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Design and evaluation of high-speed solid rotor induction machine supported by AMBs with a multidisciplinary tool

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Abstract

For high-speed electrical machines compact design is one of their advantages and further system integration is required to increase a system efficiency. A growing level of the technical system integration may cause additional design problems and increase design time. In this work the design procedure and design optimization of high-speed electrical machines supported by Active Magnetic Bearings (AMBs) are described. First, the design of the high-speed induction motor, bearings, and rotor are analyzed. Then, the boundary conditions and optimization variables are selected based on the key system performance indicators. The optimization variables include, for example, rotor outer diameter, number of rotor bars, slit depth ratio, and some other. Finally, an optimization procedure is presented, including objectives for the optimization procedure, fitness function, and selected algorithm. The presented procedure is tested with an example of high-speed induction machine with solid rotor equipped with AMBs. Based on the optimization results the prototype is constructed. An implementation of the optimization procedure prevented extra iterations during the final design stage and reduced total design time. With slight modifications this procedure is applicable for other types of high-speed electrical machines supported by AMBs.

Key words : Optimization, Differential evolution, AC machine, Electrical design, High-speed drive, Mechanical design, Rotating machines, E-core, Heteropolar AMBs.

1. Introduction

High-speed electrical drive systems get more attention both from the research community and industry (Boglietti et al., 2014; Tenconi et al., 2014). The main reasons for that are higher power density, better efficiency, smaller footprint, and direct connection to the process without gearbox. The main applications for such machines are cutting spindles, gas compressors, air compressors and blowers, flywheel energy storages, and microturbines (Gerada et al., 2014).

Machines are usually referred as high-speed when their peripheral speed exceeds 100 m/s and they are fed through frequency converter. At these speeds traditional ball bearings cannot provide enough reliability and life-time. To overcome this difficulty there is a number of options such as ceramic ball bearings, fluid film bearings, air foil bearings, or magnetic bearings. The last type proved to be useful due to completely contactless operation at all speeds, reduced noise, oil free, and build-in diagnostics (Schweitzer and Maslen, 2009). As a result of these benefits magnetic bearings are becoming popular in industry (Swann, 2009).

The process of designing a high-speed drive system is quite complex and always multidisciplinary (Gerada et al., 2014). These systems are tightly integrated and working close to the physical limits. Typically, for the design of a high-speed electrical machine electromagnetic, mechanical, cooling, and rotordynamics issues are considered simultaneously (Pyrhönen et al., 2008). This leads to a quite lengthy development process with multiple reiterations. With an addition of active magnetic bearings (AMBs) to the process the situation becomes worse. AMBs beside their benefits add a lot to the complexity of the system. Their natural open loop instability requires sensors, power electronics, safety bearings, and a controller. All these in turn affect the rotordynamics, cooling and other aspects of the whole system.

This paper presents a method to combine all design aspects of an electrical machine and AMBs. Based on analytical equations a rough solution of a high-speed solid rotor induction machine with magnetic bearings can be achieved. This solution satisfies a set of boundary conditions, and requirements, in addition ensuring optimal performance of the whole system. Analytical nature allows not only fast iteration and optimization but also gives the possibility for engineers from multiple disciplines to evaluate different cases in the rapid way.

Beside the above-mentioned design aspects of an electrical machine the tool includes in the process the dimensioning of AMBs. This adds an estimation of the necessary forces and their bandwidth, selection of a suitable bearing topology, and geometric dimensioning. Then the rotordynamic issues are evaluated. It is ensured that the flexible modes that are close to the operation region can be dampened and do not disturb the control system.

With the help of the demonstrated methodology a high-speed solid rotor induction machine with the nominal power 350 kW at frequency of 250 Hz was designed and constructed.

2. Design Procedure

The general design procedure of a high-speed electrical machine is presented in Fig.1. The scheme was adopted specifically for the case with magnetic bearings based on the procedure presented by Uzhegov et al. (2016). The steps are separated into action steps and decision steps. In each action step a certain group of engineers based on its best effort and knowledge develops one component of the system. During the decision step the results of this development are evaluated and a decision is made to proceed further or to return back. Green lines demonstrate the forward steps, while red lines denote reiterations. It can be noted that reiterations might appear quite late in the procedure and drop the development to the early stage. This brings significant difficulty and time consumption when different groups are responsible for the development of different parts.

