Single-Phase Induction Motor Design Optimization for Hermetic Rotary Compressor in Heat Pump Water Heating Applications

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ABSTRACT

Energy-efficient household appliances and the substitution of fossil fuels in heating systems are a constant matter in the development of new technologies. An example is the shift of water heating systems from fuel-burning equipment towards hermetic rotary compressors powered by the electrical power system. The hermetic compressors' original application is in air conditioning systems, where air is the objective for cooling and heating, now, in this new application, the thermal load changes for water, requiring an adaptation of the compressor operating envelope. The hermetic compressor operating envelope is the range of evaporating and condensing temperatures, that translates into the electrical motor torque requirements. The electrical motor is also required to work with a voltage range from the power supply, that changes in each country and each state, and affect the motor design. The electrical motor type is a single-phase induction motor with an aluminum squirrel cage rotor, with a permanent split-capacitor (PSC) connection. This type of motor changes significantly its behavior with the power supply voltage variation. This work presents the new application envelope and the motor design optimization workflow to achieve the highest efficiency motor with the capability to have a reliable operation in the new application with the required voltage range. The electrical motor requirements consist of three main objectives: 1) achieve the highest efficiency possible in the rated condition with the rated power supply; 2) reliable operation, without overheating, with the maximum voltage power supply under the minimum load condition in the operating envelope; and 3) reliable operation, without stalling nor overheating, with the minimum voltage power supply under the maximum load condition in the operating envelope. The electrical motor design workflow uses analytical software for electromagnetic simulation and an optimization tool coupled to it. The simulation setup can run several combinations of motor stack height, winding distribution, and capacitor values, and move toward the configuration that fulfills the constraints and optimization target. Finally, it presents the electrical motor final design test results in the dynamometer and the hermetic compressor results in the calorimeter, showing the achievement of previously determined restrictions and targets.
Keywords: rotary compressor, water heater, heat pump.

1. INTRODUCTION

According to the U.S. Annual Energy Outlook (2022), water heating is the third most energy consumer in residential buildings, making it a key factor in the study of electrical efficiency improvement and alternative energy sources. The report also shows that U.S. residential buildings have more than 50% of their energy consumption from burning natural gas, petroleum, and other liquids, instead of using electricity.
Increasing the efficiency of electrical water heaters is a turning point to decrease fuel consumption in households and impact positively the whole country's power grid energy consumption. Using rotary hermetic compressors for water heaters is one method to improve its efficiency.
This study will discuss the procedure to map a water heater appliance to determine the compressor working conditions and optimize the electrical motor design to run in this envelope with reliability and achieve the highest efficiency possible for a single-phase induction motor (SPIM) with permanent split capacitor (PSC) connection.
SPIM are widely used in domestic appliances due its simplicity and reliability, but due the high number of induction of motors in many applications, the high efficiency became of great importance (Mademlis *et al*, 2005a).
The SPIM consists of a stator magnetic core, with main and auxiliary windings, and a rotor magnetic core with a die-cast aluminum squirrel cage. The PSC connection is the use of an electrolytic capacitor permanently connected to the stator windings, since the compressor starts and up to the continuous operation, without any additional starting device.

The electrical motor optimization process evaluates the combination of the magnetic core stacking size, the winding material and distribution, and the most suitable capacitor, regarding voltage requirements, starting torque, efficiency, power factor, and overload approval.

2. METHODOLOGY

This section describes the methodology used in motor design optimization, including details of application mapping, software model creation, a general description of the equipment used in practical tests and the final results of the optimized motor.

2.1 Characterization of a water pump heating system

A water pump heating system, for sanitary water heating, was tested in several room temperatures to map the system temperatures and pressures over time. The test routine consists of stabilizing the system at room temperature, filling the tank with cold water, and measuring all the variables from when it is turned on until reaching steady state condition, where the water reaches the setpoint temperature of 65 °C (149 °F). The test is repeated in different room temperatures of 5 °C (40 °F), 20 °C (67 °F), 35 °C (95 °F) and 50 °C (120 °F). The equipment is installed with transducers to acquire temperatures, power and pressures as shown in **Figure 1**, monitoring both system and compressor.
This test determines the compressor inlet and outlet pressures and temperatures over the starting, up to reaching the steady state condition. The results are used to build a compressor application envelope for this appliance. This test routine doesn't consider the system power consumption, only the pressures and temperatures.
The defined compressor application envelope is set as the acceptance criteria for the final product in a calorimeter.

Figure 1: Heat pump water heating appliance at test facilities.

