Research & Technology Trends in Electric Machine Design for Operation with Variable Speed Drives

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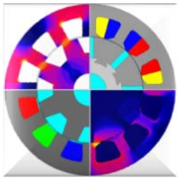
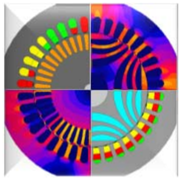
Presentation Outline



NRE Electric Machines for EV/ HEVs

- Fully-pitched MCSRM with standard VSI
- Concentrated Wound Segmented Rotor SRM (SSRM)
- Accomplishments and Next Steps



High Performance Reluctance Drives with standard VSIs

- Multilayer (ML) AC Winding for Efficiency Improvement
- Application of ML Winding for SynRM Design
- Accomplishments and Next Steps

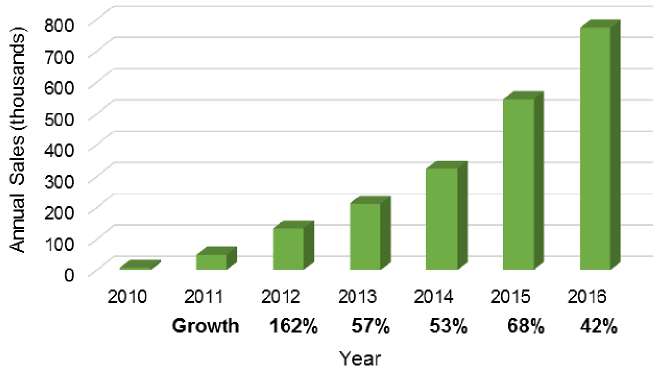
Technology Trends and Research Directions

- Cost-effective Efficiency & Performance improvement
- High P_{Den}, High Speed Motors with WBG Drives
- Integrated Motors for Industrial Automation

NRE Electric Machines for EV/ HEVs

EV/HEV Growth and Trends

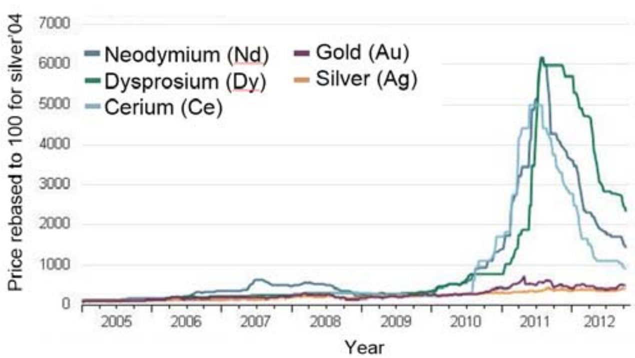
- Plug-in vehicles growth is 20 times faster than others
- Traction motor demand (high T_{Den}, P_{Den}, η) : proportional
- IPMSM most popular candidate with rare-earth (RE) PMs
- RE materials' price & supply: HEV mass production issues



Global plugin vehicles sales data (source: ev-volumes.com)

Traction Motor Challenges & Opportunities

- China mines 80% of the world's rare-earth materials
- China 2016 PEV sales growth: +85% compared to 2015
- RE price hike in July 2015 as Chine boosts RE reserve[1]
- Research on NRE alternatives are essential



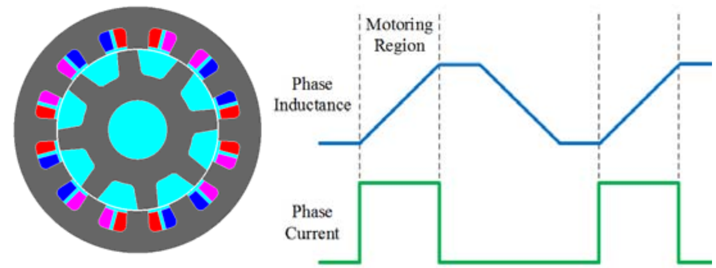
RE price vs gold & silver (source: Thomson Reuters)

[1] "Rare earths prices rise as China builds reserves" article on mining.com, June 20, 2016

NRE Electric Machines for EV/ HEVs

SRM for Traction Application

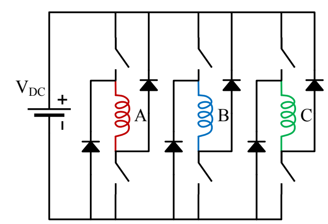
- Robust rotor, high speed, high temp., wide CPSR
- Unipolar operation, unconventional converter
- High torque ripple and acoustic noise



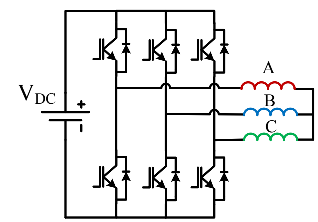
12/8 SRM (left) EM Structure (right) Operation

Research Objective

- Design of SRM using 3-phase standard VSI for EV/HEVs
- High T_{Den} and wide CPSR: competitive traction specifications
- **Mutually Coupled SRM (MCSRM)** with fully pitched winding
- Bipolar/ sinusoidal operation, 3-phase standard VSI



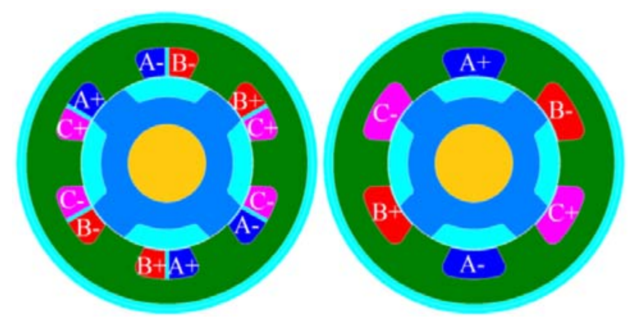
Typical SRM Converter



3φ Standard VSI

MCSRM for Traction Application

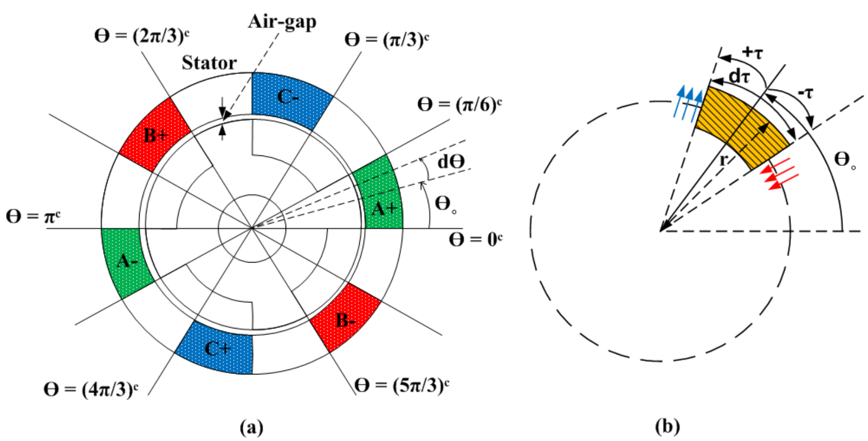
- EM torque, $T_a = \frac{1}{2}\left(i_a^2 \frac{dL_{aa}}{d\theta} + i_a i_b \frac{dM_{ab}}{d\theta} + i_c i_a \frac{dM_{ca}}{d\theta}\right)$
- Phase back EMF, $E_a = \left(\frac{dL_{aa}}{d\theta}.i_a + \frac{dM_{ab}}{d\theta}.i_b + \frac{dM_{ca}}{d\theta}.i_c\right)\omega$
- Optimization required at both ω_{Base} & ω_{Max}



(left) Conventional SRM and (right) MCSRM

Design of MCSRM for Traction Application

Analytical air-gap flux and inductance are derived from winding spatial distribution and pole shapes

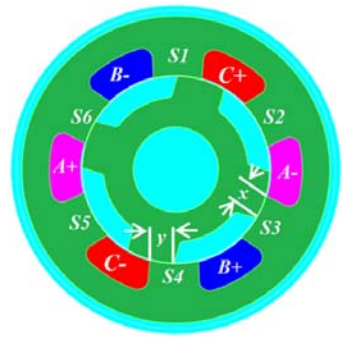


(left) MCSRM Winding spatial distribution, (right) differential flux linkage

Phase Inductance

$$L_m = \frac{\lambda_{Am}}{I_A} = \mu_0 \frac{N_{Turn}^{\ 2}}{2g} L_{stk} \cdot \beta$$

Here, $\beta = r.d\theta$, rotor-stator length of overlap



Self-inductance, $\beta = \beta_L$, sum of overlapping length x & y

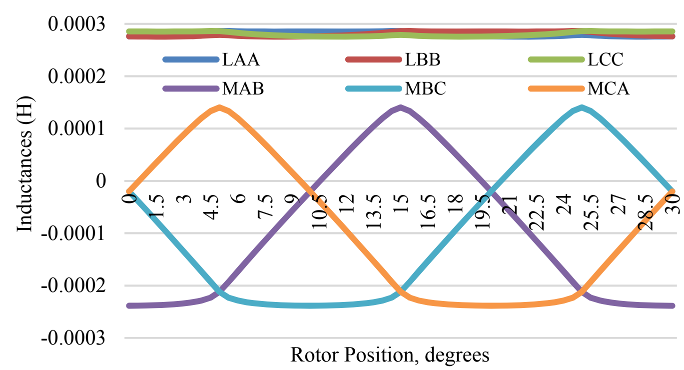
Mutual-inductance, $\beta = \beta_M$, sum of overlapping lengths $\vec{x}$ & $\vec{y}$

Constant self-inductance

$$\boldsymbol{\beta_R = \beta_S = \beta_{SG}}$$

Torque

$$T = i_a i_b \frac{dM_{ab}}{d\theta} + i_b i_c \frac{dM_{bc}}{d\theta} + i_c i_a \frac{dM_{ca}}{d\theta}$$



MCSRM inductance profiles

Design parameters are optimized targeting 3rd generation IPMSM (Toyota Prius 2010)

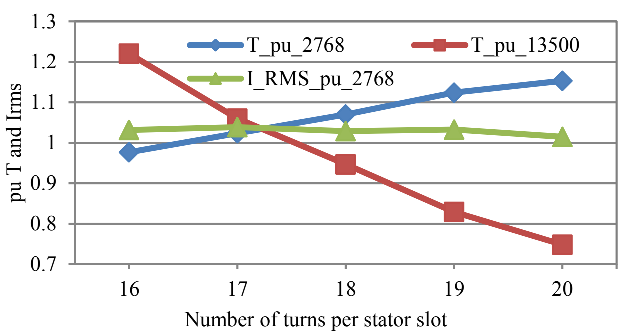
M. A. Kabir and I. Husain, "Mutually coupled switched reluctance machine (MCSRM) for electric and hybrid vehicles," *2014 IEEE PES General Meeting | Conference & Exposition*, National Harbor, MD, 2014, pp. 1-5.

2014 IEEE PES GENERAL MEETING

Parameter Sensitivity Analysis

Number of Turns (N_{Turn})

- FEA-Simulink Coupled simulations
- Parameter selection from machine model
- Optimization considers both T_{Base} & T_{Max}

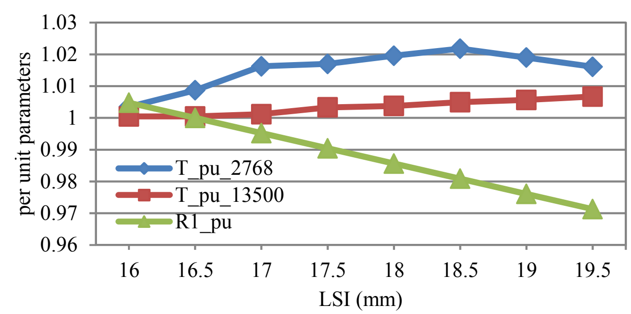


Effect of N_{Turn} variation

- Inductance depends heavily on N_{turn}
- Optimized under a given current density
- Higher N_{turn}, T_{Base} gains but CPSR reduces
- Impacts both T_{Base} and T_{Max} significantly

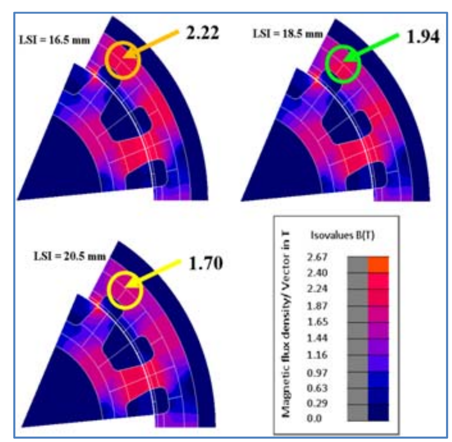
Stator Back-iron Length (LSI)

- Low LSI, saturation at low excitation (NI)
- High LSI, A_{Slot} reduces (low NI), low R_g
- More effect on T_{Base} than T_{Max}



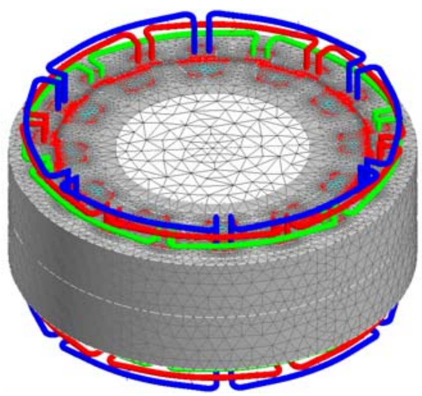
Effect of LSI variation

Back-iron saturation vs. LSI



MCSRM Performance Evaluation

- 3D FEA analysis to include axial leakage flux effect
- Performance evaluated at ω_{Base}, $3 * \omega_{Base}$ and ω_{Max}
- Designed MCSRM meets $T - \omega$ requirement



