[PS3-2-6]

Design and Analysis of Variable Flux Motor with Rotatable Magnet

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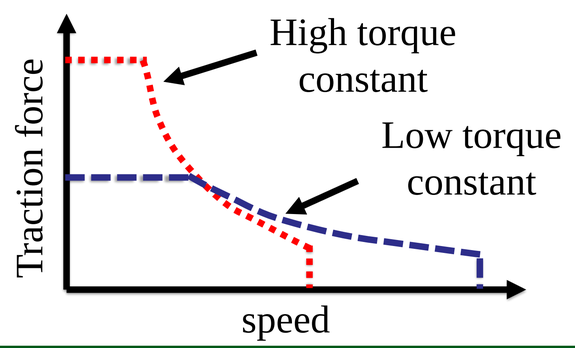
Introduction

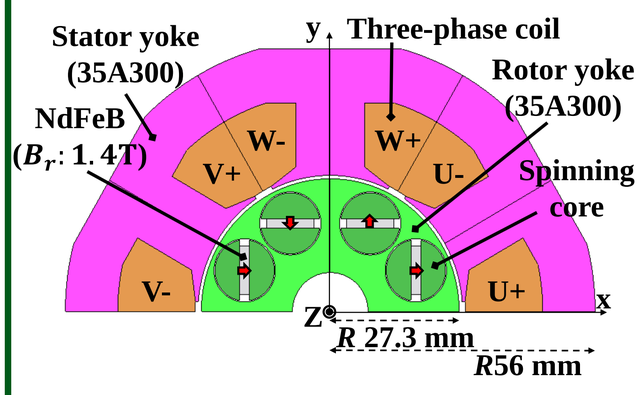
- **Electric vehicle motors require variable speed control over a wide speed range.**
- **The conventional fixed-magnetic field PMSM experiences efficiency degradation at high speeds due to field weakening control aimed at extending the speed range.**
- **Variable flux motor(VFM) can extend the variable speed range without field weakening control.**
- **This paper proposes a magnets-rotating VFM capable of passively varying the magnetic field due to the centrifugal force induced as the rotor rotates.**

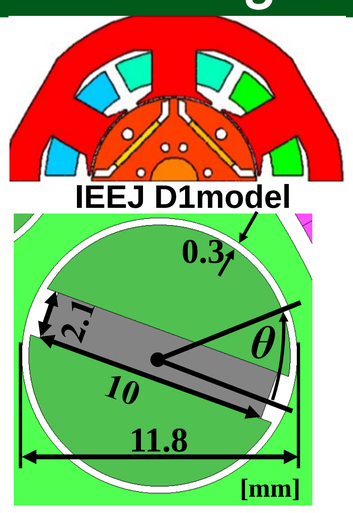


Magnet-Rotating Variable Flux Motor

Basic configuration

:Magnetic field orientation



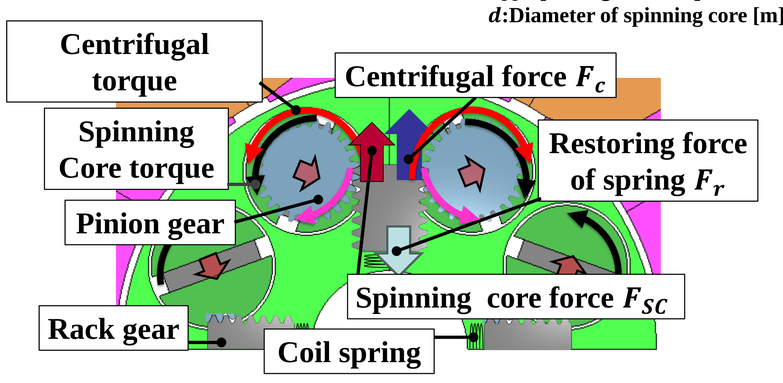


- **Proposed motor is:**
  developed based on the IEEJ D1 model.
  4-pole/6-slot concentrated winding IPMSM.
- **Each magnet is sandwiched between two semi-circular cores and rotates in the θ direction around the axis of the magnet. This is referred to as the spinning core.**

Spinning mechanism

$$M\frac{d^2r}{dt^2} = Mr\omega^2 - kr + \frac{T_{sc}}{d}$$

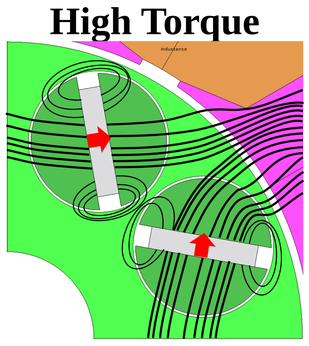
M:Mass [kg]
ω:Angular velocity [rad/s]
k:Spring constant [N/m]
T_{SC}:Spinning core torque [Nm]
d:Diameter of spinning core [m]



