Improving start up performance of single speed compressors by stator winding design

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Abstract. Some east countries have line voltage fluctuations and voltage drops which can cause cooling problems on refrigerators because compressors cannot start up at these low line voltages. That’s why not only COP, but also start up performance at low voltages is critical on single speed compressors. Torque-speed curves of single speed asynchronous motors are so critical for compressor start up performance which takes form by motor design. Depending on compressor mechanical efficiency and shaft power needed, the asynchronous motor winding design should be fine-tuned and torque speed curve should be adjusted for start up properly at low voltage values. Even when the start torque at 0 rpm and breakdown torque values are high enough to provide low voltage compressor starting, instant torque decreases along the curve negatively effects start up performance. This study analyses torque-speed curve characteristics of asynchronous motors and determines stator winding design methods to improve compressor start up performance. The findings are also validated with motor and compressor test results.

1. Introduction
Stators of single phase induction motors generate the maximum weight and cost within parts of single speed hermetic refrigeration compressors because of their concentrically winding structure, long end turns and production-quality necessities. Copper wires have been used for long years for stator windings which have good processing properties and high electrical conductivity. But ores of copper is decreasing while raw material prices are continuously increasing. In a price competitive environment of refrigeration compressor market, transition from copper to aluminium became inevitable which is lighter, cheaper and environment friendly. But if copper wire is directly changed to aluminium wire on the same motor design, the performance remarkably decreases. In order to provide the same performance obtained by copper wire stator, cross section of the aluminium wire should be 1.6 times increased, which is mostly not possible because of slot fillness limitations and productivity. That’s why the motor should be modified according to electrical and metallurgical properties of aluminium wire.

Household refrigeration compressors run at 220-240V or 115V 50/60 Hz at normal conditions. But depending on line voltage variations of different countries, the compressors should be able to start up at maximum 170-175 Volts.

Despite there are many papers regarding motor production with aluminium wire, there are very few information regarding criterias and key points of the motor design. By carrying similar copper wire design parameters to aluminium wire stators, high start-up voltage problem occured at compressors even the start torque and breakdown torque is high enough. In consideration of general induction motor
theory and design information which is scanned from literature with references [1], [2] and [3]; design studies are carried out. By software analysis and tests, it is found out that the reason of this high start up voltage is the Pull up torque. This paper will focus on determining the winding design parameters for aluminium stators in order to minimize or terminate Pull-up torque which directly effects compressor start up voltage.

2. Performance simulation and test methods
The software tool and test systems in order to use for designing aluminium wire motors, their performance simulation and prototype testing are explained below.

2.1. Motor design & simulation programme
SPEED software is provided as an aid for the design of electric motors and drives. It is based on a mathematical model which is published, recorded, or made available in sufficient detail so that the user can independently check it for accuracy and suitability. It is used to forecast motor start up performance by determining before motor prototyping and testing.

2.2. Statistical software for design of experiment (DOE)
Minitab Statistical Software is used in order to investigate the effects of aluminium wire stator design factors on pull up torque.

2.3. Compressor calorimeter test system
In order to measure the compressor input power, cooling capacity and COP values, calorimeter test system is used. The tests are done at Ashrae conditions.

2.4. Compressor start up test system
Motor prototypes are assembled to compressor and their start up performance is tested on compressor low voltage start up test system. The general view of the test system is seen in Figure 1 and schematics of the setup is given in Figure 2.
3. Design studies of aluminium wire stators

There are more than one points at torque speed curve of single phase induction motors which effects the compressor start up performance. The Locked Rotor Torque or Starting Torque is developed when starting at zero speed. The Break-down Torque is the highest torque available before the torque decreases when the machine continues to accelerate to working condition. The Pull-up Torque is the minimum torque which the motor drops off before the motor reaches from starting to break-down torque point.

Figure 3. Torque- speed curve of single speed induction motors

Depending on the motor design, production constraints, working conditions and inertia of compressor mechanical parts; one of these critical torques can be high which provides start up at low voltage by calculations, while the other can be low enough to effect start up performance negatively. This situation significantly appeared while testing the compressors with aluminium wire stator.

