ACOUSTIC NOISE AND VIBRATIONS OF ELECTRIC POWERTRAINs

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

Part 6 – Acoustic noise mitigation techniques in electric motors and passive components

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Note: this presentation is based on extracts of EOMYS technical training
NOISE REDUCTION TECHNIQUES OF PASSIVE COMPONENTS AND ELECTRIC MOTORS
Introduction

• Achieving lower vibration / noise levels can rely on three independent strategies:

1. Lower excitation magnitude
   - skewing
   - current angle
   - magnet shaping
   - pole shifting / pairing
   - slot opening
   - short pitch / winding
   - magnetic wedges
   - current injection
   - notches / slits / flux barriers
   - etc...

2. Lower structural response
   - stiffening
   - damping
   - frame/lamination contact
   - etc...

3. Avoid resonances between excitation and structure
   - slot/pole combination
   - winding topology
   - natural frequency
   - operating speed
   - etc...
Introduction

- Improving the THD of mmf or flux density does not necessarily improve the noise level
- Aerodynamic noise can dominate noise level at high rotating speed for self-ventilated open machines
- At starting, mechanical and aerodynamic noise are low, magnetic forces due to fundamental current may not be high enough in frequency to represent a high dBA level and magnetic forces due to asynchronous PWM may dominate
- Torque ripple is generally not correlated to magnetic noise, except:
  - torque harmonics can do structural-borne noise when propagating from rotor shaft line to bearings and end-shields or machine frame
  - torque harmonics can do direct noise through stator torsional deflection when stator has assymetrical boundary conditions, generating radial vibrations & acoustic noise
  - torque harmonics can do direct noise through stator torsional deflection if stator has radial fins
  - torque harmonics (r=0) combined with eccentricities create unbalance magnetic pull harmonics (r=+/-1) which is another source of structural borne noise
Choice of the topology (generalities)

- Topology: inner Vs outer rotor, axial Vs radial flux, etc...
- There is no unique choice for a low noise & vibration machine, but some topologies are more challenging
- It highly depends on the application and vibroacoustic constraints (e.g. fixed speed Vs variable speed)

- Outer rotor topology can lead to higher noise & vibration due to lower stiffness + double frequency excitations
- Fractional slot winding might lead to high noise & vibration due to lower spatial orders in stator mmf
- Best winding is the one creating the most sinusoidal mmf (double layer distributed integral winding)
Choice of the topology (SM)

- Buried PM Vs surface PM: additional saturation harmonics might lead to higher noise & vibrations

- Dovetail Vs V-shaped magnets: dovetail give less vibration levels in [E21]
- Use of multi-barrier magnets gives higher dof to reduce radial force ripple
Choice of the pole / slot / phase numbers (generalities)

- Increase the number of slot per pole per phase to reduce the harmonic density of flux and forces.
- Increase of $p$ -> thinner yoke -> higher vibration & noise.
- Increase of $p$ -> decrease of field weakening speed -> lower flux levels at high speed.
- At same power & speed, high $p$ fed at high frequency $f$ gives more vibration than low $p$ at low $f$ [E24].
- At fixed speed, changing $p$ and $f$ proportionally changes the acoustic noise frequencies and the resulting dBA (independently of resonance effects).
**Choice of the pole / slot / phase numbers (IM)**

- The number of rotor slots is a key design parameter as it influences both spatial orders and frequencies of exciting forces.
- Zs & Zr even give only even force wavenumbers for integral windings, thus avoiding UMP.
- Avoid Zs=Zr which creates high number of pulsating radial and tangential force waves.
Choice of the pole / slot / phase numbers (IM)

- Even if the lowest non zero spatial order of slotting forces under sinusoidal supply is given by $\text{GCD}(Z_r,Z_s,2p)$, contrary to PMSM the maximization of $\text{GCD}(Z_r,Z_s,2p)$ is not a good rule.

- Avoid $|Z_r-Z_s|=0, 2$ or $4$, $|Z_r-Z_s-2p|=0, 2$ or $4$ and $|Z_r-Z_s+2p|=0, 2$ or $4$.

