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Design and control contributions to high efficiency Ferrite-PMSM drives for small compressors

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Summary

The present thesis studies several topologies of Ferrite permanent magnet synchronous motors, intended for use in driving reciprocating compressors for domestic refrigeration applications, from design and control perspective.

Refrigerators are one of the main household consumers of electricity [1], the trend over the last decades being aimed at improving their energy rating. This became possible due to both improvements in the refrigerant and thermal insulation [2], and due to improvements in the efficiency of the compressor, which represents the main energy consumer component in the refrigeration system. The improvements in the compressor energy consumption were also caused by improvements brought in the drive part: the electric motors. If the refrigerators were initially equipped with line start single-phase asynchronous motors, controlled by a thermistor using only on-off states [3], the introduction of electric converters allowed both the use of higher efficiency motors like synchronous motors with permanent magnets, and optimized temperature control, by using variable speed operation [4].

Rare-earth permanent magnet synchronous motors are known for their high energy density and high efficiency, being used in applications where good performance is required [5], being also characterized by a high cost. Ferrite permanent magnets have low coercive field and remanence but benefit from the great advantages of availability and low price. The motivation behind the study conducted in this paper is to find new topologies of Ferrite based permanent magnet synchronous motors which meet the requirements of refrigeration applications, while benefiting from the advantages of Ferrite permanent magnets.

To achieve this goal, starting from the analysis of the requirements for operation in reciprocating compressor drives applications, the paper analyzes three new topologies of single-phase permanent magnet synchronous motors, two of them with permanent magnets placed on the stator where they assist magnetomotive force produced by stator winding, and the third one with permanent magnets placed on the rotor. After analyzing the characteristics and particularities of each topology, an important aspect being the possibility to start from any position, the motors are optimally designed based on sets of requirements corresponding to low power compressors: output power of 35/100 W at a nominal speed of 1600rpm / 3000 rpm. Using a FEM analysis [6] based geometry design methodology integrated in the modified Hooke Jeeves optimization algorithm [7] [5], the motors are optimized to minimize the cost of materials, additional constraints being imposed by penalty costs [5] to ensure a minimum efficiency of 88% and a minimum torque of 0.1 Nm (required to start from any position) in rated operation. The obtained solutions show a material cost of 16 $ or less, fulfilling (partially in some cases) the efficiency and minimum torque additional constraints. Subsequent finite

element method and dynamic digital simulations validations confirm the motors performance.

Next, an optimal design methodology which combines an analytical model with FEM analysis is developed, to achieve a compromise between results accuracy and low computational effort, is applied for the design of an external rotor three-phase Ferrite permanent magnet synchronous motor. The design methodology is based on an analytical model which is iteratively corrected during the optimal design routine by the finite element method. The correction coefficients (calculated based on the differences between the analytical model values versus FEM analysis extracted values for the average torque produced by the motor at rated load and for the stator synchronous inductance) correct the analytic expressions of the magnetic flux per pole and the synchronous inductance. The design methodology is used for optimizing the external rotor PMSM for a set of requirements corresponding to a small compressor drive: rated power of 1 kW developed at the rated speed of 4500 rpm. As in the previously studied cases, the optimization objectives are motor material cost minimization and the efficiency maximization for rated and low speed operation. The short optimization time, of approximately 8 minutes (compared to the calculation times of over 12 hours, in the case of FEM based optimization, obtained for the single-phase motors) allowed the deployment of the optimization program 20 times starting from randomly chosen initial points, to increase the probability of finding the global optimum, the best result being characterized by a material cost of $ 12.37 and a rated efficiency of more than 90%. The analysis of the optimization results shows that the values of the analytical model converge to the finite element method extracted values.

Several experimental results available for a prototype built on a previous design validate the efficiency analytical calculation method.

The last part of the paper performs a comparative study of position sensorless control methods, for speed (and current) control of low power three-phase PMSM drives for reciprocating compressors. The first strategy is represented by the constant V / f scalar control, improved with 2 correction loops [8] [9] [10], the second control strategy being the classic rotor field-oriented control. The two correction loops used by the scalar control serve the following purpose: - reference voltage vector speed (angle) correction based on active power oscillations, to improve stability in transient mode, respectively reference voltage amplitude correction, based on d-axis current closed loop control, to ensure an efficient operation under the maximum torque per current condition [11]. Active flux observer [12] is used for the rotor position estimation and for the calculation of the information necessary to for maximum torque per current operation.