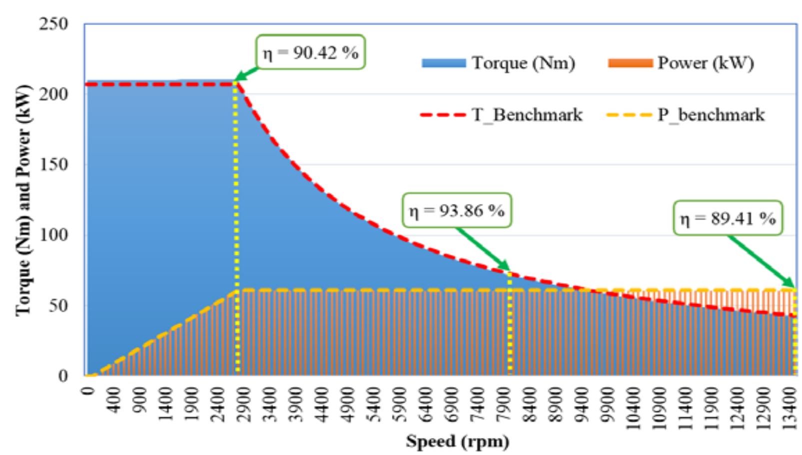
MCSRM model in 3D FEA

Performance comparison at ω_{Base}

Parameters	IPMSM	CSRM	MCSRM
T_{den}(Nm/L)	35	36	33
P_{den}(kW/L)	10.2	10.4	9.57
T/W (Nm/kg)	9.3	8.4	8.45
P/W (kW/kg)	2.7	2.4	2.45

Optimal parameter values from iterative design

Parameter	value
Number of turns, N_{turn}	18
Length of stator back-iron, LSI (mm)	18.5
Length of stator pole, LSP (mm)	11.5
Stator pole tapering angle, Tpr_s (°)	6
Rotor pole tapering angle, Tpr_r (°)	10.5



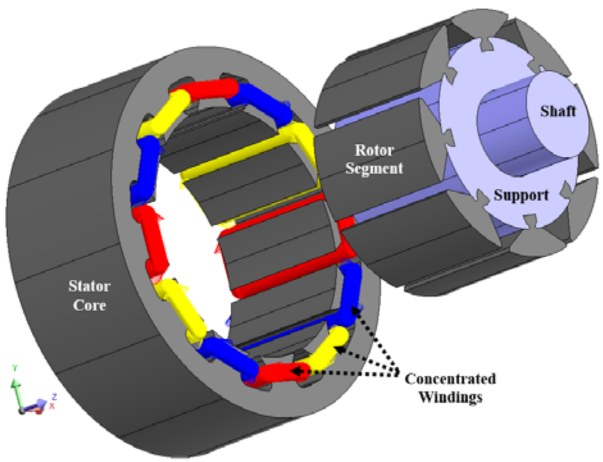
$T - \omega$ Characteristics of designed MCSRM

M. A. Kabir and I. Husain, "Design of Mutually Coupled Switched Reluctance Motors (MCSRMs) for Extended Speed Applications Using 3-Phase Standard Inverters," in *IEEE Transactions on Energy Conversion*, vol. 31, no. 2, pp. 436-445, June 2016.

Segmented Rotor SRM (SSRM)

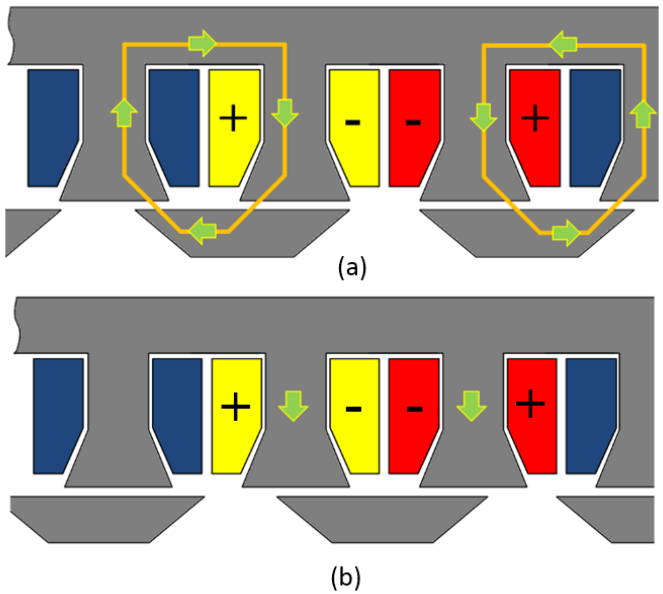
MCSRM Challenges & Alternative

- MCSRM: Large end-winding, High l_{ew-ax}, less compact
- P_{I^2R-St} (↑), low slot fill factor, High torque ripple
- SSRM is the concentrated wound alternative
- Shorter end-winding, compact, high slot fill factor
- Bipolar operation, utilizes 3-phase standard VSI



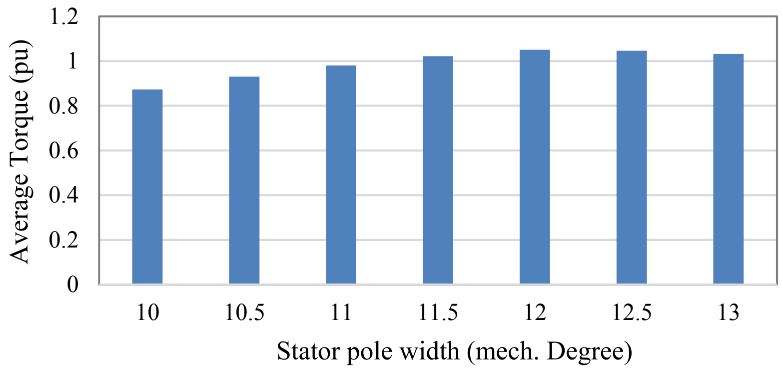
Proposed Segmented Rotor SRM (SSRM)

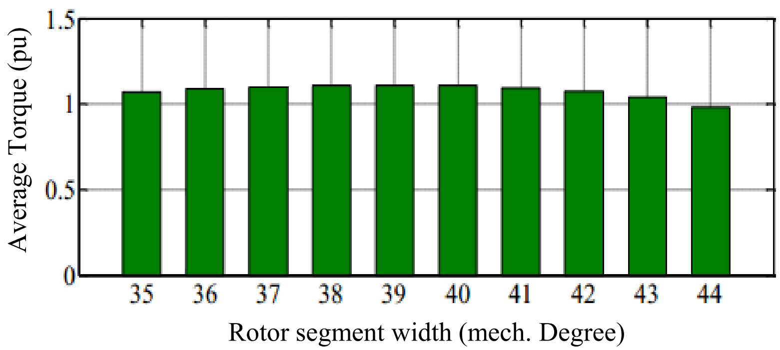
Principle of Operation



- Rectilinear SSRM representation is utilized
- Excited phase fluxes in the same radial direction
- Aligned flux carried through adjacent stator poles
- Unaligned condition (b) single rotor segment shorting opposing fluxes of excited stator poles

Parameter Sensitivity Analysis

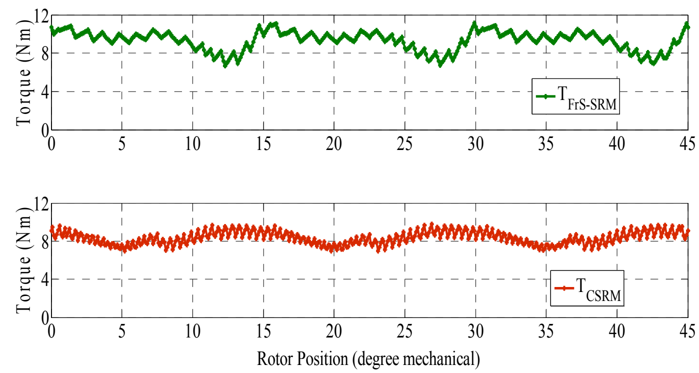




- Analyzed under same J_{SLOT}(A/mm^2) and I_{RMS}
- Parameters were optimized for max(T_{AVG})

Initial Performance Evaluation

Parameter	SSRM	CSRM
T_{AVG} (Nm)	9.30	8.34
P_{OUT} (W)	973.89	877.55
W (kg)	4.41	4.76
I_{RMS} (A)	4.25	3.88
T_{DEN} (Nm/L)	9.69	8.73
T/W (Nm/kg)	2.11	1.76



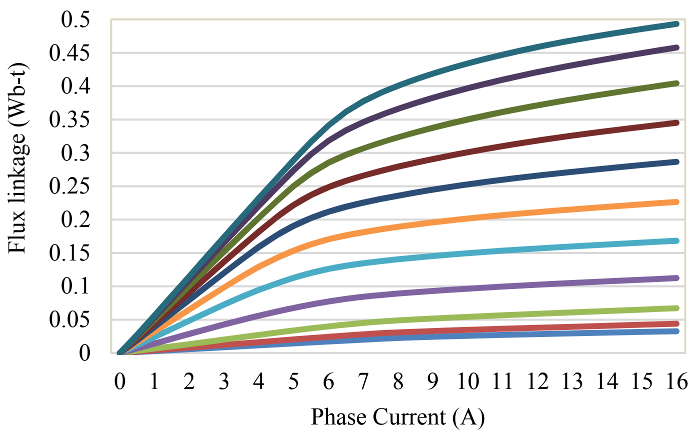
- Higher T_{Den} and T/W than CSRM
- High T_{Ripple} with SSRM, addressed next

M. A. Kabir and I. Husain, "Concentrated winding segmented rotor switched reluctance machine (SRM) using three-phase standard inverters," *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*, Montreal, QC, 2015, pp. 5567-5572.

SSRM Torque Ripple Minimization

SSRM Semi-numerical Model

- EM Torque from $\lambda - i - \theta$ (FEA) characteristic
- Adjacent stator pole carries aligned flux, δM_{xy} & δL_{xx}
- Linear magnetic circuit (direct M, L & T relations)

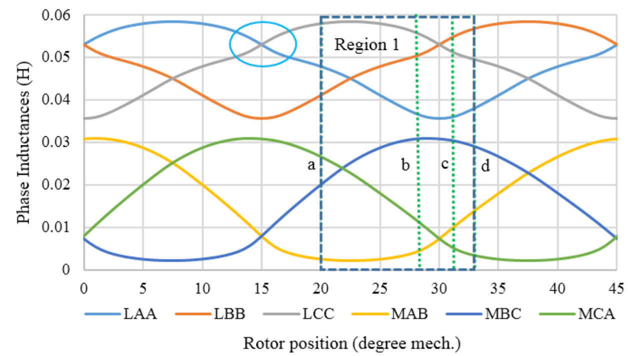


$\lambda - i - \theta$ characteristics from FEA

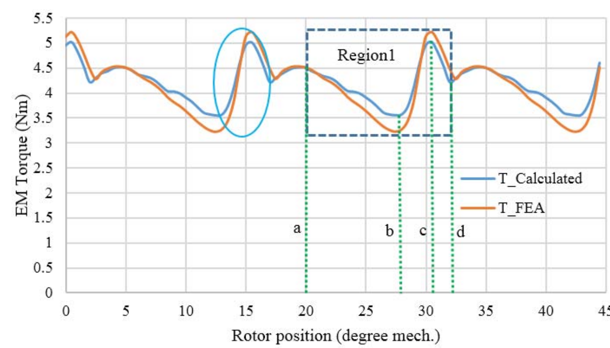
$$T_{EM} = \frac{1}{2}\left(i_A^2\frac{dL_{AA}}{d\theta} + i_B^2\frac{dL_{BB}}{d\theta} + i_C^2\frac{dL_{CC}}{d\theta}\right) + i_A i_B\frac{dM_{AB}}{d\theta} + i_B i_C\frac{dM_{BC}}{d\theta} + i_C i_A\frac{dM_{CA}}{d\theta}$$

SSRM Torque Ripple Sources

- Calculated torque correlates well with that from FEA
- Major torque ripple region : ‘Region 1’ (I_{Excs}: $+A, -C$)
- Unsmooth L_{xx} between ‘b’ & ‘d’ introduce large T_{Ripple}



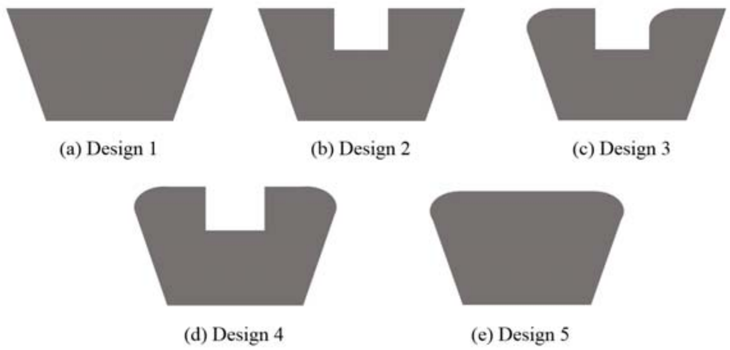
SSRM inductance profiles with rotor position



