WINDINGS
Electromagnetic Solutions

V-Shape IPM Rotors

Design Consideration and Concerns

For more than 50 years, **Windings** has provided engineered electromagnetic solutions for critical applications in Aerospace, Defense, Automotive and Oil & Gas industries. As a full-service provider, Windings is a leader in the design, test, manufacture and support of custom electric motors, generators and related components including rotors, stators, lamination stacks and insulation systems.

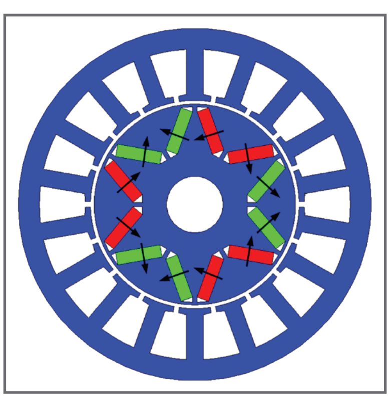
Introduction

Interior Permanent Magnet machines (IPMs) have seen wide adoption across many industries due to their inherent ruggedness, high efficiency and relatively low manufacturing cost. Among the various IPM topologies, V-shape IPMs exhibit higher power densities, higher efficiency, lower manufacturing cost and wider constant power operating range. As with Surface-mounted Permanent Magnet (SPM) machines, IPMs take advantage of magnetic torque produced by both permanent magnets and reluctance torque due to unequal reluctance between the d and q axes. Unlike SPMs, however, designing an IPM has proven challenging due to rotor structure complexity and magnetic saturation.

Advantages

One of IPM's important advantages over SPM is the simplicity of precisely manufacturing the IPM rotor lamination's outer shape as compared with the magnet's outer shape in SPMs. This advantage also creates additional desirable characteristics:

- IPMs use simple rectangular-shape magnets with parallel magnetization which reduces both magnet price and manufacturing cost;
- IPM magnets are mechanically captured within the rotor lamination, making them suitable for high speed operation without protective rings or retaining sleeves on the rotor;
- Presence of a flux bridge in provides better protection against demagnetization, offering IPMs a higher overloading capability.
- The IPM sinusoidal air gap flux density distribution minimizes cogging torque, providing superior low speed velocity regulation.

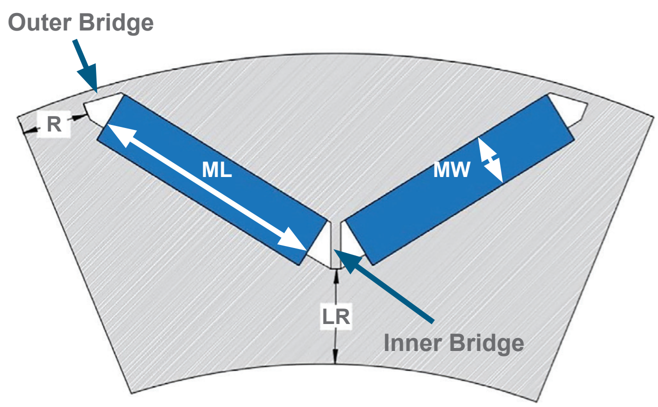


Typical Topology

The fundamental characteristics of an IPM design, such as maximum torque, resistance to demagnetization, d-axis and q-axis inductance, back EMF, etc. are significantly affected by the position and dimensional geometry of the PMs. In a typical V-shaped IPM geometry, shown below, R is half of the distance between the adjacent two PM's, LR is the distance between the bottom of the PM and the inner diameter of the rotor core and ML and MW are the PM thickness and width of one pole respectively.

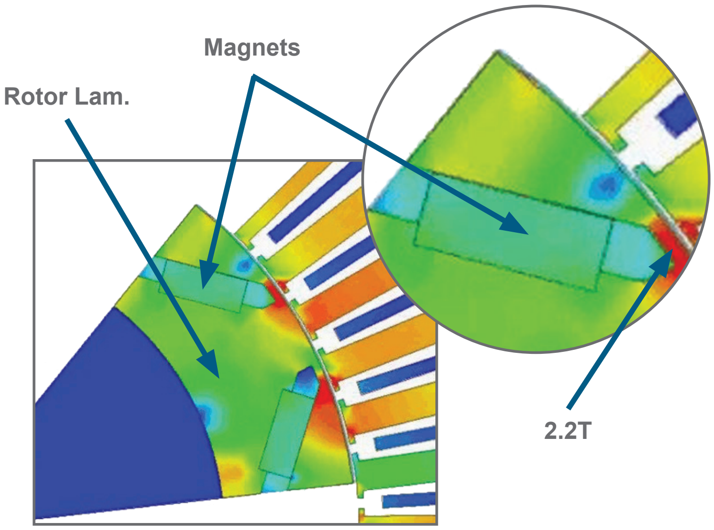
Peak torque vs PL and PW can be mapped and optimized. Although peak torque maximum can be increased by decreasing the PW thickness, the PM is prone to irreversible demagnetization if the PW is too small. Alternatively, as the PW increases and the cross-sectional area is held constant, the maximum peak torque decreases. Therefore, the thickness of the PM should not be too small or too large.