In this work a methodology is proposed to overcome that difficulty by carrying all the computations in a single run passing parameters between action steps and making evaluation on the final system not its intermediate components. In general the procedure can be separated into three big parts. The first one is design of an electrical machine active part, the next part is bearing design to support the rotor, and the third is to obtain the rotor structure. Details for each part are described in corresponding sections of the design procedure.

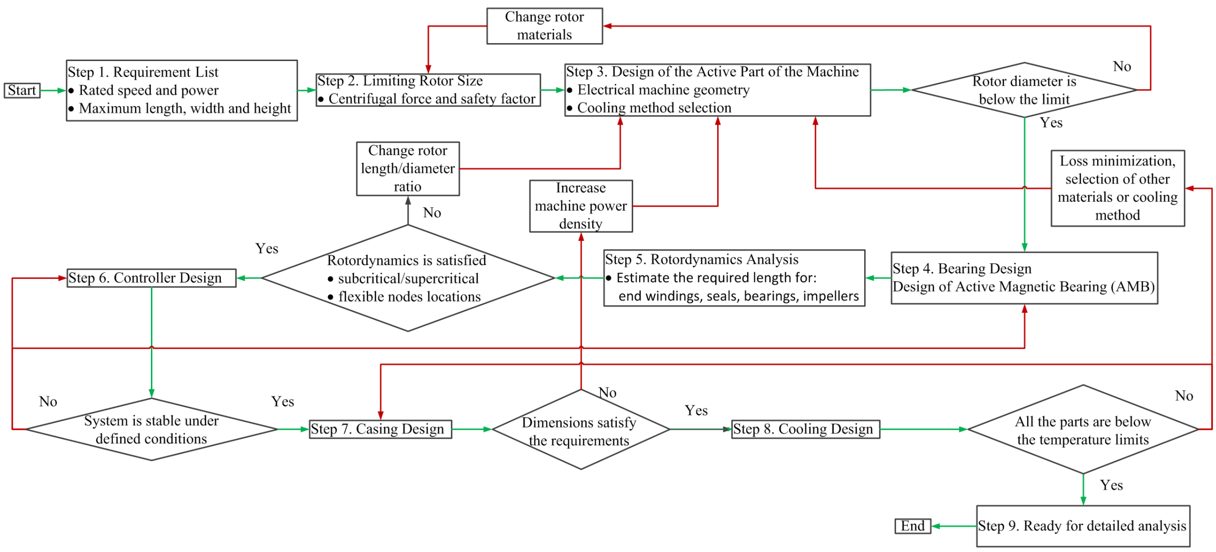


Fig. 1: Steps of design procedure

In the proposed methodology at first electrical machine is designed. Then the rotor weight is initially estimated to provide the force specifications for the bearing design. The following step is the design of axial and radial bearings. When all these elements are available the rotor structure is constructed according to the predefined pattern. This should be iterated several times to update the specifications of the weight as bearings add mass to the system. This ensures an optimum relation between the bearing force and the rotor weight. When achieving this optimal point the evaluation of the full system is done.

2.1. Electrical Machine

There is literature available on the design of an electrical machines. Quite general approach is presented by Pyrhönen et al. (2008). For the high-speed application under study a slitted solid rotor induction machine with copper end rings is selected. Solid rotor structure provides high stiffness, while end rings with slits increase efficiency and power factor. More details on the design aspects of such machines are presented by Pyrhönen et al. (2009).

