Optimal Design of PMa-synRM for electric propulsion system considering wide operation range and demagnetization

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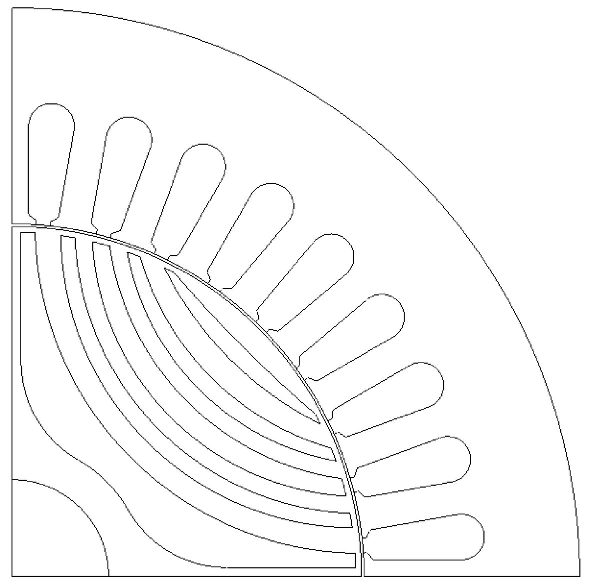
Background

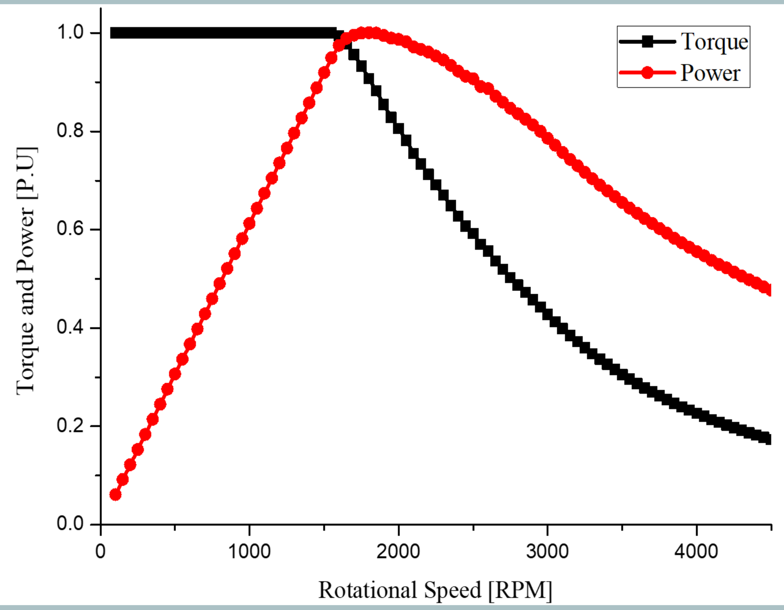
- Synchronous reluctance motor (SynRM) has advantages on torque density, price of manufacturing, and cost robustness.
- However, synRM is lack of linkage flux produced by field magnet, since it does not contain permanent magnet.
- Permanent magnet assisted synchronous motor(PMa-synRM) enables increasing operation region by supplementing reasonable amount of permanent magnet.
- Pma-synRM can guarantee higher torque density, wide operation region compared to synRM with considerate design.

Objectives

- Conducting optimal design considering wide operation range, torque density and torque ripple.
- Demagnetization of the permanent magnet is considered as well by optimizing position of the permanent magnet.