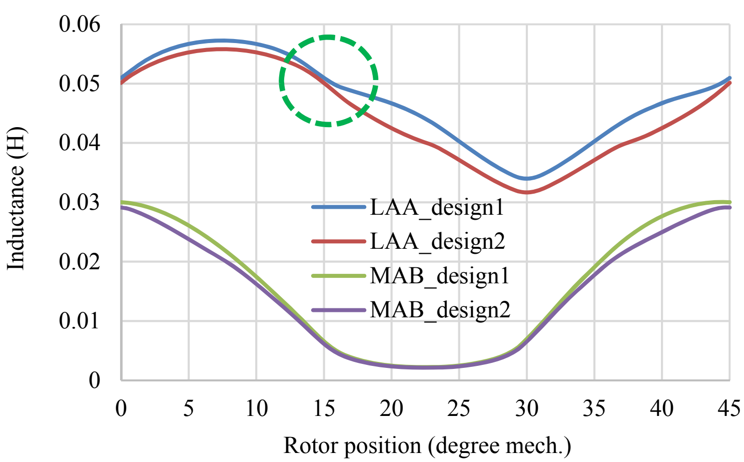
Calculated and FEA based EM Torque

Design of Rotor Segments

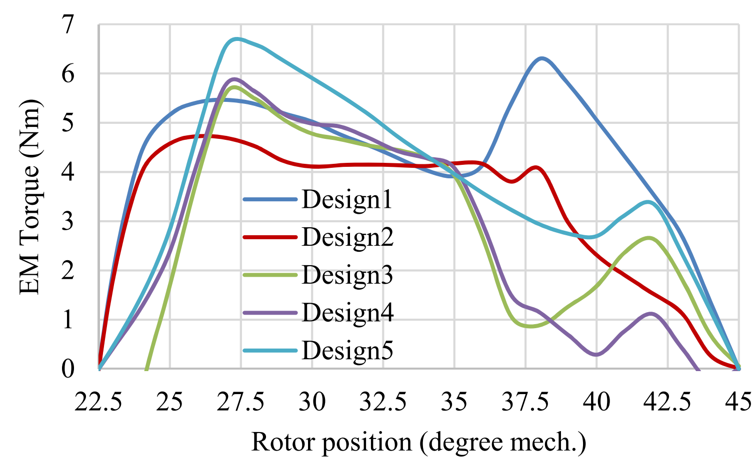
- Largest torque pulsation (‘b’ to ‘d’) occurs when rotor segment center crosses stator inter-polar gap
- Center of rotor segment is selected as design region
- Design 2 introduces segmental dip
- Smoothens self-inductance between ‘b’ & ‘d’
- Reduces inductance rate of change
- Parametric analysis required to optimize design



Initial and considered rotor segment designs



Comparison of inductance profiles

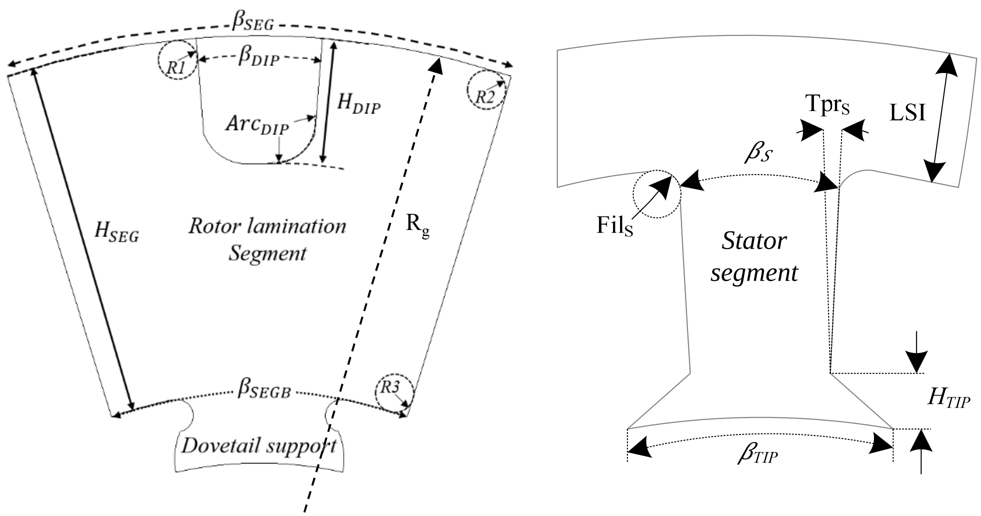


Static EM torque profiles

SSRM Design Optimization

Multi-dimensional, Multi-objective Optimization (M-Opt)

- Parameters optimized from ‘1F-Opt’ method are used for the initial design
- Rotor segmental dip is introduced for minimizing T_{RIPLLE}
- FEA tools FLUX 2D is coupled with Optimization tool GOT-It for ‘M-Opt’



Parameterized rotor and stator segments

Optimization Problem

Max(T_{AVG})

Min(T_{Ripple})

Such as;

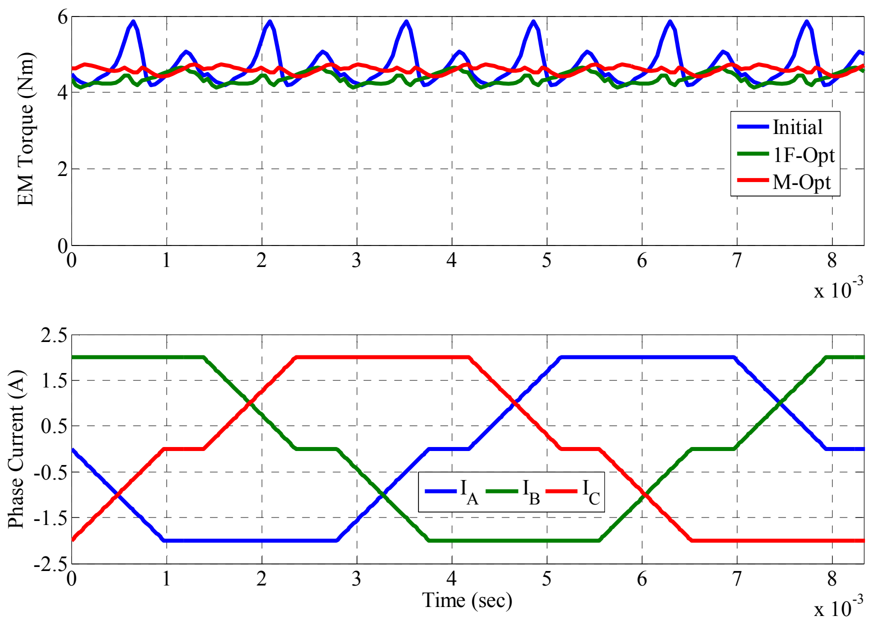
$J_{SLOT} \leq$ 4.5 A/mm^2

$D_{Stator} \leq$ 163.5 mm

$D_{Axial} \leq$ 151.2 mm

- Transient FEA analysis over an electrical cycle used for evaluation
- Genetic Algorithm (GA) is selected with population size of 200 and 600 max. generation
- T_{AVG} (Nm), T_{RIPPLE} (%) and J_{SLOT} (A/mm^2) results taken as decision variables

Performance Evaluation



Rated performance comparison under the same stator I^2R loss

Parameter	Initial	1F-Opt	M-Opt
Arc_{DIP} (°)	10	90	36.5
β_{SEG}(°)	38	36	40.95
β_{SEGB}(°)	38	40	36.47
β_{DIP}(°)	4	7.0	6.02
H_{SEG}(mm)	24.3	21.2	19.4
H_{DIP}(mm)	1	3.5	2.81
R_1(mm)	0.5	0.1	0.78
R_2(mm)	0.5	0.1	2.26
R_3(mm)	0.5	0.1	1.37
T_{AVG}(Nm)	4.68	4.37	4.6
T_{RIPPLE}(Nm)	1.68	0.52	0.32
T_{RIPPLE}(%)	35.92	11.83	6.95

Compared to initial design,

- '1F-Opt' reduce T_{RIPPLE} by 24.09% with 6.6% T_{AVG} reduction
- 'M-Opt' reduce T_{RIPPLE} by 28.97% with similar T_{AVG}

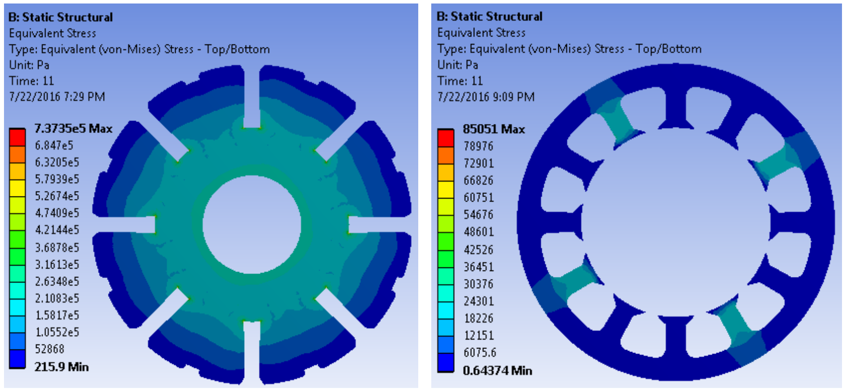
M. A. Kabir and I. Husain, "Segmented rotor design of concentrated wound switched reluctance motor (SRM) for torque ripple minimization," *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, Milwaukee, WI, 2016, pp. 1-6.

SSRM Prototype Development

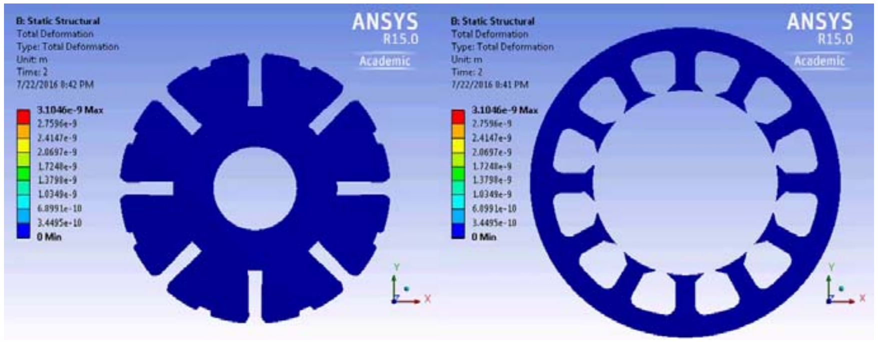
Mechanical Stress Analysis

- Stress = Force/Area
- Two types of forces need to consider
  - Radial forces (electromagnetics)
  - Centrifugal forces (mechanics)
- ANSYS workbench is utilized
  - Maxwell 2D for electromagnetic analysis
  - Static Structural is coupled in workbench
  - Radial force imported from EM analysis

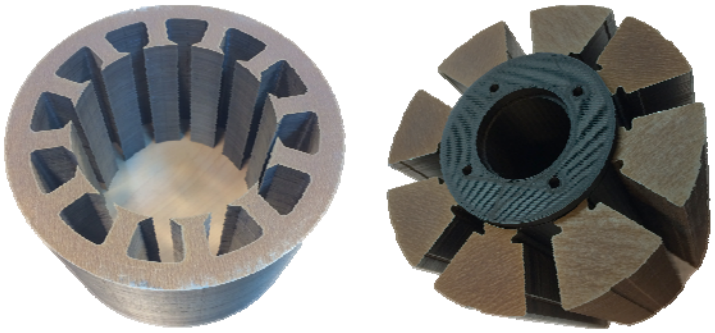
Stress Analysis Results



Deformation Analysis Results

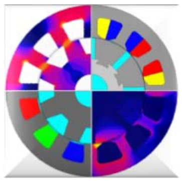


- Material yield strength = 300 Mpa
- Maximum von Mises stress = 7.4 Mpa
- Air-gap length = 0.4 mm
- Maximum deformation = 0.223 μm
- Prototype SSRM is under construction at FREEDM Lab



Phots of prototype SSRM
(left) stator & (right) rotor stack

Presentation Outline



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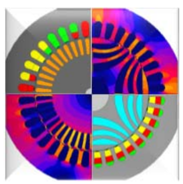


High Performance Reluctance Drives with standard VSIs

- Multilayer (ML) AC Winding for Efficiency Improvement
- Application of ML Winding for SynRM Design
- Accomplishments and Next Steps

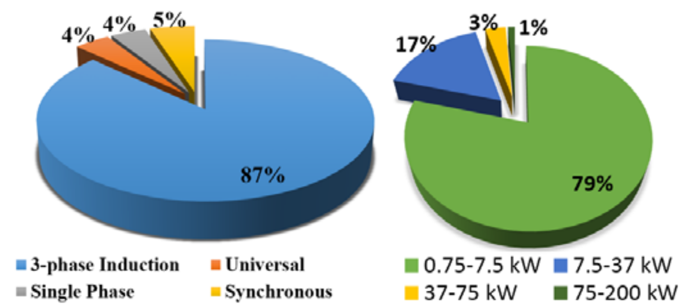
Technology Trends and Research Directions

- Cost-effective Efficiency & Performance improvement
- High P_{Den}, High Speed Motors with WBG Drives
- Integrated Motors for Industrial Automation

