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MINISTRY OF EDUCATION,
YOUTH AND SPORTS

Selected Topics in Electrical Machines (KEV/VPS)

Diagnostics of electrical machines – MCSA, vibration diagnostics

Jan Šobra

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Diagnostics of electrical machines – MCSA, vibration diagnostics

- Nomenclature
- Diagnostics of electrical machines in general
- Motor current signature analysis (MCSA)
- Vibration diagnostics

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Nomenclature** *according to ČSN ISO 13372: Condition monitoring and diagnostics of machines - Vocabulary*
  - ***Fault*** = condition of a machine that occurs when one of its components or assemblies degrades or exhibits abnormal behavior, which may lead to the failure of the machine
    - A fault can be a result of a failure, but can exist without a fauilure
    - Planned actions or lack of external resources is not a fault
  - ***Failure*** = termination of the ability of an item to perform a required function
    - Failure is an event as distinguished from fault, which is a state
    - Failure is the manifestation of a fault
  - ***Condition monitoring*** = acquisition and processing of information and data that indicate tha state of a machine over time
    - The machine state deteriorates if faults or failures occur

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Nomenclature** *according to ČSN ISO 13372: Condition monitoring and diagnostics of machines - Vocabulary*
  - ***Diagnostics*** = examination of symptoms and syndromes to determine the nature of faults or failures (kind, situation, extent)
  - ***Symptom*** = perception, made by means of human observations and measurements, which may indicate the presence of one or more faults
  - ***Syndrome*** = group of signs or symptoms, that collectivelly indicate or characterize an abnormal condition
  - ***Sign*** = charakteristic parameter of the signal, which shows information about a state

Diagnostics of electrical machines – MCSA, vibration diagnostics

- Electrical machines are essential in following sectors:
  - Industry
  - Energy
  - Transportation

- Electrical machines lifespan depends on a perfect design and manufature as well as suitable operating conditions and maintenance

- Well-timed diagnostics avoids failures

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Main reasons for electrical machine diagnostics**

- Safety
  - Health risk, property protection and environment
- Reliability
  - Unexpected down-time elimination
  - Optimal machine operation
- Predictive maintenance
  - Smaller number of spare parts in stock
  - Maintenance interval prolonging

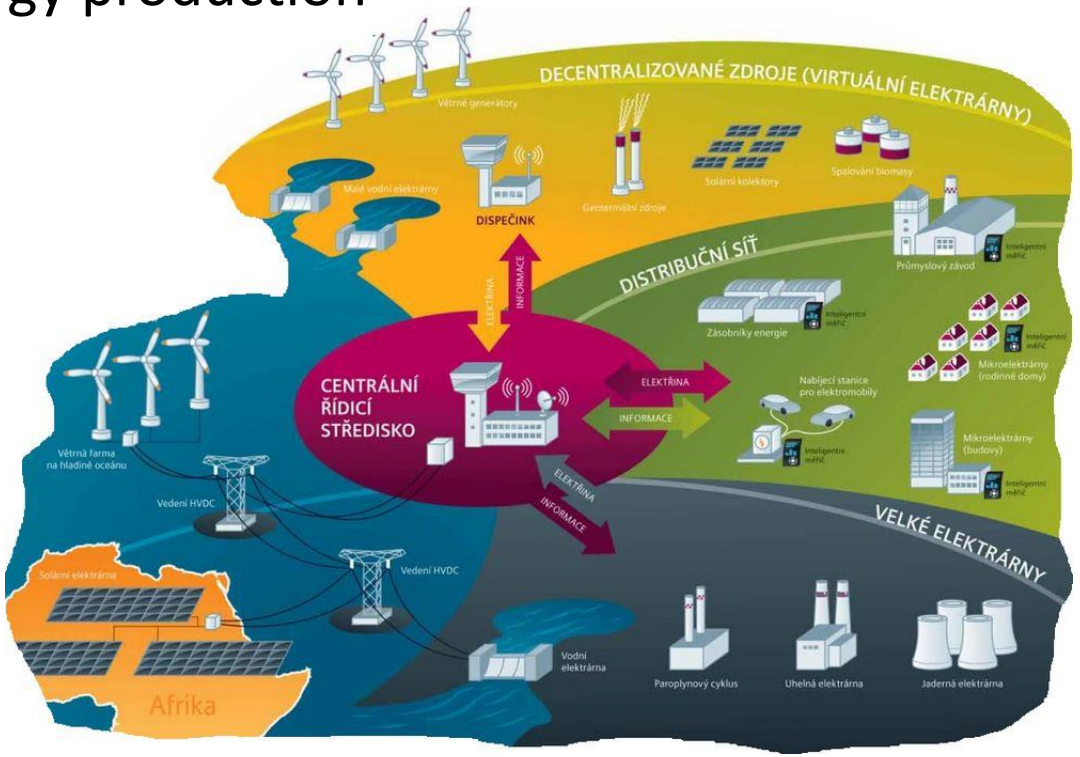


Economic losses

Diagnostics of electrical machines – MCSA, vibration diagnostics

- Trends of smart grids and distributed energy production
  - Large amount of small generators
  - Diagnostics important for distribution quality and reliability