- $Z_r/p$ multiple of $3$ or odd $Z_r$ or $Z_r/p$ fractional cancels all RSH [E61].
Choice of the pole / slot / phase numbers (SM)

- Zs even avoids unbalanced magnetic pull in open circuit
- Zs even gives only even spatial orders, at both open circuit and full load
Choice of the pole / slot / phase numbers \((SM)\)

- Maximization of \(\text{LCM}(Z_s, 2p)\) increases the frequency of open circuit 0-th order radial and tangential force harmonics (in particular cogging torque and average radial force)

- Minimization of \(\text{GCD}(Z_s, 2p)\) reduces the magnitude of open circuit 0-th order radial and tangential force harmonics (in particular cogging torque and average radial force)

- Maximization of \(\text{GCD}(Z_s, 2p)\) increases the non-zero spatial orders of open-circuit (and probably also partial load, ongoing research) magnetic forces, thus potentially reducing noise and vibration levels

- Some of these design rules can be contradictory and the slot number variation changes the magnitude of permeance harmonics, so electro-vibro-acoustic simulation is necessary

- The maximum GCD rule for low vibration and noise is a sufficient but not necessary condition

- Ex WRSM \(Z_s=180\ p=7\ \text{GCD}(Z_s, 2p)=2\) but the GCD is reached with \(25p+p=26p\ Z_s=2\) and the \(25p\ 27p\) rotor mmf harmonics have very low magnitude

\[
\text{GCD}(Z_s, 2p) = 2pZ_s
\]

\[
\text{LCM}(Z_s, 2p) = 2pZ_s
\]
Assymetries

- Eccentricities increase the spectral density (wavenumbers & frequencies) of harmonic forces.
- Mass & stiffness asymetries (and low number of teeth, introducing discrete distribution of stiffness along yoke) increase the modal density and number of resonances at variable speed.
- Uneven airgap modulates magnetic forces and increase the number of different force wavenumbers.
- The machine should be magnetically and geometrically symmetrical:
  - low tolerance on eccentricities and misalignments.
  - low tolerance on lamination roundness.
  - low tolerance on magnet magnetization.
  - low tolerance on magnet position in slots.
- In segmented stator mechanical wedge can be used to improve airgap roundness.

Fig. 5. (Top) Asymmetries of the stator without wedges, with wedges (Bottom).
Winding design (general)

- The ideal winding gives a sinusoidal mmf, it has an infinite number of phases (no « belt harmonics ») and slots (no « slot harmonics » or preferably no « step harmonics »)
- To avoid UMP the winding induced mmf should never have 2 harmonics separated of 1
- Concentrated winding / tooth-winding / fractional winding have the largest mmf distortion factor, however if properly designed they do not generate noise & vibrations
- Shorted-pitch distributed windings gives the smoothest mmf, reducing the spatial THD
• Short pitching or chording technique consists in having several winding layers and shifting the winding pattern in each layer

• **The chording cannot reduce the largest mmf step harmonics at** $Z_s-p$ **and** $Z_s+p$ **space harmonics**

• The coil pitch $Y$ (in slots, between 0 and $Z_s/(2p)-1$) can be chosen as $(5/6)\frac{Z_s}{(2p)}$ to reduce the stator mmf space harmonics 5p and 7p

**Example: $Zs=48$ $p=2$, no coil pitch**
Skewing (generalities)

- Skewing consists in rotating a 2D slice of the machine along the axis
- Skewing can be applied to stator, rotor or both
- Stator skew is generally linear, rotor skew depends on machine topology (linear for IM, stepped skew or linear for PM)
Skewing (generalities)

- Skewing can cancel a given force harmonics when considering its average longitudinal value (n=0 DC component)
  \[ F_0(t, \alpha) = \frac{1}{L} \int_0^L F(t, \alpha, z)dz \propto \frac{1}{L} \int_0^L B^2(t, \alpha, z)dz \neq \left( \frac{1}{L} \int_0^L B(t, \alpha, z)dz \right)^2 \]

- However it introduces an axial magnetic force variation and can therefore excite longitudinal structural modes of the stator (m,n>0)