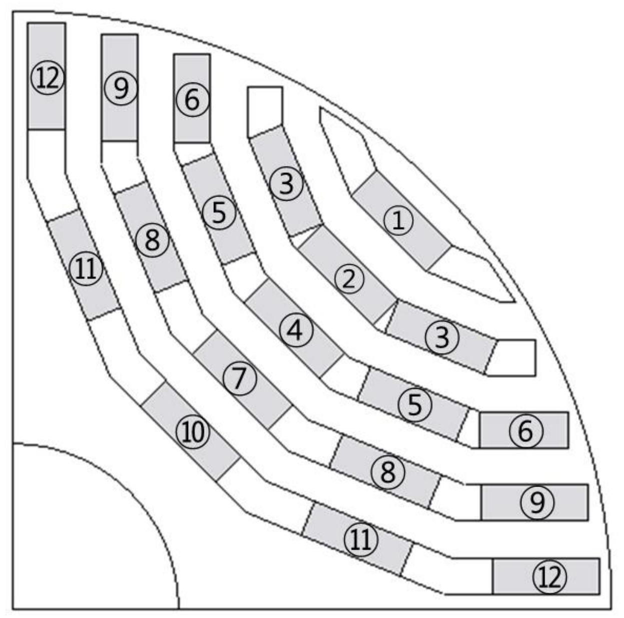
Prototype





- Prototype model is synchronous reluctance motor, which has advantages on torque density and manufacturing cost.
- SynRM has limited performance at high speed region since there is no linkage flux produced by field magnet.
- Reliable performance is required to adopt at propulsion system.
- Optimal design is conducted to have robust performance at high speed region by supplementing reasonable amount of PM.

Governing Equation



- Torque Calculation

$$T = r \times \vec{F_\theta} = r \times \oint_S \tau \cdot \vec{n} dS \text{ [Nm]}$$

- Torque Density Calculation

$$TD = \frac{T}{W_{copper} + W_{core} + W_{PM}} \; [^{Nm}/_{kg}]$$

- Torque Ripple Calculation

$$TR = \frac{|T_{max} - T_{min}|}{T_{Avg}} \times 100 \text{ [\%]}$$

- Alignment-Reluctance Torque Ratio

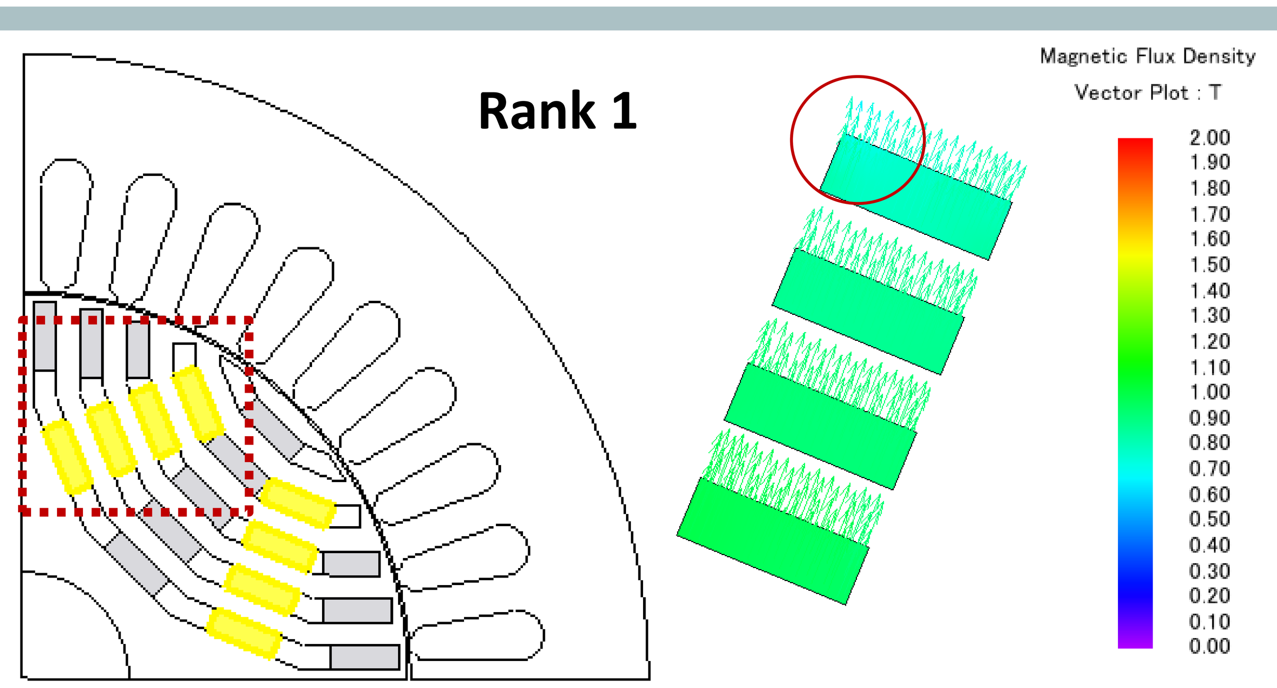
$$T = \frac{3}{2}\frac{P}{2}(\lambda_d i_q - \lambda_q i_d)$$