- Electromobility developement
  - Fault diagnostics
  - Motor and drive maintenance planning



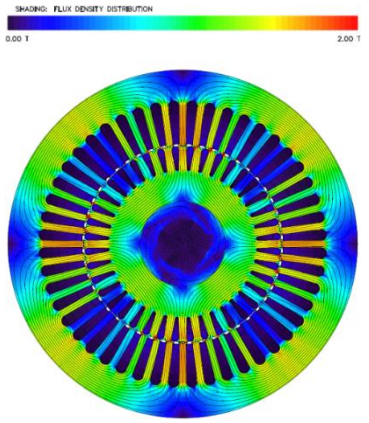
What is Smart Grid? (Co je Smart Grid?) - TZB-info
https://elektro.tzb-info.cz/12544-co-je-smart-grid

Diagnostics of electrical machines – MCSA, vibration diagnostics

- Most machines supplied by a frequency converter
  - More harmonics in diagnostic signal spectra
  - => signal noise degrades amplitudes of sidebands usually used in diagnostics

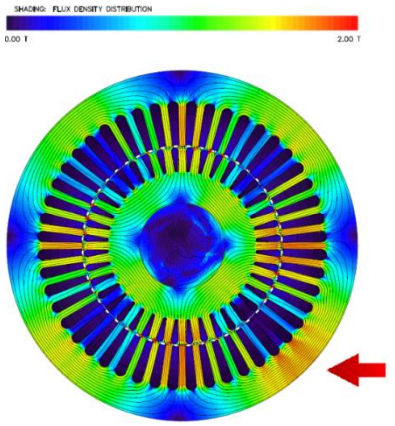
Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Local and global parameters**



- Fault propagates as a local quantity anomalies
  - Distribution of magnetic field and forces

- Local quantity distortion is averaged over the whole machine and can propagate into global quantities
  - Current, torque, noise and vibration



- Noninvasive measurement of local quantities is very difficult => usually not suitable for diagnostics and condition monitoring

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Local and global parameters**

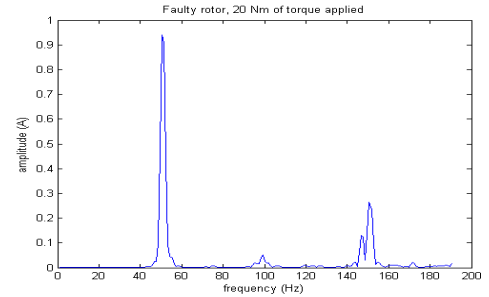
- Global parameters contains filtered a averaged information of a fault, thus give a chance to a fault identification
  - Emphasis on signal processing for useful data acquisition

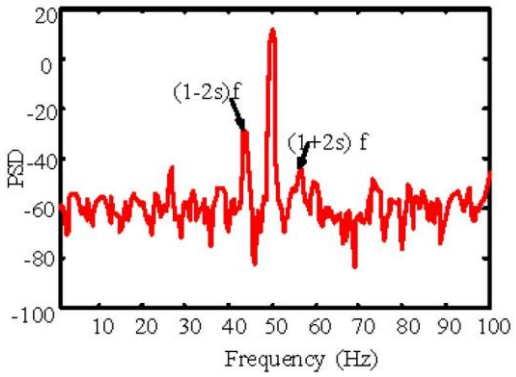
- Utilization of time-frequency analysis methods of current, vibration and noise signals
  - Short-time Fourier transform
  - Wavelet transform
  - Empirical mode decomposition
  - Hilbert-Huang transform
  - Wigner-Ville distribution

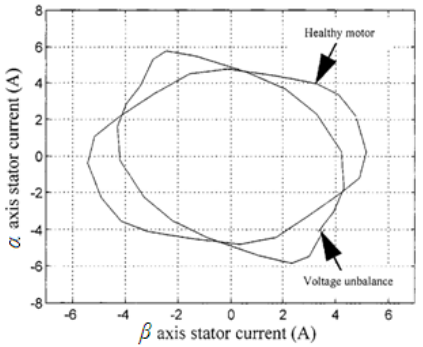
Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Motor Current Signature Analysis (MCSA)**
  - Also *Motor Current **Signal** Analysis*

- Signal processing methods
  - Fourier transform (FFT, STFT, DFT, wavelets etc.)
  - High definition spectral analysis
  - Park transformation (dq) / Clark transformation (αβ)







Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Motor Current Signature Analysis (MCSA) – measuring equipment**

- Current sensor
  - LEM sensor
  - Clamp current probe

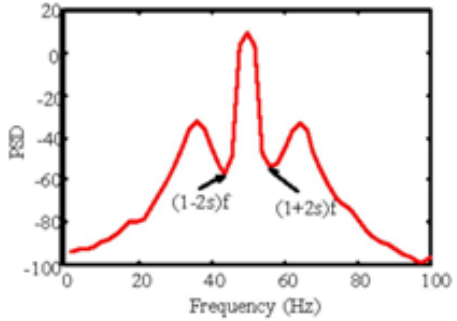




- Data acquisition system / analyzer
  - High-speed data acquisition
  - PC communication using LAN / FireWire etc.