- It can also introduce axial force DC and ripple components

- Besides changing electromagnetic flux, skewing increases the radial stiffness of the lamination (increase of circumferential mode natural frequencies) [E39]

- The skewing angle and the part to be skewed (rotor or stator) depends on the magnetic force harmonic to be cancelled

- The best skewing angle might be different when trying to minimize torque harmonics or radial force harmonics

- The best skewing angle might depend on the load condition

- Electro-vibro-acoustic simulation is necessary to check the consequences of skewing and optimize its value
Skewing (PMSM)

Rotor skew

- Skew can be applied lineary (inclined magnet bars) or by stages (stepped-skew)
- The linear stepped-skew can be done using an axial segmentation of magnets (thus potentially reducing magnet losses)

To cancel the average of the \((2n+1)p\) rotor mmf harmonic seen by the stator, the optimal value of the pole skew is given by

\[
\alpha_{Rsk} = \frac{2\pi k}{p(2n+1)}
\]

To cancel radial and tangential open circuit magnetic forces of wavenumber \(r=0\) at frequencies \(n\text{LCM}(Z_s,2p)f_s/p\), the optimal total rotor skew is given by \([E12]\)

\[
\alpha_{Rsk0} = \frac{2\pi}{n\text{LCM}(Z_s,2p)}
\]

- Indeed the rotor mmf harmonic of rank \(r=\text{LCM}(Z_s,2p)\) is involved in radial and tangential force waves \(r=0\) (cf part C)
Skewing (PMSM)

Rotor skew

- This includes cogging torque (tangential \( r=0 \)) cancellation; however, it only deals with the high frequency harmonic at \( \text{LCM}(Z_s,2p)f_R \), and not with the low frequency cogging torque that can appear at \( 2pf_R \) [E42].
- Some authors only consider high frequency content for minimization of cogging torque.
- For an integral winding \( \text{LCM}(Z_s,2p)=Z_s \) and the optimal continuous skew is one stator slot pitch.
- When considering a stepped skewed rotor with \( N_s \) stages:

\[
\alpha_{Rsk} = \frac{N_s - 1}{N_s} \frac{2\pi}{n \text{LCM}(Z_s,2p)}
\]

- The shift angle between two magnets is given by

\[
\alpha_m = \frac{1}{N_s} \alpha_{Rsk0} = \frac{1}{N_s} \frac{2\pi}{n \text{LCM}(Z_s,2p)}
\]

- \( \alpha_{Rsk} \) converges for an infinite number of submagnets to \( \alpha_{Rsk0} \).
- For a small number of slices (2,3,4) the optimal skew angle is therefore far below \( \alpha_{Rsk0} \) (one stator slot pitch for distributed winding).
Skewing (PMSM)

Exemple of Ns=2 magnets:
Cogging torque cancelled with

\[ \alpha_{Rsk} = \frac{\pi}{LCM(Z_s, 2p)} \]
Skewing (PMSM)

**Rotor pseudo-skew**

- For buried magnet PMSM if the lamination is rotated without moving the magnets this defined a pseudo skew
- The cogging torque harmonis can be reduced if the rotor lamination package is split in two and if each part is shifter of half a stator slot pitch

**Rotor herringbone-skew**

- Herringbone skew balances axial magnetic forces but increases cogging torque compared to straight skew [E58]
Skewing (PMSM)

**Stator skew**

- Stator skew is necessarily continuous
- For **stator slot skew** the skew angles minimizing the n-th harmonic of wavenumber 0 at LCM (Zs,2p)fR is also in open circuit

\[ \alpha_{sSk} = \frac{2\pi}{nLCM(Z_s,2p)} \]

- This skewing value is therefore optimal for the cancellation of cogging and radial force harmonics of order 0, but **not necessarily for radial force harmonics of order 2**

**Stator herringbone-skew**

- Herringbone skew balances axial magnetic forces but increases torque ripple compared to straight skew [E57]
• Skewing cannot fully damp radial force harmonics of wavenumber 0 independently of current angle
• For large values of $\gamma$ (in the field weakening range with $\text{id}<0$) the effect of skew decrease
• Skew is efficient for low current magnitude due to a phase change of the force to be damped

Figure 4.15: Amplitudes of the most significant multiples of $f_m$ for the shape 0 air-gap force for the unskewed and skewed machine

[C24]
To damp a given force wave the number of steps of the stepped skew is important.

