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MULTI-OBJECTIVE OPTIMIZATION OF A PM AIDED SYNCHRONOUS AVERSENESS MACHINE FOR LIGHT EV

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Abstract

Synchronous Reluctance (SynRel) machines are considered acompetitive alternative to the induction motors for variablespeed drive applications due to their comparable performancesand low cost. The absence of rare earth permanent magnetsmakes them very attractive also in the automotive sectorespecially for light electric vehicles. The design of SynRelmachines has been formalized by many authors in the last threedecades but it is still an open challenge since it involves manycompetitive design objectives and a higher number ofgeometrical variables compared to other kind of machines.This paper is focused on the joint optimization of both statorand rotor of a SynRel machine with the aim of obtaining thehighest torque density with the minimum iron and joule lossesas well as smooth torque. The aim is to carry out a machinedesign that suits best the requirements of a small electric carfor urban mobility, i.e. 30 kW with a base speed of 3000 rpmand a maximum speed of 6000 rpm. The proposed optimizationstrategy is global because it considers a geometry design thattakes into account several stator and rotor parameters together.The design method consists in a two steps procedure: in thefirst stage the torque density and the losses are optimized,while the quality of the torque profile is improved in the seconddesign stage. The results, satisfying the project requirements,are presented and compared to the initial reference machine.Finally a comparison between two design approaches allowingthe improvements of the constant power speed range ispresented and discussed.

Introduction

Synchronous reluctance machines have recently gainedincreasing interest both in industry and academia because oftheir excellent features, such as simple and robust rotorstructure, high overload capability, high efficiency and lowcost due to absence of permanent magnets [I]. It has beendemonstrated that with respect to traditional induction motors,SynRel machines are showing comparable torque density andlower rotor losses due to the absence of rotor copper losses [2].Despite these advantages, the main drawbacks of SynRelmotors are the high torque ripple and a poor power factor [3].The first is not acceptable for most applications due to thedirect effects on noise and vibration. The challenge of reducingthe torque ripple has been extensively investigated during thepast twenty year's research, and quite a number of techniqueshave been proposed with this aim [4]. It has been proved howthe torque oscillations could be minimized through differenttechniques: rotor skewing, suitable choice of the number offlux barriers with respect to the number of stator slots [5] andthrough the optimization of the flux barrier geometry [6]. Theintroduction of permanent magnets in the rotor flux barriers,even with a small amount of ferrite (Fig. 1), is beneficial for theimprovement of the power factor as well as for the constantpower speed range [7]. Although the analytical modelling anddesign of SynRel machines have been formalized by manyauthors in the last three decades [8, 9], such models aretypically used during the preliminary design stage. They areobviously based on hypothesis in order to simplity theirmodelling and restrict the design space dimension.

Consequently, the design procedure of such machines isusually divided in two steps: first an analytical model is usedto carry out a preliminary design and then a Finite ElementAnalysis (FEA) is employed to evaluate the design aspectsdisregarded in the first stage. The number and the influence ofsuch neglected aspects depend on the accuracy and on theinitial hypothesis of the considered analytical model. Duringthe finite element refinement stage several design iterations canbe needed. The computational time decreases as the accuracyof the analytical model used in the preliminary designincreases. In recent works [10-12], automated designprocedures assisted by optimization algorithms and coupledwith FEA have been presented as an alternative of theaforementioned two steps design procedure. Those designstrategy do not make use of any hypothesis and therefore havethe advantages of considering all the design aspects during theperformance evaluations such as the non-linearities which havea strong impact on the behaviour of SynRel machines.

Proposed method

Themethodology makes use of a stochastic optimization algorithmand finite element analysis. Particular attention has been paidto reduce the computational burden through a carefulsubdivision of the design procedure. This consists in two step:first the main parameters affecting torque density and lossesare optimized by a means of static FE simulations while in thesecond step, the variables which mainly influence the torqueripple are optimized through transient FE simulation. It hasbeen proved that such approach considerably decreases thecomputational time and the goal of reducing the torque ripplehas been achieved.

