2021

Force Failure Dielectric Test Design For Stators Of Inverter Compressors

Tugba Cetinturk
Arçelik A.Ş. Compressor Plant, Turkey, tugba.cetinturk@arcelik.com

FORCE FAILURE DIELECTRIC TEST DESIGN FOR STATORS OF INVERTER COMPRESSORS

Tuğba Çetintürk

Arçelik A.Ş., Compressor Plant R&D Department,
Eskişehir, TURKEY
+902222134657, +902222134344, tugba.cetinturk@arcelik.com

ABSTRACT

(PMAC) Electric motor is used at Variable Speed Refrigeration Compressors. Stator is the stationary part of a PMAC motor and stator wires directly carry the current, which energizes the motor and runs the refrigerator compressors. These wires are wound on stator stack which is made of electrical steel. The windings can be also close to other metal parts of the compressor. Stator stack is connected to compressor metal parts by metal screws. So, if a leakage current occurs through the stator stack, it is directly conveyed to compressor housing and then to refrigerator which can cause electric shock on the customer. That's why, not only the quality but also the reliability of insulation between stator wires and metal parts is so critical.

Standard dielectric strength tests are applied to both stators and compressors during production in order to check the insulation quality for product safety in the field. But it is not possible to detect the weakness and aging in this way. Most insulaton faults arise in time by repetitive voltage increase, thermal, mechanical, environmental and electrical stresses.

This study explains the test which is carried out to detect potential electrical safety, leakage current and compressor failure problems which can occur on inverter stators in process of time. The development of Forced Failure Dielectric Test for the stators aims to uncover the insulation weakness which cannot be find out by Quality Tests and which can cause functional and safety problems in the field.

1. INTRODUCTION

In order to prevent electrical safety problems of a compressor, both internal and external insulation of the stator should be provided. Internal insulation means that the stator wires should be insulated from the stator stack. It is done by using paper insulation or plastic holders and/or by providing a minimum 2,5 mm clearance between wires and stack laminations. The enamel coating quality of stator wires is also critical and it shouldn't get damaged during the stator winding or compressor assembly process.

External insulation means that the stator wires and lead terminals should be insulated from other metal parts of the compressor again by using an insulator and/or by providing a minimum 2,5 mm clearance. This should paid attention to during the structural design of the compressor. Otherwise, unworking compressors and/or electrical safety problems can occur at the site.

Stone and Culbert (2018a) mentioned the diagnostic tests such as insulation resistance, polarization index, dissipation factor, capacitance and partial discharge that can be useful to diagnose the condition of the stator winding insulation, and identify many problems that could lead to insulation failure. From all these tests; Hi-pot, Insulation and Leakage Current tests are applied to each produced compressor for 1 second each, at the end of the compressor assembly lines. But these tests cannot guarantee to reveal the ground faults that can occur in time while working on the site. Stone and Culbert (2018b) also examined the literature and practical experience using the remaining life estimation tools for stator winding. The purpose of this study is finding a force failure test method in order to prevent compressor failures, leakage current and electrical safety problems by determining the potential electrical faults on stators of inverter compressors in time. The development of the forced failure dielectric test for PMAC stators aims to find insulation defects, which cannot be detected by quality tests, and can cause functional and safety problems in the field. So, if any potential and sleeping faults or weakness exist at winding insulation, the new test can reveal it and make it possible to prevent usage of the weak insulated stators on compressors.

2. PHYSICS OF INSULATION FAILURES AT HOUSEHOLD COMPRESSORS

Factors effecting insulation resistance include temperature, humidity, insulation thickness, mechanical stress and applied voltage. Since household refrigerating compressors are hermetic and include no moisture, we skip the effect of moisture on the insulation at this paper. Instead; temperature, insulation dimensions and voltage can be used as a stress factor in order to accelerate the test for rapid aging and failing of test stators.

Ambient Temperature: Tommasini (2009a) stated Montsinger's rule, that a temperature rise of 10K halves the expected lifetime of an insulation system. ABB Industrial Systems (1997) showed the relation between temperature and insulation life at Figure 1. That is, increase of temperature decreases the insulation life.