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Motor Current Signature Analysis (MCSA) – broken rotor bars**

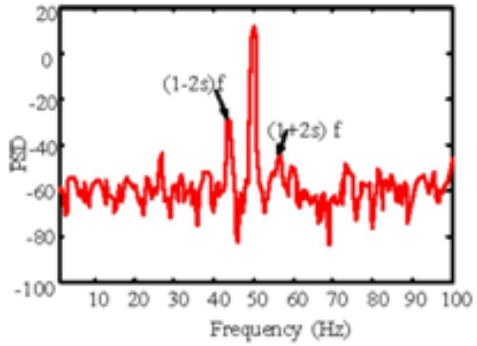


- Sidebands around current fundamental

- Lower sideband caused by electrical and magnetic asymmetry of rotor winding

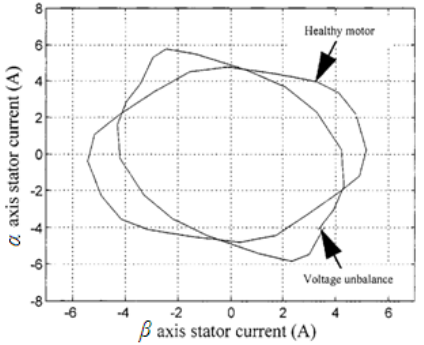
$$f_{sb} = (1 \pm 2s) f$$

- Upper sideband caused by torque pulsations due to variable rotor speed



Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Motor Current Signature Analysis (MCSA) – Park / Clarke transformation**



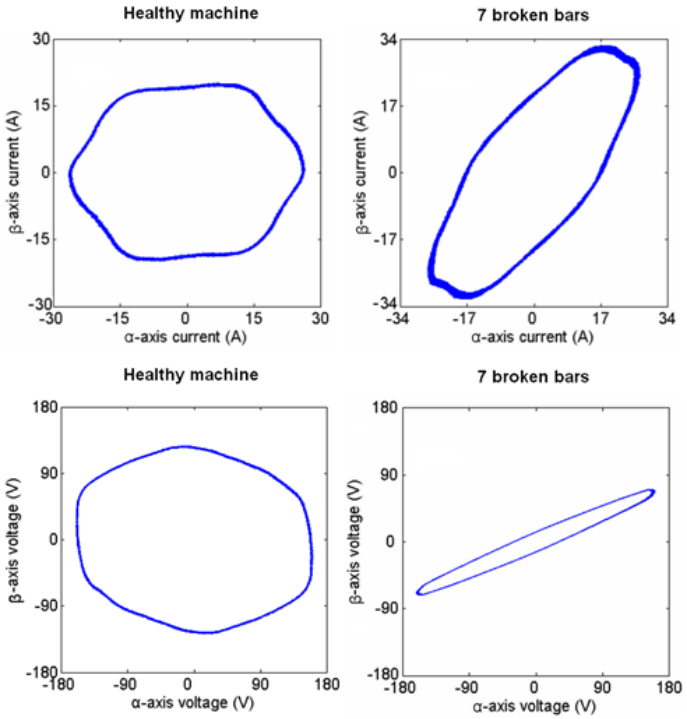
- Ones of most simple and quick transformations used in diagnostics
  - No need of large computational power
- Drawback is a lack of information and sometimes illegible graphs
- Usually adeqaute for a machine state rating

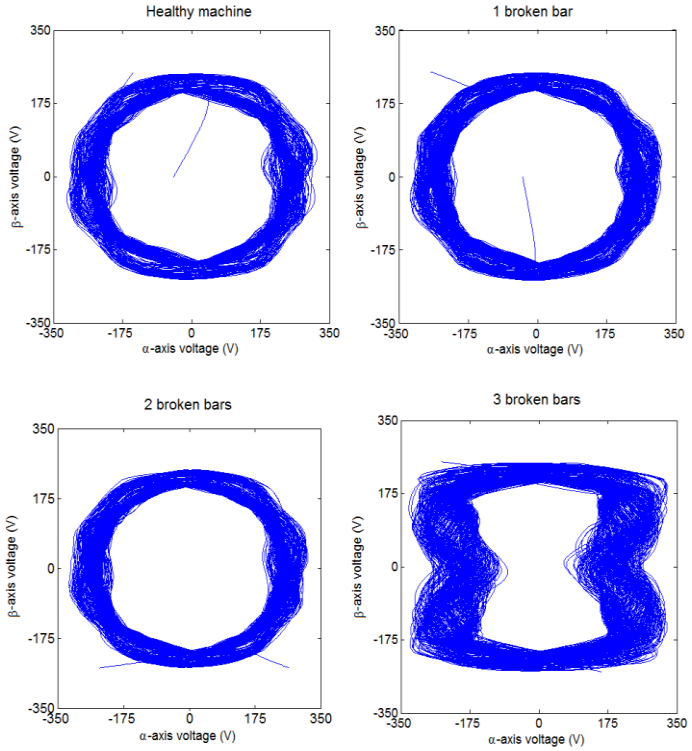
$$\begin{cases} u_d = u_a \\ u_q = \frac{1}{\sqrt{3}}(2u_b + u_c) \end{cases} \quad \begin{cases} u_\alpha = u_a \\ u_\beta = \frac{1}{\sqrt{3}}(2u_b + u_c) \end{cases}$$