High Performance Machines for Industrial Drives

Industrial Market and Technology Trend

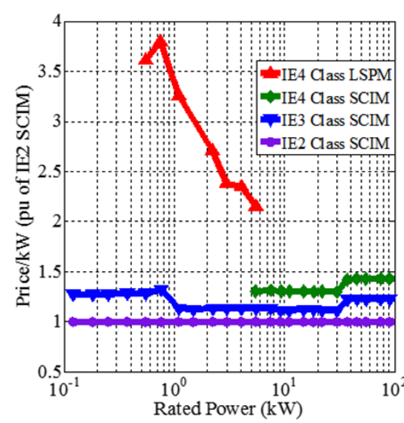
- Electric motors utilizes 70% industrial & 28% global energy
- Efficiency (η) improvement: saves energy and environment
- Premium/IE3 efficiency motors: mandatory in US since 2011
- IEC and NEMA have defined supreme efficiency standards



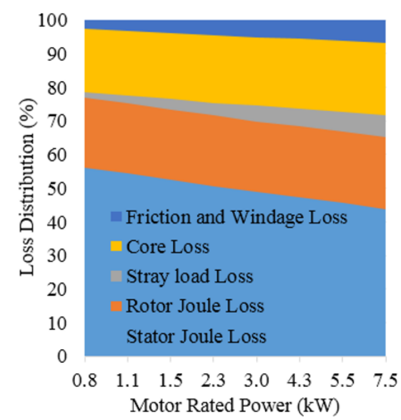
AC motors market share by type and size [2]

High η Motors: Challenges & Opportunities

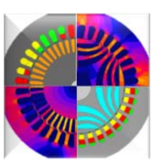
- Squirrel cage induction motor (SCIM): largest market share
- IE4 SCIM (P_{rated} ≥ 7.5 kW), IE4 PMSM (P_{rated} ≤ 7.5 kW)
- Low cost IE4 alternative is absent (P_{rated} ≤ 7.5 kW)
- Stator joule loss dominates (45-55%) the selected power range



Commercial motors $/kW [2]



SCIM losses ($P_{rated} \leq 7.5$ kW) [2]



[2] De Almeida, A.T.; Ferreira, F.J.T.E.; Ge Baoming, "Beyond Induction Motors—Technology Trends to Move Up Efficiency," *IEEE Transactions on Industry Applications,* vol.50, no.3, pp.2103-2114, May-June 2014

Machine Winding Technologies

Conventional Distributed Windings

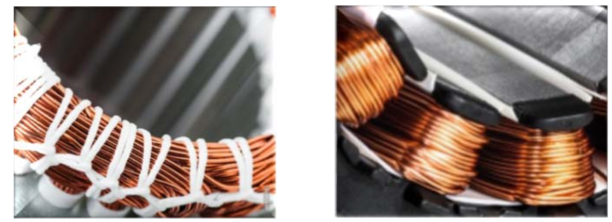
- Coil spanned over pole pitch (fully pitched), or chorded
- High winding factor, sinusoidal MMF, low induced losses
- Large end-winding, high stator joule loss, low slot fill factor

Concentrated Winding

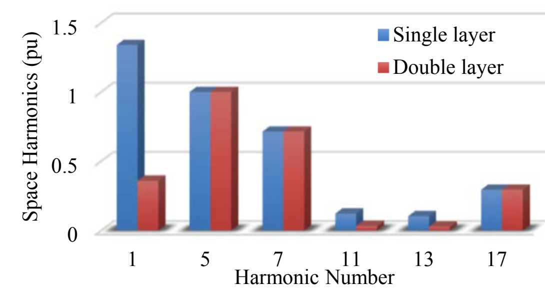
- Shorter end-turns, higher slot fill factor, more compact
- High stator MMF harmonics $P_{Core} \uparrow, T_{AVG} \downarrow, PF_{IN} \downarrow, T_{Ripple} \uparrow$
- Lower stator I^2R losses but higher induced losses, η ↓

Proposed Multilayer AC Winding

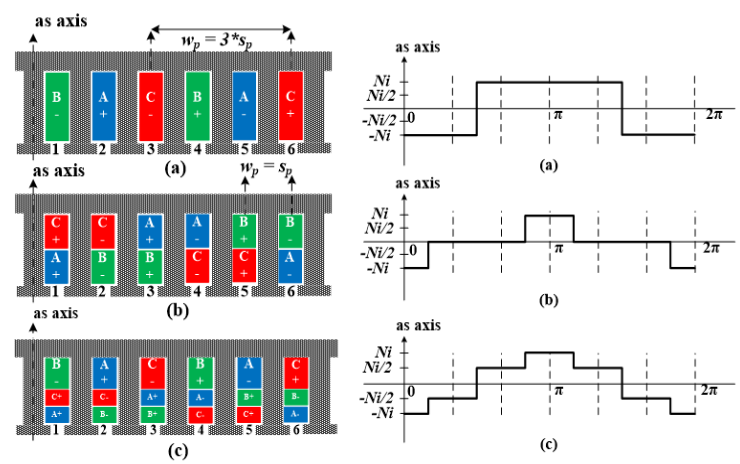
- $N_{Layer} = \emptyset_{M/C}$, provides additional design domain
- Sample stator MMF in each slot reduced MMF harmonics
- Concentrically built winding, reduced end-winding length



(left) Distributed and (right) concentrated winding



Concentrated wound stator MMF spectrum



(left) Configuration & (right) MMF distribution of six-slot (a) FP, (b) CW and (c) ML winding

Multilayer (ML) AC Winding

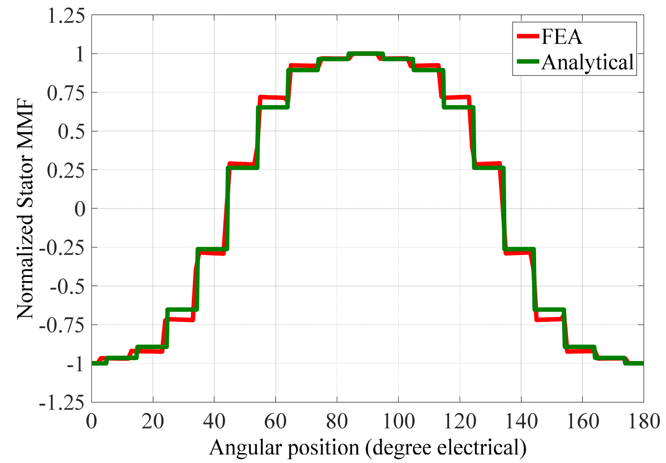
Winding Function Analysis

- Sinusoidal MMF with distributed coils and short-pitching
- Distribution factor (k_{dv}) accounts multiple-slots/coil-group
- Pitch factor (k_{pv}) considers less than pole-pitch coils
- Winding factor $k_{wv} = k_{dv} \times k_{pv}$, controls |stator MMF| (F_{st}^{v})

$$k_{dv} = \frac{\sin\left(\frac{\nu\pi}{6}\right)}{q\,\sin\left(\frac{\nu\pi}{6q}\right)}$$

$$k_{pv} = \sin\left(\frac{\nu W}{\tau_p}.\frac{\pi}{2}\right)$$

$$\widehat{F_{st}^{\nu}} = \frac{3}{\pi}.\frac{N_s}{p}.k_{wv}.\widehat{i_s}$$

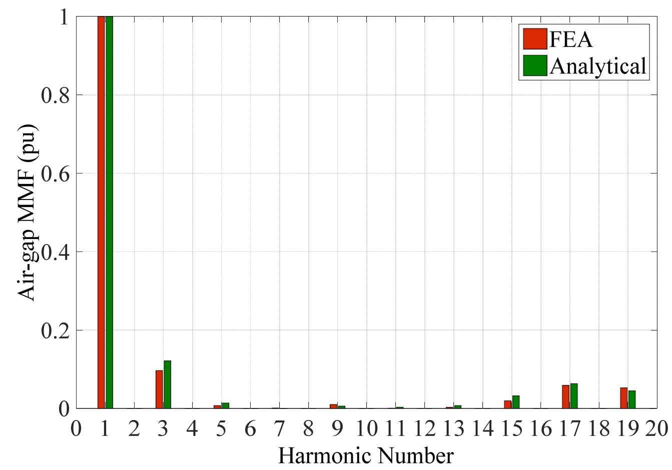


Stator MMF model verification

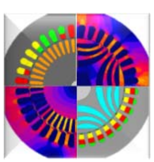
Harmonic Characteristics

- MMFs from all coils of a group: in phase making $k_{dv\_ML} = 1$
- N_{Turn} weighted average defines k_{pv_ML}, determines F_{st}^{ν}
- Analytical stator MMF model is verified against FEA

$$k_{pv} = \frac{1}{\mathrm{N_t}}\sum_{i} N_i.\sin\left(\nu.\frac{2i-1}{\tau_p}.\frac{\pi}{2}\right)$$



Analysis on stator MMF harmonics



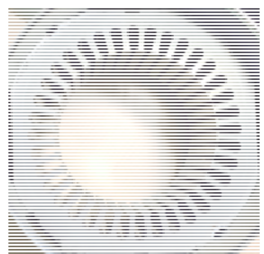
Application of ML Winding: Induction Motor

Design Benchmark Selection

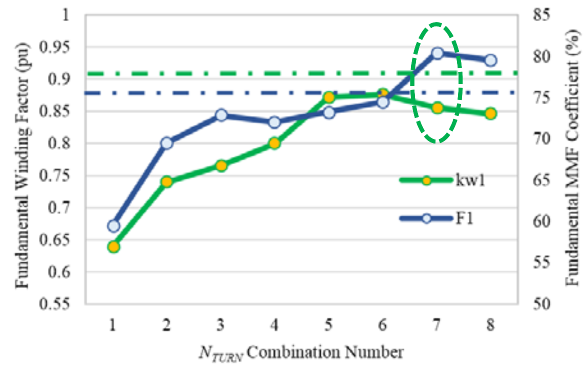
- 3-phase, 1 hp, NEMA Premium efficiency (IEC IE3) SCIM
- Highest efficiency available for SCIM ($P_{Rated} \leq 7.5\ kW$)
- 36 slot stator with double layer distributed winding (DLDW)
- Same iron core geometry for direct comparison

Specifications of Benchmark SCIM

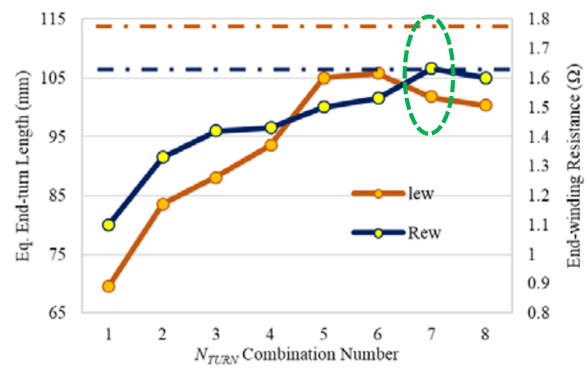
Parameter	Value	Parameter	Value
D_{STATOR}	163.5 mm	V_{supply}	460 V
L_{STK}	80 mm	I_{PEAK}	2.0 A
N_{POLE}	4	P_{RATED}	746 W
f	60 Hz	Cooling	TENV



Prototype stator lamination



Winding factor and MMF coefficient variation (v=1)

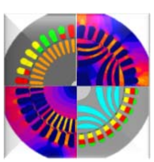


End-winding length and resistance variation

Design of ML Winding

- Slot conductor contributes to torque, end-winding doesn't
- Benchmark motor parameters, defined by straight lines
- Different N_{Turn} combinations are evaluated for ML winding
- Objective: improving F_1, minimizing l_{ew} with R_{ew} constraint

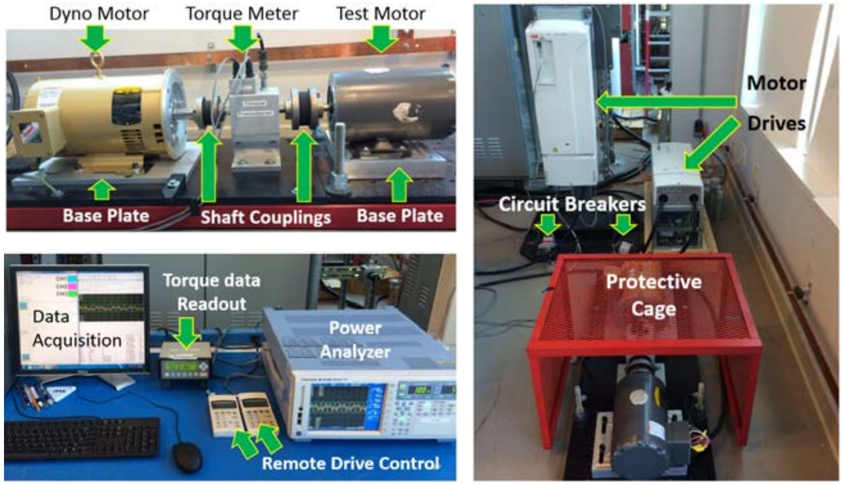
Prototype multilayer winding



M. A. Kabir and I. Husain, "New Multilayer Winding Configuration for Distributed MMF in AC Machines with Shorter End-turn Length," *2016 IEEE Power & Energy Society General Meeting*, Boston, MA, 2016, pp. 1-5.