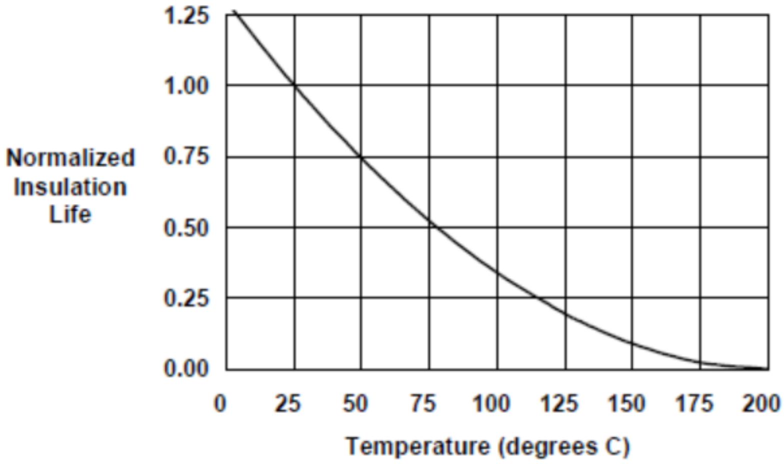

Figure 1: Insulation Life vs. Temperature

Ritamäki *et al.* (2017) said that the exposure to elevated temperature may have caused material degradation leading to more low field breakdowns. It is also pointed out that the measurements conducted in the temperature range from room temperature to 100 °C revealed a linearly decreasing trend in the characteristic 63.2 % breakdown probability after 60 °C and the presence of a smaller weak spot subpopulation.

High Dielectric Voltage: Electrical appliances are designed to operate within a defined range of voltage. If the operating temperature is increased gradually at some value of voltage, the breakdown of the insulating materials will occur. Applying a gradually increasing voltage to the stator winding or any conductor will definitely destroy the insulation. That's why breakdown voltage is always a working stress factor at stator force failure tests. ZVEI (2016) pointed out that the penetration through the insulation material, a voltage increase of 500V/sec. is commonly used. However, it is difficult to perform a Reliasoft analysis because the time data of insulation failure cannot be obtained by applying breakdown voltage.

Gupta *et al.* (2009) reported that Hipot tests fail marginal, not good windings; and AC Hipot test is better in detecting winding defects than DC hipot test. Grubic (2008) suggests the development of an online-monitoring method applicable to low-voltage machines, which is capable of diagnosing the deterioration of the turn-to-turn insulation prior to a fault and is also reasonable from a cost standpoint. In this study, both the fixed high-potential voltage and the gradually increasing high-potential voltage have undergone different test designs.

Insulation Dimensions: Tommasini (2009b) reported that failure of dielectric insulation is often determined by a direct or indirect mechanical failure and a good designer ensures the design correctly considers operation & fault conditions. These expressions can be paraphrased that in order to overcome mechanical stress that the windings are exposed during production or working conditions, choosing the correct insulation height, width and thickness is critical. For this reason, the effects of insulation thickness and height along the stator slots can be also used to prepare test samples with different insulation qualities and to check if the test properly distinguishes the good and bad stators.

Metal Burrs: Insulation thickness should be considered as not only the thickness of insulating material, but also the amount of clearance between enameled wires and metal parts. It is easy to control the design and production tolerances. But if a metal burr occurs and falls on the stator, it can provide a connection between wires and metal parts within the compressor. Preventing metal burrs inside the compressor is very difficult. That’s why it should be used as a force failure effect on this test design.

3. TEST DESIGN STUDIES

The connection between Stator Life and Stress is used to design this force failure test. Two types of stress is used in order to accelerate the test. One is the internal stress, that is caused by weak insulation of the stator itself, which simulates design faults. The other type is the external stress, that occurs by stator working conditions inside the compressor.

3.1 Preparing Test Samples

In order to generate the internal stress, two different stator models A and B are choosen as test sample, one of which has lowest and the other has highest power shaft at current product range. Arc failures occured in the past especially on these two models which couldn’t have catched by Electrical Safety tests at the production line. After some detailed examinings, it is found out that, arc failure problems are caused by low slot insulation height, thickness and high slot fillness of these stators. That’s why; insulation thickness, insulation height and slot fillness parameters are used to prepare stator samples for validation of this test design. 3 stress factors with two levels and half- fractional factorial experiment design is done for Stator A as shown at Table 1. In order to prepare samples of Stator B, only 2 levels of slot fillness is used as shown at Table 2.