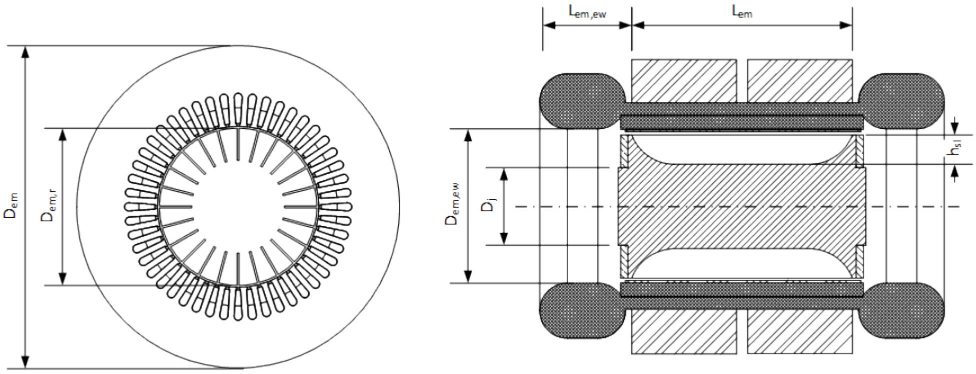


Fig. 2: Section view of electrical machine with main dimensions

The main design criteria of an electrical machine is the power or torque provided at a certain rotational speed. After that comes efficiency and power factor. The torque requirements specifies the necessary volume of the rotor active part. Using that rule the diameter $D_{em,r}$ and length of the rotor L_{em} are estimated. The maximum diameter is limited by the surface rotational speed and strength of the material.

To decrease the losses on the surface of the rotor the end rings made of the conducting material are added to both ends of a rotor active part. The inner diameter of the end rings is fixed to be 55 % of the rotor's diameter $D_{em,r}$. The variation in the width of the rings has some effect on the performance and can be varied. The slits also decrease the rotor's surface conductivity and enables deeper penetration of the flux. This increases both efficiency and power factor of the machine. The depth of the slits h_{sl} is also related to the rotor's diameter and can be varied. The deep slits in general increase the electromagnetic performance of the machine but reduce the mechanical strength (Aho et al., 2006).

The design of the electrical machine part is concluded with the stator. The outer diameter D_{em} is estimated based on the electromagnetic performance. The total length also includes the length of the end windings $L_{em,ew}$. For the distributed windings this can be quite significant part of the overall dimensions. The other issue is that the final end winding dimension depends considerably on the manufacturing process applied. However, based on empirical knowledge the value can be estimated accurately enough. The inner diameter of the end winding $D_{em,ew}$ is bigger than the inner diameter of the stator and defined by the pole structure.

2.2. Magnetic Bearings

The design of magnetic bearing in general is covered by Schweitzer and Maslen (2009). Details on certain aspects for different topologies can be also found in literature (Han et al., 2016; Khoo et al., 2007). In this work for radial bearing a common heteropolar topology is utilized. For axial bearing a C-core topology is selected.

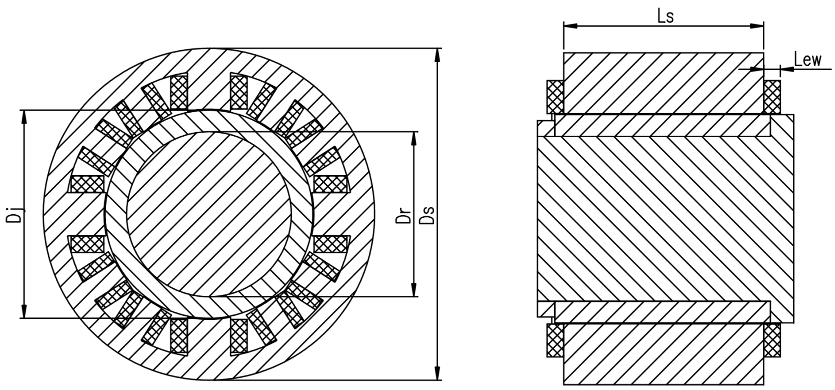


Fig. 3: Section view of radial magnetic bearing with main dimensions

Initial point for bearing geometry estimation is mean F_{avg} and maximum F_{max} force requirements. Based on the maximum force the pole are A_p is dimensioned and the mean force defines the size of coils. The second consideration is the diameter of the rotor D_r at bearing location. In this work the journal diameter D_j of the bearings is selected so that it corresponds to the inner diameter of the end ring of the electrical machine. Using this information the geometry of radial bearings is selected.