2.2 Characterization of rotary compressor in calorimeter

A rotary compressor is correctly sized to match the heating capacity and refrigerant required by the application. In this study, a system with R-134a refrigerant was considered. The compressor is evaluated in a calorimeter (**Figure 2**), with controlled conditions that were identified thought Section 2.1 tests. Calorimeter tests are performed in accordance with ANSI/AHRI Standard 540: 2004 (AHRI, 2004). The calorimeter testing gives the compressor's thermal behavior and electrical characteristics under realistic operating conditions. This evaluation enables the calculation of torque requirements for motor design optimization.

Calorimeter and dynamometer test results are compared, to identify torques, electrical efficiencies, and thermal constraints for motor design optimization.

Figure 2: Rotary compressor in a calorimeter bench.

2.3 Characterization of the motor in the dynamometer

At first, an existing electrical motor from a Tecumseh's rotary compressor is analyzed in a dynamometer (**Figure 3**) with a set of different voltages and temperatures in accordance with IEEE standard 114-2010 (Institute of Electrical and Electronics Engineers [IEEE], 2010). The SPIM test consists of stabilizing the motor at a desired temperature, rotating the rotor coupled to a servo motor, applying the desired voltage power supply, decreasing the motor speed up to zero, and measuring the torque reaction in a load cell coupled to the rotating-shaft.

In steady state condition, the SPIM is supplied by a constant frequency of 60 Hz and run in a fixed speed, that is below 3600 rpm due the slip characteristics of an induction motor. The dynamometer tests results show the relationship between the rpm and torque that the motor can withstand with the supplied voltage.

The supplied voltage has a heavy impact in SPIM torque and efficiency (Mademlis *et al*, 2005b), but this work doesn't use any voltage modulation with electronic components to keep the motor in optima condition. So, the motor must withstand with reliability all the possible voltage variations of power supply. The voltage variation is an issue of power grid and building installations that any electrical appliance can be affected.

These dynamometer results are also called the "motor down curves" where mechanical and electrical measurements are taken. The analysis consists of comparing several variables against the motor torque. In this study, two motor curves were considered in the analysis:

1) Torque vs. rpm: evaluation of motor starting torque and break down torque (maximum torque achievable) to withstand the compressor application envelope.
2) Torque vs. efficiency: evaluation of motor efficiency at rated torque, overload, and underload conditions, where the motor must run without overheating.

These data are compared with the analytical model results, aiming for adjustments to improve the simulation results' accuracy. If the simulation tune is enough to evaluate a new motor design constraints and requirements, the new design process can be started. The motor model must be adjusted if the simulation shows poor accuracy.

The motor down curves are used to compare with calorimeter results and determine the torques required to work in several conditions through the application envelope. These torques values are used as inputs and constrains variables in the motor optimization process.

Figure 3: Servo motor dynamometer for motor characterization.

2.4 Creation of Motor Design Simulation Model

The motor design simulation software utilized is Simcenter SPEED version 2022.1 (Siemens). It is an analytical software that uses a set of equations to describe the motor's magnetic and electrical behaviors. The analytical evaluation of the SIPM simplifies some magnetic variables as average values to solve the equations. These equations have fudge factor variables that the user can adjust to improve the simulation accuracy, based on practical results. The user modifies all the motor construction variables, selects the voltage power supply, and evaluates many motor characteristics.

Solving the analytical model is very fast and a good method to couple with optimization software, as it will evaluate several configurations during the design process. Checking the accuracy of the simulation model before the optimization process is a key factor in increasing the reliability of the new design and reducing loops in redesign.

Figures 4, **5**, and **6** show a comparative between motor down curves from simulation and dynamometer data. The simulation is performed without any tune in the fudge factor variables and compared in several voltages.

In the rated voltage (**Figure 4**) it is evaluated the motor efficiency at the rated condition, where the objective is the minimum efficiency required to achieve the compressor target coefficient of performance (COP). That would be the relationship of the torque required to run the rated condition and the motor efficiency in this load point verified in the "Torque vs efficiency" curve.

In the minimum voltage (**Figure 5**), it is evaluated if the motor has enough torque to start the compressor and run in the maximum load condition, with the maximum torque requirement of the application envelope. In this simulation, it is verified in the "Torque vs. rpm" curve, if the motor has enough torque capability, because, with the minimum voltage, the SPIM also reduces the torque available and there is a potential of the motor stalling. The minimum voltage also reduces the motor starting torque, so it is necessary to evaluate if it will still be able to start the compressor.

In the maximum voltage (**Figure 6**), it is evaluated if the motor has enough efficiency to run in low load condition with the minimum torque required by the application envelope. The maximum voltage increases the torque capability of the SPIM, but it is also shifts the "Torque vs efficiency" curve, creating a region of low efficiency with low torque. If the motor efficiency is too low in this low torque condition, the motor may overheat in the motor approval tests in calorimeter.