Table 1: Stress Factors Applied to Test Samples of Stator A

Stress Factors of Stator A	Stress Level (-)	Stress Level (+)
Thickness of Slot Insulation (mm)	0,25	0,35
Height of Slot Insulation (mm)	24,5	25,5
Slot Fillness %	70	85

Table 2: Stress Factors Applied to Test Samples of Stator B

Stress Factors of Stator B	Stress Level (-)	Stress Level (+)
Slot Fillness %	81	94

Stator A samples, with (-) level of thickness and height and (+) level of slot fillness are expecting to fail during the designed test. B stator samples with (+) level of slot fillness are expecting to fail during the test. The remaining samples are expecting to pass the test. Test conditions and test method, which will provide the expected test results will be assigned and fixed accordingly. Table 3 explains the coding of prepared test samples according to their properties described at Table 1 and Table 2. **A_2, A_3** and **B_6** Stators should certainly fail, **A_1** and **A_4** Stators should certainly pass the test.

Table 3: Coding of Test Samples According to Stress Factors

Sample Code	Insulation Thickness (mm)	Insulation Height (mm)	Slot Fillness %
A_1	0,25	25,4	70
A_2	0,25	24,5	70
A_3	0,25	24,5	85
A_4	0,35	25,4	70
B_5	0,25	34,5	81
B_6	0,25	34,5	94

In order to see the repeatability of the test results, 2 different samples are tested from each sample code. For example; "**A_1-1**" and "**A_1-2**" are the first and second sample that both have 0,25 mm insulation thickness; 25,4 mm insulation height and 70% slot fillness.

3.2 Test Equipments

Figure 1 shows the oven which is used to heat the stators at a fixed temperature for aging.

Figure 1: Regulated oven in order to heat the stators up to 200°C.

Adjustments of electrical safety tester are done by setting AC Hipot Voltage, AC Frequency (50 Hz), leakage current limit and testing time as shown in Figure 2.

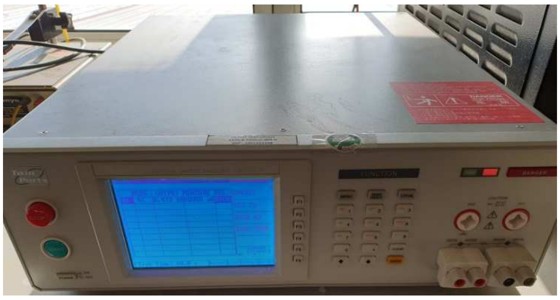

Figure 2: Electrical Safety Tester for Hi-pot (Dielectric Strength) Measurement

In order to do necessary cabling between electrical safety tester and stator sample inside the oven; additional test cables are used, which hang down from top to inside of the oven. Phase terminal of electrical safety tester is connected to stator cluster plug of which 3 phase windings are short circuited. Notr terminal of electrical safety tester is connected to stator stack from one of the screw holes as shown in Figure 4.

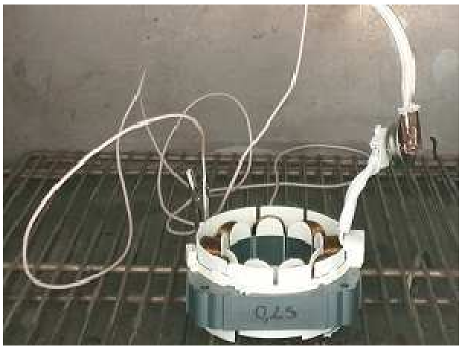

Figure 4: Application of Hi-pot Test to Compressor Stators

3.3 Determiming Test Method and Test Conditions

Temperature exposure and applying Hi-pot Voltage is chosen first in order to accelerate the failures of the stator samples. Table 4 shows the stres levels applied to stator samples for rapid aging. Design of Experiment (DOE) with 2x2 Factorial Design is generated according to Six Sigma Methodology and four different test conditions are applied to stator samples in order to accelerate the aging and failure.

Table 4: Stress Factors and Levels used at Test Design 1

Stress Factors	Stress Level (-)	Stress Level (+)
Temperature (°C)	150	200
Hi-pot Voltage (V_{ac})	2000	2500

Hi-pot Voltage is applied between live ends of stators samples and stator stack for 1 minute, before heating. 1 hour period is fixed to make the stator samples wait at the defined high temperatures. After aging the stators by heating and applying Hipot voltage, 2800 Vac constant dielectric voltage continuously applied between stator conductors and chasis (stator stack) in order to record the duration until the stator fails. Failing criteria is chosen maximum 1,8 mA leakage current. But the samples never failed. That's why, time dependent datas couldn't be generated for Reliasoft Weibull Analysis by Test Design 1.