The optimal skew depends on the load state, so ideally the skew should vary with the load.
Skewing (SCIM)

- Skewing can be done after lamination stacking or during the stacking process.
- Skewing has two effects that can change magnetic forces: reducing the high frequency rotor current magnitude due to impedance increase, and shifting the flux waves linked to rotor slotting.
- The first effect is related to load, the second not.
- Herringbone skew avoids (m,1) excitation and balances axial magnetic forces.
- Any skew shape with axial symmetry cancels axial magnetic forces.

\[ dF = i dl \wedge B \]
Pole magnetization (SM)

- Magnetization patterns allow to «tune» the rotor mmf harmonic content and thereof the vibroacoustic behaviour.
- Hallbach or sinusoidal configuration lower the spatial harmonic content of mmf.
- Sometimes the shape of magnetization itself is optimized.

From [E10] [US7902707 B2]
Pole shaping (SM)

- Magnet / pole shoe shaping [E11] allows to «tune» the rotor mmf harmonic content and thereof the vibroacoustic behaviour.

- As both constructive and destructive interference occurs, cancelling a given magnet mmf space harmonic responsible for acoustic noise does not necessarily reduce noise as it can increase other force harmonics.

- For wound rotor synchronous machines the pole arc curvature has large influence on noise [E40].

- Due to the combined effect of radial and tangential forces on radial vibrations and noise, a full electromagnetic and vibration simulation is necessary.
Pole width and position (SM)

- The pole width can be modulated to tune the mmf spectrum content
- Some different pole widths or pole positions (pole shifting technique) can also be used

- Optimal pole arc to pole width to reduce 0-th order radial and tangential open circuit forces (applicable to both SPMSM and IPMSM) [E8, E9]

\[
\alpha_{p,k_2} = \frac{k_1}{N_c/(2p)} = \frac{N_c/(2p) - k_2}{N_c/(2p)} \quad k_2 = 1, 2, \ldots, N_c/(2p) - 1
\]

- Due to fringing fields this theoretical value must be slightly increased
- This gives generally small pole arc width thus a compromise with torque must be found
- This value is for radial magnetization and depends on the magnetization type and magnet shape
• This result can also be found by expressing the magnetic field in Fourier series without slots:

\[
B_g^m(t, \theta) = \sum_{n=-\infty}^{\infty} B_{gn}^m e^{-jpn(\psi + \Omega m t - \theta)} \quad B_{gn}^m = \frac{\hat{B}_g}{n\pi} \left(1 - \cos\left(n\pi\right)\right) \sin\left(n \cdot p \cdot \frac{\beta_m}{2}\right) \frac{2}{1 + (a \cdot n \cdot p)^2}
\]

• \( r=0 \) forces are created by magnet mmf harmonics \( Nc+p \) and \( Nc-p \) so the optimal cancellation value is given by \( n \cdot p = Nc \rightarrow Nc*\beta m/2 = k1*\pi \)
Other pole displacement techniques can reduce cogging torque and zero-th average radial force:

- Radial pole-pairing technique (association of two different pole shapes to cancel a given harmonic)
- Axial pole pairing technique

![Diagram of radial pole-pairing technique](E28)

![Diagram of axial pole pairing technique](E30)
Slot and tooth shape / position (IM)

- Stator and rotor slot shapes or positions can be modulated to spread the permeance spatial spectrum or reduce / cancel a specific harmonic involved in noise and vibration generation.
- Several techniques exist:
  - Use of pairs of slot shape parameter or position.
  - Random variation of a slot shape parameter or position.
  - Sinusoidal variation of a slot shape parameter or position.
- Assymetrical rotors can lower the slotting magnetic forces (ex -7dB according to [E33]) and reduce synchronous parasitic torque [E34].
- The technique can also create new force harmonics and increase the noise & vibration level.
Slot and tooth shape / position (SM)

- Stator slot shapes or positions can be modulated to spread the permeance spatial spectrum or reduce / cancel a specific harmonic involved in noise and vibration generation.
- Slot-pairing (teeth pairing) techniques can reduce cogging and average radial forces by cancelling the first component only at $\text{LCM}(Z_s,2p)f_R$.

$$\theta_d = \frac{(2k+1)\pi}{\text{lcm}(N_s/2,2p)}, \quad k = 0,1,2...$$

From [E29]  
From [E13]
- Stator tooth tip width modulation

![Stator tooth tip width modulation diagram](E35)

Fig. 2. Sketch of PM motors with nonuniformly distributed teeth.