To improve the estimation of compressor efficiencies, motor temperature and capabilities for calorimeter approval tests, it is desired that the simulation predicts torques, rpm and efficiency with errors limits as shown in **Table 1**.

Table 1: Maximum errors desired between motor simulation and dynamometer tests.

Motor parameter	Maximum error
Efficiency	2%
SPEED	20 rpm
Torque	5%

The initial results, without adjusts of simulation fudge factors, show error above 10% in motor efficiency and torque curves. To improve the accuracy if simulation, the analytical model is coupled with the optimization software Altair Hyperworks Hyperstudy version 2022 (Altair) with a routine to modify the fudge factor variables minimizing the error between simulation and dynamometer tests results.

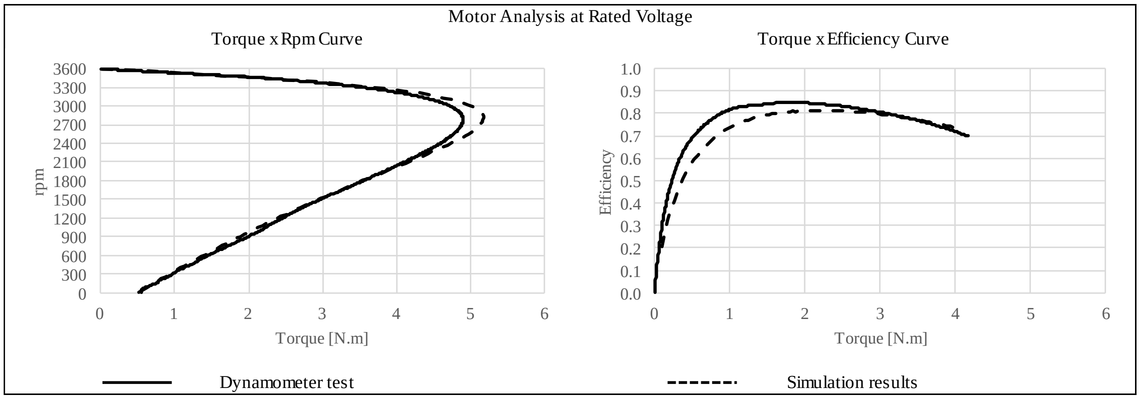

Figure 4: Rated voltage without fudge factors adjustments.

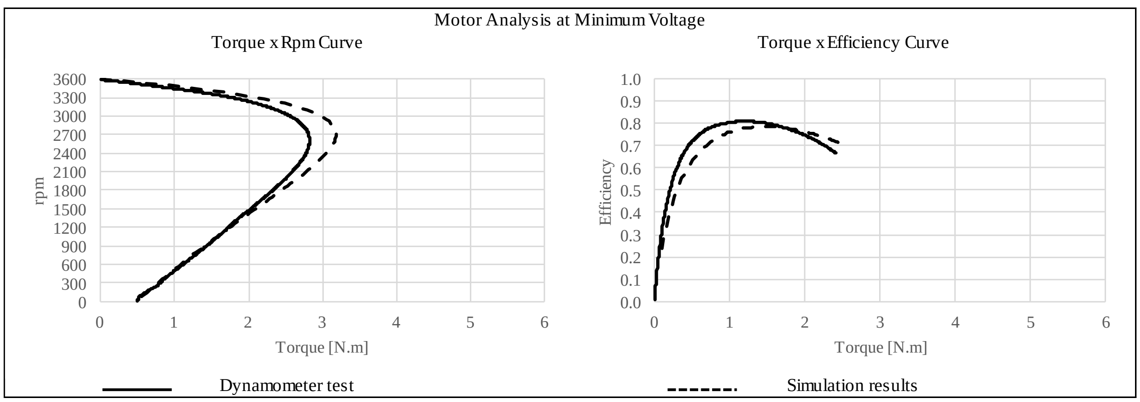

Figure 5: Minimum voltage without fudge factors adjustments.