Table 5: Stress Factors and Levels used at Test Design 2

Stress Factors	Stress Level (-)	Stress Level (+)
Iron Sand splashed on stators (grams)	5	10
Temperature (°C)	150	200
Hi-pot Voltage (V_{ac})	2000	2500

Table 5 indicates the stress levels applied to the stator samples in order to fail the stators in the second test design. This time, in addition to the same stress factors and levels of Test Design 1, some specific amount of iron sand is randomly splashed on stator samples in order to simulate metal burrs that can reach stator wires inside the compressor. After aging the samples by the stress levels shown in Table 4, 2000V ac voltage is applied continuously between stator conductors and chassis (stator stack) in order to record the duration until the stator fails. Failing criteria is again chosen maximum 1,8 mA leakage current. This time, all the samples immediately failed by the effect of metal burrs.
Since time dependent datas couldn’t be generated by the first two Test Designs, a different test method is studied. In Test design 3, a fixed amount of iron sand was sprayed on all stator samples to accelerate the test, and a high voltage of 2000V was applied to the stator again to age it, and then heated. After heating the stators at 3 temperature levels for 1 hour; a high dielectric voltage is gradually applied to the stator and the leakage current is recorded at each voltage level until it reaches 1.8 mA. If a leakage current of any sample is measured higher than 1,8 mA; it is defined as failure and test stopped at that Hi-pot voltage level. “Hi-pot” is written to show the failure of each tested stator. Table 6 shows the leakage current values obtained at each Hi-pot voltage and heating temperature level.

Table 6: Results Obtained By Test Design 3.

Test Samples	Temperature (°C)	Measured Ground Leakage Currents (mA) during application of Hi-pot Voltages for 1 Minute (Max limit: 1,8 mA)						
		500V	750V	1000V	1250V	1500V	1750V	2000V
A_1-1	25	0,068	0,103	0,139	0,179	0,225	Hi-pot	
	150	0,073	0,11	0,164	Hi-pot			
	200	0,077	0,12	Hi-pot				
A_1-2	25	0,067	0,103	0,0137	0,177	0,237	0,294	Hi-pot
	150	0,088	0,132	0,182	0,247	Hi-pot		
	200	0,09	0,137	0,188	0,251	Hi-pot		
A_2-1	25	0,081	0,124	0,167	Hi-pot			
	150	0,086	0,13	0,179	Hi-pot			
	200	0,088	0,133	0,184	0,245	Hi-pot		
A_2-2	25	0,084	0,127	0,172	0,219	0,274	0,342	Hi-pot
	150	0,083	0,127	0,174	0,237	Hi-pot		
	200	0,087	0,131	0,179	Hi-pot			
A_3-1	25	0,065	0,1	0,135	0,172	0,23	Hi-pot	
	150	0,081	0,124	0,169	Hi-pot			
	200	0,083	0,125	0,17	Hi-pot			
A_3-2	25	0,067	0,103	0,138	0,177	0,236	Hi-pot	
	150	0,075	0,114	0,156	0,212	Hi-pot		
	200	0,08	0,122	0,167	0,226	Hi-pot		
A_4-1	25	0,212	0,425	0,746	Hi-pot			
	150	0,164	0,332	Hi-pot				
	200	Hi-pot						
A_4-2	25	Hi-pot						
	150	Hi-pot						
	200	Hi-pot						
B_5-1	25	0,307	0,596	Hi-pot				
	150	Hi-pot						
	200	Hi-pot						
B_5-2	25	Hi-pot						
	150	Hi-pot						
	200	Hi-pot						
B_6-1	25	0,1	0,151	0,204	0,26	0,339	0,505	Hi-pot
	150	0,107	0,161	0,22	0,306	0,433	Hi-pot	
	200	0,112	0,168	0,229	0,31	0,419	Hi-pot	
B_6-2	25	Hi-pot						
	150	Hi-pot						
	200	Hi-pot						

The test results in Table 6 are checked to determine the temperature level and Hi-pot voltage limit that can distinguish a good insulated stator from a weakly insulated stator. **A_1** and **A_4** Stators are supposed to fail at high voltages and, **A_2, A_3** and **B_6** Stators are supposed to fail at low voltages. But on the contrary; A_4 and B_6 fail quickly, A_1, A_2 and A_3 fail at higher voltages. This complicated results are attributed to using iron sand, it is removed from stress factors of the test design.

