Acoustical Analysis of an Induction Motor

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CADFEM Elektromagnetik Technologietage 2021

Gekoppelte Simulation

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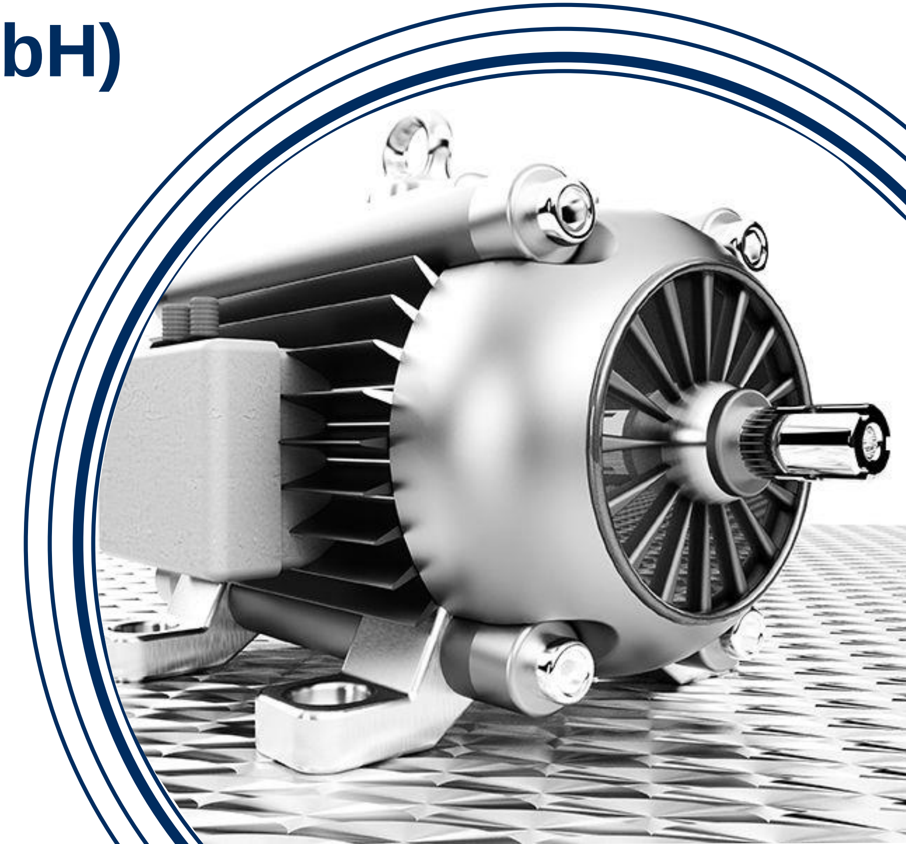

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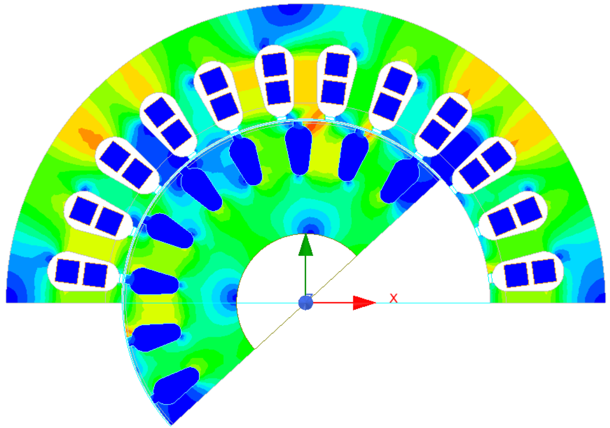
Outline

1. General NVH Analysis Procedure for E.-motors
2. Periodic Intervals
3. Case Study A: Using a Periodic Interval
4. Case Study B: Using a Non-periodic Interval
5. Case Study C: Applying a Window Function
6. Summary



1. General NVH Analysis Procedure for E.-motors

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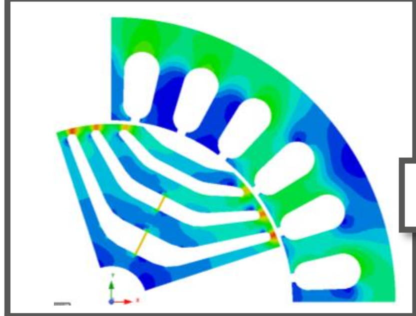
Generating Vibration and Noise Spectra

Time domain,
transient analysis type

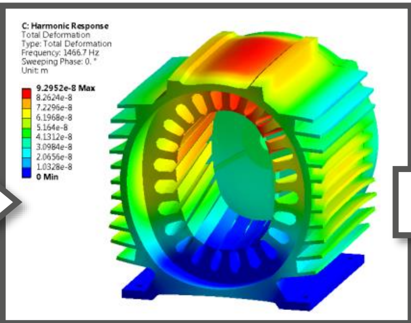
Frequency domain,
harmonic analysis type



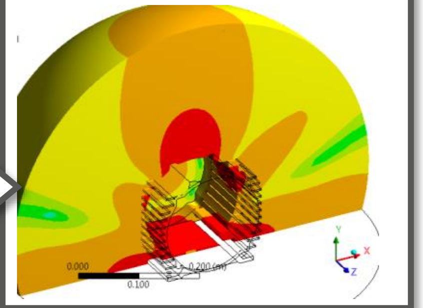
Electromagn. Anal.

Gap forces

DFT



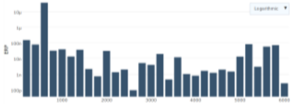
Vibration Analysis

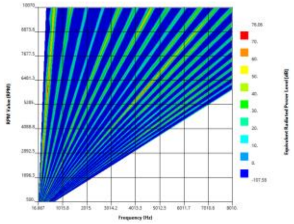


Acoustical Analysis

Question: Feed DFT with *periodic* or *non-periodic* sample window?