$$\begin{cases} i_d = i_a \\ i_q = \frac{1}{\sqrt{3}}(2i_b + i_c) \end{cases} \quad \begin{cases} i_\alpha = i_a \\ i_\beta = \frac{1}{\sqrt{3}}(2i_b + i_c) \end{cases}$$

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Motor Current Signature Analysis (MCSA) – Park / Clarke transformation**





Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics**

- Standards – electrical machines vibration in general

  - ***ČSN ISO 20816-1*** Mechanical vibration - Measurement and evaluation of machine vibration - Part 1: General guidelines

  - *ČSN EN IEC 60034-14 ed. 3* Rotating electrical machines - Part 14: Mechanical vibration of certain machines with shaft heights 56 mm and higher - Measurement, evaluation and limits of vibration severity

  - ***ČSN ISO 10816-3*** Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts - Part 3: Industrial machines with nominal power above 15 kW and nominal speeds between 120 r/min and 15 000 r/min when measured in situ

Diagnostics of electrical machines – MCSA, vibration diagnostics

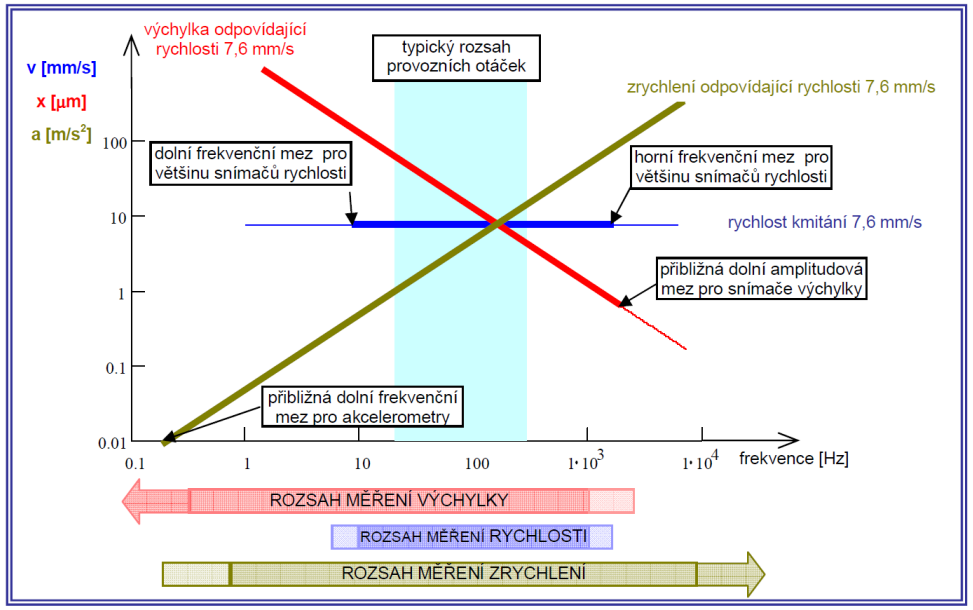
- **Vibration diagnostics**

- Measured quantities
  - Displacement (µm)
  - Velocity (mm/s)
  - **Acceleration** (m/s^2)

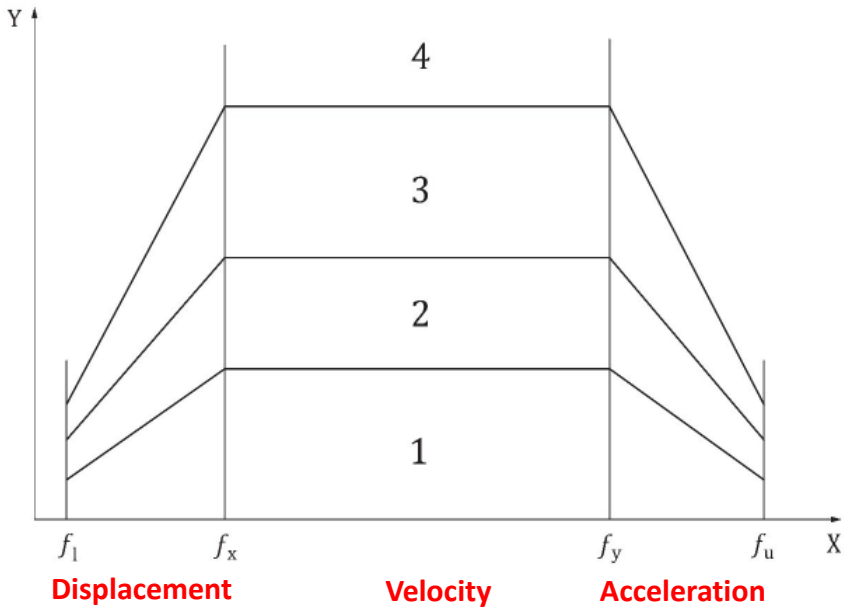
- Evaluated values
  - **RMS**
  - Zero to peak (0-p)
  - Peak to peak (p-p)