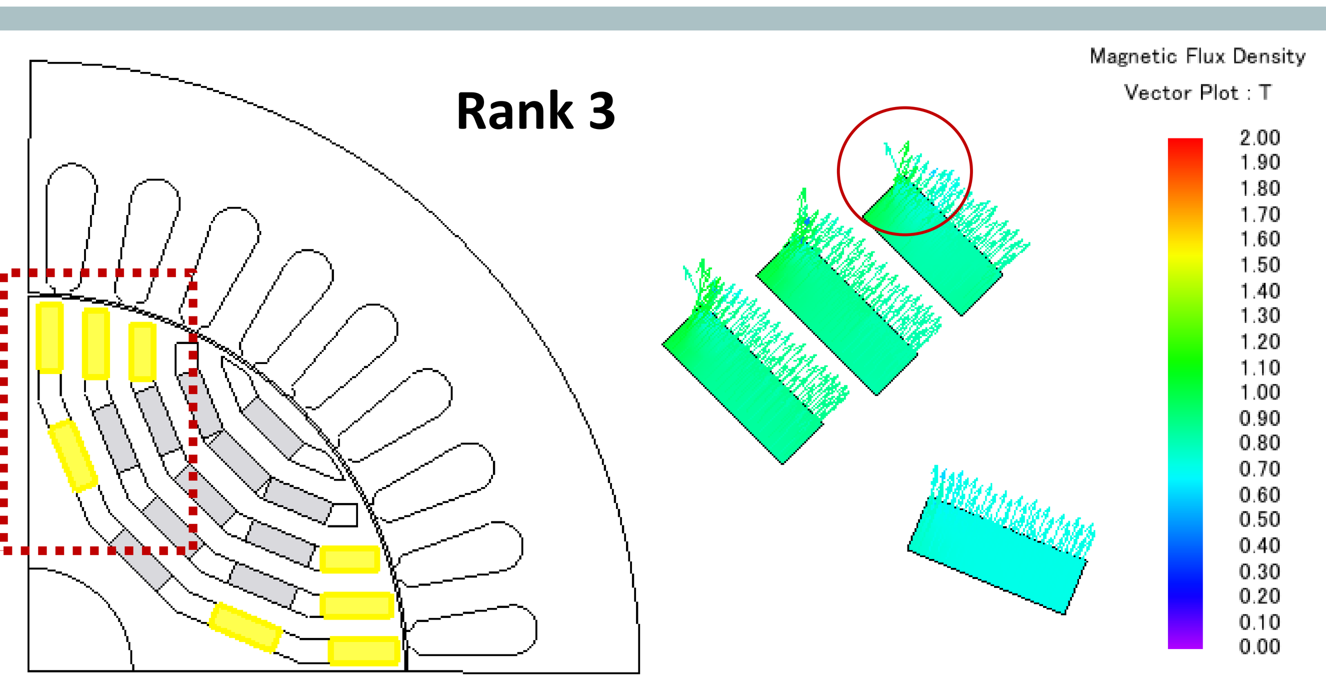
$$= \frac{3}{2}\frac{P}{2}[\lambda_f i_q + (L_d - L_q) i_d i_q]$$

