ACOUSTIC NOISE AND VIBRATIONS OF ELECTRIC POWERTRAINS

Focus on electromagnetically-excited NVH for automotive applications and EV/HEV

Part 2 – Characterization of electromagnetic NVH in electric motors

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Note: this presentation is based on extracts of EOMYS technical training
NVH RANKING OF ELECTRIC MOTOR TOPOLOGIES
Review of electric traction-related NVH issues

- Traction motor magnetic noise depend on **torque density** (full electric Vs hybrid) and **topology**
- Dominant NVH excitation frequencies depend on topology
- Some secondary NVH effects of electric traction:
  - Air-cooled self-ventilated traction motors introduces additional aerodynamic noise
  - Water-cooled traction motors can create hydrodynamic and magnetic noise due to pump motor
  - Cooling system of the electric batteries can create additional noise
  - Power Split Device of HEV introduce gear whine
Excitation harmonics in IM

• In linear case the Maxwell stress can be expressed as

\[ \sigma_r(\theta, t) = \left( \left( B_{r}^R + B_{r}^S \right)^2 - \left( B_{i}^R + B_{i}^S \right)^2 \right) / 2\mu_0 \]

\[ B_{r,t} = B_{r,t}^R + B_{r,t}^S \]

\[ B_{r,t}^R \] rotor radial/tangential airgap field

\[ B_{r,t}^S \] stator radial/tangential airgap field

• The space and time harmonic « content » (zero magnitude harmonics) of the radial and tangential stress are the same

• Three group of harmonics can be defined in both radial and tangential stress:

  (H_{SS}) stator flux harmonics interactions

  (H_{RR}) rotor flux harmonics interactions (null for induction machines at no-load)

  (H_{SR}) stator and rotor flux harmonics (null for induction machines at no-load)

• Depending on the topology and the operation point, the dominant harmonic groups differ:

  For IM \[ B_{r,t}^R << B_{r,t}^S \] and most vibration/noise issues can be explained based on stator flux harmonics H_{SS} only
Summary of harmonic fields (S=stator, R=rotor) depending on operating mode:

<table>
<thead>
<tr>
<th>Load (generator or motor)</th>
<th>No-load (null average torque)</th>
<th>Rotor-driven</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCIM WRIM</td>
<td>$H_{SS} + H_{RR} + H_{SR}$ magnetic noise Mechanical noise Aerodynamic noise</td>
<td>$H_{SS}$ magnetic noise Mechanical noise Aerodynamic noise</td>
</tr>
</tbody>
</table>
Excitation harmonics in SM

- In linear case the Maxwell stress can be expressed as
  \[ \sigma_r(\theta,t) = \frac{\left((B_{r}^R + B_{r}^S)^2 - (B_{r}^R + B_{r}^S)^2\right)}{2\mu_0} \]
  \[ B_{r,t} = B_{r,t}^R + B_{r,t}^S \]
  \[ B_{r,t}^S \text{ stator radial/tangential airgap field} \]
  \[ B_{r,t}^R \text{ rotor radial/tangential airgap field} \]

- The space and time harmonic "content" (zero magnitude harmonics) of the radial and tangential stress are the same

- Three group of harmonics can be defined in both radial and tangential stress:
  - \((H_{SS})\) stator flux harmonics interactions (null in open circuit)
  - \((H_{RR})\) rotor flux harmonics interactions (always present for PMSM)
  - \((H_{SR})\) stator and rotor flux harmonics (null for PMSM at open circuit)

- Depending on the topology and the operation point, the dominant harmonic groups differ:
  For SM \( B_{r,t}^R \gg B_{r,t}^S \) but vibration/noise issues generally comes from \( H_{RS} \) (open circuit NVH issue) and \( H_{SR} \) (NVH issue due to concentrated winding)
Summary of harmonic fields (S=stator, R=rotor) depending on operating mode:

