METHODOLOGY TO DETERMINE THE MAXIMUM ROTATIONAL SPEED FOR THE ARRANGEMENT OF BURIED PERMANENT MAGNETS IN HIGH-SPEED ROTORS OF ELECTRICAL MACHINES

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A methodology to determine the maximum technically feasible rotational speed of rotors constructed with buried permanent magnets is presented. The maximum achievable rotational speed is reached as soon as the permissible space within the rotor is no longer sufficient for the arrangement of the permanent magnets. The methodology couples mechanical and electromagnetic constraints. The results are evaluated based on a V-arrangement of a buried rotor permanent magnet system.

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I Motivation

High-speed operation of electrical machines is essential for mobile applications due to potential increases in the achievable power density [1], [2]. The synchronous machine with buried permanent magnets (IPMSM) is predominantly used in traction drives for electric vehicles when compared to other machine topologies [2].

The feasible electromagnetic design is mainly limited by mechanical constraints at high-speed operation, so that the yield strengths of rotor materials are not exceeded, and mechanical integrity is guaranteed during operation [3], [4].

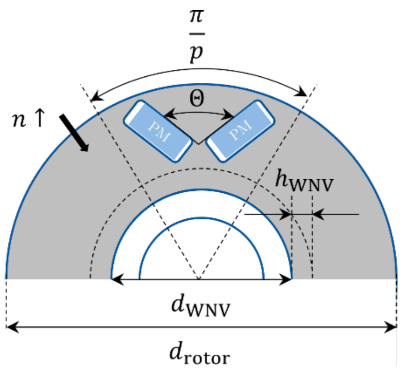

Figure 1: Allowable construction space for a V-arrangement of buried permanent magnets (VPMSM) within a rotor.

An analytical methodology to calculate the maximum mechanical stress in high-speed rotors with regard to the impact of centrifugal force and press fits between rotor components is published in [4] and [5]. The analytical approach enables a representation of the achievable circumferential speed v for different rotor topologies based on material and geometric parameters (1).

The circumferential speed is directly dependent on the ratio R_{p}/ρ between the yield strength and the density of the material used in the outer holding band of the rotor. The notch effect of magnet pockets is considered with the stress concentration factor K_{t}. The press fit between the lamination sheet and the shaft reduces the achievable circumferential speed. The impact primarily depends on the interference δ and the relative distance between the joint diameter d_{WNV} of the shaft-hub connection and the position d_σ with the maximum centrifugal load [4]. E is the homogenised *Young*'s modulus of both construction elements.

$$v \sim \sqrt{\frac{R_\mathrm{P} - \left(\frac{d_\mathrm{WNV}}{d_\sigma}\right)^2 \cdot E \cdot \frac{2\delta}{d_\mathrm{WNV}}}{K_\mathrm{t} \cdot \rho - \left(\frac{d_\mathrm{WNV}}{d_\sigma}\right)^2 \cdot \frac{1}{v_\mathrm{lift}^2} \cdot E \cdot \frac{2\delta}{d_\mathrm{WNV}}}} \tag{1}$$

As the achievable circumferential speed of a rotor cross-section is limited, the rotor diameter d_rotor decreases with increasing rotational speed n as shown in Figure 1. In addition, the shaft-hub connection limits the radial space within the rotor, in which the permanent magnets can be arranged. A minimum thickness h_WNV of the rotor lamination sheet at the bore diameter d_WNV is required to apply the necessary joint pressure to the interference fit. The number of pole pairs p determines the rotor symmetry at the circumference.

An analytical model for calculating the flux density in the air gap during the no-load operation of an IPMSM as a function of the dimensions of the buried permanent magnets and the bridge thicknesses is published in [5]. This electromagnetic model is coupled to the mechanical models in [4] and [5] to obtain a maximum achievable rotational speed n_max, above which the space within the rotor is no longer sufficient for the arrangement of permanent magnets.

Table 1: Material properties

Component	Material	Physical Properties
FL	NO27-14	R_P=416 MPa, ρ=7600 kg/m^3
PM	NdFeB	B_r=1.25 T, H_c=-992 kA/m, ρ=7650 kg/m^3

II Methodology

Figure 2 shows the process for determining the maximum technically feasible rotational speed. At the beginning of the design process, the power P, the efficiency η to be achieved and the permissible installation space V_zul must be defined. The suitable materials for the ferromagnetic lamination (FL) and the permanent magnets (PM) with their mechanical and electromagnetic properties are selected. Based on the selection for the electrical steel sheet, this is accompanied by a limitation of the maximum fundamental electrical frequency $f_{el,max}$ so that the iron losses are not becoming too large.