Alignment Torque

Reluctance Torque

Demagnetization



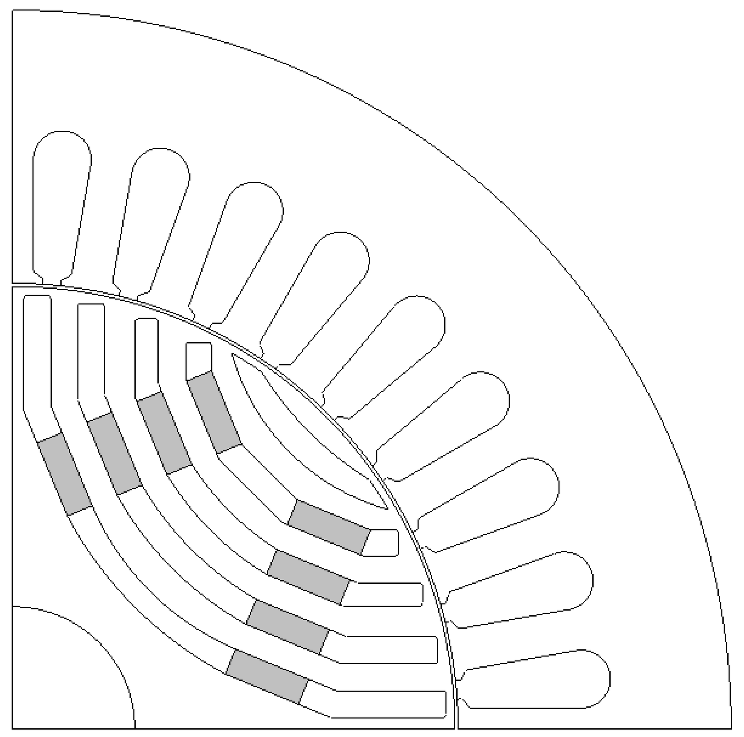


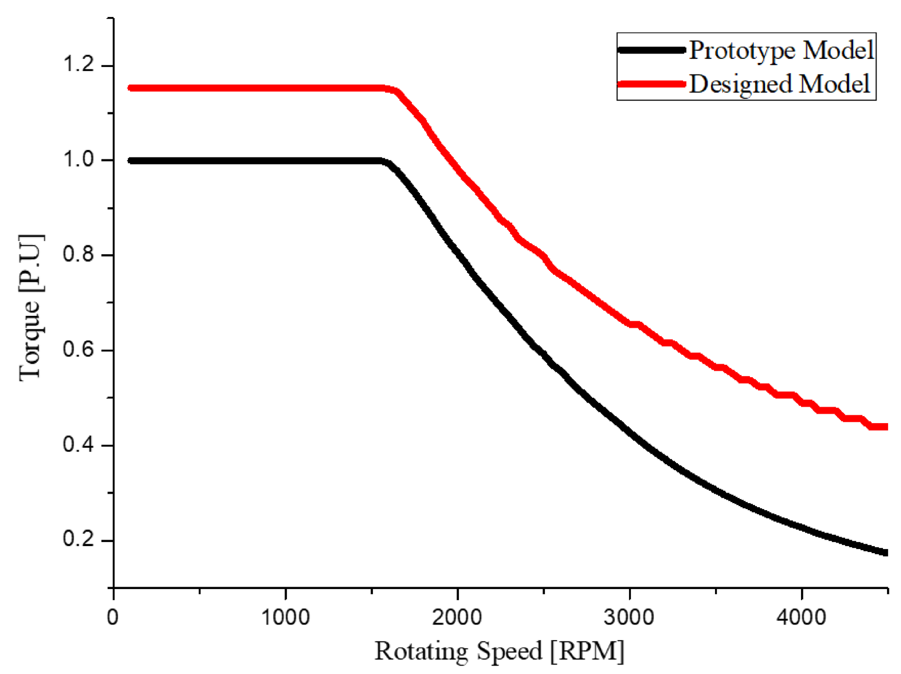
Permanent Magnet Position Optimization

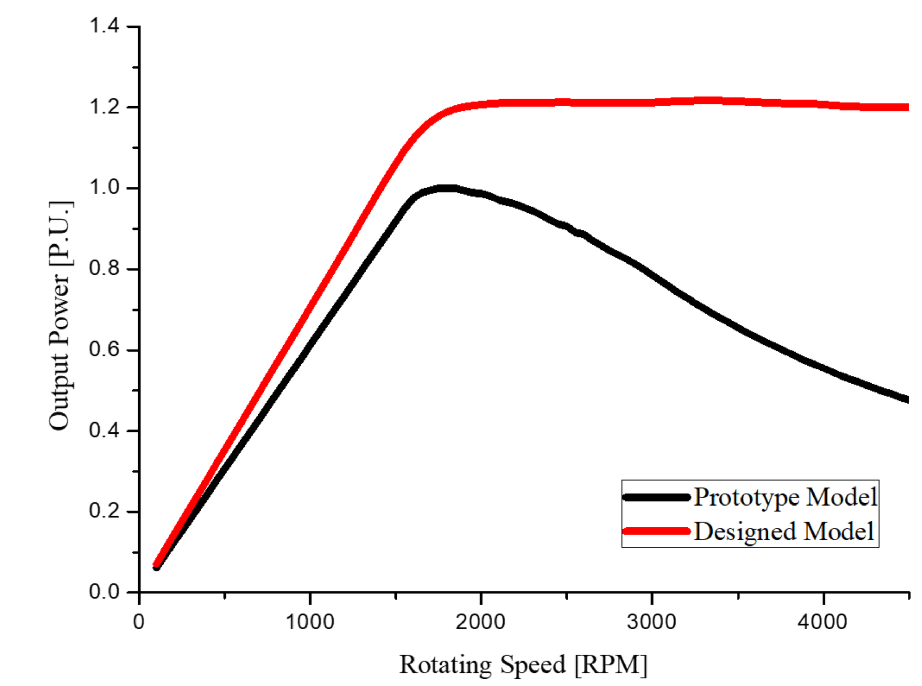
- Optimizing position of permanent magnet by considering combination of the magnet set with the number of the PM less than 8.
- PM combination of Top 10 ranks according to the equation of decision are shown below.
- The role of PM is providing reasonable field flux to widen operating region and preventing flux to penetrate through the air layers.
- Magnets located at the side (③,⑤,⑥,⑧,⑨,⑪,⑫) are more effective than those at the center (①,②,④,⑦,⑩)
- Magnets located at the end of the layer (⑥,⑨,⑫) are vulnerable to the demagnetization.

Rank	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	Torque [P.U]	Torque Density [P.U]	Torque Ripple [%]	Demag*	Reluctance Alignment Ratio [%]
Proto	-	-	-	-	-	-	-	-	-	-	-	-	1	1	13.7	-	
