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COMPUTATIONALLY PROFICIENT DESIGN ROUTE FOR SINGLE-LAYER IPM MECHANISMS

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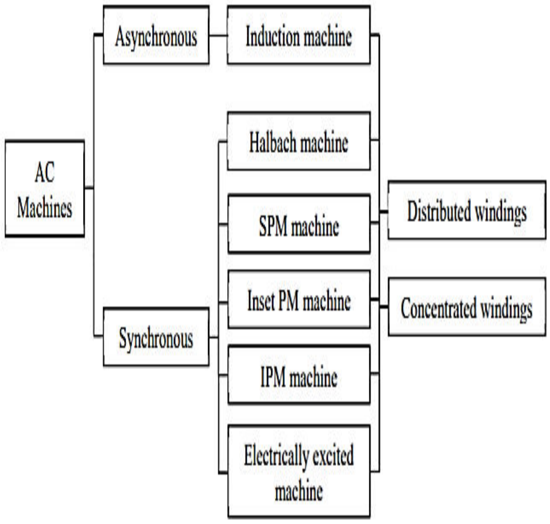
ABSTRACT

Interior Permanent Magnet machines are widely used in several applications thanks to their optimal tradeoff between torque and flux weakening capability figures. Their design process massively relies on the use of optimization algorithms coupled with Finite Elements Analysis, as dictated by the high number of input parameters and the inadequateness of design equations. This paper proposes a faster design flowchart, based on analytical models for V-type IPM machines. The proposed design procedure is validated against FEA results, referring to the known benchmark of the Toyota Prius 2010 electric motor. Although the precision of the results is not comparable to that obtainable with FEA, the proposed closed-form model is useful and insightful during the preliminary stages of the design. The limits of accuracy of the proposed equations are commented critically. Guidelines are given on how to embed the presented approach into a comprehensive design procedure.

INTRODUCTION

Synchronous reluctance motors are a viable alternative to induction motors because they allow a better torque to weight ratio. The power factor and the constant power speed range (CPSR) can be improved thanks to the insertion of permanent magnets in rotor layers. The obtained machine is referred to as a Permanent Magnet-assisted SyR motor or, simply, an Interior Permanent Magnet (IPM) synchronous motor. One key-issue in the design of such machines is to define the rotor geometry that presents many degrees of freedom (number and shape of the layers, PM grade and placement). Linear magnetic models are way too optimistic for such kind of motors, therefore analytical and lumped parameter models are always associated to Finite Element Analysis (FEA), in the literature, to account for magnetic saturation effects. Hybrid approaches such as frozen permeability have been also proposed. Another fundamental aspect is the minimization of the torque ripple that can be very high in case of poor design choices and it is difficult to be modeled by simple formulas. Optimization algorithms based on FEA evaluation of the motor performance have been proposed, but they suffer from being time-consuming, and they have often been applied to rotors with simple geometries, such as single layer rotors, for having a limited number of degrees of freedom and then keep the computational time under control.

A comprehensive design approach based on FEA optimization, like the one proposed for surface mounted PM motors is still under investigation for IPM motors because of their complicate rotor geometry that involves a higher number of parameters. It is important to underline that the current phase angle giving the maximum torque is unknown a priori, and the flux weakening capability of the motor and then the CPSR are difficult to be evaluated quickly.



Classification of AC machine types used for traction applications

This paper introduces a simpler procedure for the optimal design of multi-layer, IPM rotor machines, based on a two stage approach: first a SyR motor is designed and optimized for maximum torque and minimum torque ripple, and then the rotor layers are filled with plastic PM material, and the PM grade is calibrated, in post processing, for obtaining the required power versus speed characteristic. The aim of the paper is to contribute to the definition of a standard design methodology, applicable also by nonspecialist designers. The methodology utilizes multiobjective optimization algorithms to select rotor geometry but, with respect to previous literature, both the definition of the optimization problem and the interpretation of the results have been greatly simplified.