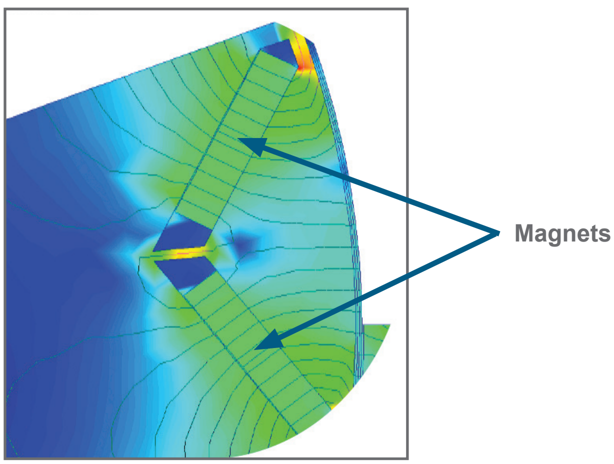
The PM V-shaped diagram



Flux Density Distribution

Typical flux density distribution and flux lines obtained from FEA software are shown below. Performance of the motor is highly dependent on the saturation level of the rotor lamination regions described below.

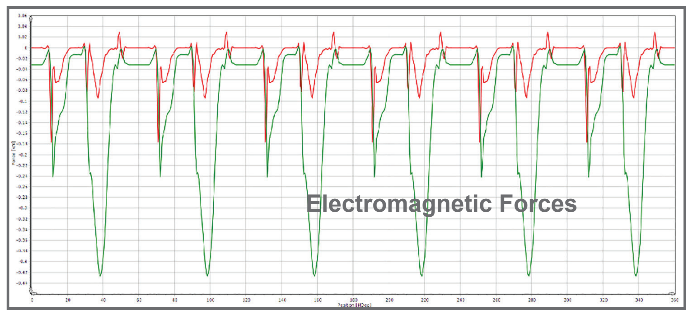




Structural Considerations

Evaluating the structural integrity of an IPM is a critical step in the design and optimization process. The objective of the analysis is to compute the stress distribution within critical regions of the machine. Mechanical stresses within the steel bridges of an IPM are mainly caused by the centrifugal force exerted by each pole-piece. Therefore, the method to compute the centrifugal force needs to be established. The radial and tangential electromagnetic forces (see typical distribution below) must be taken into account, specifically under heavy electrical load. These forces can be obtained from FEA.

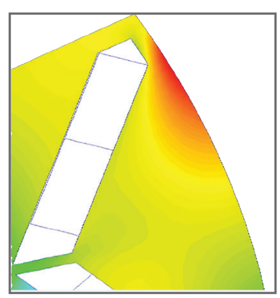
The radial deformation of the pole-piece is largely associated with the tension force exerted by the inner bridge; while the tangential deformation is dominantly influenced by the tension of the outer bridge. Therefore, the radial stiffness and the tangential stiffness can be characterized separately by considering the effect of either the inner or outer bridge, respectively. Furthermore, since the deformation of the pole-piece is considered local, it is assumed that the geometry irregularity far away from the area where the bridge and the pole-piece interact does not have a large impact on the stiffness.



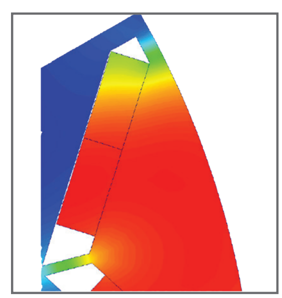
Stresses and Deformation

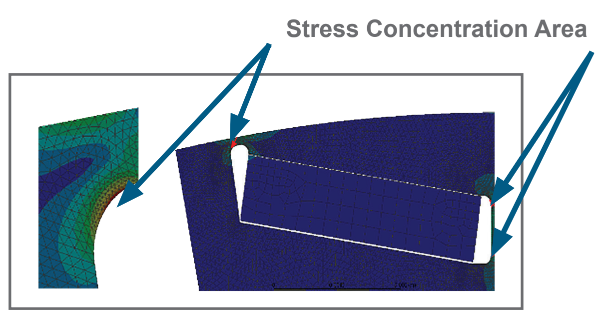
Typical stresses and deformation plots obtained from FEA software are shown below. Performances of the motor are highly depended on the saturation level of the rotor lamination regions described above.

Stress Plot



Deformation Plot





Typical Material Properties

Index	Steel Type	p, (kg/m^3)	c_s, $(\$/kg)$	B_{lim}, (T)	E, (N/m^2)	S_{sy}, (N/m^2)
1	M19	7402	3.5	1.3922	$2x10^{11}$	$1.25x10^8$
2	M36	7018	3.5	1.3652	$2x10^{11}$	$1.25x10^8$
3	M43	7291	3.5	1.3902	$2x10^{11}$	$1.25x10^8$
4	M47	7585	3.5	1.4874	$2x10^{11}$	$1.25x10^8$

Index	Steel Type	α_h	β_h	k_h, (J/m^3)	k_e, (Js/m^3)
1	M19	1.338	1.817	92.94	$50.44x10^{-3}$
2	M36	1.340	1.799	117.5	$74.21x10^{-3}$
3	M43	1.2785	1.7543	155.9	$75.92x10^{-3}$
4	M47	1.2558	1.685	273.2	$478.6x10^{-3}$

Material	Density		Modulus of elasticity		Ultimate Tensile strength		Coefficient of thermal expansion		Electrical resis-tivity Ohm-cm x 10^{-6} (at 20°C)
							Perpendicular To orientation	Parallel To orientation	
	g/cm^3	lbs/in^3	psi	Pa x 10^9	psi	Pa x 10^6	10^{-6}/°C	10^{-6}/°C	
1-5 Alloys	8.4	0.303	23 x 10^6	159	6,000	41	13.0	6.0	53
2-17 Alloys	8.4	0.303	17 x 10^6	117	5,000	35	11.0	8.0	86
Nd-Fe-B	7.4	0.267	22 x 10^6	152	12,000	83	4.8	3.4	160

For further information, please contact us!

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