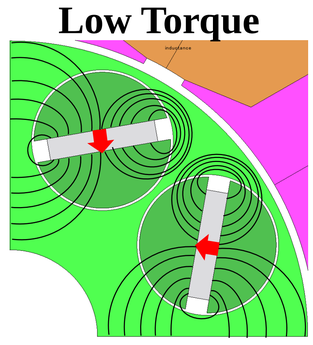
- **A pinion gear is attached to the top of the spinning core.**
- **The rack gear is connected to the shaft via a coil spring, moving radially outward due to centrifugal force.**
- **The magnet angle is determined by the balance between the centrifugal force F_c, spinning core force F_{SC} and restoring force F_r.**

Principle

High Torque



Low Torque



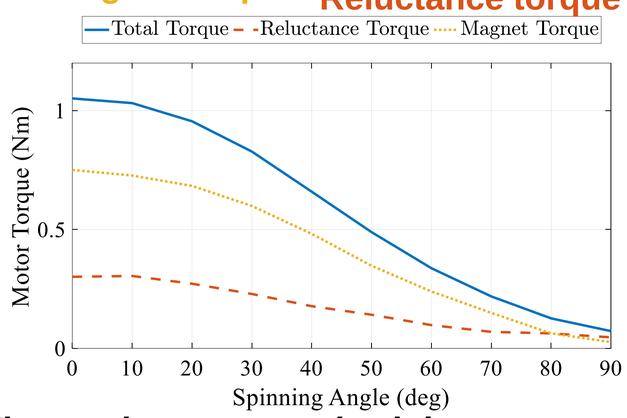
- **Short-circuit magnetic flux in the rotor varies with the magnet angle**
- **Changes in magnet angle cause variations in armature cross flux, resulting in a variable flux effect.**

Variable Torque Characteristics by 2-D FEA

Variable torque characteristics

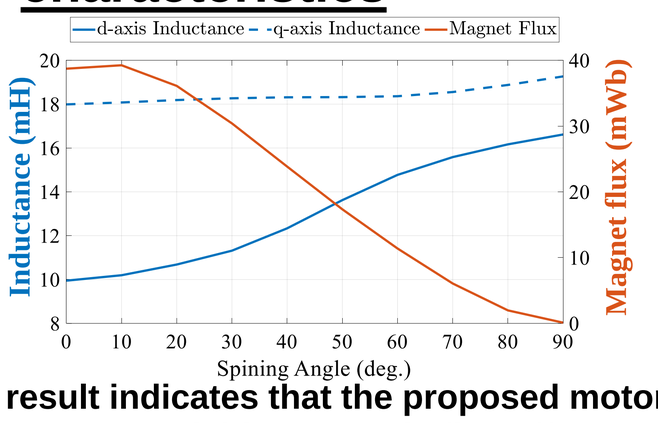
$$\tau = p\phi_m i_a \cos\beta + \frac{1}{2}p(L_q - L_d)i_a^2 sin2\beta$$

Magnet torque — Reluctance torque



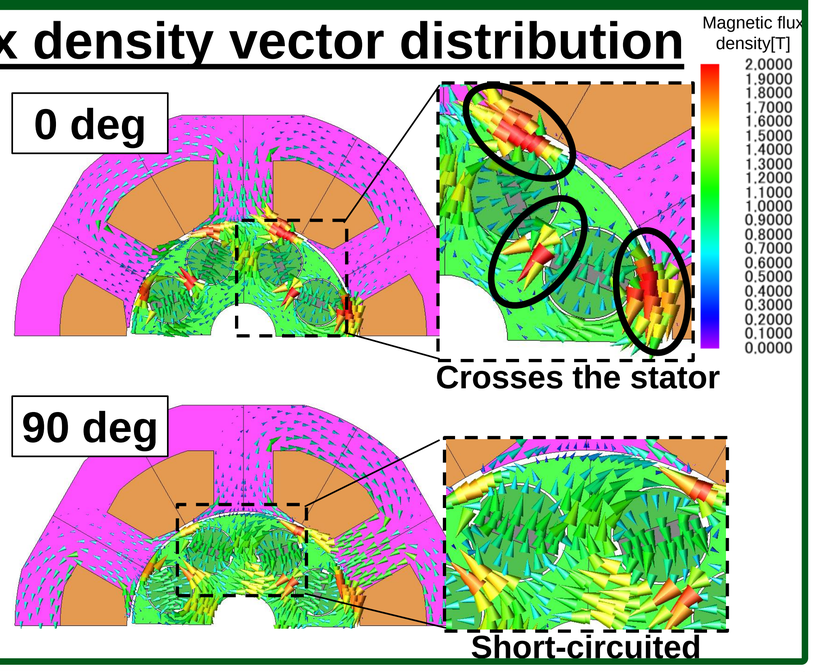
- **The maximum torque(mainly magnet torque) changes with the magnet angle.**