- Stator tooth tip chamfers

![Stator tooth tip chamfers diagram](E73)
Notches (generalities)

- Notches (sometimes called circumferential slits, auxiliary slots or windows) modulate the airgap permeance.
- If properly sized, it can artificially increase the permeance wavenumber, as if the stator slot number was increased.
- The average airgap is increased due to notches (increase of Carter coefficient) so it may slightly reduce the electromagnetic performances.
- The introduction of notches can increase the local saturation level.
- Similarly to skewing, the effect of notches can strongly depend on the operating point.
Notches (SM)

- Auxiliary slots or notches at tooth tips [E26] can reduce cogging torque and averaged radial force.

1) The relation of the number of notches $N_n$ is related to the number of teeth $N_p$ during a rotation of motor tooth, i.e., $N_p$. The best choice is obtained with $N_p ((N_p + 1), (N_p) = 1.0$.

2) Consequently, the equality $N_p ((N_p + 1), (N_p)$ has to be avoided, since it produces an increase of all of $N_p$ harmonics. For example, let us refer to the rotor of Fig. 10, which have $2p = 52$ and $(p') = 8$, thus $N_p = 2$. Since only harmonics of second order exist, the choice $N_p = 1$ implies that two identical $\tau_{cog}$ currents are summed together. The cogging torque amplitude duplicate, obtaining no improvement. On the contrary, $N_p = 2$ means that and the result of Fig. 10 is obtained.

3) An effective reduction of the cogging torque is obtained only if the harmonics excited by introducing the notches are the highest ones. As an example, Fig. 12 shows the cogging torque of a $2p = 6, 2 = 4$ motor without notches (thin line) and with $N_p = 1$ teeth in each main tooth (bold line). Since the $\tau_{cog}$ of the assessment state (present a high amplitude of the second-order harmonic), the effect of $N_p = 1$ is only to reduce the frequency twice, without reducing the amplitude of the resulting $\tau_{cog}$.

- [E72] shows that UMP can be reduce by notches on stator tooth tips but the reduction depends on the load state.
Exemple in MANATEE software of a 48s6p IPMSM
• Notches can also be applied on the rotor side on IPMSM

• [E41] shows that notches along q-axis are the most efficient to reduce torque ripple and radial forces
Example of 48s8p IPMSM traction machine in open circuit (MANATEE simulations)
Notches (IM)

- Rotor notches [E50] can reduce vibration and noise
Optimal slot opening (generalities)

- The permeance harmonics are due to reluctance variation along the airgap, and slotting effects are a source of permeance harmonics at multiples of slot number.

- Slot to tooth opening ratio can reduce some of the permeance harmonics (similarly to pole pitch to pole arc ratio for the rotor mmf), but it is influenced by saturation and sometimes several slotting harmonics are involved in noise generation.

- If the first stator slot harmonic \( (k_s=1) \) is responsible for a force wave in a machine - ex: PMSM with \( Z_s=12 \) and \( p=5 \), a harmonic force exists with \( r=(1*Z_s-1*p)-(0+1*p)=2 \) - closing the slot will cancel the permeance harmonic.