Equ. Radiated Power, P_{ERP}

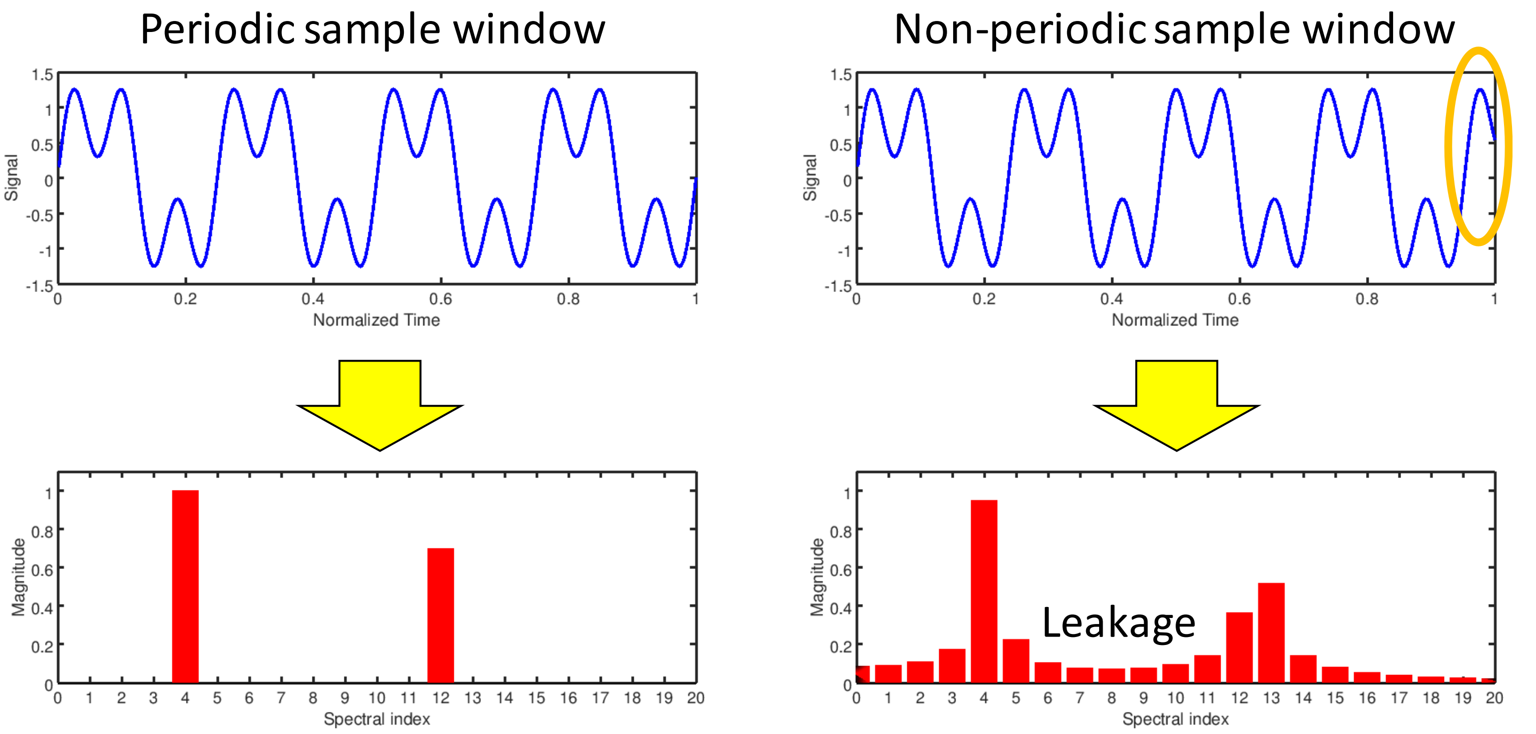




1. General NVH Analysis Procedure for E.-motors

Non-periodic Intervals of Gap Forces ➔ Leakage Effect

- Time domain:
- Frequency domain:

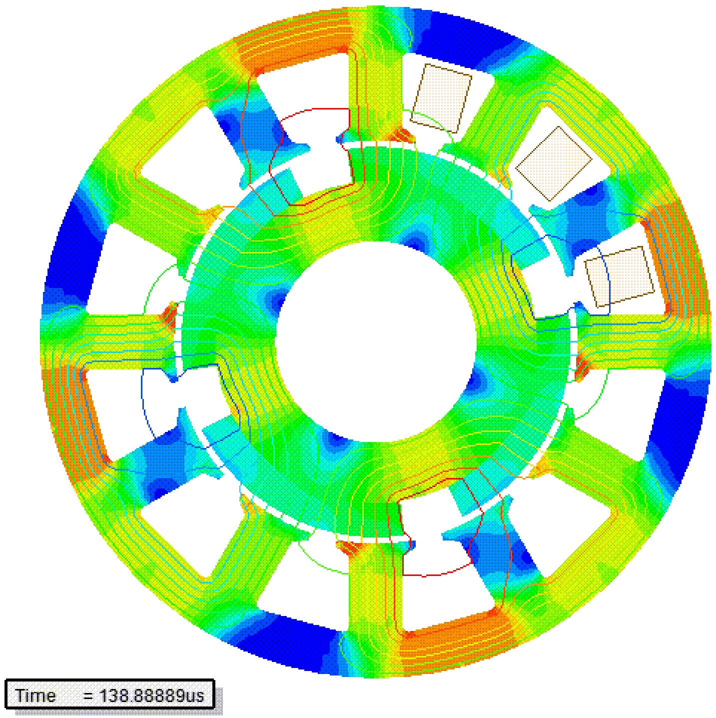


2. Periodic Intervals
Synchronous Motors

- Rotor speed = Speed of stator field

$$n = \frac{f_{el}}{p}$$

n in [s^{-1}]
p … pole pairs



- Electromagnetic fields are always periodic within an electrical period $T_{el} = 1/f_{el}$.
- Gap forces are periodic within $T_{el}/2$ (*), i.e. lowest possible excitation has a frequency of $f_1 = 2f_{el} = 2p \cdot n$.

(*) Half electrical period because forces are proportional to squared magnetic flux density and show therefore *two* periods within *one* electrical period.

2. Periodic Intervals
Synchronous Motor

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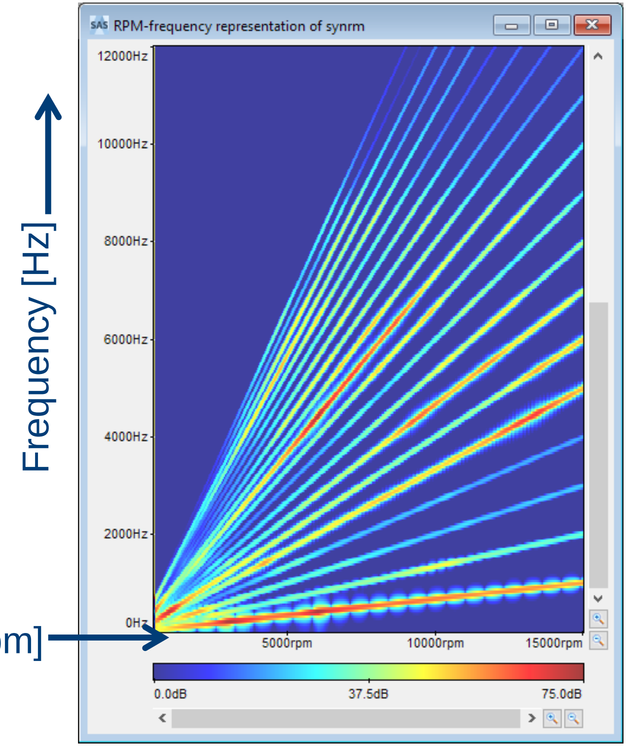
Waterfall diagram:

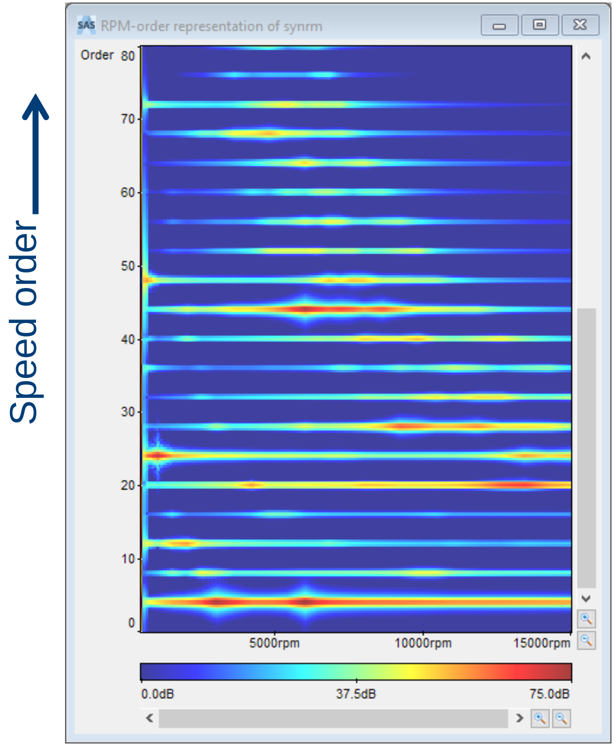
- Due to the synchronous principle excitation fre-quencies (f_1, harmonics f_2 , f_3, …) are proportional with speed.

$k_i = f_i/n$ = "speed order"

ERP-Level



ERP-Level



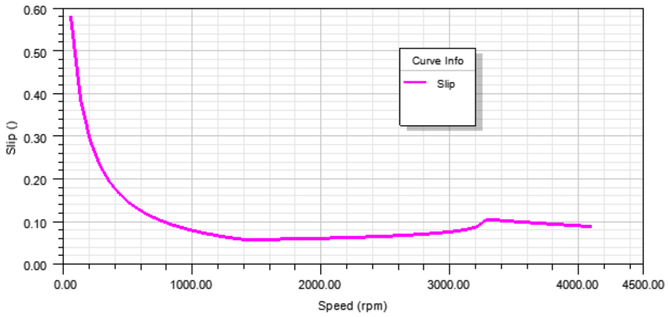
2. Periodic Intervals
Induction Motor

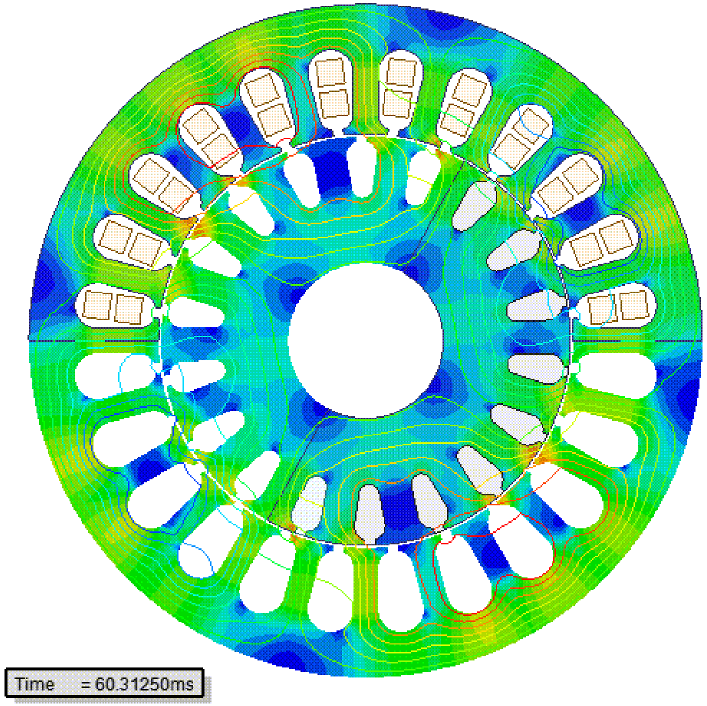
- Rotor speed < Speed of stator field

$$n = \frac{f_{el}}{p} \cdot (1 - s)$$

n in [s^{-1}]
p … pole pairs
s … slip [0…1]

- Due to slip periodic conditions are not found within T_{el} or $T_{el}/2$.
- Slip is a function of speed, $s = s(n)$:





