Electromagnetic Performances Analysis of IPMSM According to the Control Method under Flux-Weakening Region

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▣ Abstract

❖ we dealt with the design and characteristics analysis of a 130 kW interior permanent magnet synchronous motor (IPMSM) through finite element analysis (FEA) for propulsion system of electric vehicle.

❖ In order to verify effect of current property, we implement two types of current control method by simulink; one is a space vector pulse width modulation (SVPWM), generally applied to synchronous motor, and the other is six-step, generally applied to brush-less DC motor.

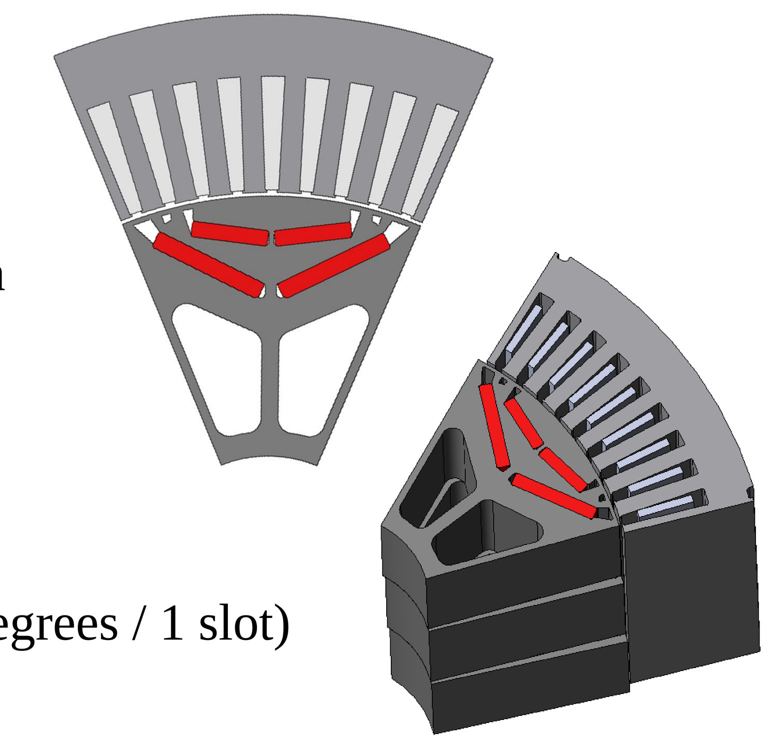
❖ We conduct co-simulation of FEA and current control to verify a difference of electromagnetic performance of IPMSM such as electromagnetic force, loss including permanent magnet (PM) eddy current loss, PM demagnetization, especially under flux-weakening control region according to these current control methods.

1. Design of 130 kW IPMSM for EV Propulsion System

Classification	Design Parameter	Specification	Unit
Input	Voltage	350	[Vdc]
Performance (Point A)	Torque	250	[Nm]
	Speed	4965	[r/min]
Performance (Point B)	Torque	112	[Nm]
	Speed	11000	[r/min]
Design Parameter	Phase / Pole / Slot	3 / 8 / 72	
	Air-gap Length	0.75	[mm]
	Outer Diameter	230.0	[mm]
	Height	117.0	[mm]
	Current Density	14.44	[A_{rms}/mm^2]
	Slot Fill Factor	45.0	[%]
Magnet	Remanence of PMs	1.3	[T]

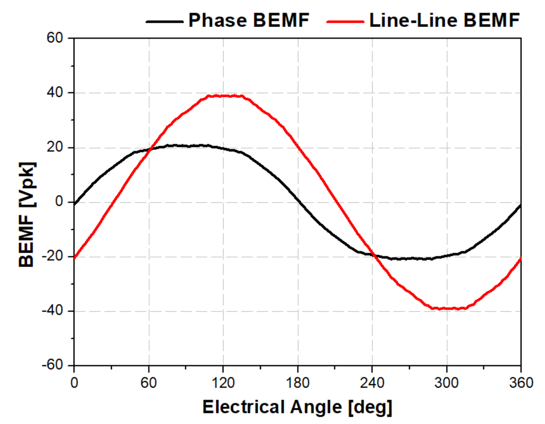
❖ 2D
= Double-layer V shape rotor
: reluctance torque / magnetic flux concentration
= Air-barrier
: spatial harmonics reduction

