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 $T_{den}$, $P_{den}$, $\eta$): proportional
- IPMSM most popular candidate with rare-earth (RE) PMs
- RE materials’ price & supply: HEV mass production issues

### 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 China boosts RE reserve
- Research on NRE alternatives are essential

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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

**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

**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 $\omega_{Base}$ & $\omega_{Max}$

(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, \( \beta = r \cdot d\theta \), 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 \( \bar{x} \) & \( \bar{y} \)

Constant self-inductance

\[ \beta_R = \beta_S = \beta_{SG} \]

Torque

\[ T = i_a i_b \frac{d M_{ab}}{d\theta} + i_b i_c \frac{d M_{bc}}{d\theta} + i_c i_a \frac{d M_{ca}}{d\theta} \]

MCSRM inductance profiles

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

Parameter Sensitivity Analysis

Number of Turns ($N_{Turn}$)

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

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 $N_{Turn}$ 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
MCSRM Performance Evaluation

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

Optimal parameter values from iterative design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Number of turns, $N_{\text{turn}}$</td>
<td>18</td>
</tr>
<tr>
<td>Length of stator back-iron, LSI (mm)</td>
<td>18.5</td>
</tr>
<tr>
<td>Length of stator pole, LSP (mm)</td>
<td>11.5</td>
</tr>
<tr>
<td>Stator pole tapering angle, $T_{\text{pr}_s}$ ($^{\circ}$)</td>
<td>6</td>
</tr>
<tr>
<td>Rotor pole tapering angle, $T_{\text{pr}_r}$ ($^{\circ}$)</td>
<td>10.5</td>
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</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>IPMSM</th>
<th>CSRM</th>
<th>MCSRM</th>
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</thead>
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<tr>
<td>$T_{\text{den}}$ (Nm/L)</td>
<td>35</td>
<td>36</td>
<td>33</td>
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<tr>
<td>$P_{\text{den}}$ (kW/L)</td>
<td>10.2</td>
<td>10.4</td>
<td>9.57</td>
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<tr>
<td>$T/W$ (Nm/kg)</td>
<td>9.3</td>
<td>8.4</td>
<td>8.45</td>
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<tr>
<td>$P/W$ (kW/kg)</td>
<td>2.7</td>
<td>2.4</td>
<td>2.45</td>
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</tbody>
</table>

Performance comparison at $\omega_{\text{Base}}$

Segmented Rotor SRM (SSRM)

MCSRM Challenges & Alternative

- MCSRM: Large end-winding, High $l_{ew-ax}$, less compact
- $P_{R-St}$ (†), 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

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

Initial Performance Evaluation

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

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

SSRM Torque Ripple Minimization

SSRM Semi-numerical Model

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

SSRM Torque Ripple Sources

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

\[
T_{EM} = \frac{1}{2} \left( i_A^2 \frac{dL_{AA}}{d\theta} + i_B^2 \frac{dL_{BB}}{d\theta} + i_C^2 \frac{dL_{CC}}{d\theta} \right) \\
+ i_A i_B \frac{dM_{AB}}{d\theta} + i_B i_C \frac{dM_{BC}}{d\theta} + i_C i_A \frac{dM_{CA}}{d\theta}
\]
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
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 $T_{RIPPLE}$
- FEA tools FLUX 2D is coupled with Optimization tool GOT-It for ‘M-Opt’

Optimization Problem

Max($T_{AVG}$)
Min($T_{Ripple}$)
Such as:
$J_{SLOT} \leq 4.5 \text{ A/mm}^2$
$D_{Stator} \leq 163.5 \text{ mm}$
$D_{Axial} \leq 151.2 \text{ mm}$

Parameterized rotor and stator segments

- 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

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 $T_{AVG}$

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

Photos of prototype SSRM
(left) stator & (right) rotor stack
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High Performance Machines for Industrial Drives