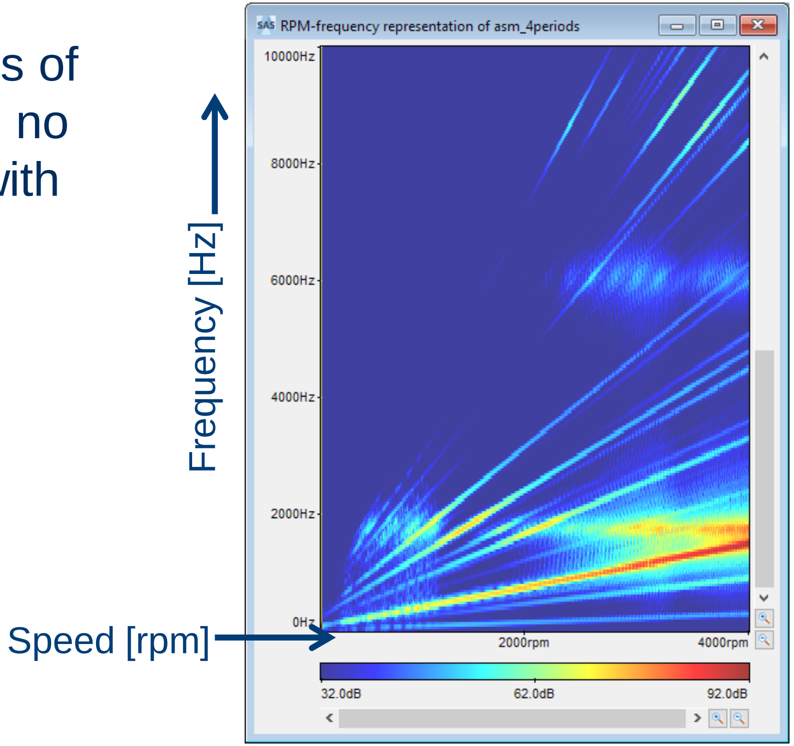
2. Periodic Intervals
Induction Motor

<u>Waterfall diagram:</u>

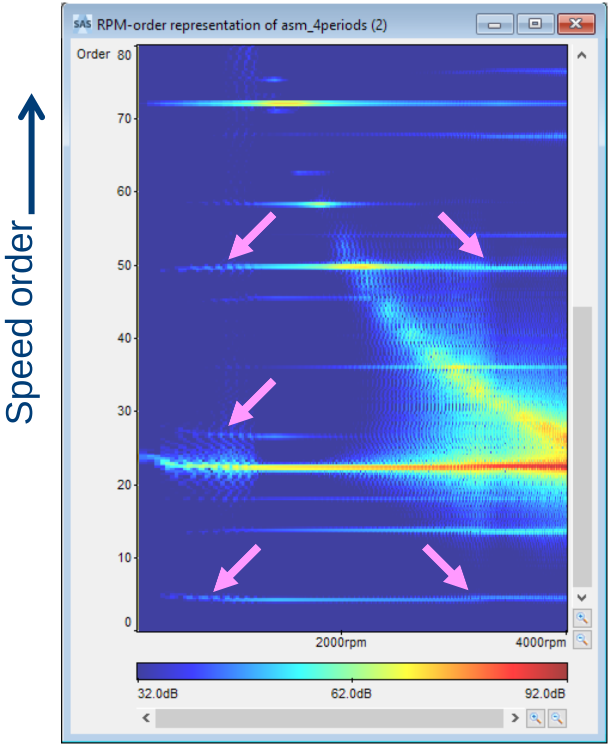
- If $s = s(n)$ frequencies of some excitations are no longer proportional with speed.

  ➔ $k_i = f_i/n \neq$ const.

ERP-Level



ERP-Level



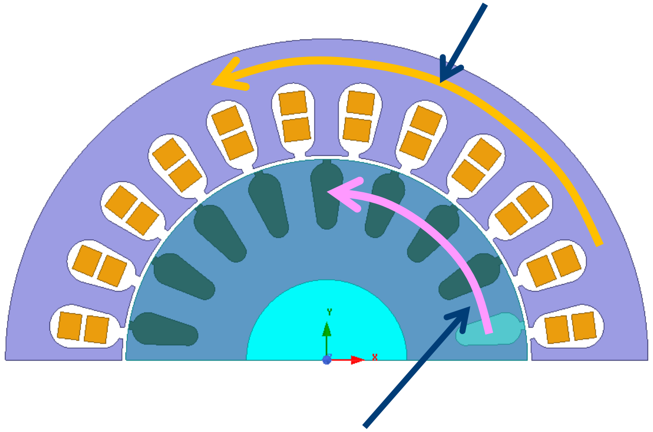
2. Periodic Intervals

How to Find a Periodic Interval of an Induction Motor?

- Periodic intervals for an induction motor can be found for discrete combinations of electrical periods and rotation angles:
- A periodic interval must contain both
  - an integer number of a half electrical periods (i.e. the stator field rotates by an integer number of stator poles) and
  - a rotation by an integer number of rotor slot divisions.
- This ensures at the stator:

  Forces at end = Forces at start of the interval

- The discrete combinations result in *discrete slip values*.



2. Periodic Intervals

Existing for Discrete Slip Values Only!

- Speed:

$$n = \frac{f_{\mathrm{el}}}{p} \cdot (1 - s)$$

- Slot rotation at $s = 0$: (synchronous speed)

$$n_{\mathrm{slot,sync}} = \Delta t \cdot n \cdot N_{\mathrm{rotor}} = \Delta t \cdot \frac{f_{\mathrm{el}}}{p} \cdot N_{\mathrm{rotor}} = \frac{n_{\mathrm{elHP}} \cdot N_{\mathrm{rotor}}}{2p}$$

- Discrete slip values:

$$s = 1 - \frac{n_{\mathrm{slot}}}{n_{\mathrm{slot,sync}}} = 1 - \frac{n_{\mathrm{slot}} \cdot 2p}{n_{\mathrm{elHP}} \cdot N_{\mathrm{rotor}}}$$

- Minimum possible slip steps at given n_{elHP}: (for $n_{\mathrm{slot}} = n_{\mathrm{slot,sync}}$, $n_{\mathrm{slot,sync}}-1$, $n_{\mathrm{slot,sync}}-2$, …)

$$\Delta s = \frac{2p}{n_{\mathrm{elHP}} \cdot N_{\mathrm{rotor}}}$$

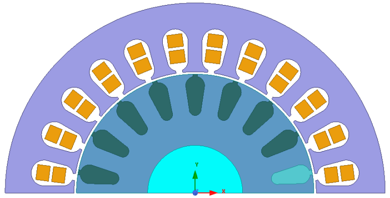
n	… rotational speed
f_{el}	… electrical frequency
s	… slip
p	… no. of pole pairs
N_{rotor}	… total no. of rotor slots
n_{elHP}	… no. of *half* electr. periods
n_{slot}	… rotated slots within Δt
$n_{\mathrm{slot,sync}}$	… rotated slots within Δt at *synchronous* speed

$$n_{\mathrm{elHP}}, n_{\mathrm{slot}} \in \mathbb{N}$$

2. Periodic Intervals

Existing for Discrete Slip Values Only!

- Example motor: $p = 2$, $N_{rotor} = 18$



$n_{elHP} = 2$		$n_{elHP} = 3$		$n_{elHP} = 4$		$n_{elHP} = 6$	
n_{slot}	*s* [%]	n_{slot}	*s* [%]	n_{slot}	*s* [%]	n_{slot}	*s* [%]
8	11.11	13	3.70	17	5.56	26	3.70
7	22.22	12	11.11	16	11.11	25	7.41
6	33.33	11	18.52	15	16.67	24	11.11
5	44.44	10	25.93	14	22.22	23	14.81
$\Delta s = 11.11\%$		$\Delta s = 7.41\%$		$\Delta s = 5.56\%$		$\Delta s = 3.70\%$	

$\Delta s \sim 1/n_{elHP}$ ➔ High resolution of the *s*(*n*)-curve requires long intervals.

3. Case Study A: Using a Periodic Interval

ERP-result at a Single Operating Point

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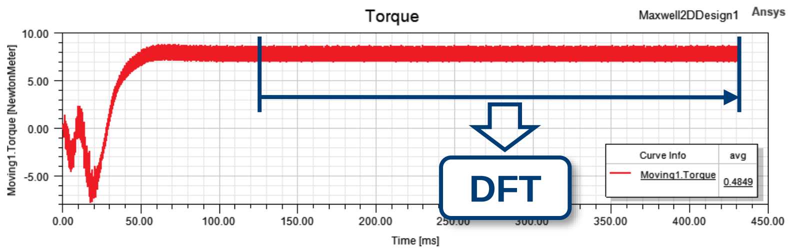
Motor Data, Given OP:

- p = 2
- N_{rotor} = 18
- n = 1400 rpm (23.333 rps)
- **s = 5.865%**
- f_{el} = 49.574 Hz

➔ No periodic interval which is practicable for simulation!