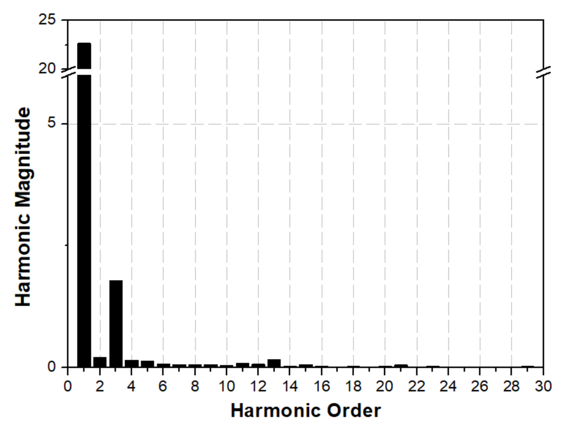
❖ 3D
= Three-stage rotor skew (5 degrees / 1 slot)
: slot harmonics reduction



2. No-Load and Load Characteristics

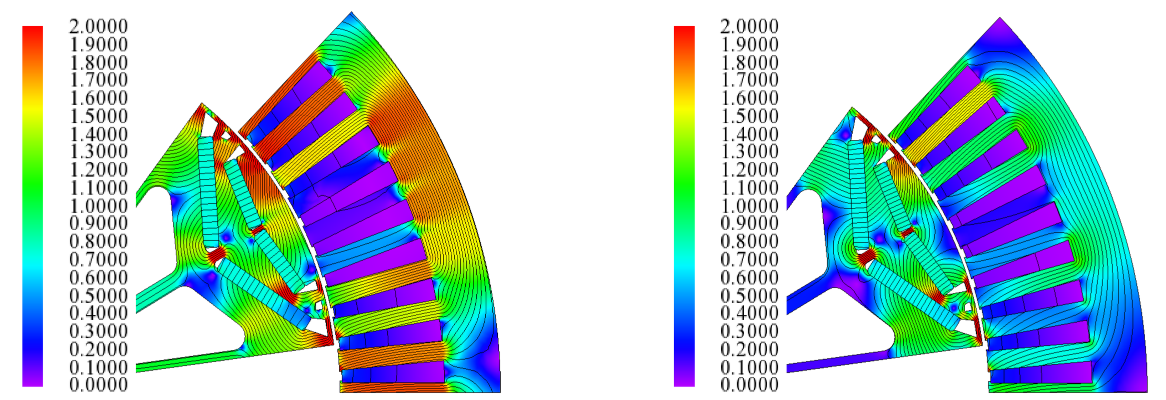
❖ No-Load Characteristics
= Phase back-EMF / Line-to-Line back-EMF
= FFT analysis of Phase back-EMF
: low-order harmonics (increase THD)





<No-load characteristics : Back-EMF (left) / FFT analysis (right)>

❖ No-Load Characteristics
= Operating point A : MTPA (maximum torque per ampere)
= Operating point B : Flux-weakening control (widening operating region)

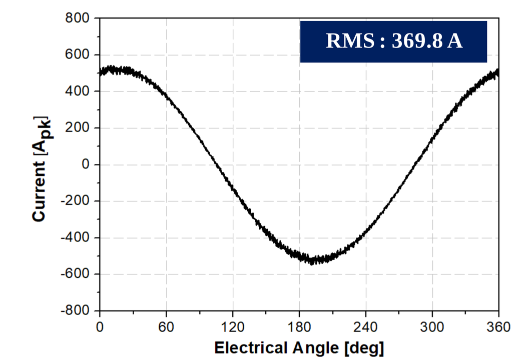


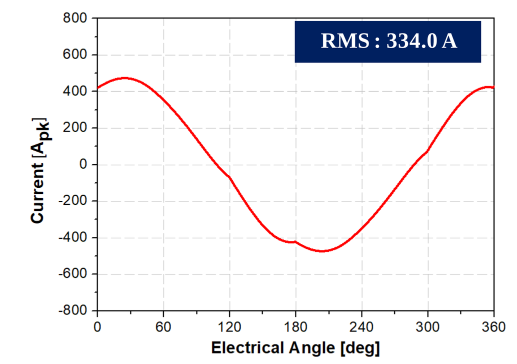
<Flux density distribution : Point A (left) / Point B (right)>