Certain decisions should be fixed regarding structure and parameters of radial bearing. The first one is the air gap which is selected to be 500 µm. Next is the saturation point for the core material which is defined by the knee in the $B - H$ curve, it is 1.2 T. The pole arrangement for the bearing is selected to be E-core type, as it allows to split the flux in the journal and thus provides thinner journal dimension.

A non dimensional parameter "iron ratio" f_i defines the ratio utilized by the poles in total radial circumference. The variation of that parameter has a direct effect on the stack length L_s of radial bearing. These parameters have the following relation:

$$A_g = D_j L_s \sin \frac{\pi f_i}{n}, \tag{1}$$

where n is the number of poles and for this case it is eight. This is done under assumption that the surface of each small pole is half of the surface of the bigger pole.

The copper area is estimated based on the allowed average current density in the windings. It is limited by the heat dissipation and available cooling. In this work the maximum current density is assumed to be $5\,\mathrm{A/mm^2}$. The coil is calculated such that it can be prewound and then inserted on the pole. Thus, the necessary area for the coil defines the inner diameter of the stator. The dimensions of end windings L_{ew} in magnetic bearings are quite predictable as they are tooth coil windings.

With the above-mentioned geometrical dimensions it is possible to estimate the necessary space for radial bearings in the total assembly of the high-speed machine.

The same procedure is applied for the axial bearing. Based on the maximum and average force the required iron surface and coil surface are selected respectively. The structure of the bearing is classical C-core shape, the air gap is selected to be 800 µm to provide some freedom in the axial directions in case of the rotor contraction or thermal expansion. It is difficult to make laminated structures for the axial bearing, therefore, the stator and rotor parts are done from a solid steel. Based on the steel properties and considering effect of eddy currents the maximum flux density is selected to be 0.6 T.

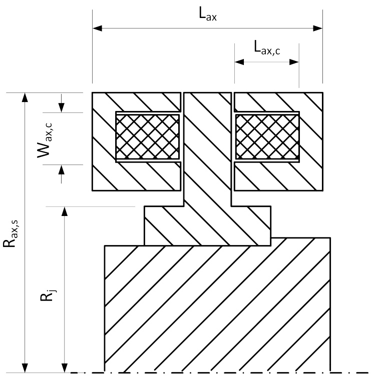


Fig. 4: Section view of axial magnetic bearing with main dimensions

The similar iron ratio parameter $f_{ax,i}$ is introduced as in radial bearings. It defines trade off between axial length and maximum diameter. The inner diameter is defined by the rotor structure and selected to be the same as the journal diameter of radial bearing. From that dimension a certain amount should be reserved to allow free rotor rotation and also to reduce the flux leakage from the electromagnets to the rotor structure.

2.3. Mechanics and Rotor Dynamics

In high-speed machines the dynamics of the rotor play an important role, especially in the case of machines supported by magnetic bearings. Lately, model based controllers are applied to stabilize the system. Those require an accurate model of the system to be efficient (Sawicki et al., 2007). Special attention should be devoted to the node locations of flexible modes. They should be far enough from the sensor and actuator positions to be observable and controllable respectively.

To estimate the frequencies of eigenmodes and their shapes the full rotor model should be composed and analyzed with finite element method (FEM). For this purpose beam elements are utilized that provide acceptable accuracy and fast calculations (Friswell et al., 2010). With all geometrical dimensions available from the previous calculations it is possible to assemble a rotor model. For that purpose a number of assumptions is done regarding the space required for the safety bearings, sensors, distance between parts and connection interfaces. The full assembly is presented in Fig 5.