Adjust OP for Periodic Interval:

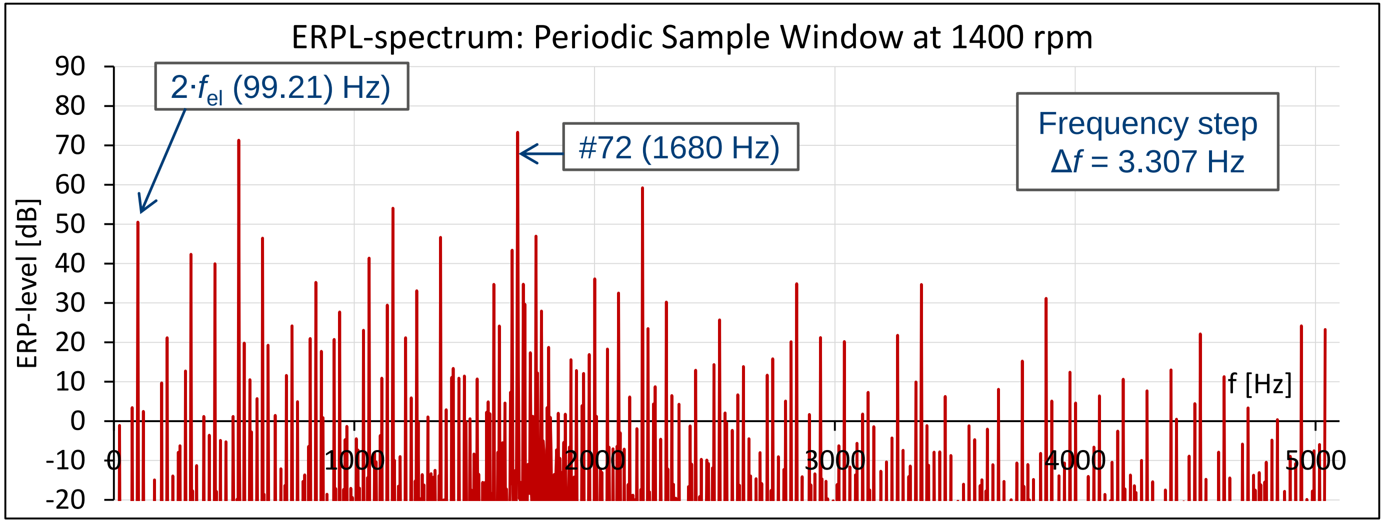
- Adjusted OP data:
  - n = 1400 rpm
  - **s = 5.926%**
  - f_{el} = 49.606 Hz
- found at periodic interval:
  - n_{elHP} = 30
  - n_{slot} = 127 (➔ 127/18 = 7.05556 rotor revs.)



3. Case Study A: Using a Periodic Interval

ERP-result at a Single Operating Point

- High quality spectrum w/o. leakage:

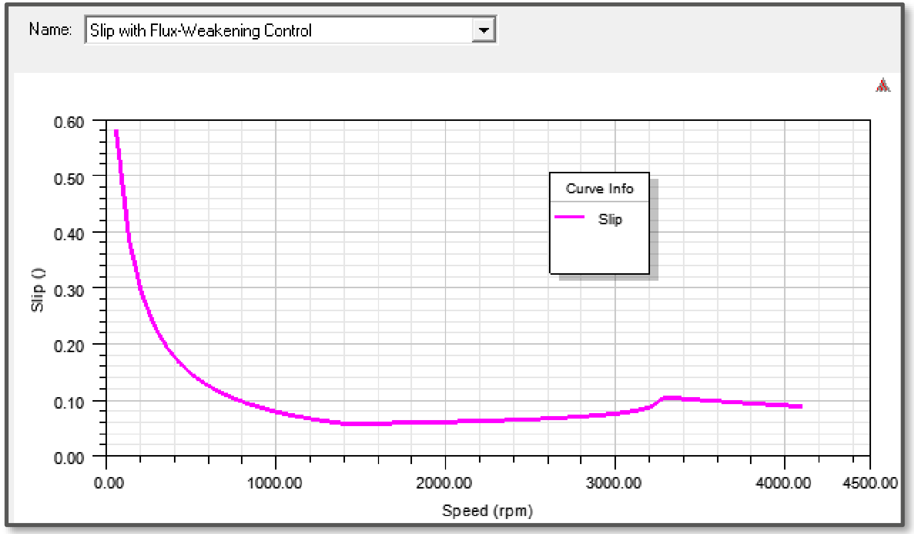


- 3048 time steps within periodic interval + additional steps to reach steady state
- Maxwell 2D runtime: ≈ 1 h

3. Case Study A: Using a Periodic Interval
Pro and Contra

- Pro:
  - Accurate spectrum
  - Good for a single or few selected OPs
- Contra:
  - Periodic intervals can be very long
    ➔ Simulation time!
  - Hard to produce a Waterfall diagram along continuous speed axis
    (*s* = *s*(*n*)
    ➔ Periodic interval changes along *n*!)

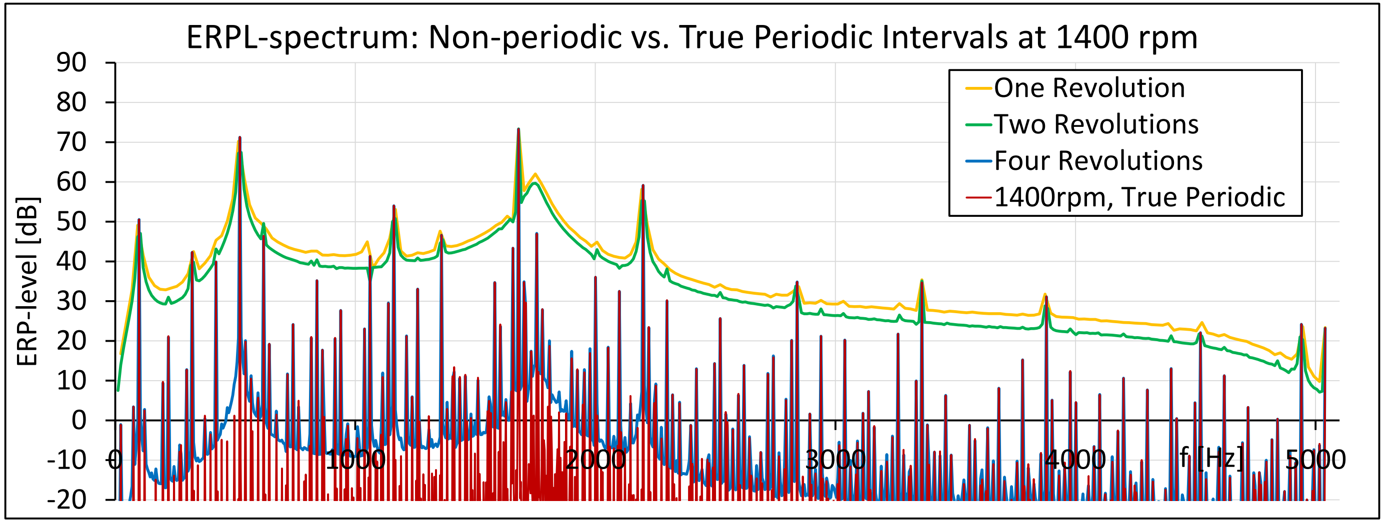
Given *s*(*n*)-characteristics



4. Case Study B: Using a Non-periodic Interval

ERP-result at Single Operating Point

- Spectrum showing leakage at sample windows of 1, 2 and 4 rotor revolutions:



- Leakage depends on length of sample window (sample window of 4 revolutions above coincidentally hits almost a periodic interval; 4 revs. won't be generally sufficient!)