Even though there are clear advantages for choosing FLM over CM, the practical application of FEA-parameterized FLM is still comparatively rare [18]. The main reason probably lies in the standard static FEA setup. The stator current being an input, FEA produces flux-linkage maps where the stator current is treated as an independent variable (direct form). As FEA-parameterized FLM actually requires an inverse relation between current and flux linkage (inverse form), the designer is typically induced to rather follow CM paradigm. Nevertheless, few authors have recently tackled the subject of inverting flux-linkage maps. Various strategies were employed in order to find the inverse form, such as the interior-point method and radial-basis function, but scarce implementation details were provided. In Reference, the lookup table-inversion process is outlined but too vaguely for easy third-party implementation. All procedures listed above are significantly more computationally demanding in comparison with the straightforward parameterization of CM. However, one should note that the principal objective of the aforementioned papers was to develop a high-fidelity statespace model per se, regardless of the possible increase in complexity of some sort (mathematical and/or computational).

Two-Axis IPM Models

Restricting the study to the case of perfect field orientation, the voltage equation of IPM is defined as

$$v_s = R_s i_s + \frac{d\psi_s}{dt} + J\omega_r \psi_s,$$

where vs = $[v_d \ v_q]^T$, is = $[i_d \ i_q]^T$ and $\psi_s = [\psi_d \ \psi_q]^T$ are real vectors defined in the rotor reference frame, Rs is stator resistance (scalar), ωr is rotor electrical speed, and J the matrix equivalent to complex unit j

$$J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

Electromagnetic torque Te is defined as a vector product of flux linkage and current

$$T_e = \frac{3}{2} p_p (\psi_s \times i_s)$$

where p_p is the number of pole pairs. Dynamic equation links the electromagnetic and mechanical domains

$$T_e - T_l = \Gamma \frac{d\omega_M}{dt}$$

where Tl is the load torque, Γ the moment of inertia, and ωM rotor mechanical speed. Equations are globally valid for any working condition. In order to obtain a full set of IPM equations, the relation between flux linkage and current (flux–current relation, flux map) ψs = f(is) needs to be defined. Specifically addressing two-axis IPM representation in the rotor reference frame, the model is linear only if saturation is not present. Therefore, function f : R 2 → R 2 is affine if the system is linear, and nonlinear if otherwise.

LITERATURE REVIEW

DW-IPM machines have been widely used in high performance industrial applications over decades. CW-IPM machines on the other hand have only more recently found their way into industrial markets. This section reviews well established work in IPM machine technology as well as recent research in CW for AC machines.

IPM Machine Technology

The IPM machine has been a popular choice for field-weakening applications. Global research on the IPM machine dates back to the late 1970s and early 1980s when the first few papers were published; there is still very significant research interest in this area today. The popularity of the IPM machine is due to the embedded structure of itsmagnets, which lowers the risk of demagnetisation, increases the mechanical robustness of the rotor and provides additional reluctance torque. The small airgap design in most IPM machines makes it excellent for flux weakening, as the negative armature reaction can effectively reduce airgap flux. The IPM machine also gives the machine designer the freedom to vary the magnet pole geometry, thereby broadening the machine’s area of application.

Leading studies in IPM machine technology has included patents and several papers setting the basis for research in this area. Steen filed a patent on synchronous motors with buried permanent magnets having several geometrical configurations. He stated that the buried magnets produced additional direct-axis (d-axis) flux in aid of the flux generated by the inductive copper bars during no-load operation. Honsinger illustrated a detailed mathematical representation of the IPM machine which included its magnetic fields and parameters. Rahman et al. presented the equivalent circuit model to determine the d-axis and quadrature-axis (q-axis) reactance. Consoli and Renna illustrated a detailed representation of the IPM machine in the rotor reference frame, and demonstrated an equivalent circuit model to determine iron losses. Chalmers et al. presented a study of the IPM machine through extensive experiments with frequency variations. They explained how the q-axis reactance can be more accurately obtained with the consideration of saturation. One of the first papers to illustrate the use of finite element (FE) analysis in IPM machine design was by Schiferl and Lipo. They showed how FE analysis is used to increase the prediction accuracy of losses at low voltage levels by considering harmonics caused by armature excitation. Noticing the IPM machine's superiority when used in flux weakening applications, Jahns et al. first addressed the IPM machine's characteristics when used as a high-performance variable speed drive. Jahns then performed a novel study on the flux weakening of the IPM machine, thereby successfully extending its constant power speed range. Since then, the use of IPM machines for flux weakening operations has soared. Soong et al. introduced the optimal field-weakening conditions for IPM machines using the parameter plane concept. They constructed and compared several rotor types and proved that the multi-barrier IPM rotor produced the most promising field-weakening performance. Soong et al. also developed a new axially laminated IPM motor capable of achieving an extremely wide CPSR. Honda et al. did a study on the effects of various winding types and rotor configuration on the field-weakening performance of the IPM machine. Jolly et al. used genetic algorithms to determine the optimal CPSR of an IPM machine confirming their results with FE analysis.