Industrial Market and Technology Trend

- Electric motors utilize 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

High η Motors: Challenges & Opportunities

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

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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 $P_{\text{Core}} \uparrow, T_{\text{AVG}} \downarrow, P_{\text{FIN}} \downarrow, T_{\text{Ripple}} \uparrow$
- Lower stator $I^2R$ losses but higher induced losses, $\eta \downarrow$

Proposed Multilayer AC Winding

- $N_{\text{Layer}} = \Phi_{M/C}$, provides additional design domain
- Sample stator MMF in each slot reduced MMF harmonics
- Concentrically built winding, reduced end-winding length
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 \(|\text{stator MMF}| (F^v_{st})\)

\[
k_{dv} = \frac{\sin \left( \frac{\sqrt{2} \pi}{6} \right)}{q \sin \left( \frac{\sqrt{2} \pi}{6q} \right)} \quad k_{pv} = \sin \left( \frac{\sqrt{2} \pi}{2} \right) \quad F^v_{st} = \frac{3}{p} \cdot k_{wv} \cdot i_s
\]

**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 \( F^v_{st} \)
- Analytical stator MMF model is verified against FEA

\[
k_{pv} = \frac{1}{N_t} \sum_i N_i \cdot \sin \left( \sqrt{2} i - 1 \cdot \frac{\pi}{2} \right)
\]
Application of ML Winding: Induction Motor

Design Benchmark Selection

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

Specifications of Benchmark SCIM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{\text{STATOR}}$</td>
<td>163.5 mm</td>
<td>$V_{\text{supply}}$</td>
<td>460 V</td>
</tr>
<tr>
<td>$L_{\text{STK}}$</td>
<td>80 mm</td>
<td>$I_{\text{PEAK}}$</td>
<td>2.0 A</td>
</tr>
<tr>
<td>$N_{\text{POLE}}$</td>
<td>4</td>
<td>$P_{\text{RATED}}$</td>
<td>746 W</td>
</tr>
<tr>
<td>$f$</td>
<td>60 Hz</td>
<td>Cooling</td>
<td>TENV</td>
</tr>
</tbody>
</table>

Design of ML Winding

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

Experimental Analysis

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

Results

- Significant (17.6%) reduction in stator $I^2R$ loss
- Induced losses: lower $\alpha_{\text{CORE}}$ & rotor $I^2R$ loss
- Total loss reduction 9%, Reaches $\eta_{\text{IE4}}$ ($\leq 87.5\%$)

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

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

RATED PERFORMANCE COMPARISON

<table>
<thead>
<tr>
<th>Winding Type</th>
<th>DLDW</th>
<th>MLW</th>
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</thead>
<tbody>
<tr>
<td>$\omega$ (rpm)</td>
<td>1748</td>
<td>1750</td>
</tr>
<tr>
<td>$P_{I^2R-St}$ (W)</td>
<td>55.77</td>
<td>45.98</td>
</tr>
<tr>
<td>$P_{\text{Loss}}$ (W)</td>
<td>109.07</td>
<td>99.59</td>
</tr>
<tr>
<td>$T_{AVG}$ (Nm)</td>
<td>3.97</td>
<td>3.97</td>
</tr>
<tr>
<td>$\eta$ (%)</td>
<td>86.95</td>
<td>87.96</td>
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<tr>
<td>$PF_{IN}$ (pu)</td>
<td>0.78</td>
<td>0.78</td>
</tr>
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</table>

Next: ML-SynRM design (no rotor $I^2R$ loss), 3% efficiency gain ($\eta_{\text{IE5}}$) 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 $\gamma$
- FEA tool Flux-2D coupled with Opt. tool GOT-It

**Optimization Problem**

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

Torque ripple, $C_{Rip}$ : $T_{Ripple} \leq 5\%$ (ceiling constraint)
Power factor, $C_{PF}$ : $PF_{IN} \geq 0.7$ (floor constraint)