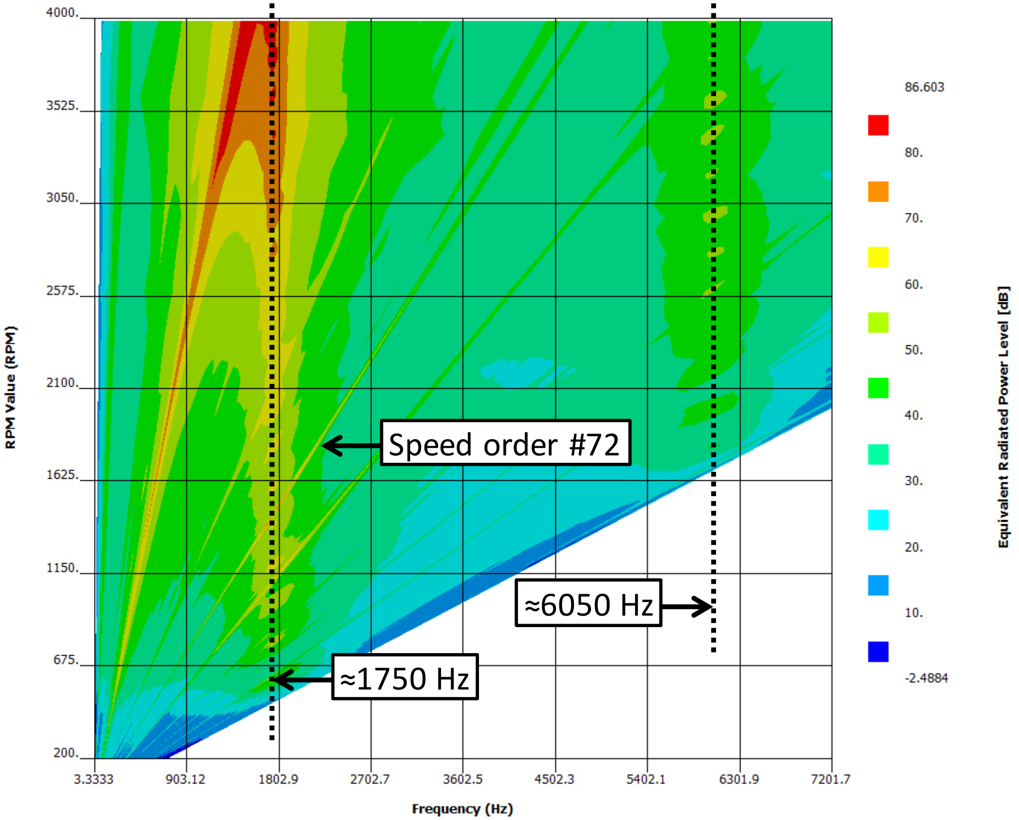
4. Case Study B: Using a Non-periodic Interval

Waterfall Diagram (ERP-level)

- Sample window length:

1 rotor revolution

(constant for all simulated speed points n = 200…4000 rpm)



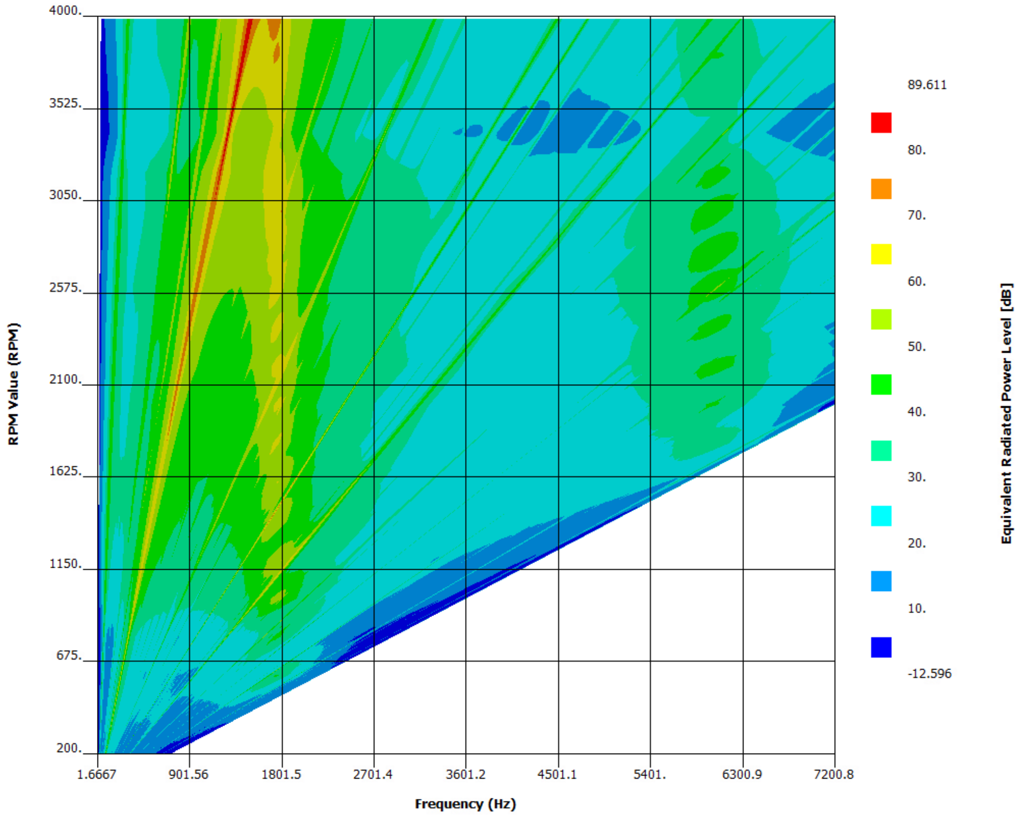
4. Case Study B: Using a Non-periodic Interval

Waterfall Diagram (ERP-level)

- Sample window length:

2 rotor revolutions

(constant for all simulated speed points n = 200…4000 rpm)