<table>
<thead>
<tr>
<th>Load (generator or motor)</th>
<th>No-load (null average torque, ( I_q=0 ))</th>
<th>Open-circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PMSM</strong></td>
<td>( H_{SS} + H_{RR} + H_{SR} ) magnetic noise Mechanical noise Aerodynamic noise</td>
<td>( H_{SS} + H_{RR} + H_{SR} ) magnetic noise Mechanical noise Aerodynamic noise</td>
</tr>
</tbody>
</table>

- For PMSM above maximum voltage there are therefore 3 different control strategies:
  - connected to DC link with fixed \( V=V_{max} \), giving energy to DC link (corresponds to regenerative mode of traction), involves switching of inverter
  - connected to DC link with \( V=V_{max} \) but keeping null torque with \( I_q=0 \), involves switching of inverter
  - open-circuit with \( V>V_{max} \), no current sent to DC link, no inverter switching
- These three strategies will not give same acoustic noise
In order to identify the frequency content of the different force harmonics groups, one method is to use Fourier series development (infinite summation of progressive rotating waves) and decompose the flux in permeance / mmf product (equivalent of Ohm’s law for magnetics)

\[ B_r(\theta,t) = B_r^r(\theta,t) + B_r^s(\theta,t) = \lambda(\theta,t) \left[ f_{\text{mm}}^r(\theta,t) + f_{\text{mm}}^s(\theta,t) \right] \]

Note: the theoretical background for the application of the same permeance function on rotor and stator mmf is weak, but this affects the harmonics magnitude and not the spectra content.

To simplify the process all the Fourier development are represented using the following wave notation in the airgap linked to stator steady frame

\[ a(t, \alpha_s) = \sum_{n,r} \hat{a}_{nr} \cos(2\pi nf_R t + r\alpha_s + \varphi_{nr}) = \sum_{n,r} \{n f_R, r\} = \{f_i, r_i\}_{i \in I} \]

By convention, frequencies are always positive and the sign of the spatial frequency gives the rotation direction.

The elementary wave rotates in anti clock wise direction for \(r_i > 0\).

Mechanical rotation frequency of the wave is \(f_i/r_i\).

Magnitude and phase information in hidden to be able to simplify wave calculations using

\[ \{f_i, r_i\} \cdot \{f_j, r_j\} = \{f_i \pm f_j, r_i \pm r_j\} \quad \{f_i, r_i\} = \{-f_i, -r_i\} \]
• The space harmonic is not defined with respect to the electrical angle but to the mechanical angle
• Using this notation the fundamental flux density wave is \{f_s, p\} (or \{f_s, -p\} depending on rotation direction) travelling at \(f_s/p\)
• \(r\) is preferably called wavenumber, the naming «space order» being reserved for the multiplication factor between \(r\) and \(p\) (for fundamental \(r=p\) wavenumber, space order is 1)

• Mechanical rotor frequency is \(f_R = f_s/p\) (SM) or \(f_R = (1-s)f_s/p\) (IM)
• Spectrum «content» of magnetic force = spectrum of vibration velocity = noise spectrum
• Considering a force wave \(\{f, r\}\) we therefore directly hear \(f\)
Summary of main design parameters and harmonics (PMSM)

\[ B_r(\theta, t) = B_r^r(\theta, t) + B_r^s(\theta, t) = \lambda(\theta, t) \left[ f_{mm}^r(\theta, t) + f_{mm}^s(\theta, t) \right] \]

Permeance «slotting» harmonics:
- \( r = k_s Z_s, f = 0 \) for stator slotting (Ps)
- \( r = k_r 2p, f = k_r 2p f_r \) for rotor inset magnets (Pr)
- \( r = k_s Z_s + k_r 2p, f = k_r 2p f_r \) for rotor / stator slotting interactions (Psr)

Magnet mmf harmonics:
- \( r = (2h_r + 1)p, f = (2h_r + 1)f_s \) (Fr)
  - magnet shaping
  - magnetization type
  - pole shifting
  - demagnetization