The work has started by switching from copper wire to aluminium wire without changing any motor design parameter for a small compressor with 55 Kcal/h at rated point. The motor was assembled to compressor and tested on calorimeter and LVS test system. COP decreased 0,08 W/W and start up voltage increased 30 Volts comparing with the original copper wire motor. In order to catch up the same efficiency and start up voltage of copper stator, 5 different design versions are studied with aluminium wire whose datas are given in Table 2. The same rotor is used for all design trials. Since the shape of stator lamination was fixed and there is a limit on slot fillness, main and start winding wire diameters were also kept the same. Only stack height and winding distributions has been changed. Ideally the winding distribution should be done in order to obtain a pure sine wave flux but it is practically changed to provide a balance between main and start winding losses and for efficiency-start up optimization. If
we give numbers to 24 slot stator lamination, the main winding and start winding distribution is as shown in Figure 4.

Figure 4. Winding Distribution Schematics

In Table 1, the number of main winding turns distributed to the first 5 slot is given in order and the number of start winding turns distributed from 7th to 10th slot is given in order which has 90°C settling with respect to main winding.

Table 1. Winding design data of aluminium wire stator designs

| Design Parameters | 55-D1 | 55-D2 | 55-D3 | 55-D4 | 55-D5 |
|-------------------|-------|-------|-------|-------|-------|
| Main Winding No of turns/slot | 163-165, 165-150-80-20 | 161-165-132-88-30 | 161-165-145-90-23 | 165-165-132-88-25 | 165-165-100-85-50 |
| Start Winding No of turns/slot | 20-55-97-97 | 18-37-84-78 | 34-81-78 | 25-33-80-78 | 50-60-97-97 |
| Stack Height (mm) | 42.5 | 42.5 | 42.5 | 38.5 | 38.5 |
| Main / Start Winding | 0.47 / 0.41 | 0.47 / 0.41 | 0.47 / 0.41 | 0.47 / 0.41 | 0.47 / 0.41 |
| Bare Wire Diameters (mm) |

Motor performance results of these 5 motors obtained by Speed software are given in Table 2. While studying different wire distributions in order to see their effect on start up performance, motor efficiencies are also tried to keep as high as possible and close to each other at rated torque value which is the steady state load of the compressor. The data in Table 2 shows that all 5 trials have similar results so that the start up performance can be checked without any hesitation.

Table 2. Motor performance data obtained by Speed software

| Performance Parameters | 55-D1 | 55-D2 | 55-D3 | 55-D4 | 55-D5 |
|------------------------|-------|-------|-------|-------|-------|
| Shaft Power (W) | 34.99 | 34.99 | 34.99 | 34.99 | 34.99 |
| Rated Torque (Nm) | 0.113 | 0.113 | 0.113 | 0.113 | 0.113 |
| Total Input Power (W) | 48.78 | 48.63 | 48.57 | 50 | 49.93 |
| Input Current (A) | 0.228 | 0.226 | 0.225 | 0.239 | 0.238 |
| Efficiency % | 71.75 | 71.96 | 72.06 | 69.98 | 70.1 |
| Wcu main | 5.03 | 5.40 | 5.46 | 6.42 | 5.74 |
| Wcu aux | 1.57 | 1.15 | 1.045 | 1.1 | 1.77 |
| Start Torque at 0 rpm (Nm) | 0.13 | 0.146 | 0.125 | 0.154 | 0.138 |
| Pull-up Torque (Nm) | 0.19 | 0.23 | 0.11 | 0.26 | - |
| Breakdown Torque (Nm) | 0.452 | 0.444 | 0.341 | 0.499 | 0.454 |
3.1. Torque - speed curves obtained by Speed software

The torque – speed curves of 5 aluminium wire designs are also given from Figure 5a to Figure 5e. It is clear to see the starting, pull up and breakdown torque points which are shown in Figure 3.

As seen in Figure 5a and 5c, there is a pull up torque with a sharp decrease on 55-D1 and 55-D3 motor curves. The common points of these two designs are that fifth slot of their main windings and the fourth slot of their start windings have the least number of turns comparing to other designs.

As seen in Figure 5e, there is no pull up torque on the curve of 55-D5. The torque value increases smoothly from start torque to breakdown torque. The main difference of this motor is that fifth slot of its main winding and the fourth slot of its start winding includes nearly double amount of turns than 55-D1 and 55-D3 motors.