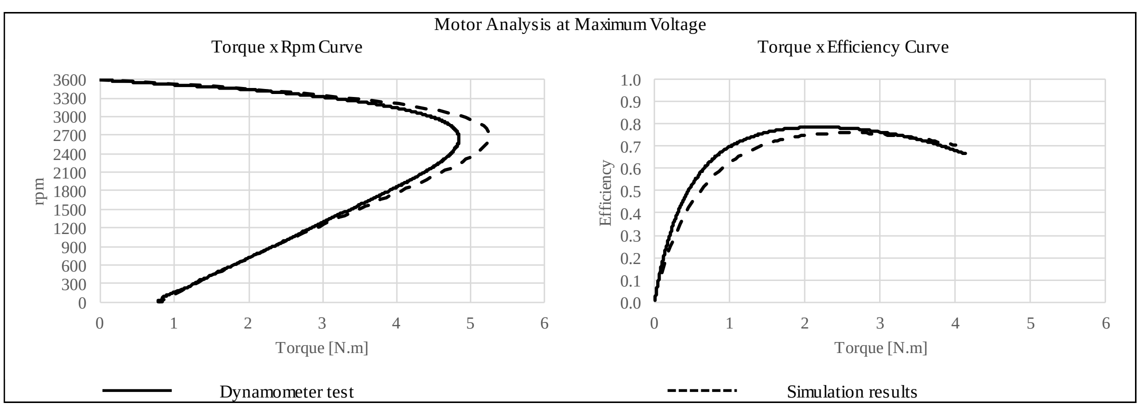

Figure 6: Maximum voltage without fudge factors adjustments.

Simulation model is adjusted with the new set of fudge factor variables and results are compared with dynamometer down curves to evaluate the improvement in simulation accuracy.

Figures 7, **8**, and **9** show the new comparative from the simulation with adjusted fudge factor variables. The torque and efficiency curves become much closer to the practical values, attending the maximum error from **Table 1**.

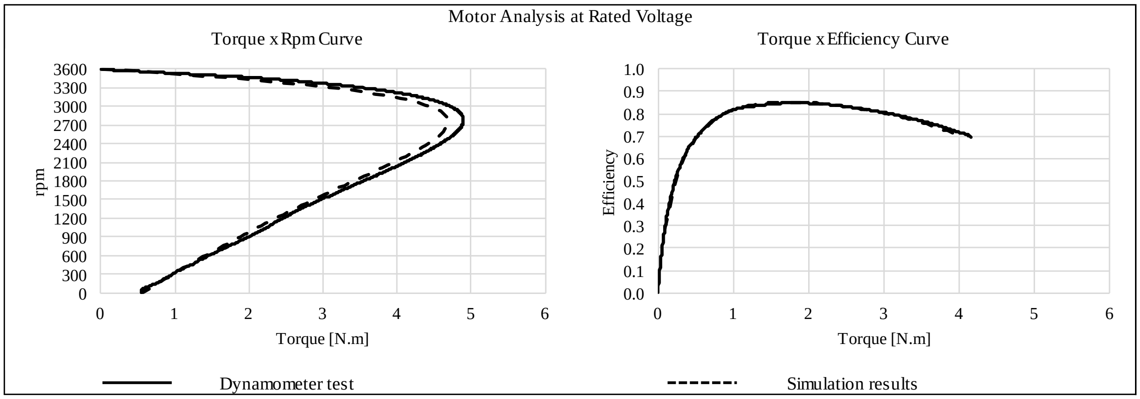

Figure 7: Rated voltage after fudge factors adjustments.

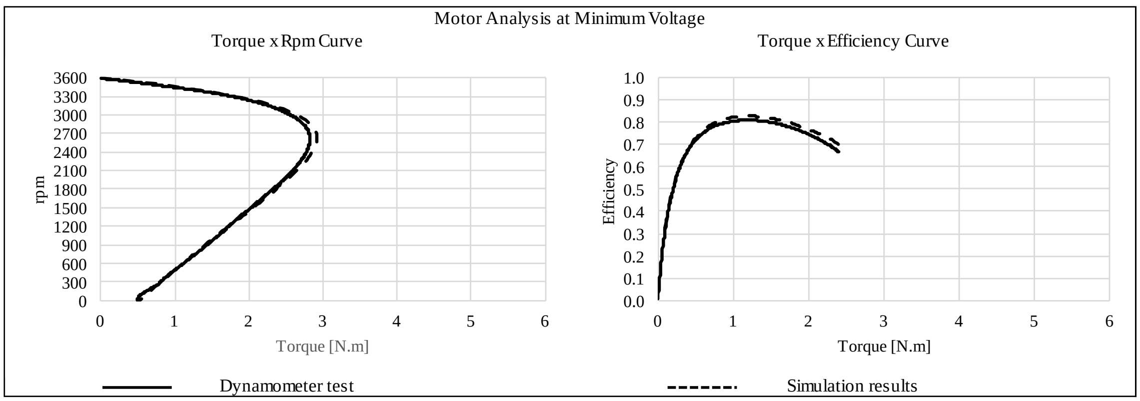

Figure 8: Minimum voltage after fudge factors adjustments.