- In practice slots cannot be geometrically closed due to winding process (a minimum slot opening is often required to pass needle and strand, or to use tooth tip as a support for winding) and magnetically closed due to saturation.
Optimal slot opening (generalities)

- The theoretical value of the slot opening to cancel a stator or rotor permeance harmonic is given by [E60]

\[
F_{\text{slot}} \propto P_s P_r \propto \frac{\sin(\pi k_r s l_r)}{k_r} \frac{\sin(\pi k_s s l_s)}{k_s}
\]

\[
b_r = \tau_r \left(1 - \frac{i_0}{k_{r0}}\right), \quad i_0 \in [1, k_{r0} - 1]
\]

\[
b_s = \tau_s \left(1 - \frac{j_0}{k_{s0}}\right), \quad j_0 \in [1, k_{s0} - 1]
\]

- In particular a slot opening to slot pitch ratio of 1/2 cancels all even harmonics of the permeance
- This means that reducing the slot opening does not necessarily reduces magnetic noise & vibrations
Optimal slot opening (IM)

- Example of a squirrel cage induction machines [E60]
Optimal slot opening (SM)

- Example $Z_s=6$ $p=2$, radial force of order 0 at $\text{LCM}(Z_s,2p)f_R=6f_s$ due to slotting $\text{LCM}(Z_s,2p)=12$-th harmonic (second stator slotting harmonic), the optimal stator slot openings are given by

$$\alpha_{\text{opt}} = \frac{2\pi}{Z_s} \left(1 - \frac{i Z_s}{\text{LCM}(Z_s,2p)}\right) \quad i=1. \frac{\text{LCM}(Z_s,2p)}{Z_s} - 1$$

- For distributed winding it gives a null optimal slot opening -> cogging torque and pulsating radial forces cannot be cancelled by an optimal choice of the slot opening

Manufacturing ++
Radial ripple / cogging torque --

Manufacturing --
Radial ripple / cogging torque ++
• The 12th harmonic force is linked to the fourth stator slotting harmonic so there are twice more slot opening optimal values: the higher is the rank of the cogging / radial force harmonic, the higher is the number of optimal solutions.
• Example of slot opening optimization of outer rotor PMSM [E62]

• Example of slot opening optimization of 9s6p PMSM [E63]

Nominal opening = 4 mm
8f due to 3Zs
14f due to 5Zs
Magnetic wedges

- Magnetic wedges allow to reduce the magnetic reluctance change in the slot opening, reducing flux density slotting harmonics and therefore cogging torque and all magnetic force harmonics related to permeance harmonics
- Due to low relative permeability of commercial wedges (max 10) the effect on noise is limited (max 3 dB)
Control (SM)

- $I_d$ or $I_q$ or load angle has a strong influence on average magnetic force magnitude [E1]
- The load angle can influence the magnitude of higher time harmonics of 0 order tangential & radial forces [E15]
- The load angle evolution of force harmonics depends on their frequency and spatial order [E12]
- $I_q$ changes both the 0-th order radial and tangential force harmonics (torque), $I_d$ changes only the 0-th order radial force harmonics [E1] [E19] [E20]
- Negative $I_d$ can reduce the 0-th order radial force, while $I_q$ can only increase the 0-th order radial force [E1]
- Field weakening (negative $I_d$) can reduce 0-th radial force ripple [E53] but increases tangential force ripple [E54]
- $I_h$ does not contribute to radial force production [E53]

From [E12]

0-th order of tangential & radial force [E1]

$$F_t = \frac{3P\pi}{8\mu_0} \left( \sum_k B_{cpm} K_{1m} + \sum_k B_{ypm} K_{2k} \right) e_{pq} R + F_r(\theta_r)$$

$$F_r = \frac{P}{4\mu_0} \left\{ \frac{9}{4} \sum_{k,k\neq 3,9,15} \left( B_{cpm}^2 - B_{ypm}^2 \right) e_{pq}^2 e_{qr} + \pi \sum_k \left( B_{cpm}^2 - B_{ypm}^2 \right) e_{pq} \right\} R + F_r(\theta_r)$$
• In [E19] negative $I_d$ reduces the $\{2p, 2f_s\}$ component but increases the $\{0, 6f_s\}$ component in an interior PMSM.