Experimental Analysis

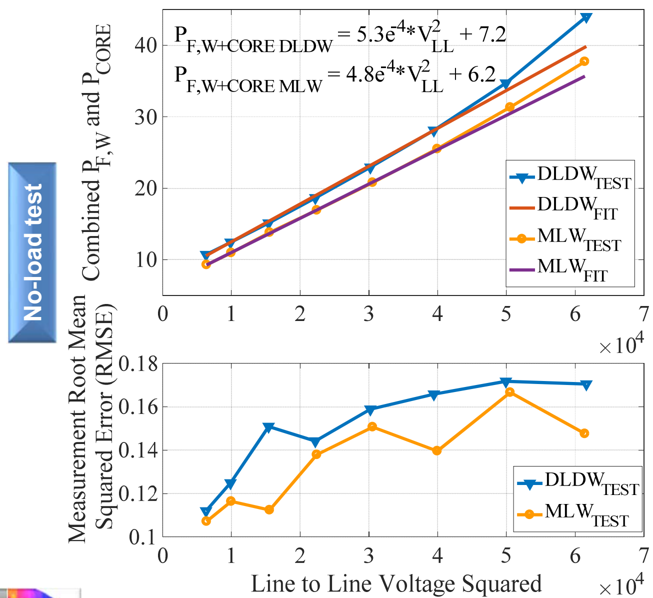
- **IEEE 112** Standard Test procedure being followed
- **Loss separation:** motor no-load and loaded test
- **Rated performance** comparison for both machines

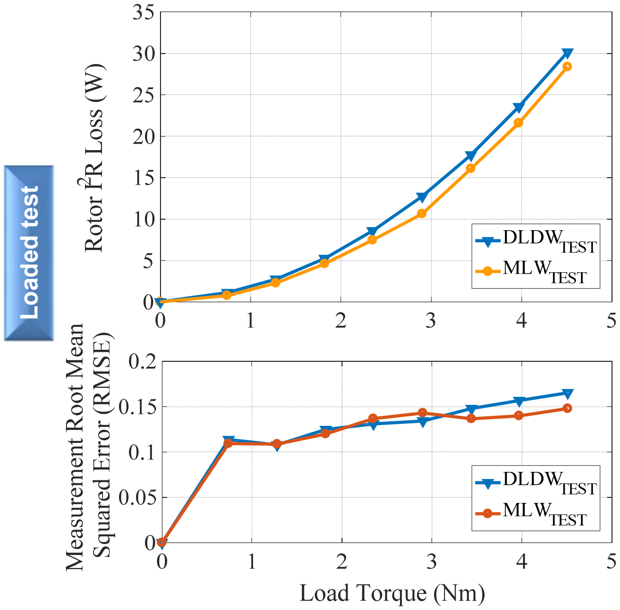


Developed 5 hp dyno test-bed at FREEDM Lab (high bay)

Results

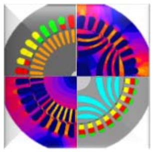
- **Significant (17.6%)** reduction in stator I^2R loss
- Induced losses: **lower** α_{CORE} & rotor I^2R loss
- Total loss reduction 9%, Reaches $\boldsymbol{\eta}_{\mathbf{IE4}}$ ($\leq 87.5\%$)





Rated Performance Comparison

Winding Type	DLDW	MLW
ω (rpm)	1748	1750
P_{I^2R-St} (W)	55.77	45.98
P_{LOSS} (W)	109.07	99.59
T_{AVG} (Nm)	3.97	3.97
η (%)	86.95	87.96
PF_{IN} (pu)	0.78	0.78



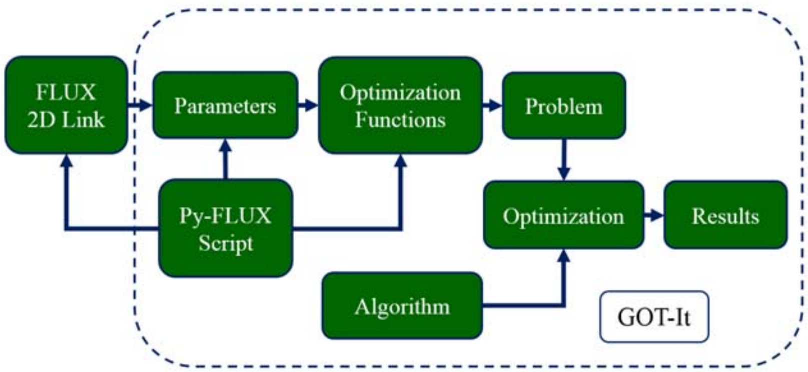
Patent application is in progress with the Office of Technology Transfer (OTT) at NCSU

Next: ML-SynRM design (no rotor I^2R loss), 3% efficiency gain (η_{IE5}) targeted

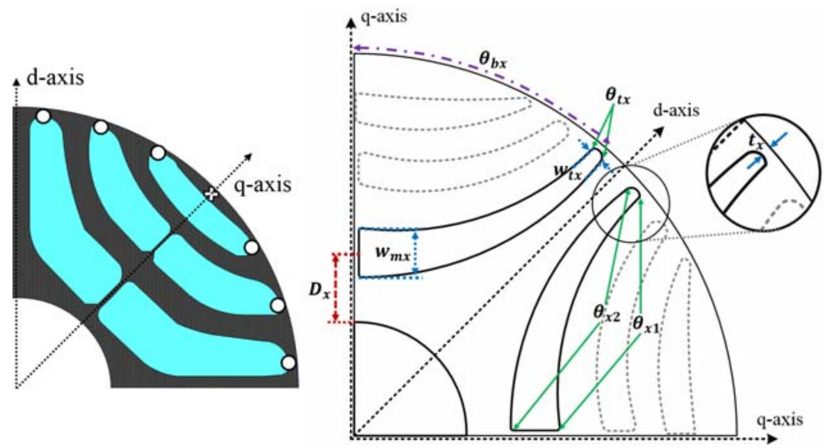
Design of SynRM with ML Winding

Design Optimization

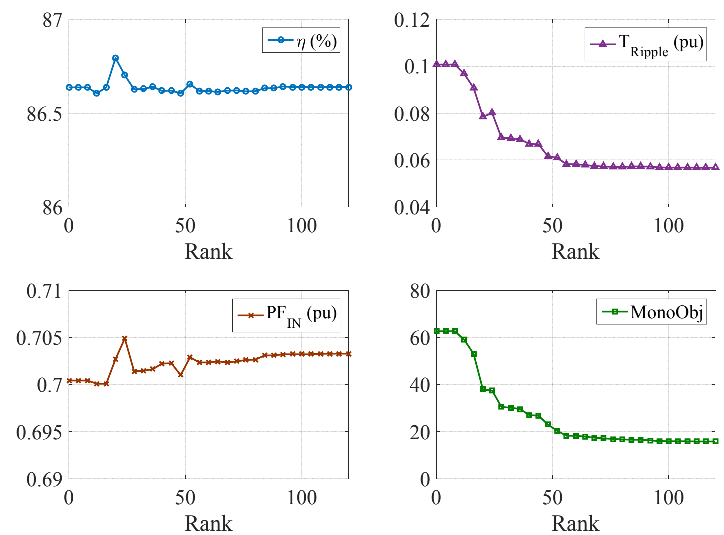
- Stator winding: Same as ML induction motor
- Stator n_s = 18, rotor n_r = $n_s \pm 4$, n_r = 14 selected
- Optimization: rotor geometry along with γ
- FEA tool Flux-2D coupled with Opt. tool GOT-It



Optimization process flow



(left) Selected 18/14 rotor structure (right) rotor design parameters for optimization



Results from optimization steps

Optimization Problem

$$\max(\eta)\big|_{\omega=\omega_{Rated}}^{95.0\%} = f(D_x, \theta_{xi}, \theta_{tx}, \theta_{bx}, W_{mx}, W_{tx}, t_x, \gamma)\big|_{x=1,2,3}^{i=1,2}$$

Torque ripple, C_{Rip} : $T_{Ripple} \leq 5\%$ (ceiling constraint)

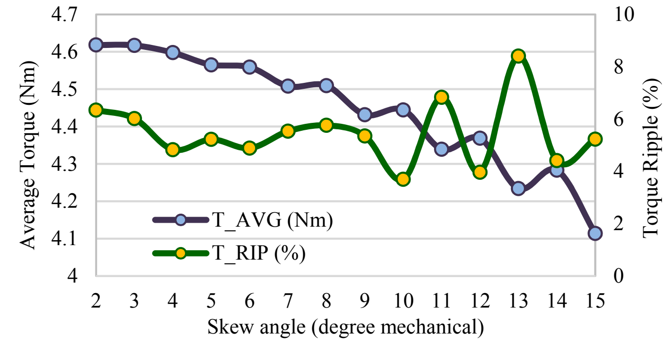
Power factor, C_{PF} : $PF_{IN} \geq 0.7$ (floor constraint)

Md Ashfanoor Kabir and Iqbal Husain, “Design of Synchronous Reluctance Motor with Multilayer AC Winding” IEEE International Electric Machines and Drive Conference (IEMDC), May 21-24, 2017

ML-SynRM Prototype Development

Effect of Rotor Skewing

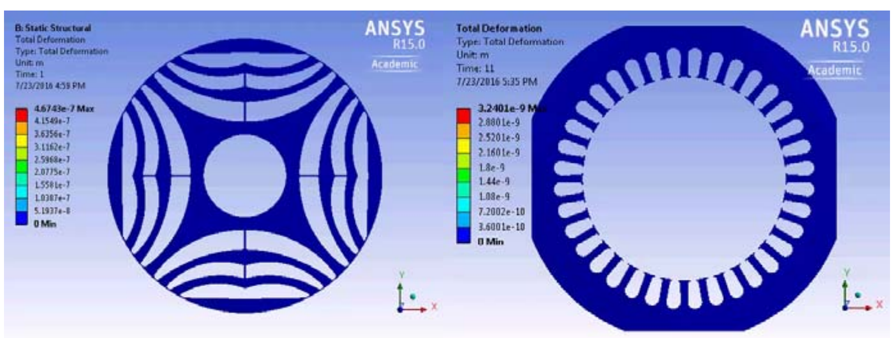
- Skewing helps AC machines with distributed windings to reduce T_{Ripple} but T_{AVG} also reduces
- $Min(T_{Ripple})$ at $\theta_{Skew} = \theta_{Slot}$ with 4% T_{AVG} reduction
- Selected $\theta_{Skew}= 4^{o}$, T_{ripple}= 4.83% with similar T_{AVG}



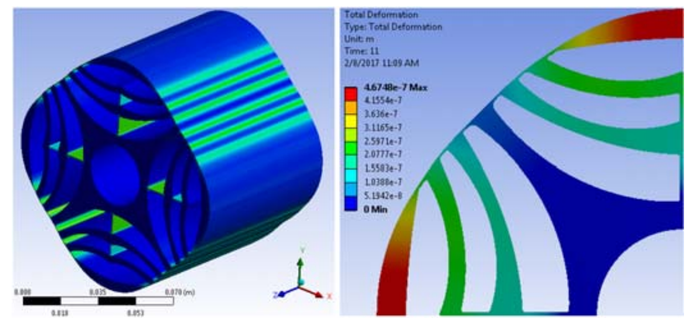
Rotor skewing results of the designed ML-SynRM

Mechanical Stress Analysis

- Multiphysics stress analysis, rated & extreme conditions
- Centrifugal force dominates these sinusoidal machines
- Stress & deformation found well below design limits
- Prototype ML-SynRM is built for experimental analysis



ML-SynRM deformation (2.5×10^4 times scaled)

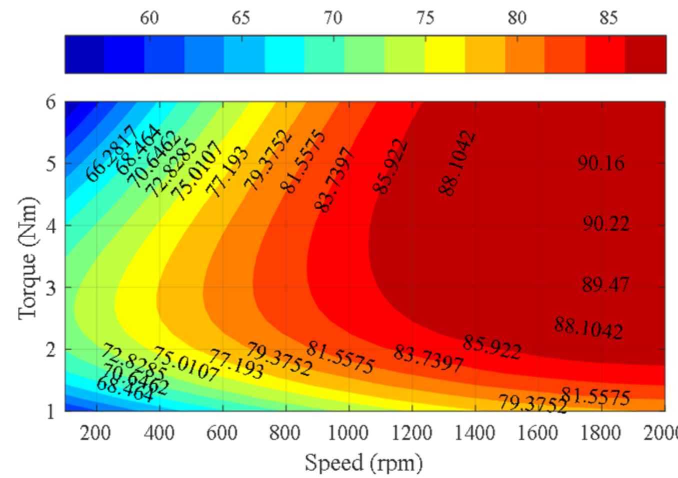


Stress and deformation analysis

Prototype ML-SynRM rotor

ML-SynRM Experimental Analysis

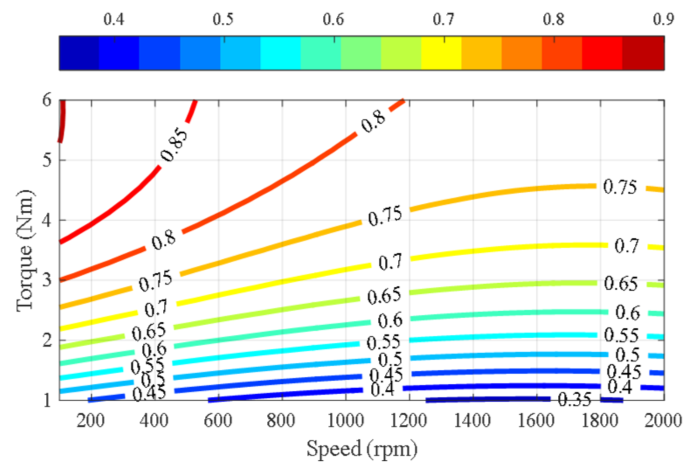
- Prototype ML-SynRM is tested & compared against SCIM
- ML-SynRM has lower stator I^2R and P_{Core}
- Rotor I^2R loss is absent in ML-SynRM, significant η gain
- Total loss reduction by 25.65% at rated condition
- Performance evaluated under different loading condition
- Reached IE5 class efficiency under TENV cooling