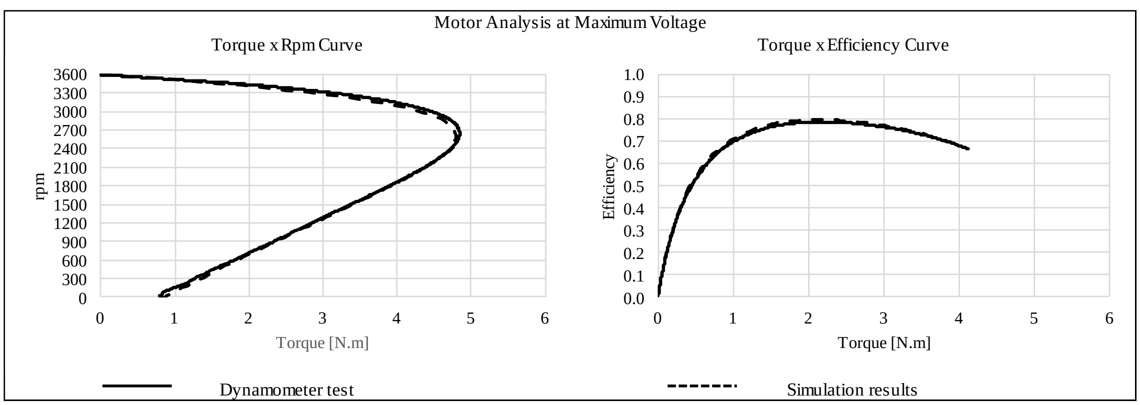

Figure 9: Maximum voltage after fudge factors adjustments.

After the adjustment process, the new simulation model is used as a starting point for the design optimization.

2.5 Motor design optimization

The motor optimization process is the coupling of the SPEED analytical model with the optimization software. The construction variables of the motor are set as input variables. The simulation results of the motor evaluated in the required torques of the application envelope (rating, maximum load, minimum load, and starting conditions) with rated, minimum, and maximum voltages power supply, are set as output variables. The most critical output variables are set as goals of the optimization process.

The optimization with SPEED and Hyperstudy consists in the following steps:

a. Create a batch file to link Hyperstudy and SPEED.
b. Select the inputs that will be modified and outputs that will be read.
c. Select the range of values to modify the inputs between the iterations.
d. Select the outputs targets for the optimization process, as variable to maximize, minimize or constrains to be kept.

This process can have loops, modifying the input ranges to match output constrains that where not fulfilled in previous rounds.

2.6 Prototype manufacturing and design validation

The optimized motor is manufactured, and its feasibility is evaluated empirically. If the motor doesn't show any issues in manufacturing, the samples are destined for dynamometer tests.

The new dynamometer tests are compared with simulation results to evaluate if the motor is attending the design criteria and if the adjusted model keeps its accuracy when the motor constructive variables are modified.

If the dynamometer results are acceptable, compressor prototype samples are assembled to be evaluated in the calorimeter, with rating verification and motor approval tests.

3. EXPERIMENTAL RESULTS

3.1 Determination of compressor application envelope

The results of the heat pump water heating system working conditions are shown in **Figure 10**. The measurements are presented at 1-minute intervals. The starting point is the system turning on with the water tank full of cold water. The endpoint is when the water reaches the setpoint of 65 °C (149 °F).

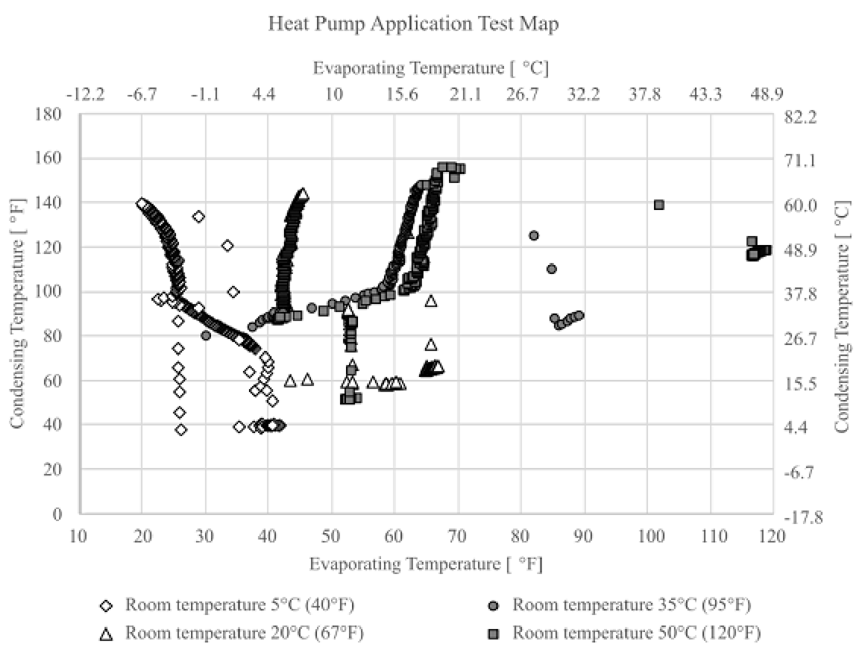

Figure 10: Heat pump water heating system mapping.

