Methodology for Cage Shape Optimization of a Permanent Magnet Synchronous Motor under Line Start Conditions

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The paper proposes a methodology for shape optimisation of the starting cage of an LSPMSM motor with the aim to improve its synchronisation performance. The parameters of the machine are established from a field-circuit model where the magnetic field is simulated using a finite element approach. To facilitate the use of commercial software bespoke procedures have been developed and model parameterization applied with the aid of the scripting language Visual Basic. A particle swarm algorithm has been adapted for design optimization purposes. The proposed strategy has been verified via test simulations.

***Index Terms*— Electromagnetic field, finite element analysis, line start permanent magnet synchronous motor, optimization methods.**

I. Introduction

THE global drive for energy efficiency inspired the search for new types of permanent magnet synchronous motors with the ability for line start (LSPMSM) where an addition of a cage allows for an asynchronous start [1]. A particular design challenge is a search strategy for a topology to achieve synchronization even under high inertia load conditions.

Magnetic saturation plays an important role in transients of such machines, making the purely circuit modelling inaccurate, while the use of field models, such as finite elements, may be impractical due to excessive computational costs of transient solutions, especially as a fully dynamic formulation is required for variable moment of inertia. Moreover, the maximum ratio of the moment of inertia of the load to that of the motor itself, k_i, is required for which synchronisation will still happen. Finding this value may involve repetitive simulations resulting in unacceptable computing times, in particular as the number of necessary function calls is often unknown in advance. The strategy first put forward in [2] has been adopted here where the criterion is based on the value of the synchronising torque defined as the asynchronous torque generated by the cage winding at a speed close to the synchronous speed. This torque may be found using finite element modelling at a prescribed speed, thus significantly reducing the computational effort to establish the component of the objective function representing the synchronising parameters of the machine. Finally, because the parameters resulting in the best starting performance are normally different to the optimal design from the normal operation point of view (efficiency, power factor), it is advisable to conduct a multi objective optimisation to account for all conflicting requirements. The appropriateness of the proposed methodology will be demonstrated on a test case.

II. A Case Study

A particular LSPMSM has been considered whose stator comes from a classical 3.5kW general purpose induction motor, the details of which may be found in [3].

The optimisation task has been defined as a search for such a shape of the starting cage rods which – with the given dimensions and distribution of the rotor permanent magnets – would maximise the previously defined parameter k_i, while maintaining high values of efficiency and power factor. Magnetic field simulation was undertaken using commercial software Maxwell [4], supplemented by parameterised shape descriptors of the starting cage, and linked – via appropriate scripting – with specially developed optimisation routines. The algorithm includes two FEM transient field simulations: (a) a model to calculate efficiency η and power factor PF under the rated load condition, and (b) calculation of the synchronising torque T_{80} (a torque generated at 80% of the synchronous speed). These simulations are carried out in parallel.

The shape of the starting cage bars has been described by six dimensions defined in Fig. 1. The cross section of the rotor teeth has been assumed to be constant along the height of the slot h_{sk}. As a result the geometry of the cage is defined by five design parameters.

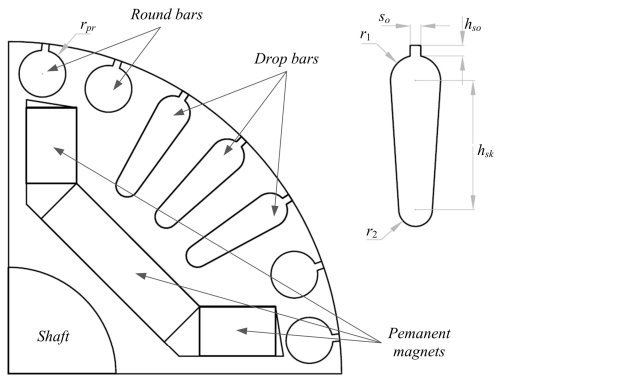

Fig. 1. Design variables describing the shape of the cage bars.

III. The Particle Swarm Algorithm

The particle swarm optimisation (PSO) algorithm, inspired by the flocking and schooling patterns of birds and fish, was first introduced in 1995 [5]. This population-based stochastic method has since been applied effectively to many different engineering problems. In this study a specially modified version of the PSO algorithm has been utilised, adapted to address particular requirements of the design of electromechanical devices. The particles in the swarm represent design variables, with each ith particle described by its position $\boldsymbol{x}^i$ and velocity $\boldsymbol{v}^i$. The particle remembers its best position $\boldsymbol{x}^i_L$ and the position of the leader $\boldsymbol{x}_G$, that is the fittest particle. In the kth time step the position vector of the particle is derived from

$$\boldsymbol{x}_k^i = \boldsymbol{x}_k^i + w\boldsymbol{v}_{k-1}^i + c_1 r_1\left(\boldsymbol{x}_L^i - \boldsymbol{x}_{k-1}^i\right) + c_2 r_2\left(\boldsymbol{x}_G - \boldsymbol{x}_{k-1}^i\right) + c_3 r_3\left(\boldsymbol{m}_c - \boldsymbol{x}_{k-1}^i\right) \quad (1)$$

where w is the inertia factor; $\boldsymbol{x}^i_{k\text{-}1}$ the position vector in the previous step k–1; c_1, c_2 and c_3 the learning coefficients; and r_1 and r_2 are random numbers from the range (0, 1) [6]. The vector of coordinates of the centre of gravity of the swarm in (1) is given by

$$\boldsymbol{m}_c = \sum_{i=1}^{N} \boldsymbol{x}^i f^i(\boldsymbol{x}) \Big/ \sum_{i=1}^{N} f^i(\boldsymbol{x}) \quad (2)$$

where $f^i(\boldsymbol{x})$ is the objective function and N the number of particles in the swarm.