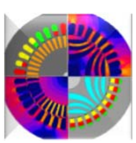
Efficiency Map of Prototype ML-SynRM

Comparison of ML-SynRM test results against benchmark SCIM

Machine Type	SCIM	ML-SynRM	Machine Type	SCIM	ML-SynRM
α_{CORE} (W/V²)	5.3e-4	3.7e-4	$P_{F,W}$ (W)	7.2	7.3
ω_{Rated} (rpm)	1748	1800	P_{LOSS} (W)	109.07	81.09
P_{I^2R-St} (W)	55.8	52.2	T_{AVG} (Nm)	3.97	3.97
P_{I^2R-Rt} (W)	23.57	-	η (%)	86.95	90.22
P_{CORE} (W)	22.53	21.59	PF_{IN} (pu)	0.78	0.72

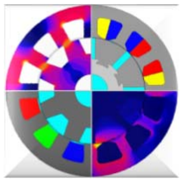


Power factor map of Prototype ML-SynRM



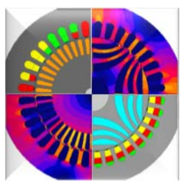
M. A. Kabir and I. Husain, "Application of Multilayer AC winding to Design Synchronous Reluctance Motors," in Special Section of *IEEE Transactions on Industrial Electronics*, (submitted)

Presentation Outline



NRE Electric Machines for EV/ HEVs

- Fully-pitched MCSRM with standard VSI
- Concentrated Wound Segmented Rotor SRM (SSRM)
- Accomplishments and Next Steps



High Performance Reluctance Drives with standard VSIs

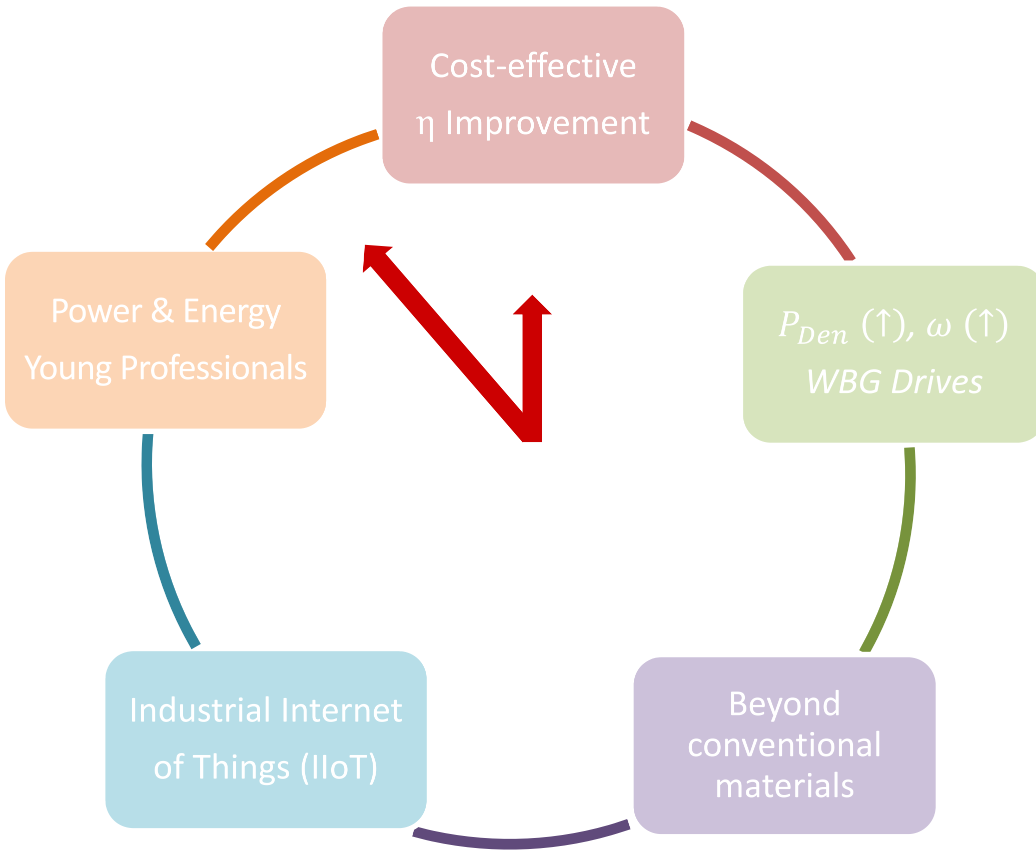
- Multilayer (ML) AC Winding for Efficiency Improvement
- Application of ML Winding for SynRM Design
- Accomplishments and Next Steps

Technology Trends and Research Directions

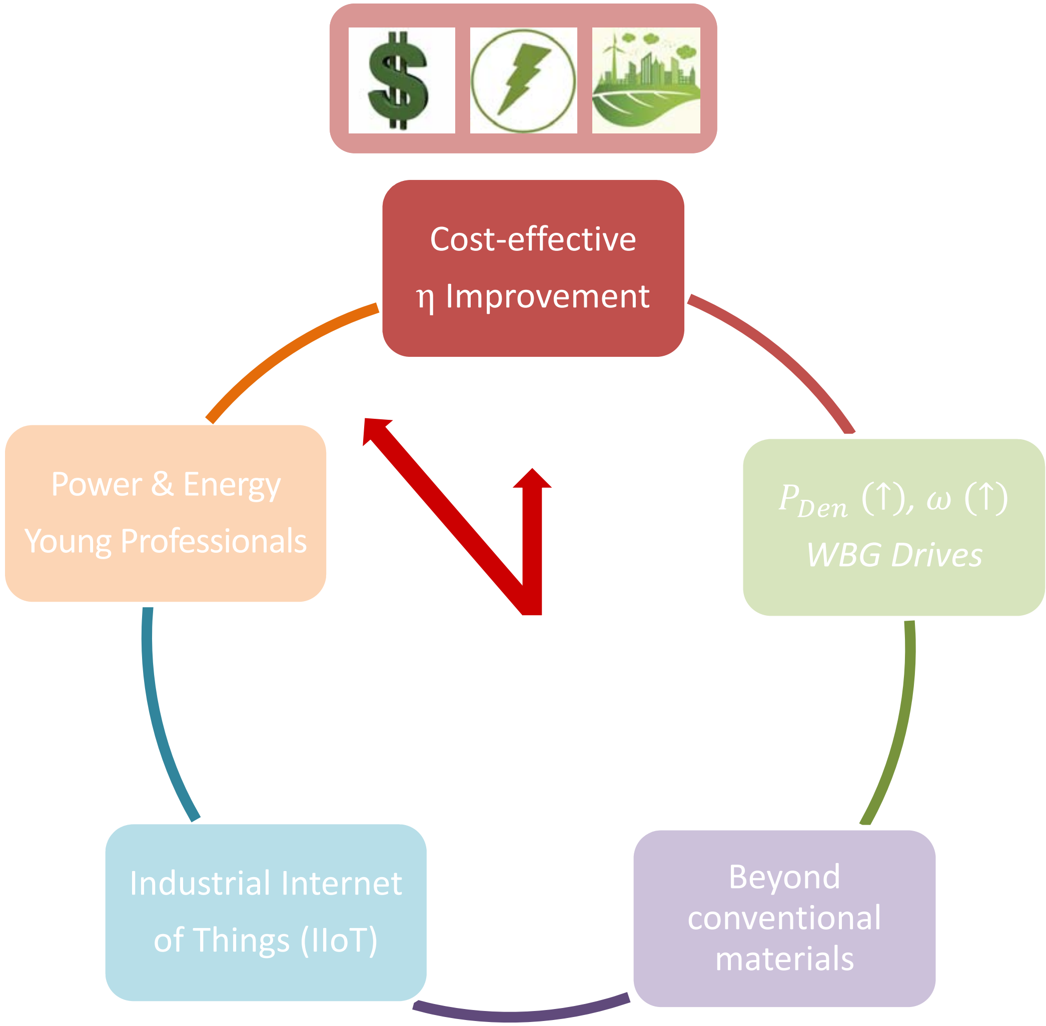
- Cost-effective Efficiency & Performance improvement
- High P_{Den}, High Speed Motors with WBG Drives
- Integrated Motors for Industrial Automation