Both strategies were implemented and tested comparatively by digital simulation and experimentally on a dSpace system, using a prototype PMSM designed for this application. Extensive experimental results at high and low speeds show a better transient response for the vector control strategy, the scalar control strategy also being characterized by a stable operation, being able to operate under the same acceleration and load conditions, which makes it suitable for being used in compressor control applications, where the dynamics are not high, bringing as benefits the simplicity of implementation and the reduced time of parameters tuning.

Thesis structure

The thesis is organized in the following chapters / sections:

Chapter 1 presents the motivation behind the subject selection, followed by a presentation of the refrigeration system and the types of compressors used in household refrigeration applications as well as the types of motors used or proposed for drives. The main requirements which must be fulfilled by a motor employed in this application are also presented [13].

The second chapter presents a set of theoretical elements used within the thesis, such as: the preprocessing and post-processing part of the finite element method, the properties of the materials used in FEM models, the types of used FEM analyses and the motor torque, winding inductance and iron losses used calculation methods. Additionally, the structure of the modified Hooke Jeeves algorithm and the mathematical model of the reciprocating compressor are presented in detail.

The third chapter presents the first studied motor topology: the single-phase permanent magnet synchronous motor with Ferrite permanent magnets placed in the stator, with two stator poles and four rotor pole pairs. Initially, the single-phase motor category this motor belongs to ("flux reversal motors" [13]) is presented, followed by a presentation of the FEM analysis-based motor operating principles, with special attention given to the starting issues, characteristic to this type of motor. Next, the finite element method based geometric design methodology and the cost-based multi-objective function component are introduced. Starting from a case-study requirement, the motor optimization results are presented and analyzed in detail, followed by additional FEM-analysis based validation. The optimized motor performance is also analyzed by dynamic digital simulation, based on a circuit model which uses FEM analysis extracted information, integrated in a rotor speed and stator current close loop control strategy. Preliminary experimental results for a prototype built on a previous design are presented at the end.

Chapter 4 presents the second studied single-phase synchronous motor topology, which, unlike the motor studied in Chapter 3, contains four stator poles, the two additional poles being expected to provide a higher power density. Same steps are followed in the motor study presentation: finite element-based analysis of the operating principles followed by the optimal design results presentation and validation, the optimization being done using the optimal design methodology used in chapter 3.

Chapter 5 presents the third studied single-phase motor, which uses permanent magnets placed in the rotor, providing additional benefits such as: operation at half of the supply frequency and shorter coil ends. Being designed based on the same requirements used in the design of the Chapter 4 single-phase motor, the optimization results and performance analysis of the two motors are comparatively presented.

Chapter 6 presents an optimal design methodology for designing an external rotor three-phase ferrite permanent magnet synchronous motor, which uses an analytical model iteratively corrected by FEM analysis. For this, the motor topology, the analytical model, the FEM-analysis based correction coefficients and the design algorithm are presented. Using case-study requirements, the optimization algorithm is run, the optimization results analysis being followed by FEA based validation for the optimum solution. Few preliminary experimental results of the efficiency curves experimentally obtained for a previously designed prototype are presented at the end.

Chapter 7 is dedicated to the comparative study of the two position sensorless control strategies: V / f scalar control with stabilization (or correction) loops versus rotor field-oriented control. The chapter presents: the mathematical model of the PMSM, two of the main mathematical model-based rotor position observers: the active flow observer [12] and the extended EMF observer [14], followed by the structure of the two control strategies and digital simulation results, as well as a study of the motor parameters variation influence on the rotor position estimation. After experimental platform presentation, experimental results performed at medium, high, and low speeds for different load levels are comparatively presented.

Original contributions

The main thesis contributions are:

- Presentation of an overview of the solutions of low power compressor drives based on PMSM and their requirements which must be met for this application.
- Proposal and analysis of three new single-phase Ferrite PMSM topologies.
- Development of FEM-based design methodologies, or FEM analysis combined with analytical calculations-based design methodologies, which can be used for motor

optimization in terms of material cost, considering additional aspects such as efficiency maximization and starting torque improvement.

- Study and implementation of control strategies by digital simulation for the single-phase / three-phase Ferrite PMSMs
- Experimental comparative study of two sensorless control strategies (based on the active flow observer) for three phase PMSMs. The novelty element in the studied strategies is the implementation of the reference voltage amplitude correction loop by d-axis current close loop control for operation under maximum current torque per current condition, the MTPA condition being expressed using magnetic energy and active flux amplitude.

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