Armature winding mmf harmonics:
- \( r = r_q s h_s + p, f = f_s \) for fundamental (Fs)
- higher time harmonics due to PWM
- space subharmonics or harmonics due to winding types
  - winding pattern
  - slot / pole combination
  - PWM strategy
  - slot opening
  - short circuit

- Radial and tangential flux density have same harmonic contents
- The combination of high wavenumber harmonics of flux density can create low order of radial force
- The largest noise and vibration come from «low wavenumber» forces
• Summary of main design parameters and harmonics (IM)

\[ B_r(\theta, t) = B_r^s(\theta, t) + B_r^s(\theta, t) = \lambda(\theta, t)[f_{nm}^r(\theta, t) + f_{nm}^s(\theta, t)] \]

Permeance « slotting » harmonics:
- \( r = k_s Z_s, f = 0 \) for stator slotting (Ps)
- \( r = k_s Z_s + k_r Z_r, f = k_r Z_r f_R \) for rotor / stator slotting interactions (Pr)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>airgap width</td>
<td></td>
</tr>
<tr>
<td>slot geometry</td>
<td></td>
</tr>
<tr>
<td>eccentricities</td>
<td></td>
</tr>
<tr>
<td>slot and pole numbers</td>
<td></td>
</tr>
<tr>
<td>saturation, magnetic wedge</td>
<td></td>
</tr>
</tbody>
</table>

Rotor mmf harmonics:
- \( r = h_r Z_r + p, f = v_r f_R + f_r (Fr) \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>rotor slot number</td>
<td></td>
</tr>
<tr>
<td>rotor slot opening</td>
<td></td>
</tr>
<tr>
<td>broken bar</td>
<td></td>
</tr>
<tr>
<td>slip / load state</td>
<td></td>
</tr>
</tbody>
</table>

Armature winding mmf harmonics:
- \( r = (2p q_s h_s + 1)p, f = f_s \) for fundamental (Fs)
- higher time harmonics due to PWM

winding pattern
slot / pole combination
PWM strategy
slot opening
flux level
short circuit

• Radial and tangential flux density have same harmonic contents
• The combination of high wavenumber harmonics of flux density can create low order of radial force
• The largest noise and vibration come from « low wavenumber » forces
**Most significant magnetic force harmonics – stator reference frame (SM)**

- « Pole slotting lines » (open circuit case) : $P_s F_{0r} P_0 F_r$

<table>
<thead>
<tr>
<th>Name</th>
<th>Case</th>
<th>Wavenumber $r$</th>
<th>Frequency $f$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{rrA}$</td>
<td>$P_s F_{0r} P_0 F_r$</td>
<td>$k_r'=0$ $v_r'=2ph_r+p$ $v_i=p$</td>
<td>$k_r Z_s + \mu_{sr} p + \mu_{2sr} (2ph_r+p) = 0$</td>
<td>Pole / slot interaction ($n_r$ in $N^*$) $k_s$ and $h_r$ varies with $n_r$</td>
</tr>
<tr>
<td>$H_{rrB}$</td>
<td>$P_s F_{0r} P_0 F_r$</td>
<td>$k_r'=0$ $v_r'=2ph_r+p$ $v_i=p$</td>
<td>$k_r Z_s + \mu_{sr} p + \mu_{2sr} (2ph_r+p) = \pm m_r \text{GCD}(Z_s, 2p)$</td>
<td>Pole / slot interaction ($n_r$ in $N^*$) $k_s$ and $h_r$ varies with $n_r$ and $m_r$</td>
</tr>
<tr>
<td>$H_{rrC}$</td>
<td>$P_s F_{0r} P_0 F_r$</td>
<td>$k_r'=0$ $v_r'=2ph_r+p$ $v_i=p$</td>
<td>$k_r Z_s + \mu_{sr} p + \mu_{2sr} (2ph_r+p) = 2p(h_r+1) - k_s Z_s$</td>
<td>Rewriting without involving GCD / LCM $h_r$, $&gt;=1$ $k_s$ fixed to 1 $</td>
</tr>
</tbody>
</table>