Variable motor parameter characteristics

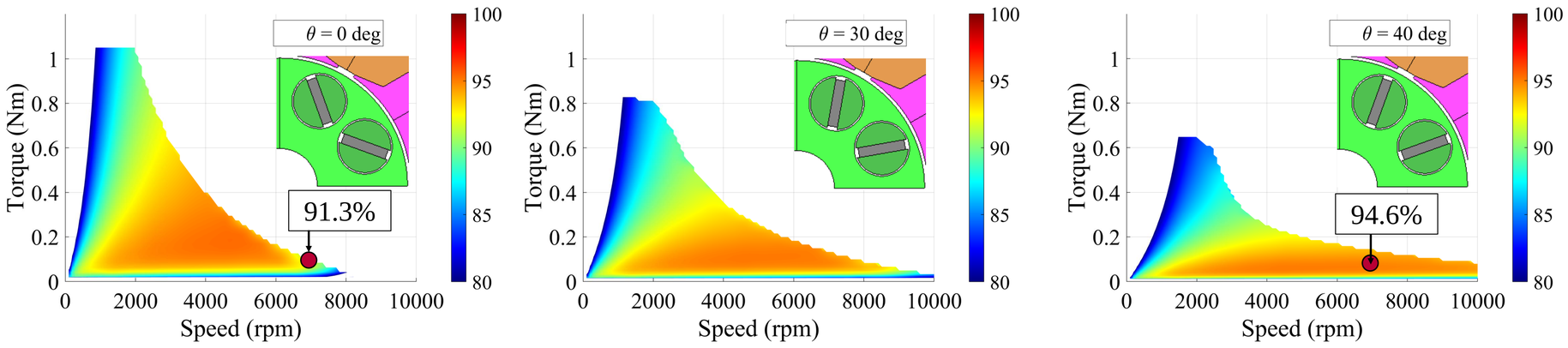


- **This result indicates that the proposed motor possesses a variable magnetic flux effect.**
- **Magnetic saturation on the d-axis changes significantly, primarily affecting the d-axis inductance.**

Flux density vector distribution

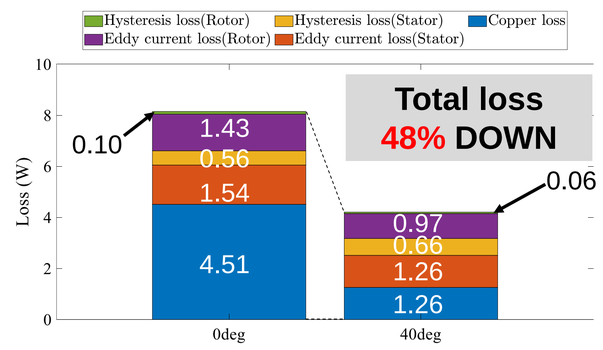


Efficiency map



- **The results indicate that by increasing the spinning angle, the high-efficiency region transitions towards the low-torque and high-speed range.**
- **The apparent weakening of the magnetic flux led to a reduction in the back EMF, which consequently expanded the operational speed range.**

Loss at 7000 rpm / 0.1Nm



- **Low rotor iron loss due to high short-circuit flux in the rotor at 40deg.**
- **Low Joule loss due to no field weakening control at 40 deg.**

Conclusion

- **This paper proposes a new Variable Flux Motor (VFM) in which the magnets embedded in the rotor can rotate around their own axis.**
- **The proposed motor demonstrates a variable flux effect, allowing not only the PM flux but also the dq-axis inductance to be adjusted. This capability enables the motor to extend its speed range and shift the high-efficiency region towards the high-speed, low-torque side.**

*1Committee on Practical Implementation of 3D Electromagnetic Field Analysis for Rotating Machines. Practical Implementation Technology of 3D Magnetic Field Analysis for Rotating Machines. *IEEJ Technical Report*, No.1296, 25-40. (in Japanese)