4. Case Study B: Using a Non-periodic Interval

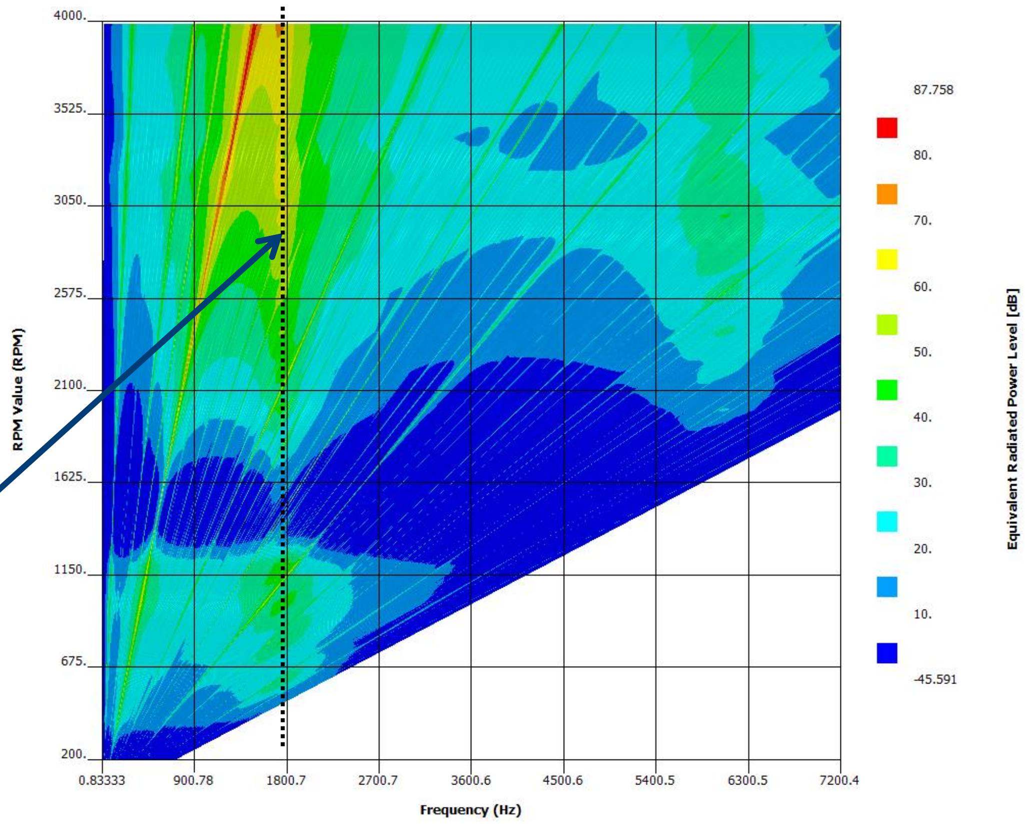
Waterfall Diagram (ERP-level)

- Sample window length:

4 rotor revolutions

(constant for all simulated speed points n = 200…4000 rpm)

Non-physical excitations by leakage disappear with increased length of the sample window.



5. Case Study C: Applying a Window Function

Treatment of Non-periodic Samples with a Window Function

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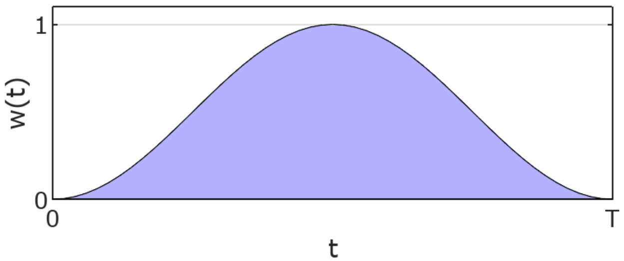
- e.g. Hann window:

$$w(t) = \frac{1}{2}\left(1 - \cos\frac{2\pi t}{T}\right)$$

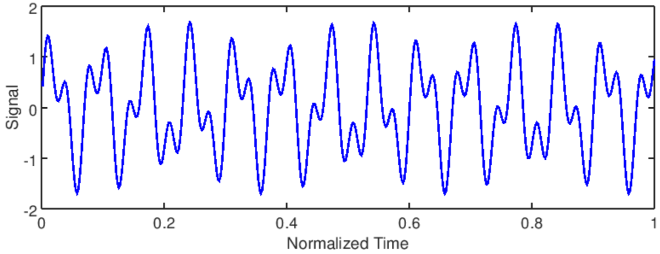
t = 0…*T* ➔ sampling window



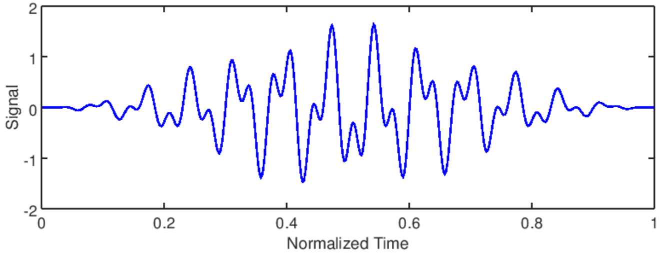
- Weighting the signal *f*(*t*) before DFT:

$$f^{(\mathrm{Hann})}(t) = f(t)\cdot w(t)$$

Original *f*(*t*)



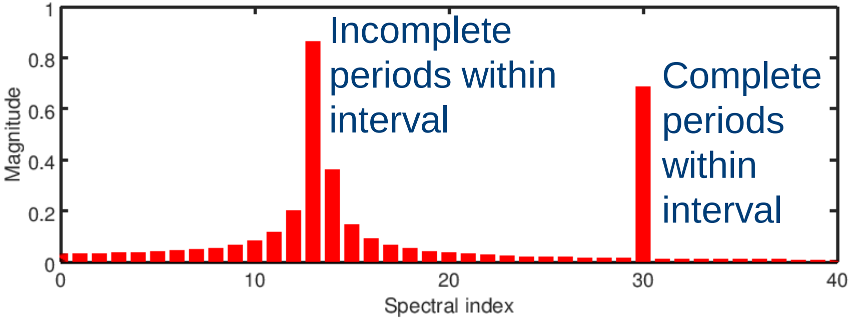
f(*t*)·*w*(*t*)



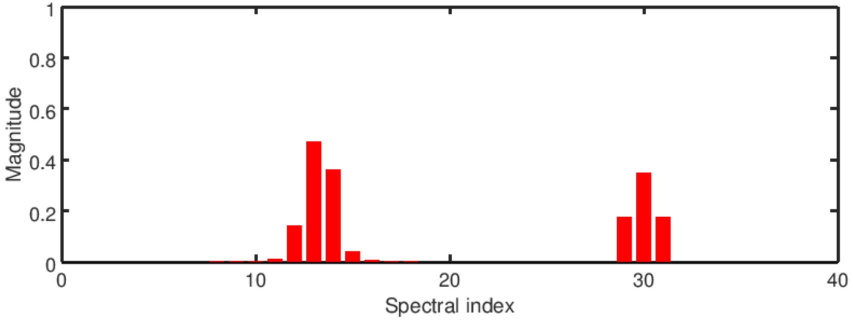
5. Case Study C: Applying a Window Function