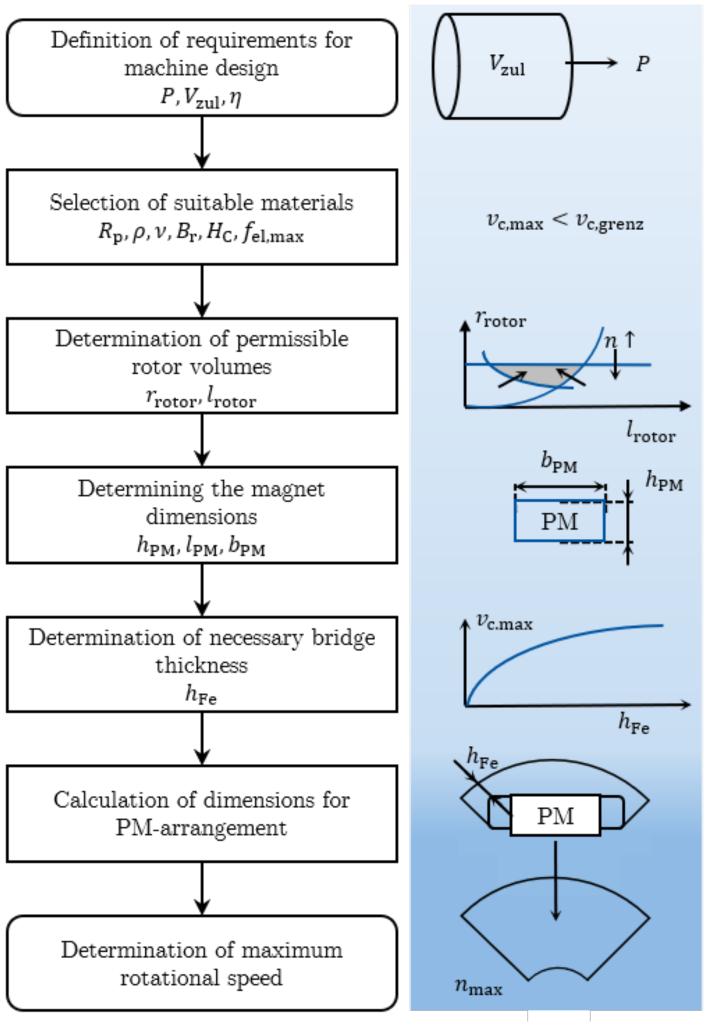

Figure 2: Methodology for determining the maximum technically feasible rotational speed.

The permissible rotor dimensions are calculated based on relationships for structural mechanics and structural dynamics in [5] and [6]. The electromagnetic model in [5] enables the determination of the dimensions of the buried permanent magnets. The required bridge thickness to ensure the rotor integrity is then calculated using the mechanical model.

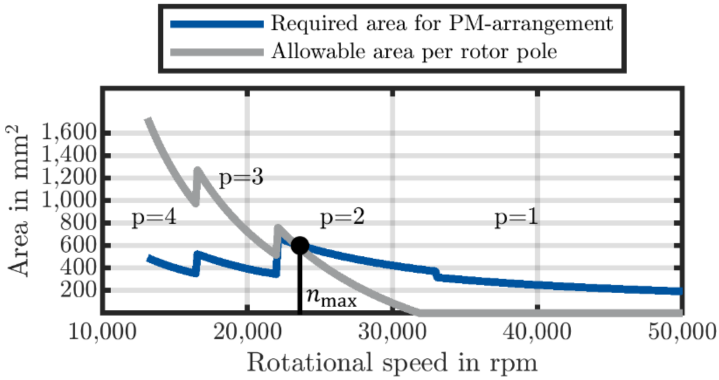

Figure 3: Comparison of space requirement for PM arrangement and allowable space.

Now that the dimensions of a magnet arrangement have been determined, it can be assessed whether the permanent magnets can be arranged inside the rotor. The rotational speed n_{max} above which the arrangement is no longer possible, is the maximum technically feasible rotational speed.

The required area of a PM-arrangement is compared in Figure 3 to the allowable area per rotor pole based on the material parameters given in Table I. At low rotational speed, there is no space restriction for the arrangement of the permanent magnets. The number of pole pairs is abruptly reduced when the defined frequency $f_{\mathrm{el,max}}$ is reached. This results in an instantaneous increase of the allowable and required area. The required area increases so that adequate pole coverage is achieved with the permanent magnets. Overall, the permissible area decreases faster than the required area with increasing rotational speed, so both curves intersect. The intersection point determines the maximum rotational speed n_{max}.

As shown in Figure 4, this intersection point dependent on the required power and the achievable circumferential speed. The smaller the angle Θ of the V-arrangement, the smaller the maximum rotational speed becomes.

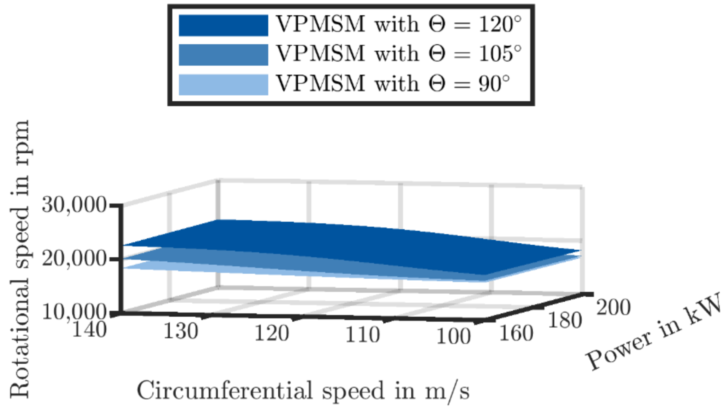

Figure 4: Influence of the angle Θ of the V-arrangement on the achievable maximum rotational speed.

III Conclusion and Outlook

The presented methodology enables the determination of a maximum technically feasible rotational speed with regard to the arrangement of buried permanent magnets. The solution space of possible circumferential and rotational speeds for a PM-arrangement is morphologically limited. This method can be used in the following to compare different PM arrangements such as tangential- and / or spoke-arrangement with regard to the limits of high-speed operation.

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