Table 7: Results Obtained By Test Design 4.

Test Samples	Temperature (°C)	Measured Ground Leakage Currents (mA) during application of Hi-pot Voltages for 1 Minute (Max limit: 1,8 mA)										
		500V	750V	1000V	1250V	1500V	1750V	2000V	2250V	2500V	2750V	3000V
A_1-1	25	0,078	0,118	0,159	0,206	0,268	0,34	0,43	0,522	0,605	Hi-pot	
	150	0,082	0,124	0,175	0,254	0,358	0,46	0,579	0,756	Hi-pot		
	200	0,084	0,127	0,175	0,258	0,347	0,456	0,597	Hi-pot			
A_1-2	25	0,071	0,108	0,144	0,187	0,256	0,342	0,434	0,523	0,597	Hi-pot	
	150	0,08	0,121	0,177	0,253	0,35	0,454	0,558	0,668	Hi-pot		
	200	0,084	0,127	0,175	0,26	0,352	0,456	0,583	Hi-pot			
A_2-1	25	0,078	0,118	0,159	0,21	0,285	0,375	0,468	0,549	0,605	Hi-pot	
	150	0,084	0,127	0,182	0,26	0,363	Hi-pot					
	200	0,084	0,127	0,174	0,26	Hi-pot						
A_2-2	25	0,076	0,115	0,154	0,207	0,276	0,362	0,456	0,542	0,598	Hi-pot	
	150	0,081	0,124	0,176	0,253	0,35	0,453	0,555	0,699	Hi-pot		
	200	0,083	0,126	0,171	0,255	0,346	0,448	0,585	Hi-pot			
A_3-1	25	0,073	0,11	0,147	0,187	0,26	0,344	0,435	0,524	0,606	Hi-pot	
	150	0,078	0,118	0,163	0,229	0,317	0,417	0,511	Hi-pot			
	200	0,079	0,119	0,164	0,224	0,307	0,402	Hi-pot				
A_3-2	25	0,071	0,108	0,145	0,188	0,257	0,342	0,433	0,521	Hi-pot		
	150	0,077	0,116	0,159	0,225	0,315	0,414	0,501	Hi-pot			
	200	0,077	0,116	0,161	0,22	0,302	0,325	Hi-pot				
A_4-1	25	0,069	0,105	0,142	0,177	0,222	0,288	0,365	0,443	0,51	0,572	Hi-pot
	150	0,073	0,112	0,151	0,206	0,277	0,36	0,439	0,519	Hi-pot		
	200	0,075	0,114	0,152	0,211	0,278	0,354	0,44	0,558	Hi-pot		
A_4-2	25	0,066	0,101	0,136	0,171	0,214	0,276	0,35	0,43	0,495	0,554	Hi-pot
	150	0,071	0,107	0,145	0,203	0,274	0,354	0,436	0,522	Hi-pot		
	200	0,073	0,11	0,15	0,204	0,271	0,347	0,438	0,617	Hi-pot		
B_5-1	25	0,091	0,137	0,184	0,231	0,322	0,429	0,552	0,677	0,739	Hi-pot	
	150	0,098	0,149	0,209	0,304	0,425	0,563	0,705	Hi-pot			
	200	0,103	0,155	0,215	0,315	0,433	0,572	0,719	Hi-pot			
B_5-2	25	0,086	0,129	0,174	0,219	0,299	0,4	0,516	0,645	0,759	0,879	Hi-pot
	150	0,093	0,14	0,194	0,284	0,4	0,534	0,665	0,812	Hi-pot		
	200	0,097	0,147	0,203	0,293	0,409	0,544	0,68	Hi-pot			
B_6-1	25	0,095	0,143	0,192	0,241	0,331	0,442	0,578	0,712	Hi-pot		
	150	0,104	0,156	0,217	0,324	0,448	0,595	0,746	Hi-pot			
	200	0,109	0,165	0,225	0,331	0,449	0,601	Hi-pot				
B_6-2	25	0,093	0,141	0,189	0,237	0,325	0,434	0,564	0,702	0,826	Hi-pot	
	150	0,101	0,152	0,214	0,314	0,436	0,581	Hi-pot				
	200	0,105	0,159	0,218	0,315	0,436	Hi-pot					

When we check the test results in Table 7; after heating at 200°C, most of the weakly insulated stators will fail, and the good insulated stators will pass 2000 V high voltage application. Leakage current values of all samples at 2250, 2500 V and 2750V are also checked. Decreasing leakage current limit from 1.8 mA to 0.75 mA, seems to distinguish the good and weak stators more clearly at 2000 V dielectric voltage.