• In [E45] negative $I_d$ cancels the $r=2$ force wave due to slot/pole interaction in a $Z_s=12$ $p=5$ SPM SM but the technique is only effective at low $I_q$ current.
• BLDC motor commutation is sensitive to position sensor accuracy, errors on commutation times increase speed ripple and magnetic noise & vibrations

• A higher number of pole pairs makes it more difficult to have high position accuracy

• Field Oriented Control (FOC) or sine-wave gives lower current harmonics compared to 6-step / block commutation

Table 2. Characteristics of commutation methods for the BLDC motor and PMSM

<table>
<thead>
<tr>
<th>Commutation Methods</th>
<th>Speed Control</th>
<th>Torque Control</th>
<th>Required Feedback Devices</th>
<th>Algorithm Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Speed</td>
<td>High Speed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trapezoidal</td>
<td>Excellent</td>
<td>Efficient</td>
<td>Hall</td>
<td>Low</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>Excellent</td>
<td>Inefficient</td>
<td>Encoder, Resolver</td>
<td>Medium</td>
</tr>
<tr>
<td>FOC</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Current Sensor, Encoder</td>
<td>High</td>
</tr>
</tbody>
</table>
• BLDC (square current) Vs BLAC (sine current): BLDC operation gives higher vibration and noise due to higher current harmonics

Fig. 10. Measured radial vibration spectrum of the prototype motor (1200rpm).

Fig. 11. Measured tangential vibration spectrum of the prototype motor (1200rpm).
Harmonic current injection (generalities)

- A given vibration harmonic can be compensated by injecting additional currents, depending on the spatial order to be cancelled.

- As the current modulates the spatial harmonics of mmf winding functions, the current injection cannot create new spatial orders than those already present in the magnetic forces.

- Current injection introduces new time harmonics and thereof new force harmonics (cf PWM lines), one must check that this does not worsen the vibration or noise level nor torque ripple.

- High frequency noise is more difficult to damp with current injection (requires higher controller bandwith & higher reactance can induce higher DC bus voltage).

- **Harmonic injection at** $nf_s$ **in DQH frame can damp r=0 pulsating harmonic force at** $nf_s$

<table>
<thead>
<tr>
<th>current</th>
<th>current</th>
<th>flux</th>
<th>force</th>
</tr>
</thead>
<tbody>
<tr>
<td>${(n+1)f_s}_{ABC}$</td>
<td>${(n+1)f_s, p}$</td>
<td>${(n+2)f_s, 2p}$ = parasitic force</td>
<td></td>
</tr>
<tr>
<td>${nf_s}_{DQH}$</td>
<td>${f_s}_{ABC}$</td>
<td>${f_s, p}$</td>
<td>${nf_s, 0}$ = damping force</td>
</tr>
<tr>
<td>${(n-1)f_s}_{ABC}$</td>
<td>${(n-1)f_s, p}$</td>
<td>${(n-2)f_s, 2p}$ = parasitic force</td>
<td></td>
</tr>
</tbody>
</table>
Harmonic current injection (SM)

- For synchronous machines, the 0-th order radial / tangential force waves magnitude at frequencies proportional to $\text{LCM}(Z_s,2p)f_s/p$ can be damped using current injection \[E15\]

- Ex: $Z_s=60$ $p=5$ $\text{LCM}(Z_s,2p)/p=12$, the 12-th time harmonics of torque ripple (and $m=0$ radial force) can be damped by harmonic current injection at $12f_s$ in Park frame

- For radial force damping either $i_d$ or $i_q$ harmonic injection theoretically works

- In \[E19\] $6f_s i_d$ harmonic injection successfully reduces the radial vibration, without significant change of torque ripple

- $6f_s i_q$ harmonic injection successfully reduces the radial vibration, but increases torque ripple at $6f_s$
Switching strategies - generalities

- Voltage inverter switching strategies fix the voltage harmonic content
- Voltage harmonics contain harmonics linked to the switching frequency ($f_{swi}$, $2f_{swi}$) and harmonics linked to fundamental (ex: 5f, 7f)
- A voltage harmonic $f$ creates a harmonic current $f$ which generate magnetic forces \{f+$f_s$, 2$p$\} and \{f-$f_s$, 0\}
- The sign of the harmonic $f$ (rotation direction of the harmonic voltage compared to fundamental) is important
- Voltage harmonic rates also depend on dead times, voltage drop, non linear behaviour of IGBTs
- Increasing the switching frequency generally reduces the acoustic noise (dBA reduction above 2.5 kHz), in some cases it can be chosen out from human’s ear sensitivity