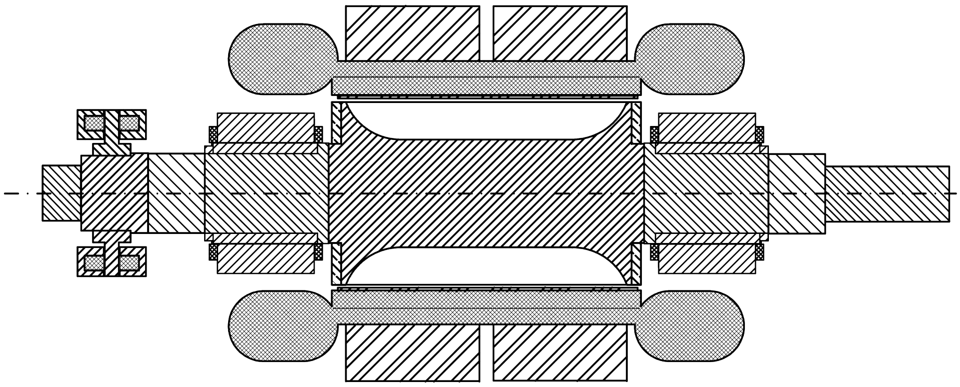


Fig. 5: Cross section of the assembly

The other consideration is the maximum stress of the rotor components resulting form the rotational speed. In the case of a hollow cylinder such as AMB lamination stacks, axial disc, and end rings the maximum stress σ can be defined analytically as

$$\sigma = \frac{3+\nu}{4}\rho\omega^2\left(r_o + \frac{r_i^2(1-\nu)}{3+\nu}\right), \tag{2}$$

where ν is Poisson's ratio, r_o and r_i are outer and inner diameters of the part, respectively, ρ is the material density and ω is the rotational angular velocity. This estimated stress should not exceed the yield strength of the selected material. For complex geometry of the rotor slitted part the stress definition based on analytical and empirical data is presented by Aho et al. (2006).

Besides the stress limit the parts should be tightly mounted to the shaft at all conditions. One of the common ways to attach elements is shrink fit. Based on equations by Ugural and Fenster (2003) the shrink fit connection is loose because of the rotational speed under the following stress

$$\sigma = \frac{\rho\omega^2}{4}\left((1-\nu)r_i^2 + (3+\nu)r_o^2\right). \tag{3}$$

These stress values are acting as boundary conditions on possible design variations. The design flow shown in Fig. 1, desired output performance, and boundary conditions enable performing an optimization of the high-speed electrical machine with AMBs.

2.4. Optimization

A set of parameters for the electrical machine and bearing is selected as variables. For the electrical machine it is the rotor outer diameter $D_{em,r}$, width of the end rings $L_{em,er}$, number of rotor bars n_b, and the ratio between depth of the slits and rotor diameter. For the radial and axial bearings only variable parameter is the iron ratio. Based on the changing dimensions of the electrical machine part and bearing parts in some cases it is possible to fit bearings under the end windings of an electrical machine. For that purpose the part of the algorithm responsible for the rotor model makes appropriate changes. The variables are presented in Table 1.

The objectives for the optimization procedure are selected first to fulfill the machine specifications regarding efficiency η_{em} and power factor φ_{em} in the nominal operating point. Therefore, these two parameters are maximized. As the electrical machine has the biggest outer diameter of the rotor unit it encounters the maximum stress σ_{em} and this value is minimized. To avoid supercritical system and make bearing control easier the frequency $\omega_{fl,1}$ of the first flexible mode is maximized. In general it is beneficial to have light and compact system, thus, the mass of the rotor m_r is minimized.

Beside optimization some of the parameters must be in certain limits to make the system feasible. This includes mostly mechanical considerations regarding stress and shrink fits. However, the power factor and efficiency of the electrical machine cannot be below certain value. A single objective algorithm is indented to be used. Therefore, the fitness

Parameter	Notation	Min. value	Max. value
Rotor outer diameter	$D_{\mathrm{em,r}}$	100 mm	250 mm
Number of rotor bars	n_{b}	14	32
Slit depth ratio	f_{slit}	30 %	50 %
End ring width	$L_{\mathrm{em,er}}$	5 mm	30 mm
Radial bearing iron ratio	$f_{\mathrm{rd,i}}$	20 %	70 %
Axial bearing iron ratio	$f_{\mathrm{ax,i}}$	20 %	70 %

Table 1: Variable parameters for the system optimization

function is modified to include logarithmic barrier for such objectives and parameters. As it is described above very different objectives are included into the same fitness function. Thus, to provide an even inputs each parameter is scaled in the range from 0 to 1. The boundary conditions are presented in Table 2. The last condition defines that on average the distance from the two actuator and two sensor nodes to the shape of the first flexible mode is above 0.2. The node shape is dimensionless and scaled to the interval $[-1..1]$.