IV. Results of the Cage Shape Optimization

Calculations were performed for the following values of the control parameters of the swarm: N=40, c_1=1.2, c_1=1.4, c_3=1.2. The values of the components of the objective function (for the leader) in selected PSO time steps have been summarized in Table I, where k_z describes the ratio of the angular width of the cage bar to the angular value of the rotor slot pitch, while the remaining symbols are described in Fig. 1 and the associated text. The average values of η, PF and T_{80} at the start of the iterations were: 92%, 0.94 and 25Nm, respectively. In order to validate the proposed approach field simulations were undertaken of the starting of the LSPMSM for various values of the parameter k_i.

The initial and optimised shapes are shown in Fig. 2. Fig. 3 illustrates the speed waveforms for the initial parameters, whereas Fig. 4 contains the results for the optimised machine. It can be seen that the optimised machine can synchronise even for the value of k_i =48, whereas the original motor would only do this for the maximum value of k_i =27.

TABLE I
Summary of the Optimization Results

k	s_o [mm]	h_s [mm]	r_{pr} [mm]	h_{sk} [mm]	k_z [-]	$\eta(x)$ [%]	$PF(x)$ [-]	$T_{80}(x)$ [Nm]
1	1.67	1.28	4.99	9.11	0.72	95.18	0.963	37.55
2	0.87	0.48	3.18	5.09	0.33	93.03	0.994	43.71
5	1.16	1.41	4.86	9.40	0.73	93.73	0.994	46.82
15	1.16	1.41	4.86	9.40	0.73	93.73	0.994	46.82

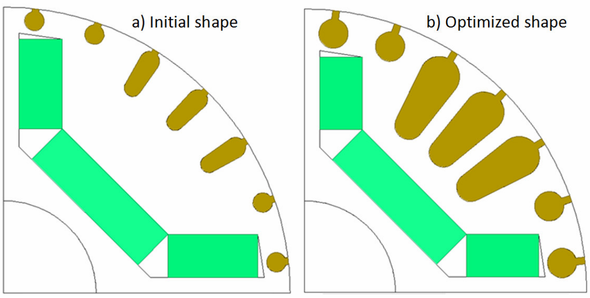

Fig. 2. Initial and optimized shapes of the cage of the LSPMSM.

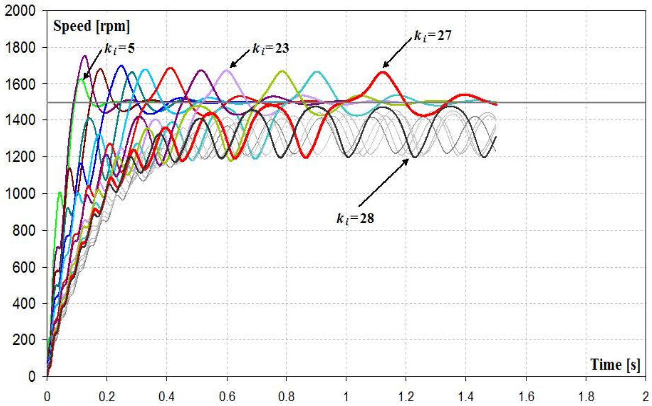

Fig. 3. Speed waveforms during the start-up for the initial shape of the cage.

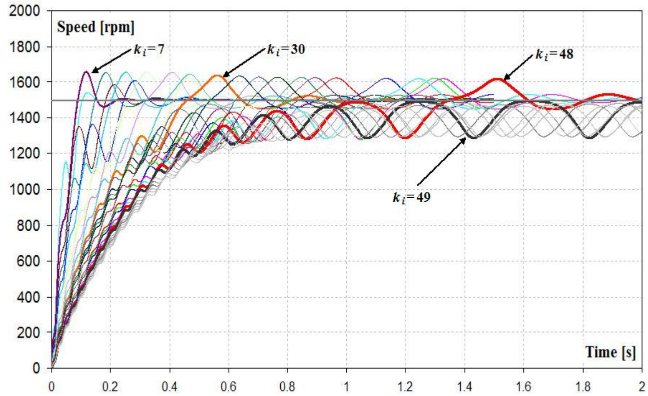

Fig. 4. Speed waveforms during the start-up for the optimized cage.

In the full version further details will be provided regarding the proposed methodology, especially regarding the coupling between field and circuit formulations. The procedure by which an acceptable compromise may be achieved between good starting performance and normal operation characteristics will be elaborated upon.

V. Conclusion

In the paper an effective strategy has been put forward for the LSPMSM design optimisation. The start-up and operating parameters are established using the full field modelling techniques while the optimisation relies on the use of the PSO approach. The results for the test case are very encouraging.

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