- Obtained combining permeance stator harmonics ($P_s$) with fundamental rotor mmf ($F_{0r}$) and rotor mmf harmonics ($F_r$)
- All the force harmonics are proportional to $2f_s$
- $2f_s$ vibration can include the effect of several different wavenumbers
- The force harmonics are all rotating force waves, except the 0 order ones at multiples of $N_c = \text{LCM}(Z_s, 2p)$
Example of a 48s8p IPMSM (Prius type) in open circuit case [C35]

### Table III: Origin of 0-Order Space Force Rotor Field of 48-Slot-8-Pole Machine

<table>
<thead>
<tr>
<th>$P_{m_1}$</th>
<th>$P_{m_2}$</th>
<th>$P_{m_1}$</th>
<th>$P_{m_2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_1$</td>
<td>$m_2$</td>
<td>$m_1$</td>
<td>$m_2$</td>
</tr>
<tr>
<td>12f</td>
<td>11/1, 15/3, 17/5, 19/7, 21/9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18f</td>
<td>13/11, 15/9, 21/3, 23/1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Pulsating forces ($r=0$) at $12f_s$ are created by the interactions of rotor mmf $m_1p$ and $m_2p$ such as $m_1+/m_2=12p$
- In particular $H48=12f_s$ involves $13p$ and $11p$ rotor mmf harmonics
1D schematics of SM force/vibration/noise harmonics

- each group has «replicates» around the multiples of \( N_c f_R \) and of the switching frequency
- the magnitude of symmetrical lines is symbolic, it depends on the wavenumber & control
- for the PWM lines the symmetry of magnitude around the switching frequency holds
- the same pattern holds for both tangential and radial forces
Conclusions on the NVH excitations of synchronous machines

- The frequency content is theoretical and does not take into account destructive interferences.
- Particular value of the slot openings and pole arc width can cancel some groups of harmonics in permeance or mmf.
- The load angle can change the 0-th order radial force harmonics magnitude.

- The lowest non-zero wavenumber in open circuit is given by $\text{GCD}(Z_s,2p)$ for both tangential and radial forces.
- It is also the case for distributed winding at full load.
- Both $r=0$ tangential (cogging, ripple torque) and radial (pulsating radial force) frequencies are proportional to $\text{LCM}(Z_s,2p)$.
- For concentrated windings (alternate teeth or all tooth wound), the winding pattern generates $r=1$ unbalanced pull if and only if $Z_s=2p+/-1$ (this gives $\text{GCD}(Z_s,2p)=1$) [C1].
- Static eccentricity only introduces new force wavenumbers, while dynamic eccentricity introduces both new wavenumbers and new frequencies (can be seen on a spectrogram).

Note that $\text{GCD}(Z_s,2p) \times \text{LCM}(Z_s,2p)=Z_s2p$.
Pole/slot open circuit interaction, example 3 (WRSM) [C6]

- $Z_s = 48$, $p = 2$
- $\text{LCM}(48,4)/2 = 24 \rightarrow \{24f_s,0\} (H_{rrA})$

- $\{24f_s + 2f_s, 2p\} = \{26f_s, 4\} (H_{rrB})$
- $\{24f_s - 2f_s, -2p\} = \{22f_s, -4\} (H_{rrB})$

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>Bending of the stator housing covers</td>
</tr>
<tr>
<td>1200</td>
<td>Ovalization mode $m = 2$</td>
</tr>
<tr>
<td>4800</td>
<td>Ovalization mode $m = 4$</td>
</tr>
<tr>
<td>5700</td>
<td>Ovalization mode $m = 0$</td>
</tr>
</tbody>
</table>
Pole/slot open circuit and load interaction, example 9 (BPMSM for traction) [C36]

- $Z_s = 48, \ p = 4$
- $\text{GCD}(48, 8) = 8$
- $\text{LCM}(48, 8)/4 = 12$
Claw pole synchronous machines: most significant magnetic force harmonics