Treatment of Non-periodic Samples with a Window Function

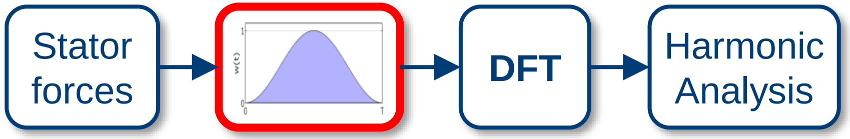
Without window function



Hann window applied



- Effects:
  - \+ Increases signal-to-noise ratio in excitations
  - − Reduces amplitudes
    (≈ factor 1/2 ≙ −6 dB for Hann window,
    ➔ Apply result correction of +6 dB!)
  - − Reduces spectral resolution

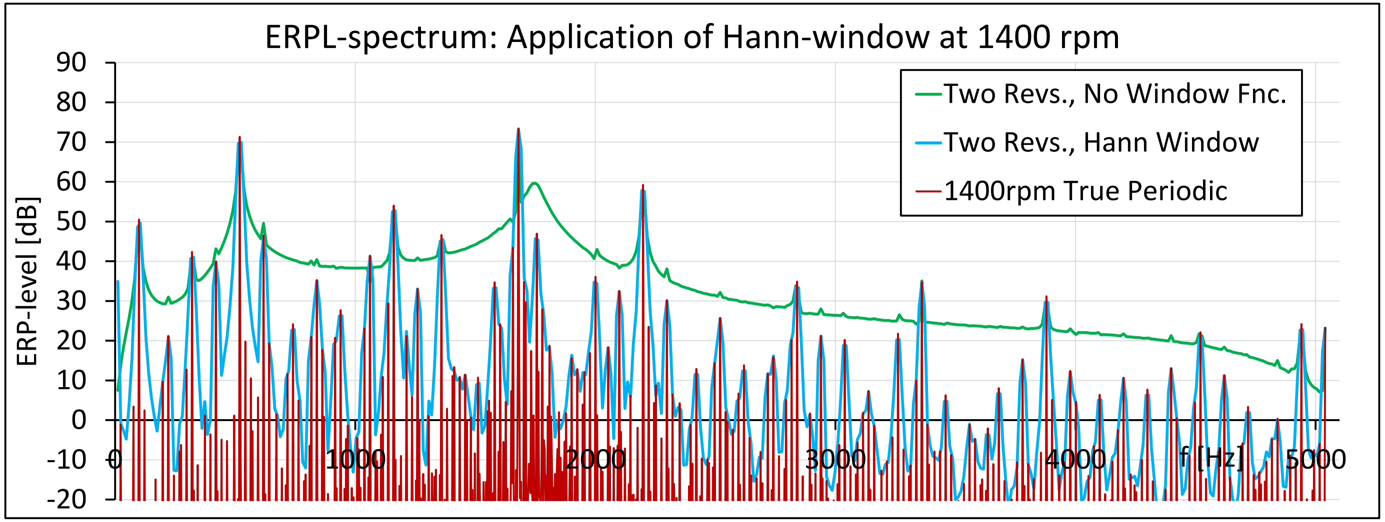


Promising for non-periodic intervals

5. Case Study C: Applying a Window Function

ERP-result with Hann Window Applied (Single Operating Point)

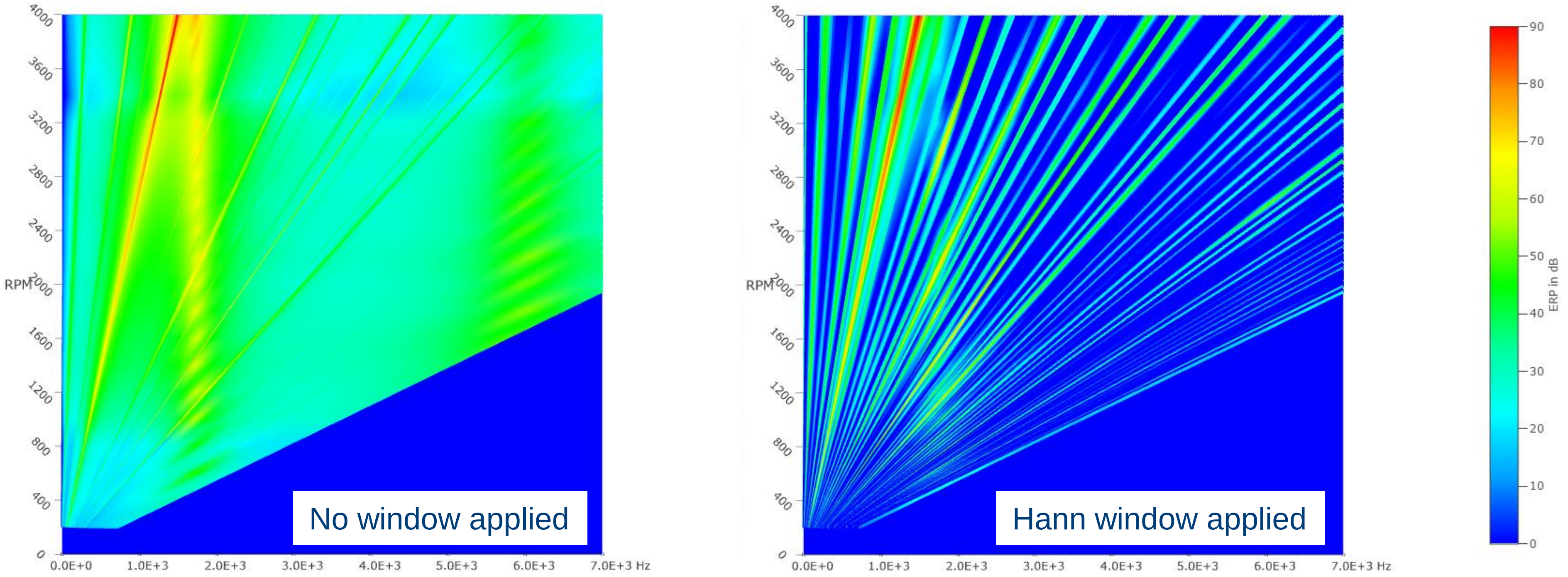
- Spectrum for sample window of 2 rotor revolutions, with correction of +6 dB:



- Strongly improved result quality at moderate size of sample window
- Remaining error < 2 dB at important signal levels!

5. Case Study C: Applying a Window Function
Waterfall Diagram with Hann Window Applied (ERP-level)

- Spectrum for sample window of 2 rotor revolutions, with correction of +6 dB:



(Comparison done using *E.D.A. inside ANSYS*)

6. Summary

- Slip of induction motors:
  - Long periodic time intervals for DFT, for discrete slip-values only
  - Not suitable for producing Waterfall diagrams
- Single operating points:
  - Adjust slip slightly to find a periodic interval
- Waterfall diagram (series of operating points):
  - Use non-periodic intervals
  - Application of window function returns strongly improved results