Based on the system test results, an application envelope was built as target for compressor design and electrical motor optimization (**Figure 11**). This envelope represents the steady state window that the compressor should run continuously, without overheating and not triggering any overload protection with all the voltage range variations.

The compressor is mapped in a calorimeter through all the application envelopes and the torques for motor design are set. These results are used as inputs and constrains for the motor optimization process.

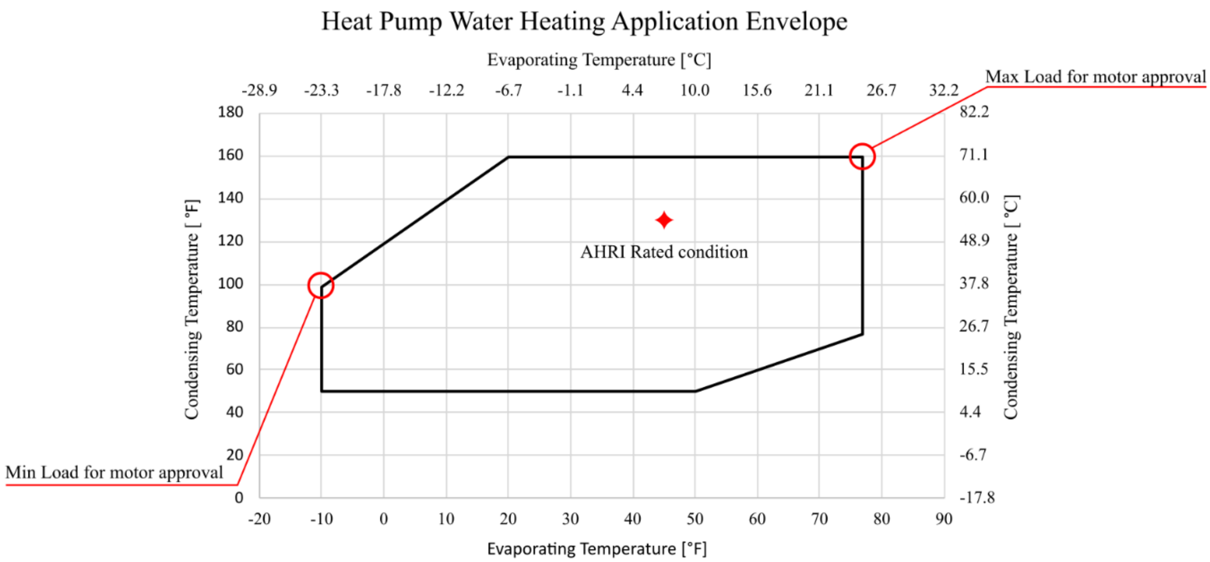

Figure 11: Compressor application envelope.

3.2 Motor design optimization

The optimization process, have the goals to reach the maximum motor efficiency, with feasible manufacturing limits, as stator slots filling factor below 82%, motor efficiency above 65% in overload conditions (maximum load with minimum voltage and minimum load with maximum voltage), minimum breakdown torque of 1.7 N.m (20 oz.ft) and minimum starting torque of 0.4 N.m (4.5 oz.ft). The results show that the optimization software targets these goals, creating a region in the chart where there is more concentration of motor combinations (**Figure 12**).

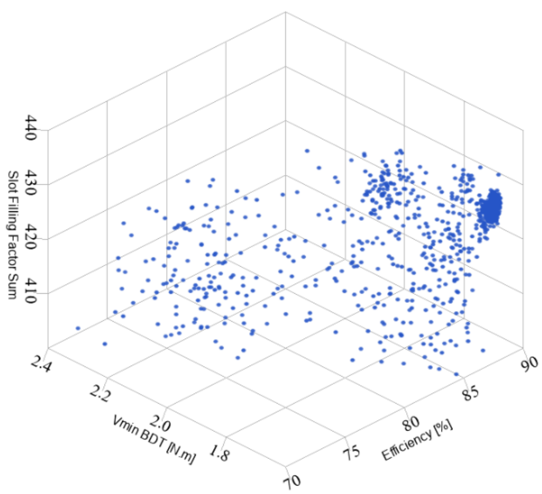

Figure 12: Optimization process chart.