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – measured quantity selection**



Source: J. Biloš and A. Bilošová, Aplikovaný mechanik jako součást týmu konstruktérů a vývojářů: část Vibrační diagnostika, 1. Ostrava: VŠB-TU Ostrava, 2012, ISBN978-80-248-2755-1.



X Frequency
Y RMS value
1 Zone A
2 Zone B
3 Zone C
4 Zone D

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – measured quantity selection**
- **Harmonic** oscillations – quantity relations
- Displacement $x = A\sin(\omega t + \varphi)$
- Velocity $v = \frac{dx}{dt} = A\,\omega\,cos(\omega t + \varphi)$
- Acceleration $a = \frac{dv}{dt} = -A\,\omega^2\,sin(\omega t + \varphi)$

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – measured quantity selection**

- Measured quantities
  - Displacement, velocity, **acceleration** close to machine bearings (broadband RMS value)

- Minimal frequency range 10 Hz to 1 kHz

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – measuring equipment**

- Vibration sensors
  - IEPE (ICP) or charge piezoelectric accelerometers
  - Electrically insulated case or base recommended (high frequency interference – PWM etc.)
  - Single axis / tri-axial – single axis for a common vibration diagnostics



- Data acquisition system / analyzer
  - Handheld analyzers
  - Multichannel data acquisition systems

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – measuring equipment**

- IEPE (ICP) piezoelectric accelerometers
  - Integrated Electronics Piezo-Electric (IEPE), resp. Integrated Circuit Piezoelectric (ICP) => sensors with integrated electronic circuits (charge amplifier) => voltage output
  - Fed with a constant current 2 mA to 20 mA, typical value 4 mA

- Charge piezoelectric accelerometers
  - Electric charge output – not suitable for a longer distance signal transmission => charge amplifier for charge – voltage conversion necessary

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – measuring equipment**



- Handheld (route) analyzers
  - Limited channel number – 1, 2 or 4
  - Measurement of large amount of machines – only data reccording or a quick assessment of vibration change trend
  - Possibility of further analyses using PC
  - Modules for a common „steady-state“ analysis, run-up / coastdown, rotor balancing, fault diagnostics, bearing lubrication etc.



Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – measuring equipment**



- Multichannel data acquisition systems
  - Modular system – measuring module selection for a specific setup
  - Measurement of different quantities – electrical and non-electrical
  - Worse portability, external power source needed
  - Data processing and vizualization using PC – dedicated SW
  - PC communication using LAN / FireWire etc.



Diagnostics of electrical machines – MCSA, vibration diagnostics

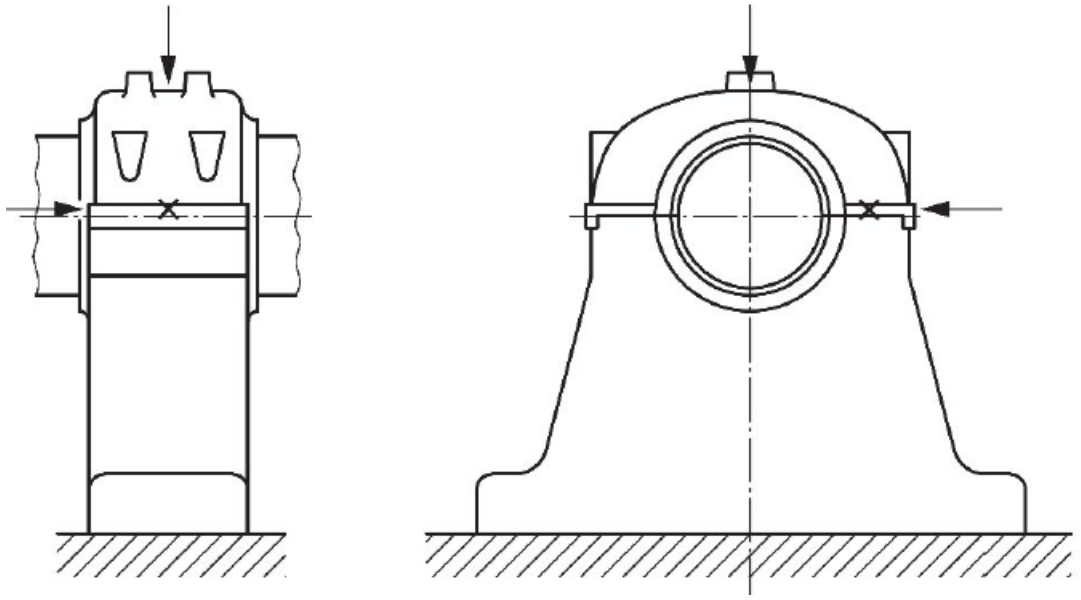
- **Vibration diagnostics – sensor placement**