<table>
<thead>
<tr>
<th>Name</th>
<th>Case</th>
<th>Wavenumber $r$</th>
<th>Frequency $f$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td></td>
<td>$n,2pq_s f_R$</td>
<td>$Z_s=2pq_sm_s$</td>
</tr>
<tr>
<td></td>
<td>+/-kp</td>
<td></td>
<td>($n,2pq_s+/^-kp)f_R$</td>
<td></td>
</tr>
</tbody>
</table>

- **Force harmonics are not proportional to** $2f_s$
- **Pulsating radial force as cogging torque is at multiples of stator slot number for integral winding**
- The force harmonics are rotating force waves, except the 0 order ones at multiples of $N_c=\text{LCM}(Z_s,2p)$
- **Lowest force wavenumber is given by** $\text{GCD}(Z_s,p)$ **and not** $\text{GCD}(Z_s,2p)$, it is therefore given by $p$ **for integral winding**
**Induction machines: most significant magnetic force harmonics**

- « Pure slotting lines » at no-load: \( P_s F_{0s} P_r F_{0r} \)

\[
\text{Ex: } Z_r = 36, \quad Z_s = 48, \quad p = 2
\]

- \( k_r = 4 \) and \( k_s = 3 \) give a slotting line of order

\( 4 = 4Z_r - 3Z_s + 2p \) of frequency \( f_s(4Z_r/p+2) \)

\( Z_r, Z_s \): stator and rotor slot numbers

\( f_s \): supply frequency

\( p \): number of pole pairs

\( k_r, k_s \): strictly positive integers (rank of permeance harmonics)

\( s \): slip

---

**Table:**

<table>
<thead>
<tr>
<th>Name</th>
<th>Case</th>
<th>Wavenumber ( r )</th>
<th>Frequency ( f )</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_{ssA} )</td>
<td>( = P_s F_{0s} P_r F_{0r} )</td>
<td>( v_s = v_s' = p )</td>
<td>( k_r Z_r - k_s Z_s - 2p )</td>
<td>( f_s(k_r Z_r(1-s)/p - 2) )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( k_r Z_r - k_s Z_s )</td>
<td>( f_s(k_r Z_r(1-s)/p) = k_r Z_r f_R )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( k_r Z_r - k_s Z_s + 2p )</td>
<td>( f_s(k_r Z_r(1-s)/p + 2) )</td>
</tr>
</tbody>
</table>
Sound Power Level at variable speed
Case of a squirrel cage induction machine
Zr=96 Zs=84 p=4

WITHOUT SATURATION

Frequency $f_s(Zr/p+2)$
Order $Zr-Zs+2p=4$

WITH SATURATION

Frequency $f_s(Zr/p+4)$
Order $Zr-Zs+4p=+4$
- "Pure PWM lines" at no-load: $P_0 F_s P_0 F_s$

<table>
<thead>
<tr>
<th>Group 1 ($2f_c \pm f_s$)</th>
<th>Group 3 ($4f_c \pm f_s$)</th>
<th>Group 0 ($f_c \pm 2f_s$)</th>
<th>Group 2 ($3f_c \pm 2f_s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{pum}^+$</td>
<td>$2f_c - 2f_s$</td>
<td>$4f_c - 2f_s$</td>
<td>$f_c + f_s$</td>
</tr>
<tr>
<td>$F_{pum}^-$</td>
<td>$2f_c$</td>
<td>$4f_c$</td>
<td>$f_c + 3f_s$</td>
</tr>
<tr>
<td>$F_{pum}^-$</td>
<td>$2f_c$</td>
<td>$4f_c$</td>
<td>$f_c - 2f_s$</td>
</tr>
<tr>
<td>$F_{pum}^+$</td>
<td>$2f_c + 2f_s$</td>
<td>$4f_c + 2f_s$</td>
<td>$f_c - f_s$</td>
</tr>
</tbody>
</table>

$Z_r, Z_s$: stator and rotor slot numbers  
$f_s$: supply frequency  
$p$: number of pole pairs  
$f_c$: carrier frequency