Methodology

Optimization strategy

The general design procedure of an electrical machine dependson the considered machine topology and on the initialconstraints given by the specific application. In this study themain aim is to design a SynRel machine with the highest torquedensity without any envelope constraints and the minimumlosses and torque ripple. The accurate evaluation of theseobjectives would require a considerable amount of FEsimulations and therefore computational time. In fact, theaccurate calculation of the torque profile requires a set of FESimulations over one sixth of the electrical period while theevaluation of the iron losses needs the FE simulation of a fullelectrical period. However in a first design stage, the torquedensity and the total losses Goule and iron) can be estimated bymeans of static FE simulations for each machine candidate;during this step several static FE simulations are carried out inorder to evaluate the maximum torque per phase angle(MTP A). In the second refinement design stage the torqueprofile can be calculated with a set of FE simulations over onesixth of the electrical period at the MTPA previouslydetermined. In order to apply such methodology the designspace is split in two subspaces:

1. in the first design step, the optimization focuses on the firstsubspace which contains the geometrical parameters thatmainly affect the torque density and the losses, i.e. externaldiameter (D,e), stack length (Lstk), split ratio (SR=D,/Dse),slot geometry (//, WI) and insulation ratio (katr) as defined in[16];

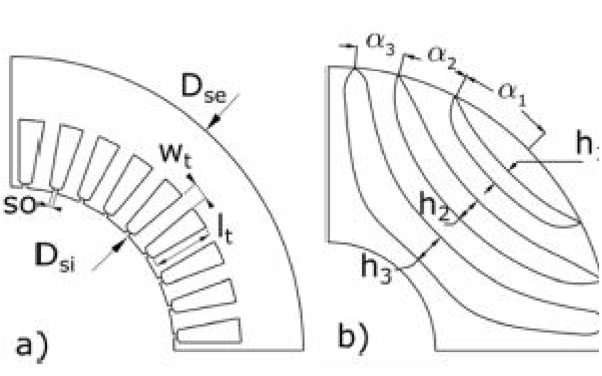

Figure 2: a) Stator parametrization, b) Rotor parametrizatio

2. In the second one, the optimization focuses on the secondsubspace which mainly affects the torque ripple, i.e. rotorflux barrier geometry (angular displacements at the airgapof the barrier a1,2,3 and the insulation ratio katr) and slotopening width (so), see Fig. 2.It is worth to underline that several assumptions have to bemade for each design step, in particular:

• in the first design step, the distribution of the angulardisplacements at the airgap of the flux barriers ispreliminary identified according to [17]; moreover the slotopening (so) is fixed to 0.3 pu;

• in the second design step, the main stator parameters arekept constant and equal to the optimum values obtained inthe first step whereas the angular displacements at theairgap of the flux barriers, the insulation ratio and the slotopening width are refined.

The per-unit parametrizations of the stator and rotor variablesare shown in Fig. 1 and have been defined respectively in [18,19]. A stator configuration with a 36-slot 4-pole distributedwinding is considered along with a rotor structure with threeflux barriers per pole. Regarding the geometry of the fluxbarriers, several alternatives have been presented in literature .It has been shown [21] that adopting a flux barrierprofile which follows the flux lines that the stator windingwould produce in a solid rotor (i.e. laminated rotor withoutbarriers) gives better electromagnetic performance. The lattergeometry has been adopted in this work. The current density inthe slot is set to 9 Almm2 and the torque requirement is reachedup to the base speed of 2500 rpm. The louie losses arecomputed considering a slot fill factor of 0.4 and the length ofthe end windings which is proportional to the external diameterof the stator and to the coil pitch. The iron losses have beenestimated according to the following expression:

$$Pfe = \rho_{fe}\left(\frac{B_{max}}{B_{ref}}\right)^2\left[k_{hy}\left(\frac{f}{f_{ref}}\right)+k_{ed}\left(\frac{f}{f_{ref}}\right)^2\right]$$

Where the maximum flux densities are extracted from the fieldsolution in the different parts of the machine. The coefficientskhy, ked are the hysteresis and

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eddy current constantsrespectively. Their value is depending on the laminationproperties and (M290) and has been carried out through datasheet curve fitting.