[E23]
Switching strategies – spread spectrum strategies

- Spread spectrum principle (cf blades in fans, or slots in electric machines)
- Deterministic (sinusoidally modulated PWM) or stochastic strategies (random PWM)
- Random strategies consists in a stochastic variation of one PWM parameter (e.g. pulse width, pulse position)
- They spread the spectrum: lower exciting forces but wider excitation spectrum
- In some cases this can lead to lower or higher noise depending on damping and natural frequency position with respect to exciting forces
- RPWM can also be heard as unpleasant
Structural response (passive techniques)

- Lower noise & vibration can be achieved by putting the natural frequencies further away from the excitations.
- The yoke can be stiffened to reduce vibration and noise levels; in this case one must check that the natural frequency change due to the yoke geometry change does not compensate the noise & vibration reduction due to yoke stiffening.
- The m=0 circumferential order behaves differently compared to m>1.

\[
\begin{align*}
\omega_0 & \propto \left( \frac{E}{\rho} \right)^{1/2} R^{-1}, \\
\omega_m & \propto \left( \frac{E}{\rho} \right)^{1/2} \frac{h}{R^2} m^2,
\end{align*}
\]

\[
\begin{align*}
U_{0w} & \propto F_{0w} \frac{1}{E h} R, \\
U_{mw} & \propto F_{mw} \frac{1}{Em^4} \frac{R^3}{h^3}, \\
L_{0w} & \propto 20 \log \left( \frac{R}{h} \right), \\
L_{mw} & \propto 20 \log \left( \frac{R^3}{h^3} \right).
\end{align*}
\]
• External diameter change with fixed yoke height (effet of stiffness change and radiating surface change):

(Study under MANATEE software)

• Yoke height change with fixed external diameter (effet of stiffness change only):
• Yoke height change together with external diameter (effect of stiffness and radiating surface change):

![Graph showing noise change vs yoke height change](image)
• Effect of an external diameter increase with yoke increase on the breathing mode natural frequency (m=0):

![Graph](freq_v_stator.png)

- Mode 0

• Depending on (h/R) ratio the breathing natural frequency can be very sensitive or not at all to yoke height increase
• Play on the yoke geometry itself

• Change the number of couplers between frame and lamination to play on mode spatial aliasing

• Convert radial vibration in tangential vibrations (breaking impedance concept)
• Use of structural spacers [E65]
• Use of higher damping magnetic sheets

• Addition of damping materials between laminations
Summary of most important design parameters (SM)

At design stage:
- Winding type: distributed winding preferred
- GCD(2p, Zs): high value preferred (sufficient but not necessary)
- Stator slot opening: can be chosen to minimize noise & vibrations
- Magnet shape (V-shape angle, pole arc to pole pitch ratio, flux concentration radius): can be chosen to minimize noise & vibrations
- Control of all symmetries during production & assembly (eccentricities, airgap shape)

After manufacturing (if the machine is noisy)
- Apply skewing (value to be optimized at the noisy operating point)
- Introduce notches
Summary of most important design parameters (IM)

At design stage:
- GCD(2p, Zr, Zs): high value preferred (sufficient but not necessary)
- Avoid RSH
- Avoid skewing
- Control of all symmetries during production & assembly (eccentricities, airgap shape)

After manufacturing (if the machine is noisy)
- Change Zr
- Apply skewing
- Introduce notches / optimize slot opening
Noise mitigation of inductors / transformers

- Reduction of winding vibrations:
  - varnishing, gluing, potting
  - reduction of magnetic leakage field (smaller airgaps but more airgaps, increase distance from winding to core)

- Reduction of magnetostriction in magnetic cores:
  - change material type to lower magnetostrictive coefficients
  - reduction of steel sheet prestress
  - reduction of column height

- Avoid match between magnetic forces & structural modes

- Spread spectrum strategies of ripple currents

- Destructive interference of magnetostrictive & Maxwell forces in inductors by playing on airgap
  Young modulus / core dimensions / number of airgaps
Noise mitigation of passive components

• Change of magnetic core topology