1	-	-	✓	-	✓	-	-	✓	-	-	✓	-	1.15	1.12	17.7	-	80.59
2	✓	✓	-	-	✓	-	-	✓	-	-	✓	-	1.12	1.09	17.1	-	79.94
3	-	-	-	-	-	✓	-	-	✓	-	✓	✓	1.10	1.07	18.0	✓	74.23
4	✓	-	-	✓	✓	-	-	✓	-	-	✓	-	1.09	1.06	15.1	-	76.74
5	-	-	-	-	-	✓	✓	-	✓	✓	-	✓	1.13	1.09	21.5	✓	76.80
6	-	-	-	-	-	✓	-	-	✓	✓	-	✓	1.10	1.07	20.1	✓	79.50
7	-	✓	-	✓	-	-	✓	-	✓	✓	-	✓	1.10	1.07	21.0	✓	74.27
8	-	✓	-	✓	✓	-	-	✓	-	-	✓	-	1.09	1.05	18.9	-	74.62
9	✓	-	-	-	✓	-	-	✓	-	✓	✓	-	1.08	1.05	15.2	-	74.80
10	✓	-	-	-	✓	-	-	✓	-	-	✓	-	1.09	1.06	20.9	-	81.57

Design Validation







Conclusion

- Finally, optimally designed model produces about 15% more torque, 12% more torque density with 14.0% of torque ripple.
- Designed model is robust to the demagnetization at 180 degrees celcius with N38UH permanent magnet.
- Operating range is dramatically increased at high speed region as intended.
- Designed motor produces 19% of alignment torque, and 81% of reluctance torque at base speed.