As seen in Figure 5b and 5d, 55-D2 and 55-D4 motors have similar torque-speed graphs. They have similar winding distributions. Their start up torque and pull up torque values close to each other. The only difference is that 55-D4 have higher breakdown torque which is the result of lower stack height.

4. Compressor tests with motor prototypes

4.1. Compressor LVS test results

In order to avoid the effects of variability coming from compressor mechanical parts, the first LVS tests are done by changing the stator on the same compressor. The start up voltages of 55-D2 and 55-D3 compared with 55-D1 motors are given in Table 3. The worst start up performance within these 3 motors belongs to 55-D1 which is even couldn’t start even at rated voltages.
Table 3. Test results by changing the stator on the same compressor

| Compressor No | STATOR CODE | START UP VOLTAGE (V) |
|---------------|-------------|----------------------|
| Sample 1      | 55-D1       | 186                  |
|               | 55-D2       | 176                  |
| Sample 2      | 55-D1       | No start             |
|               | 55-D2       | 174                  |
| Sample 3      | 55-D1       | 191                  |
|               | 55-D2       | 177                  |
| Sample 4      | 55-D1       | 217                  |
|               | 55-D3       | 193                  |
| Sample 5      | 55-D1       | No start             |
|               | 55-D3       | 182                  |
| Sample 6      | 55-D1       | No start             |
|               | 55-D3       | 178                  |
| Sample 7      | 55-D1       | No start             |
|               | 55-D3       | 180                  |

The start up performance of 5 motor prototypes which are assembled to different compressors can be seen in Table 4. This time test results of compressor with copper wire mass production stators are also shown for comparison. The given start up voltage values for each stator design are the average values of multi-tests. Depending on the production varieties, the results of 55-D1 varies from 180V to No Start case. The best start up performance is obtained by 55-D5 stator which has no Pull up torque value.

Table 4. Compressor LVS test results with all stator designs

| STATOR CODE          | START UP VOLTAGE (V) |
|----------------------|----------------------|
| 55-D0 (Copper Wire) | 173                  |
| 55-D1                | 210                  |
| 55-D2                | 174                  |
| 55-D3                | 183                  |
| 55-D4                | 164                  |
| 55-D5                | 160                  |
| 55-D5 (increased test numbers) | 165 |
| 55-D5 (increased Stack height) | 171 |

Mostly, the test results of prototypes with limited numbers gets worse when the numbers increase or when it is taken into production. That’s why the number of tests were increased with 55-D5 stator which have the best start up performance. Since 165 V is still a safe value and there is a margin up to 175 Volts, stack height of 55-D5 is increased with the same winding distribution in order to increase COP value.
4.2. Compressor calorimeter test results

Since improving only start up performance is not enough and mostly the improved design parameter generates inverse proportion between start up and rated performance, the COP values and electrical data of all compressors with all designs have been measured. All test results given in Table 5 are average values of multi-tests for each stator design.

| Cooling Capacity (Kcal/h) | Input Power (W) | C.O.P | Input Current (A) | PWRFC | Stator Code |
|---------------------------|-----------------|-------|-------------------|-------|-------------|
| 53.5                      | 50.2            | 1.24  | 0.24              | 0.963 | 55 - D0     |
| 53.9                      | 51.0            | 1.23  | 0.24              | 0.955 | 55 - D1     |
| 54.4                      | 51.4            | 1.23  | 0.25              | 0.930 | 55 - D2     |
| 52.8                      | 50.3            | 1.22  | 0.25              | 0.925 | 55 - D3     |
| 53.1                      | 50.8            | 1.22  | 0.25              | 0.905 | 55 - D4     |
| 52.8                      | 51.0            | 1.21  | 0.27              | 0.846 | 55 - D5     |
| 54.1                      | 52.0            | 1.21  | 0.26              | 0.906 | 55 - D5     |

(Increased test numbers)

The summary of each motor design data and their test results are given in Table 6. According to these generated information, some points have been caught which are:

- However 55-D1 has the least main winding number of turns and highest breakdown torque, the compressors cannot start up at even rated voltages.
- Even 55-D3 has lower breakdown torque and pull up torque, the compressors’ start up performance with 55-D3 is better than with 55-D1 stator.
- 55-D2 has no start winding number of turns at 4th slot and it has the biggest Pull up torque decrease which gave high start up voltage.