Ex: $Z_r=38$, $Z_s=48$, $p=2$  
-> main asynchronous PWM lines are $2f_c$ of order 0 and $2f_c \pm/\mp 2f_s$ of order 4
Fig. 6. The frequencies of the dominating voltage harmonics in SVM and the corresponding radial force waves with their spatial orders. The characteristic patterns that appear around $f_{sw}$ and $2f_{sw}$ repeat themselves for the frequencies $3f_{sw}$ and $4f_{sw}$, $5f_{sw}$ and $6f_{sw}$ and so on. The amplitudes of the harmonics depend on the modulation index.
- each group has «replicates» around the multiples of the rotor passing frequency and of the switching frequency
- the magnitude of symmetrical lines is symbolic, it depends on the wavenumber & control
- for the PWM lines the symmetry of magnitude around the switching frequency holds
- the same pattern holds for both tangential and radial forces
Analysis of acoustic noise and vibrations due to PWM

- PWM strategy influence the frequency content and magnitude of PWM force harmonics (mainly 0 and 2p wavenumbers)

- Different PWM strategies:
  - Intersective Symmetrical or asymmetrical ISPWM
  - Space Vector Modulation (equivalent to intersective symmetrical in term of frequency content) SVM PWM
  - Direct Torque Control DTC
  - Randomization techniques RPWM

- For traction application the following strategies are often used during starting from 0 to max speed
  - « asynchronous » ISPWM : carrier frequency $f_c$ fixed independently of speed $f_s$
  - « synchronous » ISPWM : $f_c = m f_s$ with progressive reduction of the ratio to avoid high switching losses
  - calculated PWM strategy (optimized switching angles for torque ripple and loss reduction), $n$ CA per a quarter period gives an equivalent switching frequency $f_c = (2n+1) f_s$
  - « full wave » ISPWM : the input voltage is a square pulse, inducing main exciting force at $6f_s \ 12f_s$ etc. of order 0
• The ISPWM current harmonics vary with speed due to increasing voltage / modulation ratio during the constant torque phase

• Main PWM exciting force frequencies therefore vary with speed

• Depending on the carrier shape (symmetrical, forward or backward asymmetrical) the frequency content of voltage and thereof current harmonic also change
• Same conclusions apply to SVM, equivalent to intersective PWM

• Main PWM forces have 0 wavenumber with sidebands of wavenumber 2p

• These lines are separated with 2f_s, the frequency gap is increasing with speed

• This makes the roughness vary with speed, worst case is a 75 Hz gap
Figure 3.9: Spectrograms of stator voltage and current during run-up including spatial-harmonic and SVM-related current harmonics (machine PM-B)
Effect of operating conditions on Maxwell forces in electrical machines

- Magnetic noise & vibrations are due to varying magnetic fields
- What magnetic fields are present in electrical machines?

<table>
<thead>
<tr>
<th></th>
<th>Load (generator or motor)</th>
<th>No-load (null average torque)</th>
<th>Rotor driven by another machine (open circuit) / run-down</th>
</tr>
</thead>
<tbody>
<tr>
<td>IM</td>
<td>Stator</td>
<td>AC winding field (Id)</td>
<td>AC winding field (Id)</td>
</tr>
<tr>
<td></td>
<td>Rotor</td>
<td>AC winding field (Iq)</td>
<td>None</td>
</tr>
<tr>
<td>PMSM</td>
<td>Stator</td>
<td>AC winding field (Iq)</td>
<td>AC winding field (Id)</td>
</tr>
<tr>
<td></td>
<td>Rotor</td>
<td>PM DC field</td>
<td>PM DC field</td>
</tr>
<tr>
<td>WRSM</td>
<td>Stator</td>
<td>AC winding field (Iq)</td>
<td>AC winding field (Id)</td>
</tr>
<tr>
<td></td>
<td>Rotor</td>
<td>DC winding field</td>
<td>DC winding field</td>
</tr>
</tbody>
</table>
• For IM & WRSM magnetic forces are null if the machines is current-free (on both stator & rotor sides)