Results

Optimization results

A. Torque density, joule and iron losses optimizationTorque density, iron losses and joule losses are the objectives of the first design step. Those performance indexes have beenevaluated by means of static FE simulations carried out fordifferent current phase angles in order to identify the MTP Awhich is a-priori unknown and obviously the maximum torque.Table I depicts the limit of the design variables used during theoptimizations. Two additional constrains have been consideredthroughout the design procedure: 1) the maximum fluxdensities in the tooth and in the back iron have been constrainedto be less than 1.85 and 1.65 [T] respectively, 2) the maximumtorque has to be in the range 90-I 50 Nm. Fig. 3 shows thePareto front of the optimization in the plane iron losses – joulelosses with the torque density represented by the colouredscale. It is clear the trade-off between total losses and torquedensity: as the losses increases, the torque density growths. Inparticular, a 60% increment of losses causes a 25% incrementof torque density. For a given value of total losses, severaldesigns having slightly different distribution of the losses areavailable; however those differences are almost negligible andare due to the different magnetic saturations of those solutions.Four different designs have been picked up from the Paretofront and analysed in details as shown in Table II and III. Thosefour designs correspond to four different cooling capabilities;in fact the ratio between the total losses and the external statorsurface areas kj increases as the torque density increases asshown in table III. The optimal machines show the same splitratios and stack length and almost the same insulation ratio andslot geometry. They differ for the external diameter and

Table I: Design variables boundaries

Parameter	*Lower limit*	*Upper limit*	*Unit*
D_{se}	100	400	mm
L_{st}	50	300	mm
SR	0.35	0.75	p.u.
l_{t_pu}	0.3	0.8	p.u.
w_{t_pu}	0.3	0.8	p.u.
k_{air}	0.35	0.55	p.u.
α_1	15	19	deg.
α_2	26	30	deg.
α_3	36	40	deg.
k_{air}	0.4	0. 5	p.u.
so	0.2	0.8	p.u.

Therefore aspect ratio AR; in particular as the torque densityincreases, the AR increases as well. The distribution of thelosses is practically the same between iron and joule losses.

This design step has been carried out with an optimization thatperform 3000 functional evaluations (50 individuals iteratedover 60 generations); each individual takes lO s to be evaluated, leading to a total computational time of 8.5 hours.

Solution number 3 has been selected as the initial design of thesecond refinement design stage described in the next section.

Table II: Design variables of the selected solutions

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Design	D_{se} [mm]	L_{stk} [mm]	SR [p.u.]	k_{air} [p.u.]	l_t [p.u.]	w_t [p.u.]
1	320	70	0.556	0.42	0.54	0.56
2	300	70	0.556	0.44	0.54	0.56
3	**290**	**70**	**0.556**	**0.45**	**0.54**	**0.58**
4	280	70	0.556	0.45	0.52	0.6

B. A verage torque, torque ripple optimization

During the first design stage, the main stator parameters havebeen identified with the aim of obtaining the highest torquedensity with the minimum losses without considering thetorque ripple. In the second design step the latter is improvedacting on the geometrical variables which mainly influence thetorque profile,

The latter, compared with the initial machine shows a reductionof the torque ripple from 44% to 8%, isworth to highlight how the refinement optimization have takento an improvement of the torque ripple without affecting theaverage torque. Table IV summarizes the design variables ofthe final machine as well as the variables of the initial machine.

It is clear that the angular position at the airgap of the fluxbarriers and the slot opening width play a key role in the torqueripple minimization. [n fact, they significantly influence thetorque ripple and almost do not affect the average torque. Thisdesign step has been carried out with an optimization thatperform 2400 functional evaluations (40 individuals iterated over 60 generations); each individual takes lO s to beevaluated, leading to a total computational time of 6.5 hours. Fig. 5 depict the flux density distribution of the optimalmachine with the maximum values highlighted.