4. RELIASOFT ANALYSIS

"Temperature-Nonthermal" method is used for analysis at Reliasoft ALTA module, because voltage and insulation quality is used as a stress factor together with temperature. The graph of "Stator Reliability change vs Time" is given in Figure 5, according to metal burr and temperature exposing. The figure shows that the effect of high temperature is small, but no matter whether the insulation quality of the stator is good or weak, metal burrs will have a significant impact on the life of the stator.

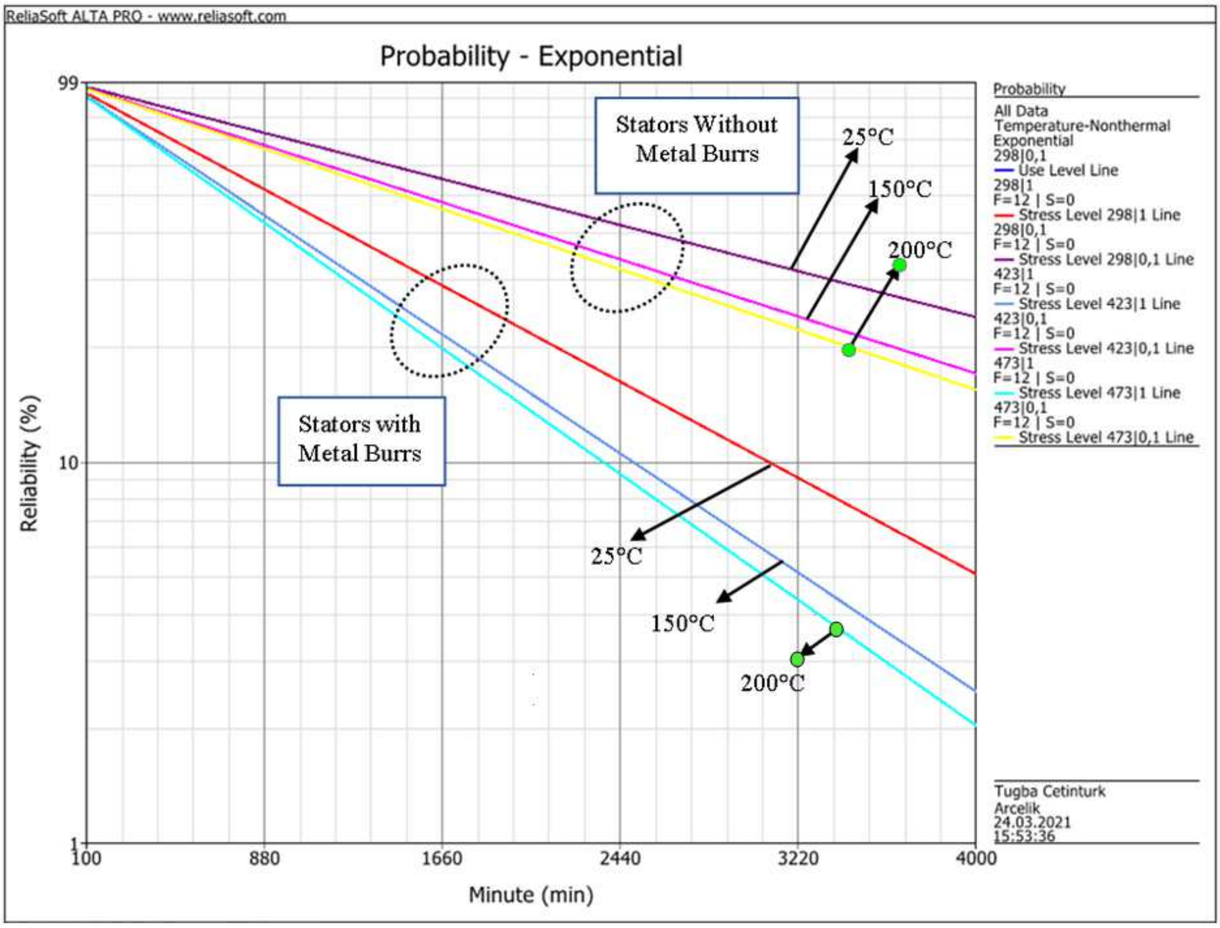

Figure 5: Effect Of Metal Burrs and Temperature on Stator Reliability

The graph in Figure 5 also verifies that a temperature level of 200°C should be used as the stress factor to accelerate