3.3 Motor validation in dynamometer

Figures 12, **13**, and **14** compare the optimized motor tests and simulations. It is noticeable that changing the motor construction parameters reduces accuracy in the simulation. It is more evident in the minimum and maximum voltage power supply, where the electrical steel nonlinearities, regarding the magnetic polarization, can increase the discrepancies between test and simulation. If the discrepancies are too big, the simulation model must be readjusted and the optimization process restarted. If the accuracy is acceptable and the motor attends the compressor requirements with reliability, the prototype compressors are assembled and the process moves forward to calorimeter analysis.
The presented results show that the motor is attending to the requirements and the process can move to further analysis without a redesign.

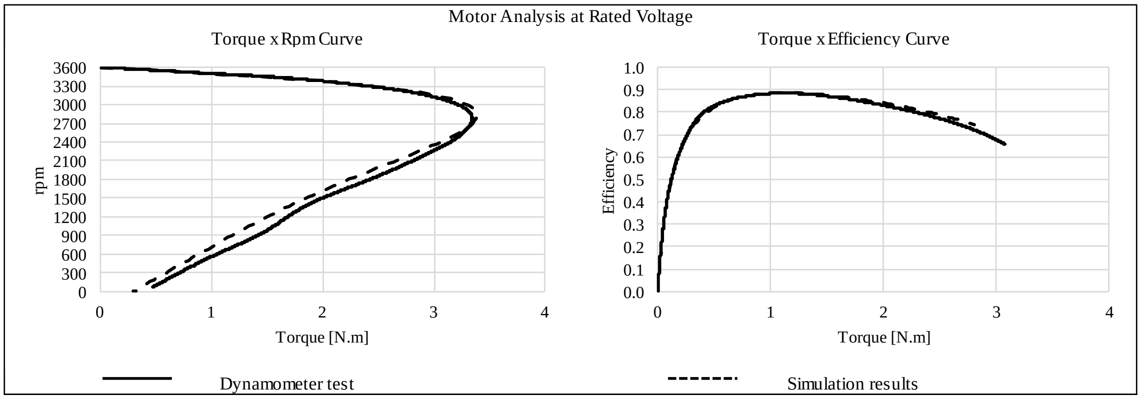

Figure 13: Optimized motor at rated voltage.

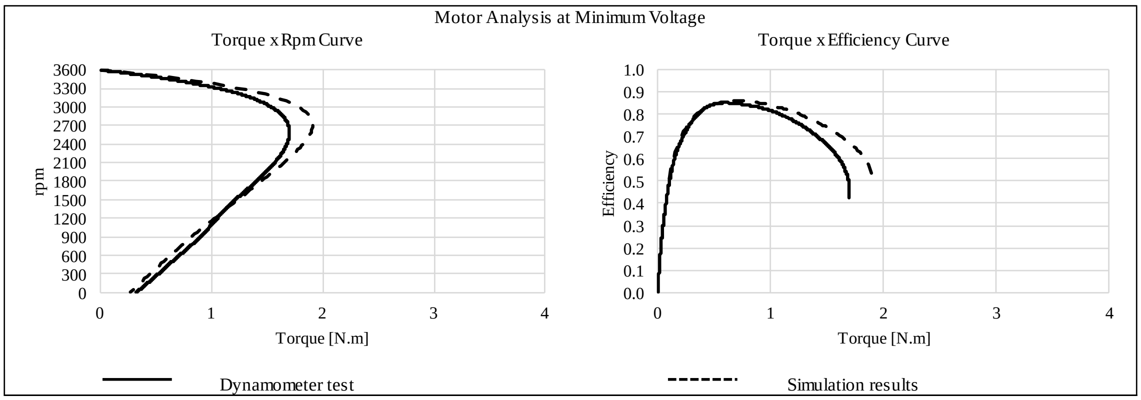

Figure 14: Optimized motor at minimum voltage.

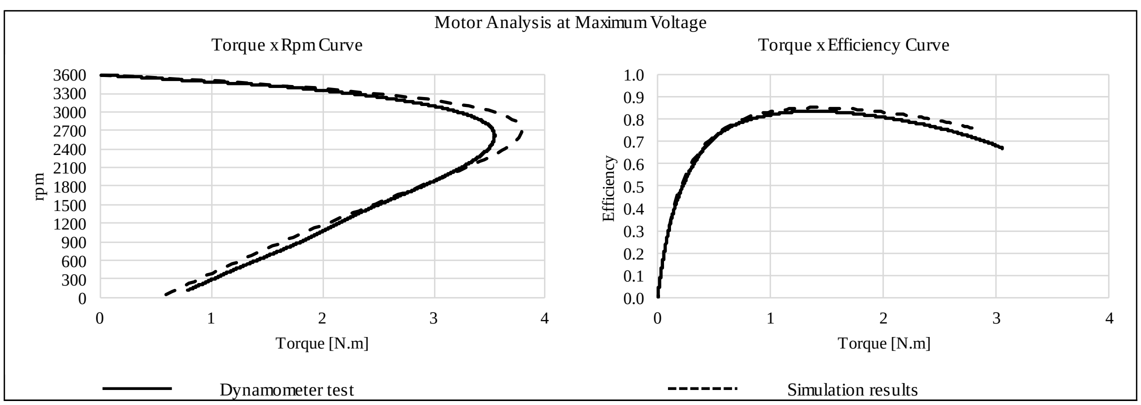

Figure 15: Optimized motor at maximum voltage.