Parameter	Notation	Boundary
Machine efficiency	η_{em}	≥90 %
Machine power factor	φ_{em}	≥80 %
Stress on machine active part	σ_{em}	≤275 MPa
Stress on bearing lamination	σ_{rd}	≤450 MPa
Stress on axial disc	σ_{ax}	≤275 MPa
Frequency of the first flexible mode	$\omega_{\mathrm{fl,1}}$	≥250 Hz
Observability and controlability of the first mode	$0.25 \sum \zeta_{\mathrm{i}}$	≥0.2

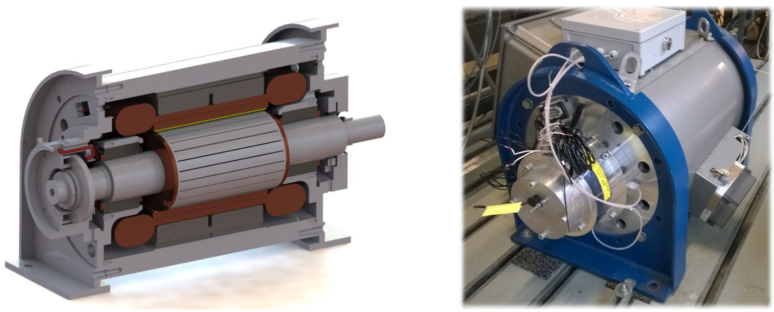
Table 2: Boundary conditions

The final fitness function with objective for minimization has the following form:

$$f = \sigma_{\mathrm{em}} - \eta_{\mathrm{em}} - \varphi_{\mathrm{em}} - \omega_{\mathrm{fl,1}} + m_{\mathrm{r}} + \varepsilon, \quad (4)$$

where ε includes the boundary conditions. The optimization algorithm should take into account the limits of variables, reasonable manufacturing tolerance and possibility to have only integers as variable values. In addition the objective function is nonlinear. The most suitable algorithm for such purpose is differential evolution (Price et al., 2005). In this work the differential evolution with *DE/best/1/exp* strategy has been applied. This means that the *best* vector will be perturbed. The number of difference vectors for perturbation is *one* and *exponential* crossover is used. The number of population members is equal to 50. After 30 iterations the algorithm converged to the steady solution with the following values of design variables: $D_{\mathrm{em,r}}$ =195 mm, n_{b} =26, f_{slit} =48 %, $L_{\mathrm{em,er}}$ =10 mm, $f_{\mathrm{rd,i}}$ =36 %, and $f_{\mathrm{ax,i}}$ =47 %.

Based on the achieved optimization result the system was fine-tuned by experts and prepared for manufacturing. The total weight of the rotor is 109 kg, nominal power is 350 kW at rotational speed of 15 000 rpm. The model of the system and its photo are presented in Fig. 6.



(a) Model of the system (b) Photo of the system

Fig. 6: High-speed electrical machine supported by AMBs

3. Conclusions

The growing complexity and integration level of high-speed electrical machines supported by active magnetic bearings requires the appropriate design techniques to avoid prolonged design process. In this work the analytical tool aimed for the design of the high-speed induction machine with AMBs is demonstrated. The tool is based on the design procedure containing nine action steps, five decision steps, and advices to overcome the design problems. The procedure includes preliminary design of the electrical machine, magnetic bearings, controller, cooling, and casing. The key design parameters of the electrical machine, AMBs, and rotor unit are explained in detail. The system optimization aimed to take into account both the machine and bearing structures is presented. It includes the set of variables with their own limitations, boundary conditions, fitness function, and optimization algorithm. The optimization procedure is implemented for a high-speed induction motor with conducting rotor end rings and the rotor equipped with AMBs. The prototype is constructed based on the optimization results. The presented design and optimization procedures can be implemented for other types of high-speed electrical machines and active magnetic bearings.

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