Technology Trends in Electric Machine Design

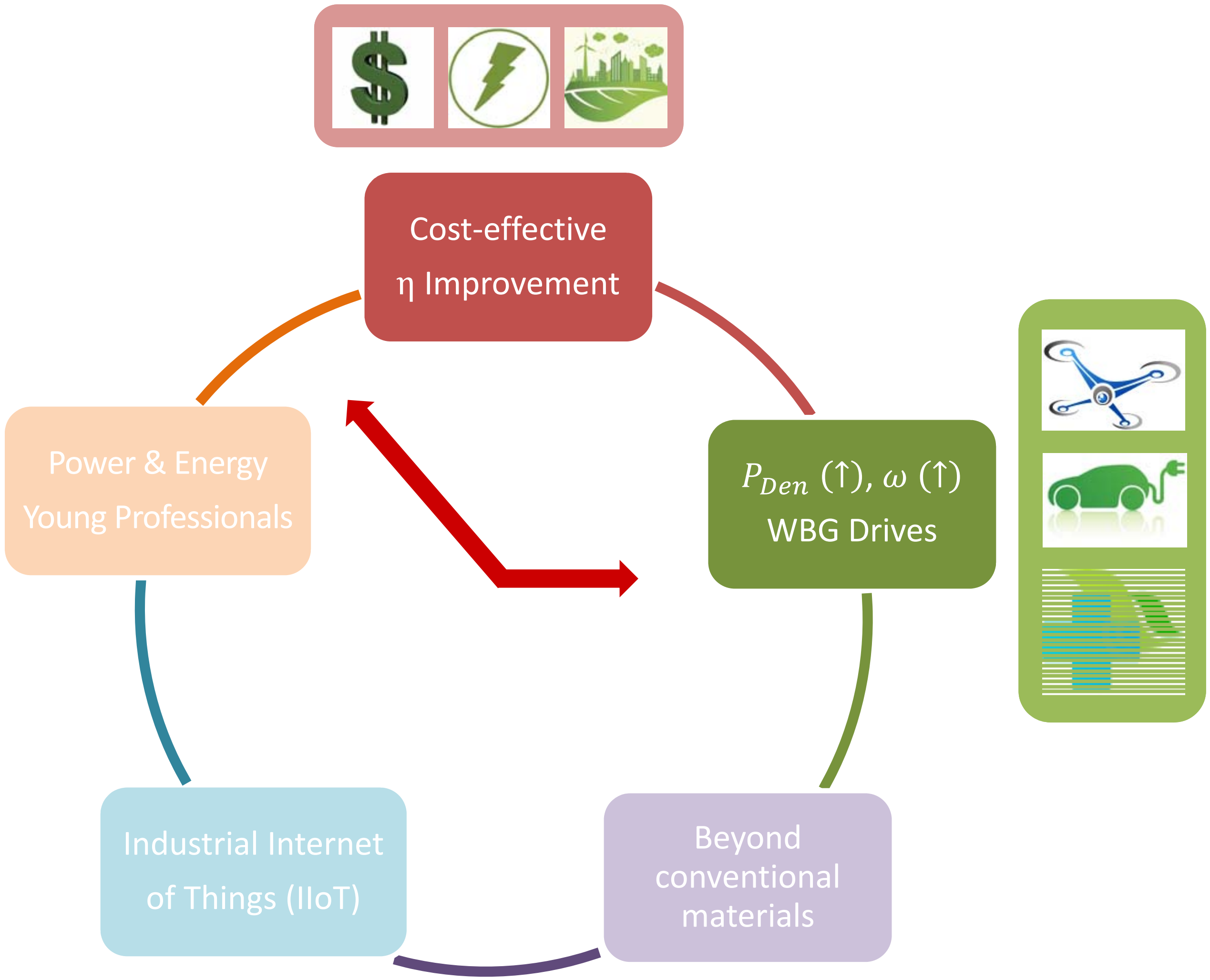
Key Objectives & Research Initiatives



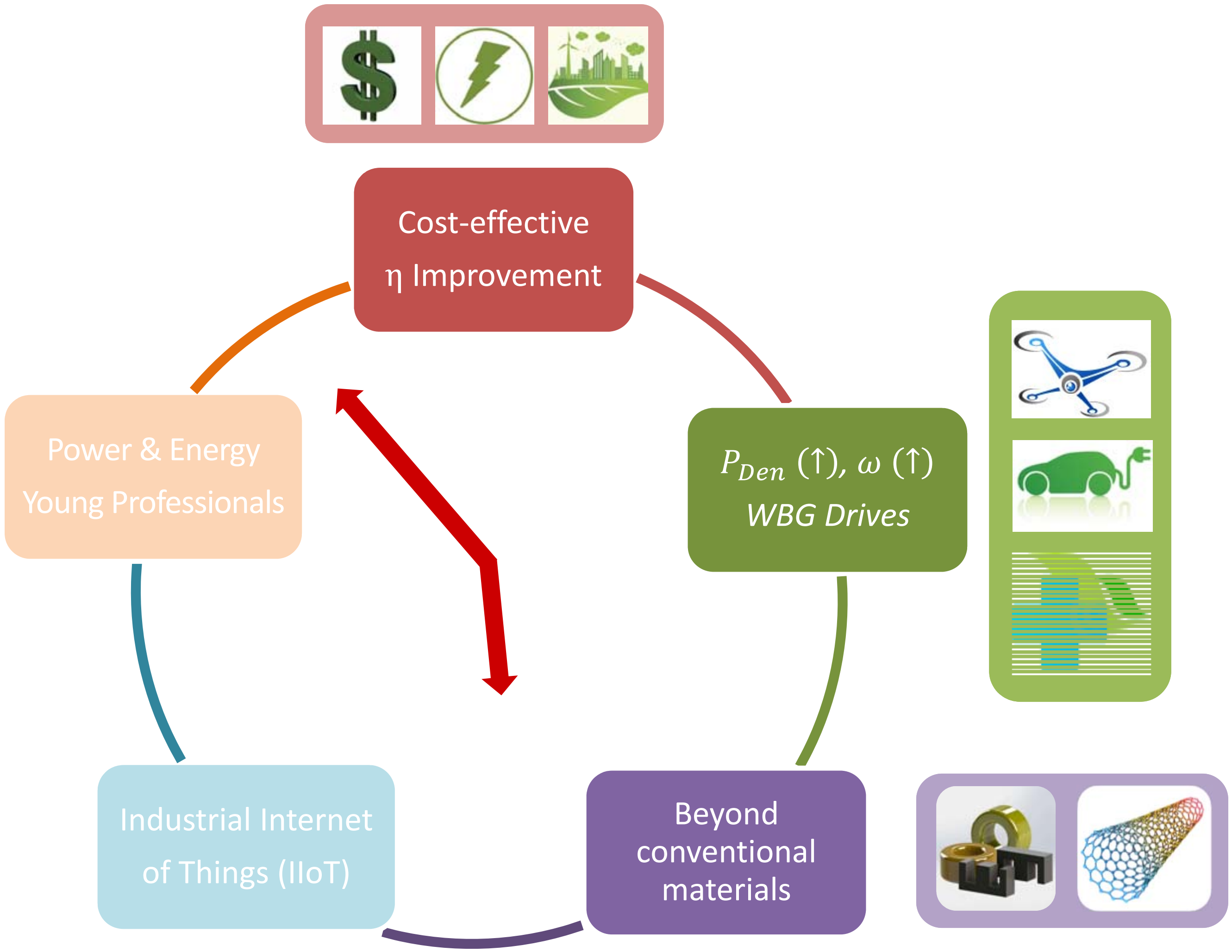
Technology Trends in Electric Machine Design



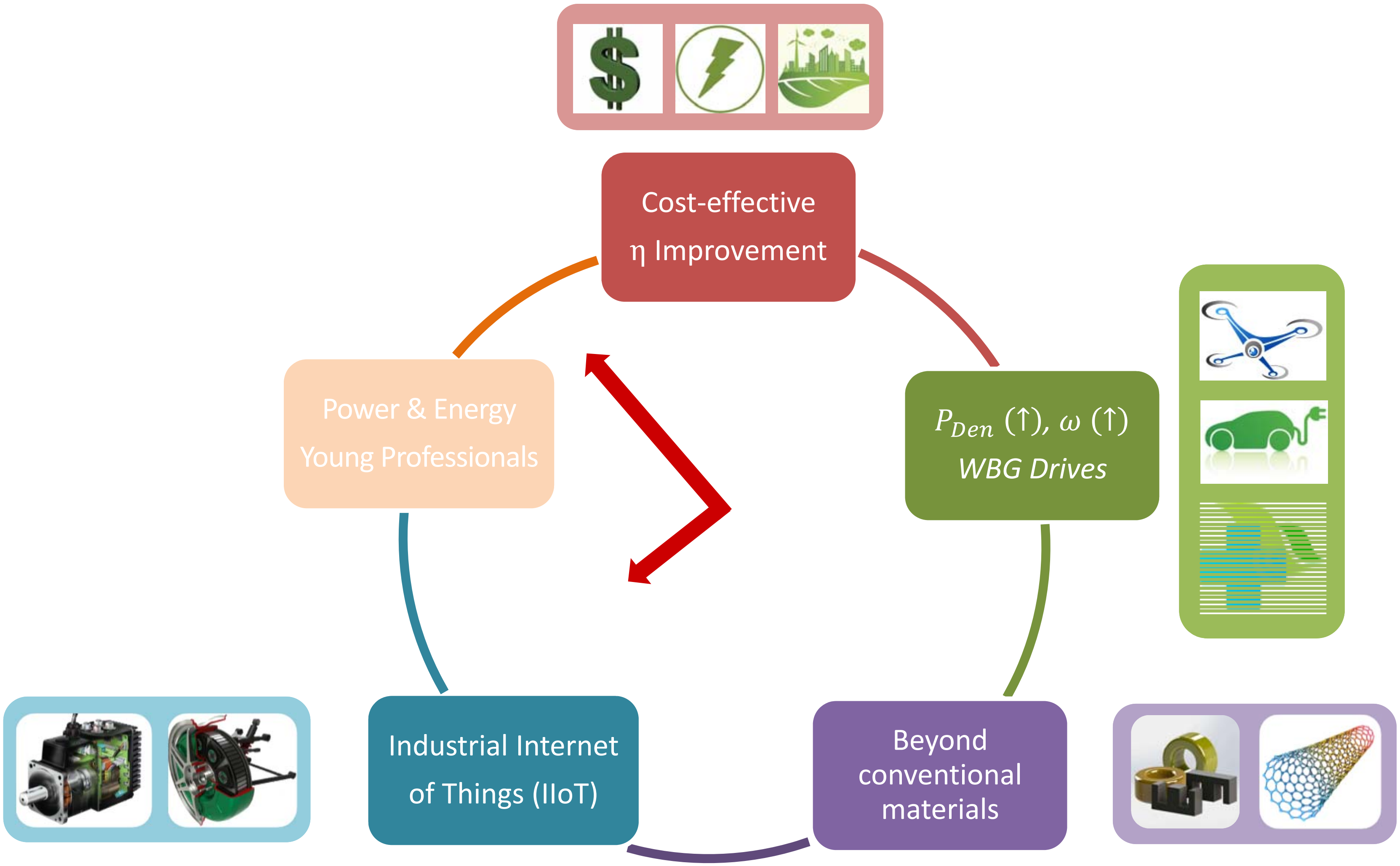
Technology Trends in Electric Machine Design



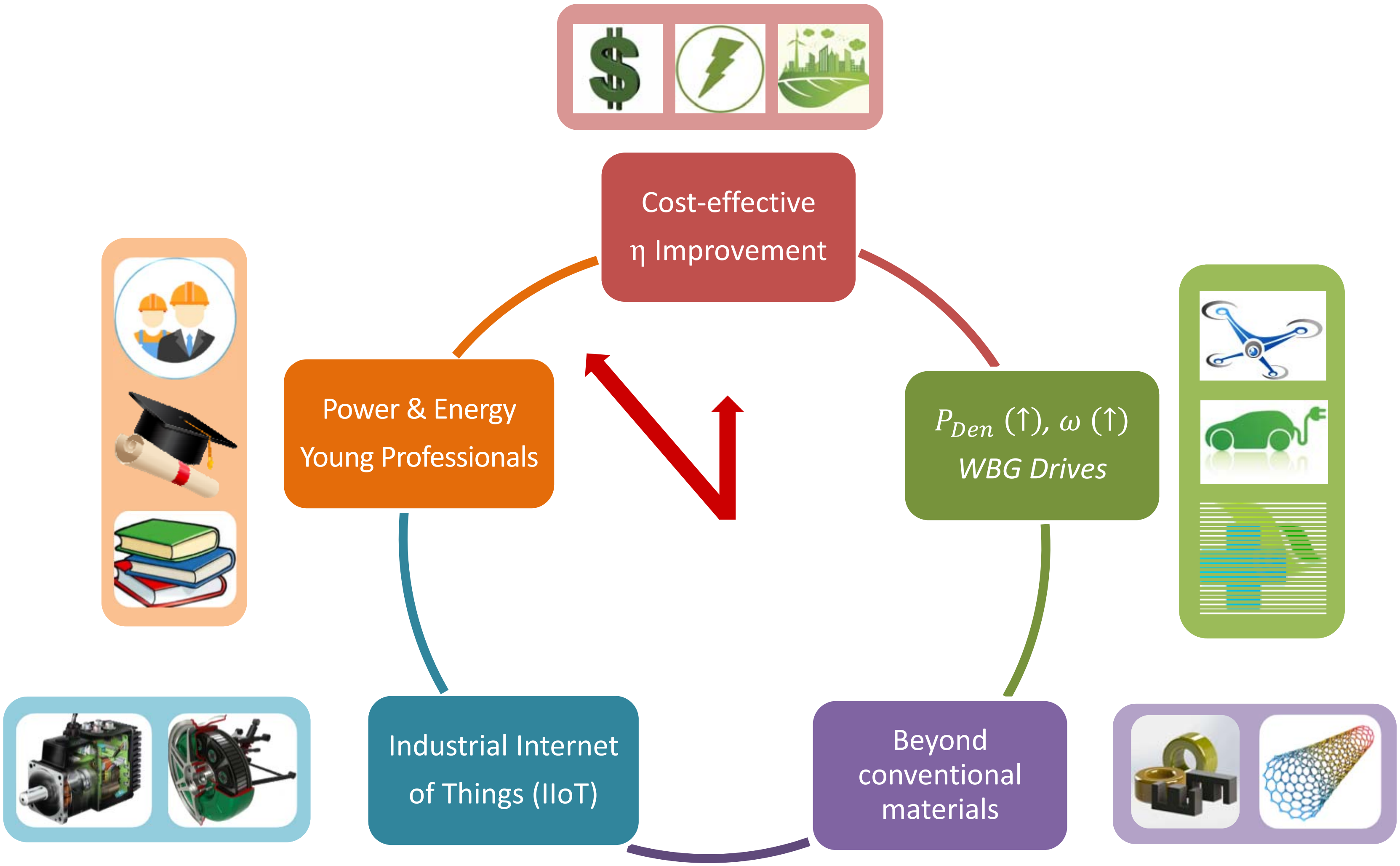
Technology Trends in Electric Machine Design



Technology Trends in Electric Machine Design



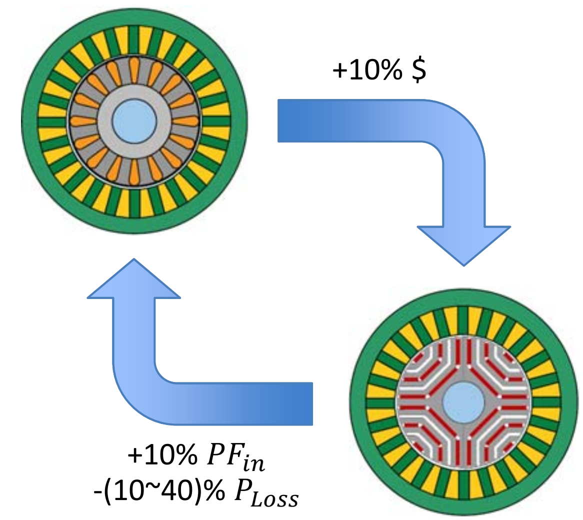
Technology Trends in Electric Machine Design



Low-cost, Ultra-premium Efficiency Industrial Machines

Background & Motivation

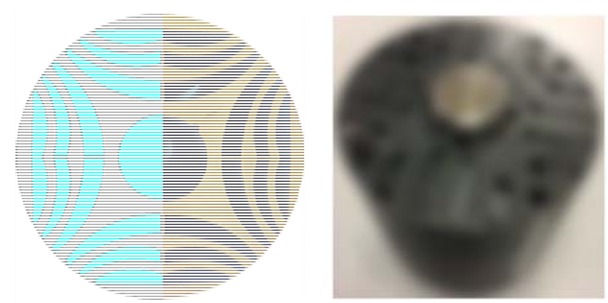
- Designed ML-SynRM achieves IE5 efficiency with TENV cooling
- Power factor lower than IM, increases drive rating
- Higher power level, stator I^2R loss(%) ↓ & induced loss(%) ↑
- PMA-ML-SynRM will be an IE5 alternative with high pf (≥ 0.85)



IM to PMA-SynRM Design Tradeoffs

Challenges & Opportunities

- T_{Ripple} minimization without skewing (asymmetric pole, δ_{q-lam})
- De-magnetization under heavy loading ($H_{c\_Ferrite} \approx \frac{1}{3} H_{c_{NRE}}$)
- Loss based rotor and stator (modular) material selection
- Design rules establishment for performance improvement