The IPM machine's characteristics were constantly compared to those of other AC machines. Fratta et al. compared the torque density and flux weakening ability of the IPM machine with the induction machine, and highlighted that the IPM would have better electromagnetic performance if mechanical issues were resolved. A controllability comparison between the IPM and SPM machines under various operating requirements of the current vector control scheme was done by Morimoto et al. They concluded that the IPM machine offered better flux-weakening capability. Zhu et al. compared the iron loss between the IPM and SPM machines. They indicated that the iron loss of the IPM machine would be lower under open-circuit conditions but significantly higher in the field-weakening region compared to the SPM machine, due to the increased harmonic content in the armature field. Kyung-Tae et al. compared the effects of rotor eccentricity on the IPM and SPM rotor, in which they concluded thatthe IPM is more prone to the effects of rotor eccentricity. Jung Ho et al. studied the inductance variation of a hybrid synchronous reluctance/IPM motor and found out that the addition of buried magnets increased the saliency ratio, thus increasing output torque and power factor.

The end of the 20th century saw drastic improvements in computational resources and techniques. This allowed machine designers to efficiently determine parameters and perform optimisation strategies. Novel attempts to reduce cogging torque with the aid of two-dimensional (2D) FE analysis by rotor pole or stator tooth shaping was done by Filho et al. Fujishima et al.as well as Kano and Matsui adopted the FE and genetic algorithm search method to derive optimal multi-objective designs. Yamazaki illustrated a method to calculate IPM machine parameters, including rotor and stator iron losses, with FE analysis. Efficiency optimisation by geometric variation was carried out by Sim et al. using finite element models. Dong-Hun et al. attempted to reduce cogging torque by producing the rotor stack with unequal lamination in the outer diameters. Ki-Chan et al. studied the effects on machine parameters and torque performance by varying the shape of rotor link sections. They showed by FE analysis that small variations of the link sections could significantly affect cogging torque and saliency ratio. Parsa and Lei studied the effects of torque ripple and performance characteristics when key machine parameters were varied. Kioumarsi et al. attempted to reduce torque ripple and increase field-weakening performance by drilling additional holes in the rotor. Kang et al. also attempted to reduce cogging torque by rotor surface shaping and by adding notches in the steel. They showed that the EMF harmonics and cogging torque amplitude could be effectively reduced. Han et al. attempted to reduce torque ripple by varying the number ofslots and number of rotor barriers. They showed that multi-barrier rotors with an odd number of slots per pole pair resulted in low torque ripple. Sanada et al. experimented with several designs and proved that the use of asymmetric flux barriers was beneficial in reducing torque ripple in multi-barrier IPM machines. Fang at al. showed that torque ripple and cogging torque can be reduced with a double-layer rotor. Kim at al. studied the effects of geometric variations of magnets in the IPM machine to reduce torque ripple.

Up to the early 21st century, CW were mostly applied to DC machines. Earlier published papers on the application of CW in PM AC machines recognised increased EMF harmonics, lower torque density and narrower CPSR compared to machines with DW. Later studies by Cros et al., as well as Magnussen and Sadarangani proved that a winding factor very close to unity and low cogging torque are achievable if an appropriate slot and pole combination is chosen. These studies sparked global research interests in fractional slot CW for use in 3-phase PM AC machines.

METHODOLOGY

The proposed design procedure can be divided into three consecutive steps, referred to as:

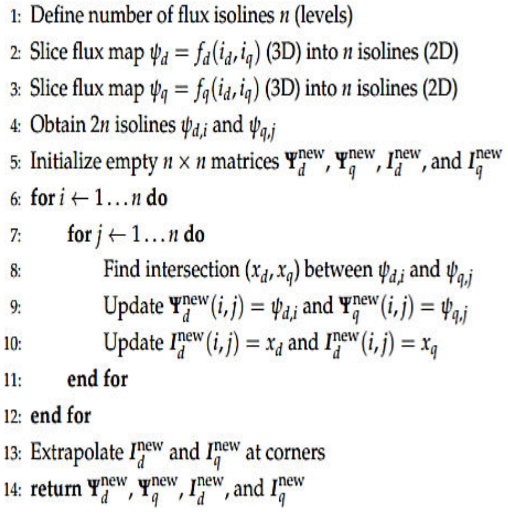
1. Global Search MOGA (GS-MOGA) of a SyR machine
2. Local Search MOGA refinement (LS-MOGA)
3. Off-line definition of the PM remanence Br