- Sensor placement on non-rotating parts
  - Bearings
  - Bearing brackets
  - Other structural parts close to bearings which are sensitive to dynamic forces transmitted from rotating elements
  - In any selected spot measurement in three perpendicular directions or at least radial vibration in both horizontal and vertical plane

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – sensor placement**

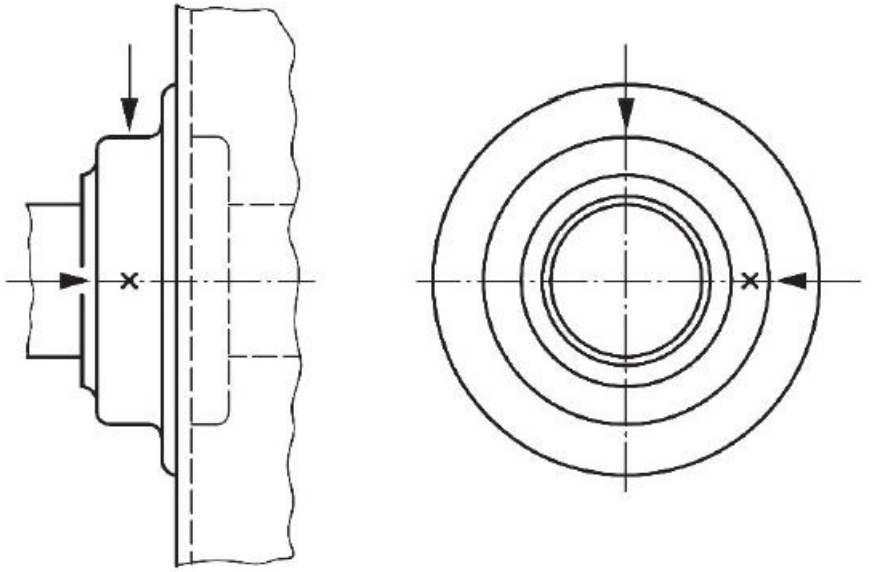
- Measurement spots on bearing blocks



Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – sensor placement**

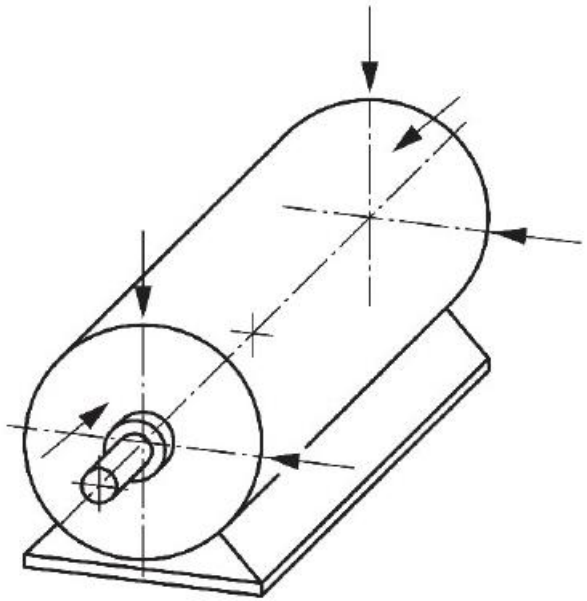
- Measurement spots on bearing brackets



Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – sensor placement**

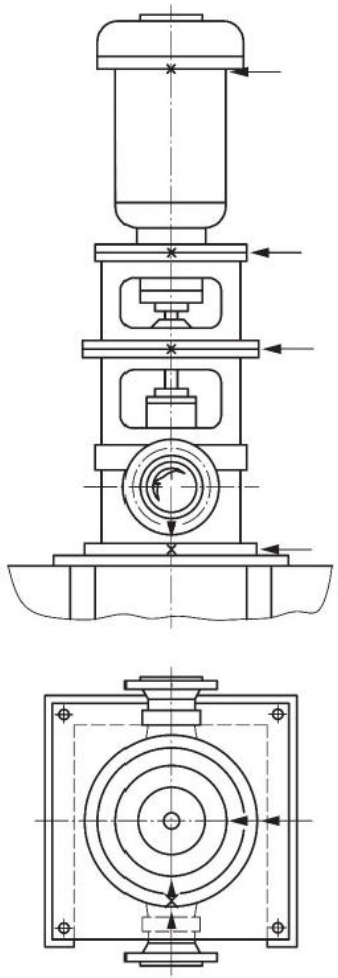
- Measurement spots on small electric machines



Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – sensor placement**

- Measurement spots on vertical mounted machines



Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – vibration level evaluation**

