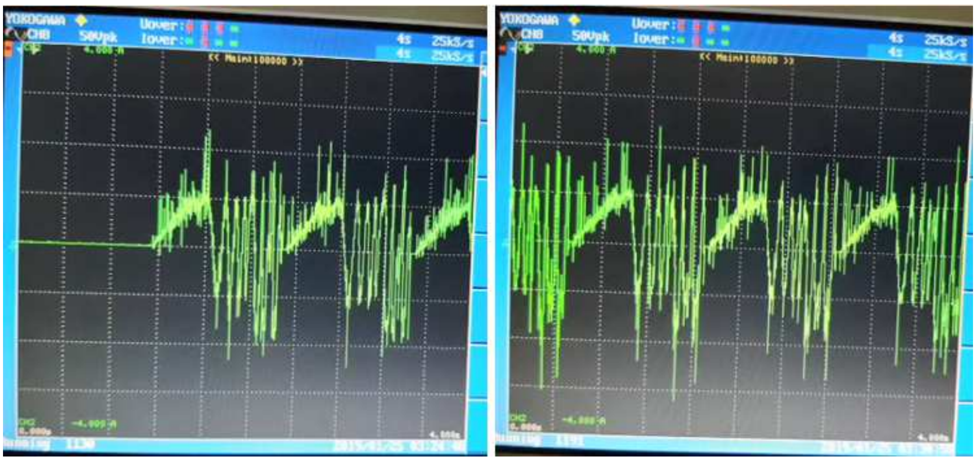

Figure 9: Oscilloscope Views of Motor Phase Current During Compressor Restart Test
No Start-up, No Locked Rotor Alarm (Infinite Trial Loop) Condition

6. CONCLUSIONS

In the beginning, some faults found in the refrigerator restart test triggered this research, and there was a need for compressor restart tests to reduce the workload and time allocated to refrigerator tests. Due to a software error, an infinite loop of continuous running trials were detected in the power off/on simulation. In particular, these malfunctioning compressor and inverter pairs are used to check whether the compressor restart test works properly, and detects the same malfunction seen in the refrigerator restart test. Therefore, the compressor restart test matches the refrigerator restart test, and the new test design is successful. With this new test, the motor software can be corrected and improved under test conditions that the compressor cannot pass. Tests are repeated by the improved software and good results of mutual verification will be obtained in the restart test of the compressor and the refrigerator.

The listed conditions determined for the new compressor restart test cover all possible compressor loads that may occur on the refrigeration system during any restart case of a household refrigerator.

In order to perform systematically, the new compressor restart test has become a standard procedure before engaging new platform compressor designs, the derivative of the existing designs, motor design change and motor control software change. Therefore, it is now possible to simulate all possible restart loads on the compressor in a short period of time without waiting for the pressure of the refrigerator to equalize. Through the compressor restart test, the detected faults can be seen and resolved in the early stages of the works, and then tested on the refrigerator to avoid wasting time.

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