At first the PM remanence is set to zero and the rotor geometry is optimized (i.e. the Δαj angles and the layer heights hcj are defined). A two objectives GA run that maximizes the torque and minimizes the torque ripple is adopted. A set of geometrical constraints is imposed to ensure that the output geometry is mechanically feasible and has the adequate mechanical robustness. This first step is the global search (GS-MOGA). At the end of GS-MOGA, one solution machine is manually selected from the Pareto front (referred to as GS-solution) on the basis of both its performances (torque, torque ripple), feasibility, andmechanical robustness (regularly spaced layers tend to be preferred).

The second optimization step consists of a refinement of the machine output by GS-MOGA. A second two objectives GA run is performed but this time the constrains are close to the parameters of the GS-solution: a plus or minus 15% change is allowed for each single parameter. This second optimization step is referred to as local search (LS-MOGA). The two steps procedure allows a good precision in finding a good approximation of the optimal solution with a reasonably low computational time (e.g. 10 hours for a three layer geometry).

As an alternative, a computationally intensive single MOGA run with a higher number of iterations could be adopted. Furthermore the use of hybrid algorithms based on both global and local search algorithms were investigated but revealed to be more expensive in terms of computational cost. The third and final design step consists of the introduction of permanent magnets. Keeping the layer geometry of the LS-solution, the remanence of the permanent magnets is chosen according to the flux weakening range required by the application.

ALGORITHM



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Define number of flux isolines $n$ (levels)
Slice flux map $\psi_d = f_d(i_d, i_q)$ (3D) into $n$ isolines (2D)
Slice flux map $\psi_q = f_q(i_d, i_q)$ (3D) into $n$ isolines (2D)
Obtain $2n$ isolines $\psi_{d,i}$ and $\psi_{q,j}$
Initialize empty $n \times n$ matrices $\Psi_d^{new}$, $\Psi_q^{new}$, $I_d^{new}$, and $I_q^{new}$
for $i \leftarrow 1 \dots n$ do
    for $j \leftarrow 1 \dots n$ do
        Find intersection $(x_d, x_q)$ between $\psi_{d,i}$ and $\psi_{q,j}$
        Update $\Psi_d^{new}(i,j) = \psi_{d,i}$ and $\Psi_q^{new}(i,j) = \psi_{q,j}$
        Update $I_d^{new}(i,j) = x_d$ and $I_d^{new}(i,j) = x_q$
    end for
end for
Extrapolate $I_d^{new}$ and $I_q^{new}$ at corners
return $\Psi_d^{new}$, $\Psi_q^{new}$, $I_d^{new}$, and $I_q^{new}$
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CONCLUSION

In this paper, a fast design procedure for single layer, V-type rotor IPM machines was presented. The design procedure is based on the torque and characteristic current plane, where the latter is index of the flux weakening capability of each design. The two performance figures are estimated using an analytical model, less accurate but extremely faster than FEA simulations. Of the two goal functions, the most critical to be estimated is the output torque. This is mostly related to the imprecision of the Lq parameter, variable with saturation and current phase angle. Conversely, the results reported for theper-unit characteristic current are encouraging, and represent, in the authors' opinion, the main contribution of the paper. FEA is used to validate the model and design procedure, highlighting a level of precision adequate to the preliminary design stage. Besides accuracy, the key contribution is the ability to identify the area of the plane where the machines having the best trade-off between torque and flux weakening capability reside. This feature, applied to the preliminary design stage, can reduce the computational effort of an optimization algorithm to converge to the optimal design. By way of the proposed design plane, the designer can have a preliminary estimate of which designs comply with the flux weakening (that is constant power speed range) requirements of the application, and cross that area of the plane with the one of maximum torque designs. Such information is useful even in absence of a precise torque estimate, provided that the torque trends are respected across the plane. The proposed design flowchart is then included in the design tool SyR-e.

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