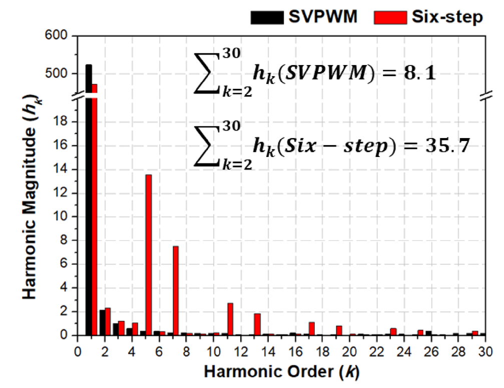
3. Current Control Method for Flux-weakening Control

❖ SVPWM
= Generally applied to PMSM
= Fundamental component of maximum phase voltage : $V_{dc}/\sqrt{3}$
= high-order harmonics (switching freq.)

❖ Six-step (One-pulse)
= Generally applied to BLDC motor
= Fundamental component of maximum phase voltage : $2V_{dc}/\pi$
= low-order harmonics (switching freq.)

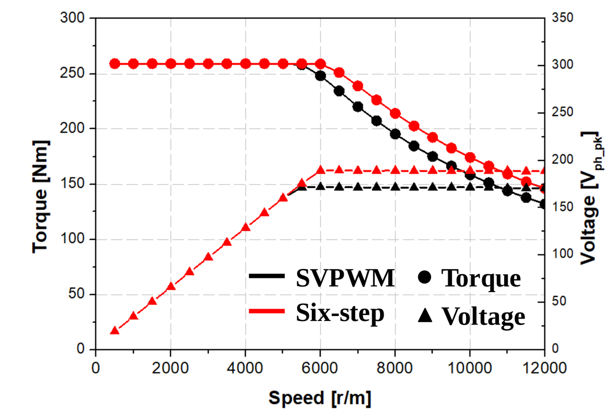






<Output current : SVPWM (left) / Six-step (middle) / FFT analysis (right)>

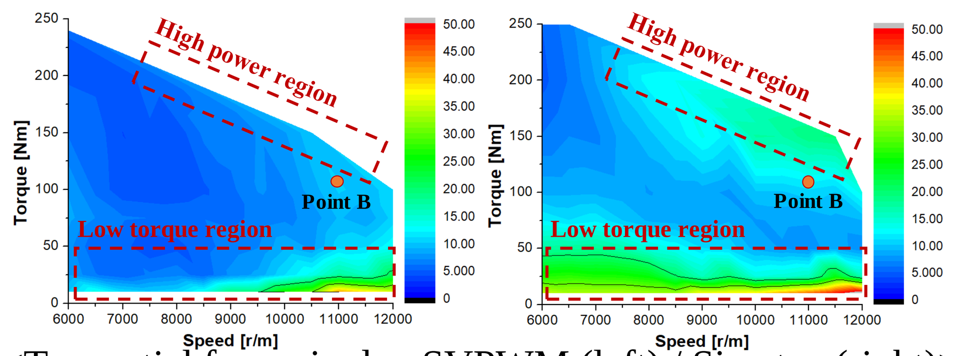
❖ IPMSM with Six-step
= Maximum power utilization
= Widened flux-weakening region
= Reduction of switching loss



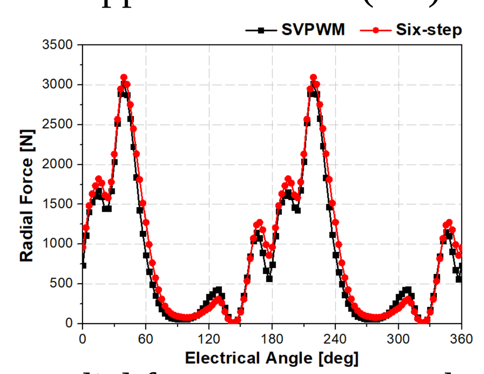
<TN curve & phase voltage curve>

4. Electromagnetic Performance of 130 kW IPMSM according to Current Control Method (at operating point B : flux-weakening)