the aging of the stator in the forced failure dielectric test. On the other hand, metal burrs shouldn't be used for this test, because it fails both good and weak insulated stators.

Figure 6 compares the reliability of the stators with good and weak insulation under abnormal conditions used for the Forced Failure test design. The purpose of this test is failing all the stators with a distinct aging speed at good and weak insulated stators. The graph at Figure 6 shows that it is achieved. So that the reliability slope of the weak insulated stators is sharper than the reliability slope of the good insulated stators.

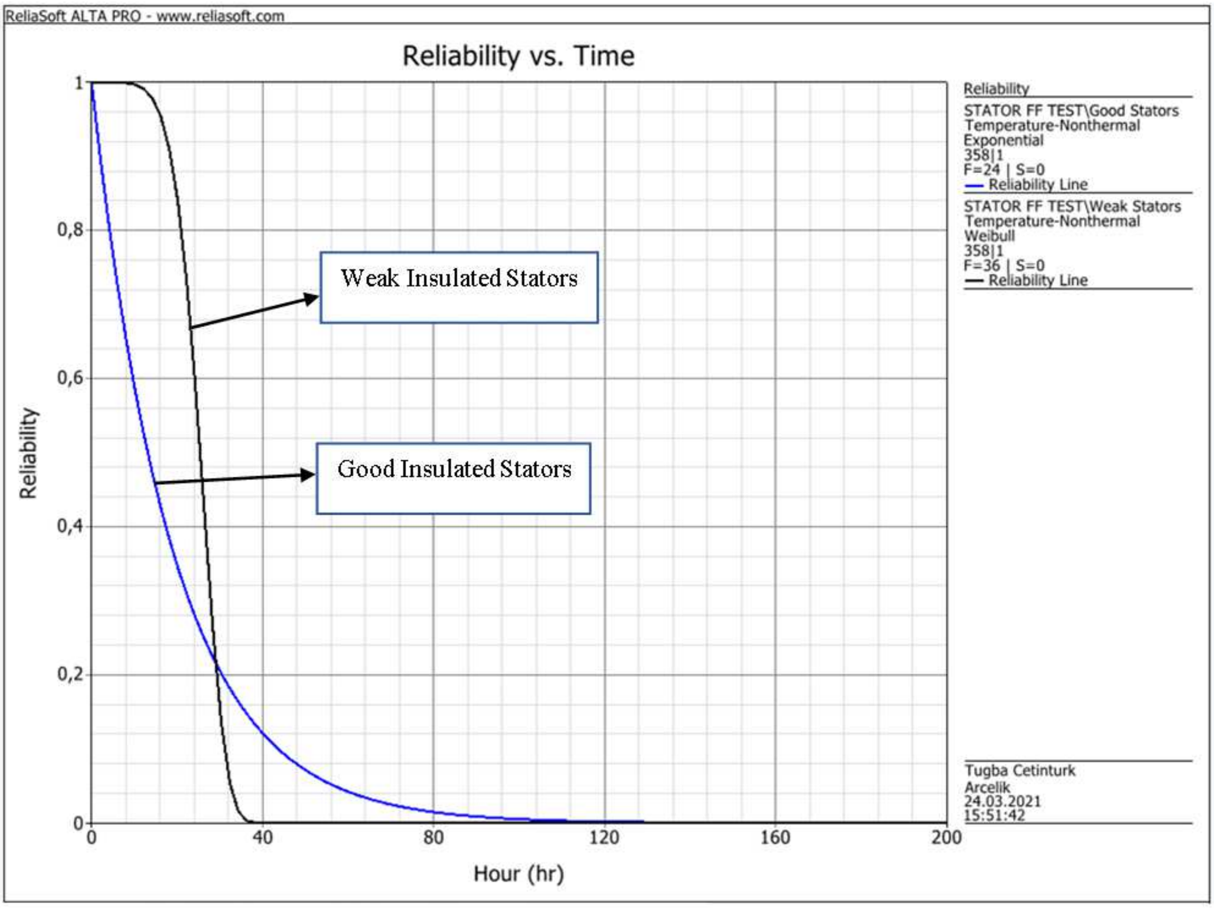

Figure 6: Effect of Insulation Dimensions & Slot Fillness On The Stator Reliability