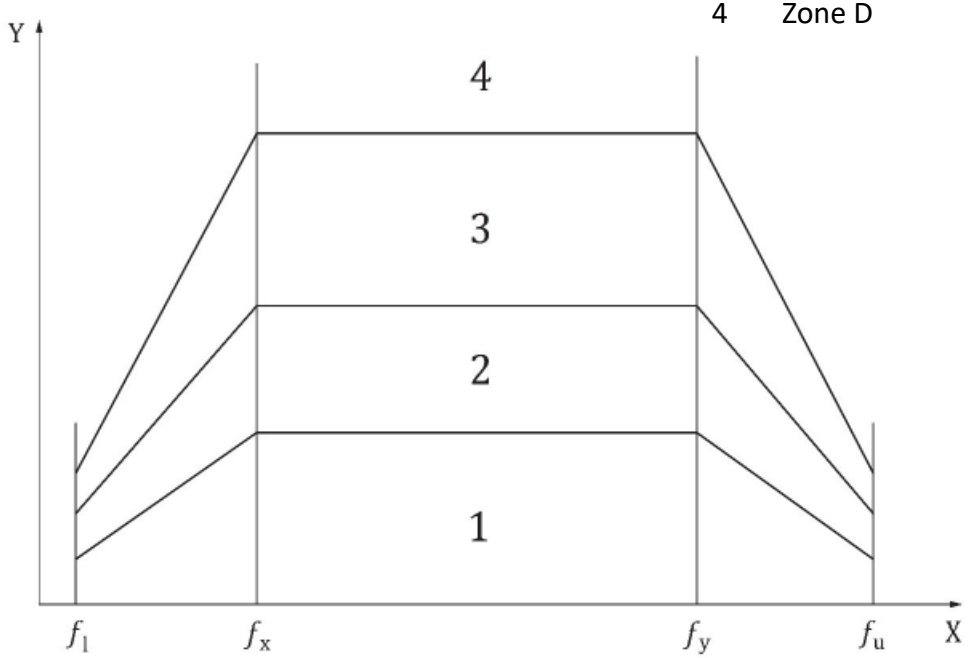
- Evaluation criteria
  - Table with A/B, B/C a C/D severity zone threshholds (displacement, velocity)
  - Flexible / rigid foundation

- Machine foundation
  - Rigid foundation (maximal vibration velocity on motor feet or base =< 25% of maximal velocity on the closest bearing bracket)
  - Flexible foundation (spring suspension or flexible element placement – springs, rubber)

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – vibration level evaluation**

- Vibration severity zones
  - Zone A: vibration of a new machines
  - Zone B: usually unlimited operation time period
  - Zone C: not suitable for a long –term operation (maintenance ASAP)
  - Zone D: risk of machine damage



Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – fault diagnostics**

- Frequency spectra evaluation

- Typically evaluated frequencies:
  - Rotating frequency ***1X*** (mechanical) and its harmonics, eventually subharmonics
  - Twice line frequency ***2L*** and its harmonics

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – fault diagnostics table for induction machines**

CAUSE	FREQUENCY OF VIBRATION	PHASE ANGLE	AMPLITUDE RESPONSE	POWER CUT	COMMENTS
Misalignment: ① Bearing	Primarily 2 x Some 1 x Radial High at DE and Axial	Phase angle can be erratic.	Steady.	Drops slowly with speed.	① 2 x can dominate during coast-down. ② 2 x is more prevalent with higher misalignment.
Misalignment: ② Coupling	Primarily 1 x Some 2 x Radial High at DE and Axial	Drive 180º out Phase with NDE.	Steady.	Level drops slowly with speed.	① Parallel causes radial forces and angular causes axial. ② Load dependent.
Rub - ① Seal/or bearing	1/4x, 1/3x, 1/2x or 10-20x can be seen Primarily 2 x Some 1 x. Radial.	Erratic.	Erratic depending upon severity.	Disappears suddenly at some lower speed.	① Full rubs tend to be 10 to 20x higher. ② Bearing misalignment can give rub symptoms.
② Rotor	1/4x, 1/3x, 1/2x, & 1x with slip freq. side bands. Radial.	Erratic.	High.		① Severe pounding.
Looseness: ① Bearing (non-rotating)	2 x 3 x may be seen Radial	Steady.	Fluctuates	Disappear at Some lower speed	① Bearing seat looseness. ② Looseness at bearing split.
② Rotor Core (rotating)	1-10x with 1, 2, & 3 predominant. Radial	① Can exist relative to type of looseness ② General core loose gives erratic symptom.	Erratic, high amplitude	① Drops with speed. ② Can disappear suddenly.	① End plates loose. ② Core ID loose.
③ Pedestals (non-rotating)	1-10x with 2 & 3 predominant Radial & Axial	Steady.	Fluctuates.	Disappears at some lower speed.	
④ External Fans	1 & 3 x Radial & Axial – OE (fan end)	N/A	Fluctuates.	① Drops with speed. ② Can disappear suddenly.	