3.3 Motor validation in calorimeter

Table 2 shows the motor approval tests in the calorimeter applying overload conditions. The first overload condition requires the minimum torque of the motor with a maximum voltage power supply, where the motor may overheat due to low efficiency and low mass flow of refrigerant gas. In this condition, the motor and compressor housing temperatures must not exceed 150 °C (302 °F). The second overload condition requires the maximum torque of the motor with a minimum voltage power supply, where the motor may overheat or stall because of lacking breakdown torque. In this condition, the motor temperature must not exceed 130 °C (266 °F) and the compressor housing temperature must not exceed 150 °C (302 °F).

Table 2: Motor approval results in calorimeter.

Condition	Power Supply	Housing Temperature	Motor Temperature
Minimum Load	Maximum Voltage	68 °C / 154 °F	78 °C / 172 °F
Maximum Load	Minimum Voltage	86 °C / 187 °F	95 °C / 203 °F

3.3 Compressor performance data

Finally, the compressor is tested to evaluate its performance and map it around the application envelope.
The heating-rated tests of this rotary compressor are performed in AHRI condition (AHRI, 2004*)*, with 18.3 °C (65 °F) return gas temperature, 35 °C (95 °F) room temperature, and 8.3 °C (15 °F) of subcooling.
Table 2 shows the results obtained with an arbitrary compressor sample assembled with the optimized motor.

Table 3: Final compressor performance results in calorimeter.

				Condensing Temperature				
				-17.8 °C	**-12.2 °C**	**-3.9 °C**	**7.2 °C**	**12.8 °C**
				0 °F	**10 °F**	**25 °F**	**45 °F**	**55 °F**
Evaporating Temperature	**32.2°C**	**90 °F**	**Heating Capacity (W)**	767	929	1233	1765	2090
			Power Consumption (W)	231	243	253	246	231
			Heating COP (W/W)	3.32	3.83	4.88	7.18	9.04
	43.3 °C	**110 °F**	**Heating Capacity (W)**	738	889	1170	1659	1958
			Power Consumption (W)	260	276	296	308	305
			Heating COP (W/W)	2.84	3.22	3.96	5.39	6.43
	54.4 °C	**130 °F**	**Heating Capacity (W)**	710	849	1106	1552	1824
			Power Consumption (W)	294	315	344	374	383
			Heating COP (W/W)	2.41	2.70	3.21	4.14	4.76
	60.0 °C	**140 °F**	**Heating Capacity (W)**	698	831	1076	1499	1757
			Power Consumption (W)	314	337	371	411	425
			Heating COP (W/W)	2.22	2.47	2.90	3.65	4.13
	65.6 °C	**150 °F**	**Heating Capacity (W)**	689	815	1047	1447	1692
			Power Consumption (W)	337	362	401	449	470
			Heating COP (W/W)	2.04	2.25	2.61	3.22	3.60

In the target rated condition with an evaporating temperature of 7.2 °C (45 °F) and condensing temperature of 54.4 °C (130 °F), the optimized compressors achieved a heating COP of 4.14 W/W, a value 5.6% better than the existing compressor and achieving the goal above 4.11 W/W.

4. CONCLUSION

Using optimization software to adjust the electric motor analytical model simulation, can greatly increase its accuracy, improve the product quality, and decrease the time to market new designs, reducing the need for redesigns due to deviation between theoretical and practical results. Although the modification in motor constructive variables may require a new evaluation of the fudge factor variables in the analytical model, the model was still able to predict the new motor performance with great accuracy. Further evaluation can be done with several motors compared at the same time and define a set of fudge factor variables that reduces all the simulation errors simultaneously. This proposal may take a lot of computational time due high amount of data, but the results can greatly increase the analytical model's robustness to input variable modifications.
The motor optimization process resulted in a compressor capable of attending the application envelope and achieving the highest efficiency in the rated tests, with improvement of 5.6% in compressor heating COP, which will allow the water heater to achieve the efficiency levels required by U.S. regulations. A power consumption test, with a water heating system, is necessary as the final validation of compressor design.

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