5. CONCLUSION

The most important parameter on stators is electrical insulation in order to provide both compressor quality and safety. If the stators have not apparent insulation faults but weaknesses that can emerge after working for a while at site, the standard tests can not reveal them. There is no time for long life tests for ongoing productions either. That's why, determining the potential or sleeping insulation problems of stators in a short time is very important.

By evaluating the results of 4 different testing methods and reliasoft analysis, the forced failure test of the inverter compressor stator is shaped and designed. The test instruction is finalized as follows:

At ambient temperature, a fixed 2500 Vac dielectric voltage will be applied to the stator sample for 1 minute. If the stator fails during this test, test result is recorded as "negative" and the test is stopped. If the stator passes the 1 minute 2500 Vac Dielectric voltage test, it is kept inside a 200°C oven for 1 hour. After heating for 1 hour; without taking it out of the oven, apply 500 V/min gradually increasing high voltage voltage to the stator, up to 2000V. Maximum 0,75 mA leakage current limit is defined for each 500 V, 1000 V, 1500 V and 2000 Vac voltage application to the tested stator. If the stator fails at any of these voltages, test result is negative.

This Force Failure Dielectric Test is put into use systematically on control plans of both inhouse stator production and outsourced stators for inverter compressors.

This test study showed that heating stators at high temperature values, which are higher than thermal resistance of the stator wires and paper insulations do not provide rapid aging. Continuous application of high dielectric voltage will not accelerate stator failures in isolation and reveal their insulation defects. But applying gradually increasing dielectric voltage has a big effect to find out the stator sleeping weaknesses.

If the size of the insulating layer is not large enough to cover the steel wall in the slot, the dielectric strength of the stator will decrease in a short time. Also, if the slot fillnesses of stators are so high, mechanical stress occurs on stator insulation, wires and paper insulations can be damaged or torn; plastic insulations can be deformed.
It should also be noted that if any number of compressor metal burrs fall or reach the stator, both good and weak stators will fail quickly rather than in time. Since permanent magnets are used at inverter compressors, it is difficult to keep the metal burrs away from compressor components, but it is essential to provide compressor safety.

6. REFERENCES

ABB Industrial Systems, Inc. (1997). *Technical Guide No. 102 - ABB*. https://library.e.abb.com/public/fec1a7b62d273351c12571b60056a0fd/voltstress.pdf.

Failure Reasons for Insulations - ZVEI. (2016). https://www.zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/2015/mai/Failure_Reasons_for_Insulations/Failure_Reasons_for_Insulations-Rev-May2016.pdf.

Grubic, S. (2008). *A Survey on Testing and Monitoring Methods for Stator Insulation Systems of Low-Voltage Induction Machines Focusing on Turn Insulation Problems*. IEEE Xplore. https://ieeexplore.ieee.org/document/4624549/.

Gupta, B. K., Stone, G. C., & Stein, J. (2009). *Stator winding hipot (high potential) testing*. IEEE Xplore. https://ieeexplore.ieee.org/document/5166381.

Ritamäki, M., Rytöluoto, I., & Lahti, K. (2017). Temperature Effect on Breakdown Performance of Insulating Polymer Thin Films. *Proceedings of the Nordic Insulation Symposium*, (24). https://doi.org/10.5324/nordis.v0i24.2288

Stone, G. C., & Culbert, I. (2018, June 5). *Prediction of Stator Winding Remaining Life From Diagnostic Measurements*. Iris Power. https://irispower.com/learning-centre/prediction-stator-winding-remaining-life-diagnostic-measurements/.

Tommasini, D. (2009). *Dielectric Insulation & High Voltage Issues*. https://cas.web.cern.ch/sites/cas.web.cern.ch/files/lectures/bruges-2009/tommasini.pdf.