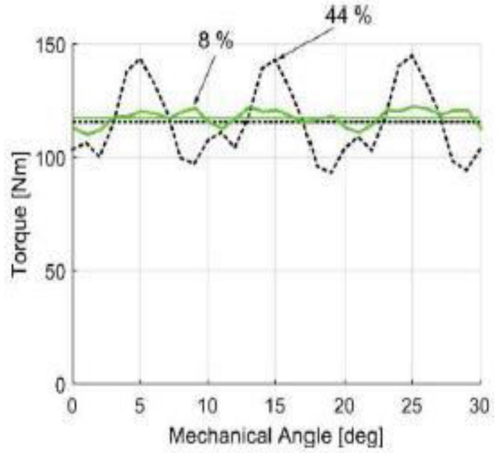

Figure : Pareto front of the second design step: averagetorque - torque ripple optimization.

Table IV : Design variables of the initial and final solutions

Design	k_{air} [p.u.]	α_1 [deg.]	α_2 [deg.]	α_3 [deg.]	so [p.u.]
Initial	0.45	18.8	28	38	0.3
Final	0.42	15.3	27.1	39.2	0.64

4 Constant power speed range improvementsIt is well know that the insertion of permanent magnets insidethe rotor flux barriers improves the constant power speed rangeas well as the power factor. [deally an infinite CPSR ISachieved if the following equations is satisfied [refl :

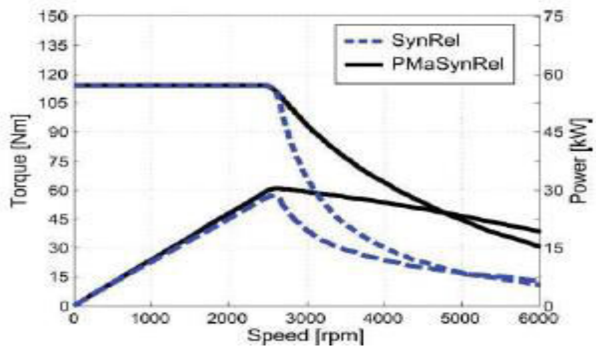

Figure 7: Electromechanical performance: Torque andPower vs speed characteristics.

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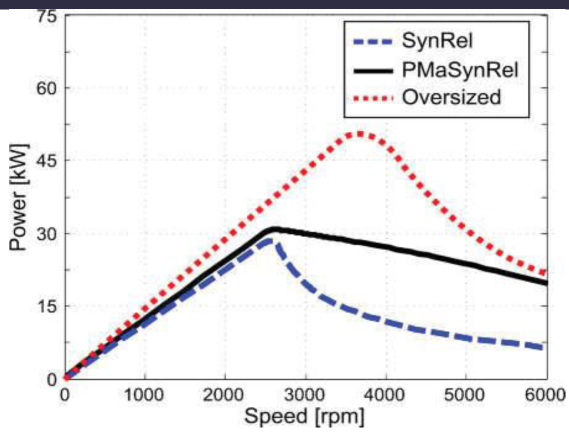

Figure 8: Power vs speed characteristics comparison witha SynRel oversized.

Conclusions

This paper presents an automated design procedure of asynchronous reluctance machine having the aim of optimizingthe torque density, the losses and the torque ripple. Themethodology makes use of a stochastic optimization algorithmand finite element analysis. Particular attention has been paidto reduce the computational burden through a carefulsubdivision of the design procedure. This consists in two step:first the main parameters affecting torque density and lossesare optimized by a means of static FE simulations while in thesecond step, the variables which mainly influence the torqueripple are optimized through transient FE simulation. It hasbeen proved that such approach considerably decreases thecomputational time and the goal of reducing the torque ripplehas been achieved. Moreover, the comparison between thePMaSynRel and a pure SynRel machine having the samepower at maximum speed shows that the latter needs a 40%increment in terms of overall volume.

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