5. Applying design for six sigma on a bigger motor frame

In order to verify the determinations on a small frame motor and see if the same keypoints are valid for bigger frame motors, design for six sigma is applied on a motor of a compressor with 170 kcal/h cooling capacity and Minitab software is used to analyse and monitor the results. The stator is named 170-D0 which has low slot fillness, so that winding parameters can be easily changed within high and low levels of Design of Experiment (DOE). DOE is created by using ‘Full Factorial’ approach by minimized design factors of 170 aluminium stator wire.
According to the prioritization matrix, it is defined that the most effective factors on compressor start up performance are main winding wire diameter, turns ratio (a), harmonic distribution of start winding and number of turns per each slot.

Since Speed Motor Simulation Software is based on mathematical calculations and modellings, there is no need to check its repeatability and reproducibility by Gage R&R analysis.

5.1. Full factorial approach
A DOE design is made by determining 2 levels for each factor with minimized design parameters. The low and high level values of each design factor is determined as given in Table 7.

| Factors used for DOE                                      | Low  | High |
|----------------------------------------------------------|------|------|
| Main Winding Wire Diameter                               | 0.67 mm | 0.73 mm |
| Start Winding Wire Diameter                              | 0.53 mm | 0.58 mm |
| No of turns / first main winding slot                    | 90    | 110   |
| No of turns / first start winding slot                   | 25    | 55    |
| No of turns / last main winding slot                     | 20    | 45    |
| No of turns / last start winding slot                    | 70    | 100   |

5.2. Pareto diagram
The most effective factors and interactions on Pull-up torque can be clearly seen on the Pareto Diagram given in Figure 6. These are the number of turns at fourth slot of start winding, first and last slots of the main winding and the main wire diameter.

![Figure 6. Pareto chart of the standardized effects](image)
5.3. Main effects and interaction plots
The most active factors on Pull up Torque is seen at main effect plots given in Figure 7 which shows that all the main effects are important. However, the least critical effect with respect to others is Start Winding First Slot.

![Figure 7. Main effect plots](image1)

![Figure 8. Interaction plots](image2)

According to the plots in Figure 8, the only interaction between first and last slots of the main winding seems important. The other interaction plots are not critical since the interaction curves are almost parallel to each other.

| Table 8. Comparison of before-after design data |
|-----------------------------------------------|
| Current Design Parameters | Parameters used for optimum results |
| Main Winding Wire Diameter | 0.70 | 0.73 |
| No of turns / first main winding slot | 100 | 90 |
| No of turns / first start winding slot | 35 | 45 |
| No of turns / last main winding slot | 42 | 55 |
| No of turns / last start winding slot | 85 | 70 |

According to DOE results, the optimum winding parameters are determined which are given in Table 8 together with Current design parameters of 170-D0 stator. With the new design, Pull up torque value 20% increased which remarkably improved the compressor start up performance.

6. Conclusions
Even the breakdown torque is high enough, existence of pull up torque negatively effects start up performance of compressors. If the pull up torque increases or disappears, the start up performance gets better which means that compressors start up at lower voltages.
Pull-up torque can be minimized or even prevented by adjusting main and start winding distribution through the slots / pole.
Start winding distribution has a remarkable effect on compressor start up performance.
The amount of torque decrease through the Pull up torque point is more effective than Pull up torque value.
There is no relation between pull up torque and turns ratio. Number of turns at main Winding first slot and start winding last slot should be kept as low as possible. Main winding wire, number of turns at the last main winding slot and the first start winding slot should be kept as high as possible. Pull up torque generation is more dependant to these specified criterias at aluminium wire motors than at copper wire motors. These criterias should be taken into notice by also optimizing motor efficiency and noise and will be used as input for single phase induction motor designs for hermetic refrigeration compressors.

References

[1] Cyril G. Veinott, D.Eng,(1994) Theory and Design of Small Induction Motors
[2] Fort Wayne, Ind. (1958) General Electric Design Data and Standards Small Integral Motor Engineering
[3] Speed Consortium PC-IMD Version 2.5 User’s Manual (1999) University of Glasgow Department of Electronics and Electrical Engineering