❖ Electromagnetic Force
= Tangential force [Transfer NVH]
: harmonics, related to torque ripple, increase in six-step (especially, low torque region and high power region)
= Radial force [Radiative NVH]
: magnitude and harmonics are almost identical (it depends on the pole and slot combination and flux density on the stator)



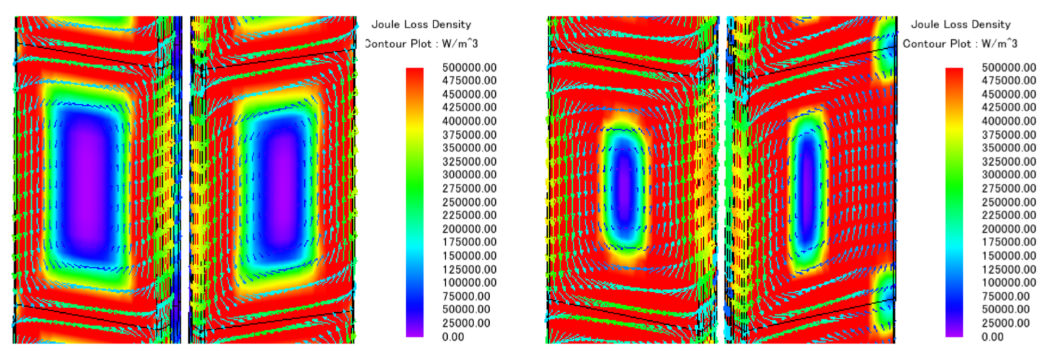
<Tangential force ripple : SVPWM (left) / Six-step (right)>



<Radial force on stator teeth>

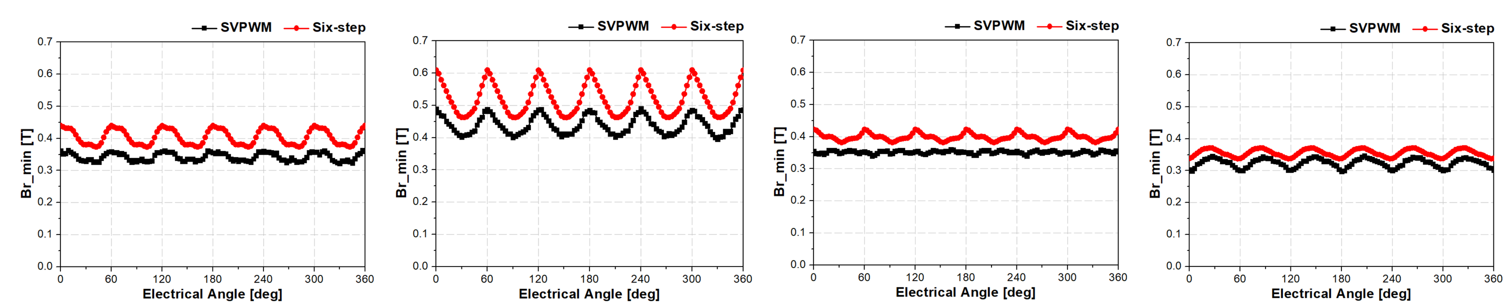
❖ Electromagnetic Loss (under identical output power condition)
= Copper loss & Iron loss
: the lower RMS value of six-step current, the lower copper loss and iron loss
= Eddy current loss of PM
: low-order harmonics of six-step current affect and produce more eddy current loss of PMs

Unit [W]		SVPWM	Six-step
Copper loss		2490.8	2032.6
Iron loss	Stator	1428.5	1379.6
	Rotor	213.7	200.7
Eddy current loss		52.2	135.7
Total loss		4185.2	3748.6



<PM eddy current loss density : SVPWM (left) / Six-step (right)>

❖ PM Demagnetization (under identical output power condition)
= Neglecting temperature rise due to eddy current loss (140℃ fixed)
= Fundamental component of six-step current is smaller, and it results in smaller magnetic field strength against the magnetic flux of PMs
= Six-step operation is more efficient in terms of demagnetization



<Minimum value plots of magnetic flux density inside PMs>