• For all electrical machines with permanent magnet (PMs), e.g. surface PM synchronous machines, some sources of magnetic fields are present even if the machine is current-free

• When there is no PM, the nature of noise & vibration (magnetic or non magnetic) can be easily determined

• PM machines can be noisy even in open circuit due to Maxwell forces
Main market electric motors topologies for EV / HEV

(a) PMM
(Toyota/Nissan/Honda/BMW)

(b) IM
(Tesla)

(c) SRM
(Jaguar Land Rover)

(d) SynRM
(ABB)

WRSM
(Renault)
Main market topologies

- Toyota Prius - IPM
- Nissan Leaf - IPM
- Toyota Lexus & Camry – IPM
- Tesla - IM
- BMW i3 - IPM
- Range Rover - SR
Winding topologies for SM

- Overlapping winding
  - Long end-winding
  - Reluctance torque
  - Distributed
  - Concentrated
  - Toyota Prius: overlapping distributed stator winding / IPM rotor PMM

- Non-overlapping winding
  - Short end-winding
  - Limited reluctance torque
  - All teeth wound
  - Alternate teeth wound
  - Honda insight: non-overlapping concentrated stator winding / IPM rotor PMM

- Concentrated winding gives higher efficiency and higher compacity but are more challenging for NVH due to higher space harmonic
NVH comparison

• The most challenging machine is the Switched Reluctance Machine (control strategy is very important)
• NVH behaviour of SynRM is still a reasearch topic
• NVH behaviour of WRSM and PMSM are equivalent, but the WRSM offers more control possibilities
• IM have lower torque ripple than SRM & PM so they are more robust to structural borne noise due to eccentricities

• IM Vs PMSM: for PMSM magnetic noise starts at LCM(Zs,2p) (H48) whereas for IM noise it occurs at H44 -> magnetic force harmonics occur in similar frequency ranges for IM and SM with distributed windings
Comparison of different motor types

<table>
<thead>
<tr>
<th>Technology</th>
<th>Maturity / costs</th>
<th>Efficiency / power factor</th>
<th>Field weakening capability</th>
<th>Power density</th>
<th>Safety on short circuit</th>
<th>Control complexity</th>
<th>Sensitivity noise excitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCIM</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>SPMSM</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>1-2</td>
</tr>
<tr>
<td>IPMSM</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>SRM</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>SyRM</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>1-2</td>
</tr>
<tr>
<td>WRSM</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1-2</td>
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</tbody>
</table>
- Ranking by EO MYS

<table>
<thead>
<tr>
<th>Motor Type</th>
<th>Current harmonics</th>
<th>Rotor permeance harmonics</th>
<th>Stator permeance harmonics</th>
<th>Stator mmf space harmonics</th>
<th>Rotor mmf space harmonics</th>
<th>Overall NVH (qualitative !)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCIM</td>
<td>+</td>
<td>+ (Zr can be chosen)</td>
<td>+</td>
<td>+</td>
<td>+ (negligible even at full-load)</td>
<td>-</td>
</tr>
<tr>
<td>IPMSM</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+ (distributed)</td>
<td>++ (shaped poles) + (V shape)</td>
<td>++</td>
</tr>
<tr>
<td>SPM SM</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+ (distributed)</td>
<td>+ (shaped magnets) - (unshaped magnets)</td>
<td>-</td>
</tr>
<tr>
<td>WRSM</td>
<td>+</td>
<td>- (fixed to 2p)</td>
<td>+</td>
<td>+ (distributed)</td>
<td>+ (shaped pole-shoe)</td>
<td>+</td>
</tr>
<tr>
<td>SRM</td>
<td>--</td>
<td>-- (fixed to 2p)</td>
<td>-</td>
<td>--</td>
<td>NA</td>
<td>--</td>
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<tr>
<td>SynRM</td>
<td>+</td>
<td>+ (fixed to 2p)</td>
<td>+</td>
<td>+</td>
<td>+ (optimized flux barriers)</td>
<td>+</td>
</tr>
</tbody>
</table>