Prototype (left) ML-SynRM & (right) PMA-SynRM rotors

Relevant Experience

- PhD research on ML-SynRM
- Design optimization, prototype development, control
- Internship experience on PMA-SynRM (machine prototyping)

High Performance Traction Motors with WBG Drives

Background & Motivation

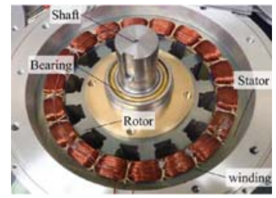
- Reliability, fault tolerance, lower cost, and lower emission
- High T_{den}, high $^{T}/_{W}$, low inertia, wide CPSR, high temperature
- High efficiencies, minimal T_{Ripple}, low noise and vibration
- Facilitate plug-&-play on-board fast battery charging system

Research Opportunities

- Designs: SRM, PMA-SynRM, FSPM with ML/FSCW & NRE PM
- Multi-phase machine & converter: control flexibility, improved fault tolerance, higher power with limited rated devices, charging
- WBG: higher f_{sw}, sinusoidal current, smaller filters, capacitors

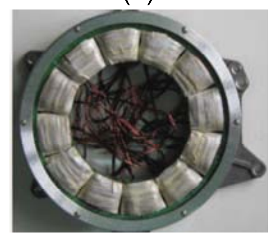
Relevant Experience & Exposures

- PhD research: EV/HEV machine design, SynRM, FSPM
- NCSU: 55 kW (peak), 650 V SiC based traction drive
- NCSU: Machine design inputs for 100 kW SiC based drive



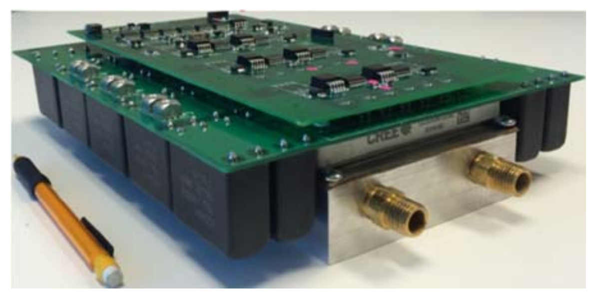
(a)

(c)

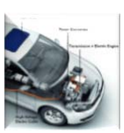


(b)

Prototype Motors
(a) 12/8 SRM[3],
(b) FSPM stator[4] &
(c) 12/10 PMA-SynRM[5]
for traction application



650V, 55kW SiC traction drive[6]



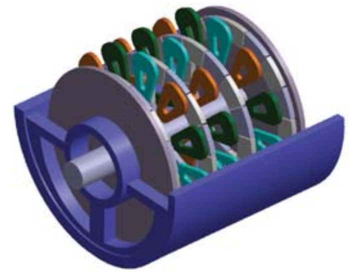
[3] Tokyo Institute of Tech., Japan; [4] Southeast University, Nanjing, China; [5] Univ. of Padova, Italy; [6] NCSU PowerAmerica

Ultra-high Speed, High P_{Den} Motors with WBG Drives

Background & Motivation

- WBG devices enables high frequency, high temperature operations
- Electric machines with high $f_{Fund.}$ for high speed possible
- Enables non-conventional designs (weight advantage)
- Potential application: UAV, medical instrument, traction

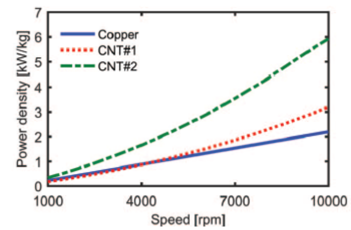
Slot-less machine [7]



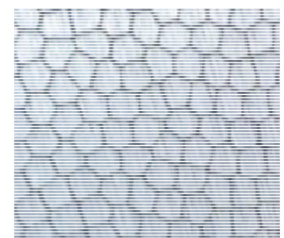
Core-less AFPM [8]

Challenges & Opportunities

- Topologies: Slot-less, core-less, axial-flux, transverse-flux
- Immature technology compared to radial flux counterparts
- Non-conventional core materials for the cores: SMC, AMM
- Non-conv. conductor materials: CNT, pre-compressed AL



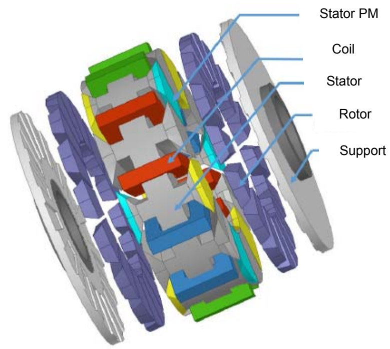
kW/kg vs speed [8]



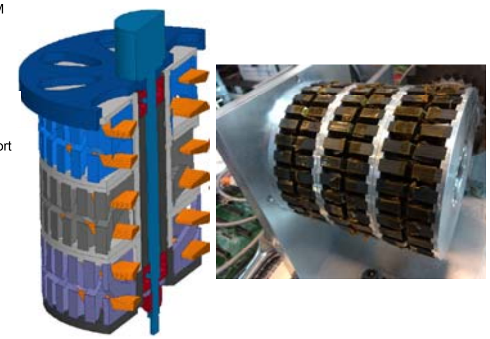
Pre-compressed *Al*

Relevant Experience & Exposures

- Segmented rotor AF-FSPM (ECCE 2015)
- NCSU: TFM research with claw-pole & SMCs
- NCSU: Slot-less machines for high speed applications



Toroidal wound AF-FSM



32 pole Transverse-flux Motor [9]

Md Ashfanoor Kabir, Adeeb Ahmed and Iqbal Husain, " Axial flux segmental rotor flux-switching synchronous motor," 2015 IEEE Energy Conversion Congress and Exposition (ECCE), Montreal, QC, 2015, pp. 2148-2152.

[7] www.thingap.com; [8] Univ. of Kentucky; [9] NC State Univ.

Integrated Motor Drives (IMDs)

Background & Motivation

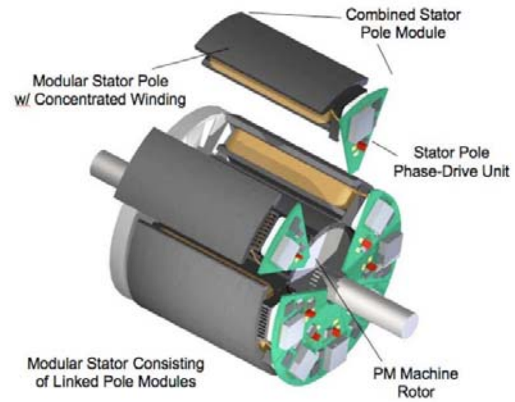
- Compact motor drives & built in electronics (no drive cabinet, cables)
- Expected 40% market growth by 2017 (source: NYSE IHS)
- Revolutionize manufacturing, energy efficient, compact technologies
- Potential application: servo, direct drive, industrial drives

Challenges & Opportunities

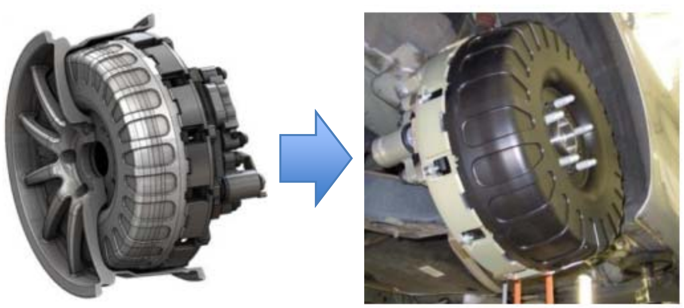
- Compact system, EM, electronic and mechanical constraints
- Application specific, non-explosion-proof, sensor-less control
- Opens up multidisciplinary research opportunities
- Modular design improves reliability, adds controller complexity

Relevant Experience & Exposures

- ABB USCRC internship on integrated motor drives
- PCB designing, rapid prototyping, transient & loaded testing
- Position sensor-less control at low and high-speeds



Integrated modular motor drives (IMMD) [10]



Protean 75 kW in-wheel electric motor [11]

[10] Univ. of Wisconsin Madison; [11] proteanelectric.com

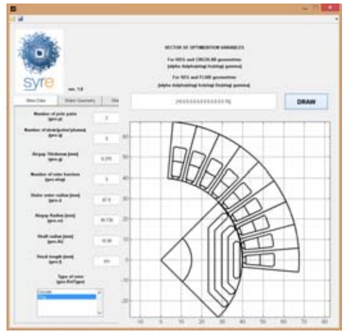
Open-source Design Tools for Electric Machines

Background & Motivation

- 40% of workforce at US utilities will be eligible for retirement in next 5 year
- The power sector will need 100,000 new skilled workers by the year 2018
- It is essential to develop skilled young professionals in power & energy
- Attract young talents to power engineering areas

Objectives and Impacts

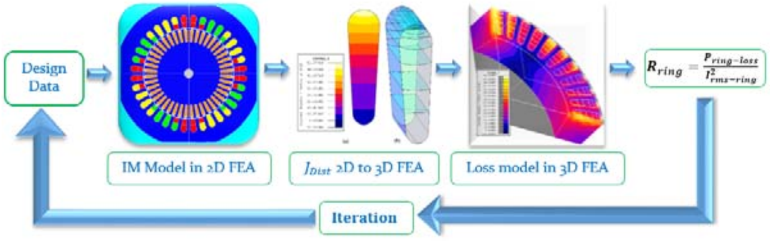
- Electric machine design tool using FEA & optimization algorithms
- Use open-source software FEMM & GNU Octave
- Help students in gaining exposures in EM design engineering
- Provide timely and accurate design solutions to engineers



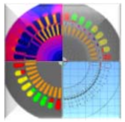
SyR-e : Synchronous Reluctance – evolution[12]

Relevant Experience & Exposures

- Initial objective: develop tools for induction motor design
- ABB Internship: research on IM 3D parameters' model
- Dr. Boglietti's works on geometry based IM modeling



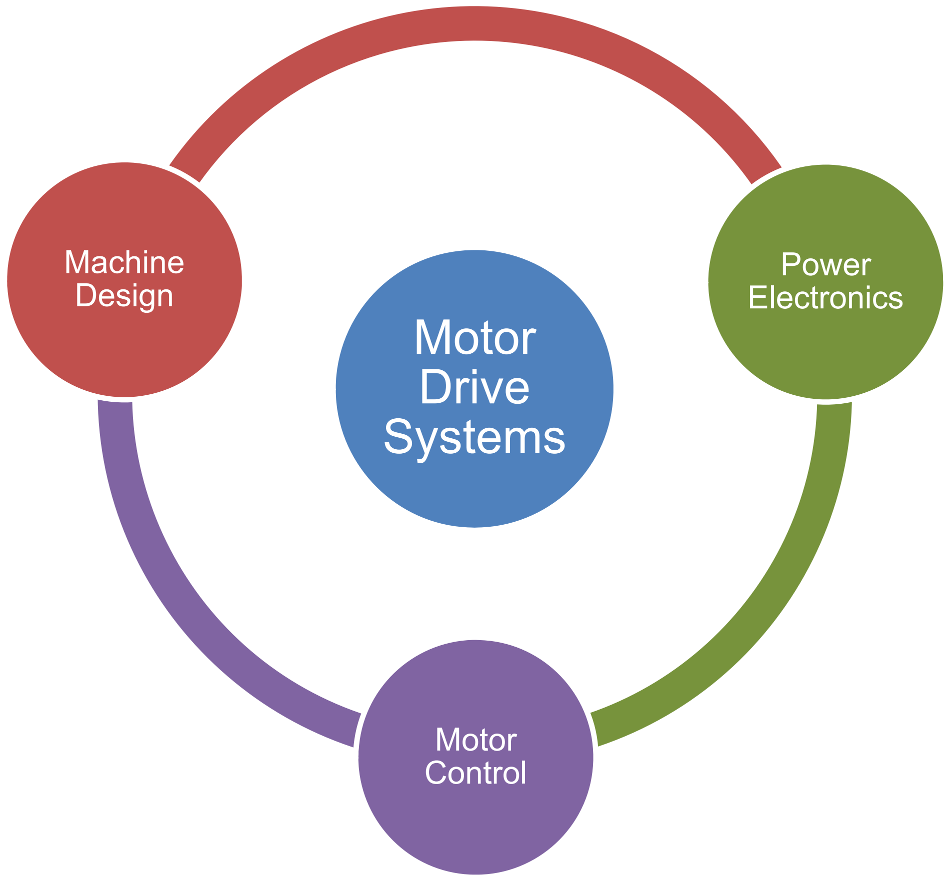
IM ring parameter estimation model



M. A. Kabir, R. Mikail, S. Englebretson and I. Husain, "3D FEA based squirrel cage rotor model for design tradeoffs and performance analysis," *2015 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Charlotte, NC, 2015, pp. 2696-2702.

[12] sourceforge.net/projects/syr-e/

Concluding Thoughts



- Optimization
- Compatibility
- Integration

- Electromagnetic
- Mechanical
- Materials

- Configuration
- Devices
- Strategies

- Algorithms
- Real time DSP
- Sensors

Thank you

“To find the secrets of the universe, think in terms of energy, frequency and vibration”

Nikola Tesla (1856-1943)