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 $\theta_{Skew} = 4^\circ$, $T_{Ripple} = 4.83\%$ with similar $T_{AVG}$

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 ($2.5 \times 10^4$ times scaled)

Rotor skewing results of the designed ML-SynRM

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 $\eta$ gain
- Total loss reduction by 25.65% at rated condition
- Performance evaluated under different loading condition
- Reached IE5 class efficiency under TENV cooling

Comparison of ML-SynRM test results against benchmark SCIM

<table>
<thead>
<tr>
<th>Machine Type</th>
<th>SCIM</th>
<th>ML-SynRM</th>
<th>Machine Type</th>
<th>SCIM</th>
<th>ML-SynRM</th>
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<tbody>
<tr>
<td>$a_{Core}$ (W/V$^2$)</td>
<td>5.3e-4</td>
<td>3.7e-4</td>
<td>$P_{FW}$ (W)</td>
<td>7.2</td>
<td>7.3</td>
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<tr>
<td>$\omega_{Rated}$ (rpm)</td>
<td>1748</td>
<td>1800</td>
<td>$P_{Loss}$ (W)</td>
<td>109.07</td>
<td>81.09</td>
</tr>
<tr>
<td>$P_{I^2R-St}$ (W)</td>
<td>55.8</td>
<td>52.2</td>
<td>$T_{AVG}$ (Nm)</td>
<td>3.97</td>
<td>3.97</td>
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<tr>
<td>$P_{I^2R-Rt}$ (W)</td>
<td>23.57</td>
<td>-</td>
<td>$\eta$ (%)</td>
<td>86.95</td>
<td>90.22</td>
</tr>
<tr>
<td>$P_{Core}$ (W)</td>
<td>22.53</td>
<td>21.59</td>
<td>$P_{FIN}$ (pu)</td>
<td>0.78</td>
<td>0.72</td>
</tr>
</tbody>
</table>

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- High \( P_{Den} \), High Speed Motors with WBG Drives
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Technology Trends in Electric Machine Design

Key Objectives & Research Initiatives

- Cost-effective \( \eta \) Improvement
- Power & Energy Young Professionals
- \( P_{\text{Den}} \uparrow, \omega \uparrow \) WBG Drives
- Industrial Internet of Things (IIoT)
- Beyond conventional materials
Technology Trends in Electric Machine Design

- Cost-effective η Improvement
- Power & Energy Young Professionals
- Industrial Internet of Things (IIoT)
- Beyond conventional materials
- \( P_{\text{Den}} \uparrow, \omega \uparrow \)
- WBG Drives
Technology Trends in Electric Machine Design

1. **Cost-effective \( \eta \) Improvement**
2. **Power & Energy Young Professionals**
3. **Industrial Internet of Things (IIoT)**
4. **Beyond conventional materials**
5. **\( P_{Den} \uparrow, \omega \uparrow \)**
6. **WBG Drives**
Technology Trends in Electric Machine Design

- Cost-effective improvements
- Power & Energy Young Professionals
- Industrial Internet of Things (IIoT)
- Beyond conventional materials
- $P_{Den}$ ($\uparrow$), $\omega$ ($\uparrow$) WBG Drives
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- Cost-effective
- $\eta$ Improvement
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Technology Trends in Electric Machine Design

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- $P_{Den}$ (↑), $\omega$ (↑) WBG Drives

- Young Professionals
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 ($\geq 0.85$)

**Challenges & Opportunities**
- $T_{Ripple}$ minimization without skewing (asymmetric pole, $\delta_{q-lam}$)
- 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

**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

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 enable 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

**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

**Relevant Experience & Exposures**

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


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

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 years
- 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

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

Concluding Thoughts

Motor Drive Systems

- Machine Design
- Power Electronics
- Motor Control

- Electromagnetic
- Mechanical
- Materials
- Optimization
- Compatibility
- Integration
- 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)