Source: W. R. Finley, M. M. Hodowanec, and W. G. Holter, “An analytical approach to solving motor vibration problems,” IEEE Trans. Ind. Appl., vol. 36, no. 5, pp. 1467–1480, 2000.

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – fault diagnostics table for induction machines**

CAUSE	FREQUENCY OF VIBRATION	PHASE ANGLE	AMPLITUDE RESPONSE	POWER CUT	COMMENTS
Unbalance Rotor	1x rotor speed. Radial	① NDE & DE in phase. ② Couple gives out of phase condition	Steady.	Level drops slowly.	Rotor has unbalance - can be due to thermal problems.
Unbalance of External Fan	① 1X Radial high at NDE (fan end). ② 1X Axial with high at fan end.	① Couple DE 180^{o} out of phase with EO.	Steady.	Level drops slowly.	
Coupling Unbalance	1 x Radial & higher on drive end		Steady	Level drops slowly	Unbalance due to coupling or key
Bent Shaft Extension	2 x Primarily 1 x may be seen Axial	EO 180^{o} out of phase with DE.	Steady.	Level drops slowly.	DE runout should give higher 2x axial at that end. Normal runout on core - 1-2 mil.
Eccentric Air Gap	Strong 120 Hz Radial	N/A	Steady	Immediately drops	Difference between max. and min. air gap divided by ave. should be less than 10%.
Soft Foot Eccentric rotor.	1x Primarily Some 60 & 120 Hz Radial	Unsteady.	Modulates in amplitude with slip	Immediately drops	① Eccentricity limit 1-2 mil. ② Slip beat changes with speed/load.
Loose stator core.	120 Hz. Axial & radial	Frame & bearing brackets in phase at 120 Hz	Steady	Immediately drops	① Look for relative motion of core with respect to housing.
Rotor Bow (Thermal Bow)	1x Primary Some 120 Hz may be seen May have Modulators on 1X & 2X vib. - Radial	Unsteady	① Changes with temperature. ② Time or load related. ③ Varies at Freq. slip x poles	Some drop but high level would come down with speed.	① Heat related. ② Examine rotor stack for uneven stack tightness or looseness. ③ Shorted Rotor Iron ④ Check bar looseness.

Source: W. R. Finley, M. M. Hodowanec, and W. G. Holter, “An analytical approach to solving motor vibration problems,” IEEE Trans. Ind. Appl., vol. 36, no. 5, pp. 1467–1480, 2000.

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – fault diagnostics table for induction machines**

CAUSE	FREQUENCY	PHASE ANGLE	AMPLITUDE OF VIBRATION	POWER CUT	COMMENTS
Broken rotor bars	1x and modulates at slip x # poles May have high stator slot frequencies On slower speed Motors	Dependent upon where broken bars are located.	STRONG BEAT POSSIBLE. - Varies @ Freq. Slip x poles - Amplitude increased with load	Immediately drops	① Sparking in the air gap may be seen. ② Long term variation in stator slot frequencies can be indicator of bar problems. ③ Broken bars cause holes in magnetic field. ④ Large current fluctuations. ⑤ Current analysis shows slip frequency side bands.
Loose bars.	① 1 x Possible balance effect with thermal sensitivity. Radial ② Stator slot freq. plus sidebands @ ±(# Poles*Slip)	1. 1 x vibration will be steady 2. Stator slot freq. will modulate causing a fluctuation in phase angle on overall vibration	Steady	① Stator slot freq. will immediately disappear. ② Imbalance effect can suddenly disappear at some lower speed.	Excessive looseness can cause balance problems in high speed motors.
Interphase fault	60 & 120 Hz Radial	N/A	Steady and possible beat.	Immediately disappears.	
Ground fault	60 Hz & 120 Hz slot freq. - Radial	N/A	Steady and possible beat.	Immediately disappears.	
Unbalanced Line Voltages	120 Hz Radial	N/A	Steady 120 Hz & Possible beat.	Immediately disappears.	
Electrical Noise Vibration	(RPM x # of Rotor slots)/60 +/-120, 240, etc. - Radial	Due to modulation overall vibration will fluctuate	Steady	Immediately disappears	Increases with increasing load.
System Resonance	1 x RPM or other forcing frequency One plane – usually Horizontal	Varies with load and Speed	Varies	Disappears rapidly.	Foundation may need stiffening- may involve other factors

Source: W. R. Finley, M. M. Hodowanec, and W. G. Holter, “An analytical approach to solving motor vibration problems,” IEEE Trans. Ind. Appl., vol. 36, no. 5, pp. 1467–1480, 2000.

Diagnostics of electrical machines – MCSA, vibration diagnostics

- **Vibration diagnostics – fault diagnostics table for induction machines**

CAUSE	FREQUENCY	PHASE ANGLE	AMPLITUDE OF VIBRATION	POWER CUT	COMMENTS
Strain	1 x RPM		Steady		Caused by casing or foundation distortion from attached structure (piping).
Poorly shaped Journal	2x Rotational Usual	Erratic	Steady	May disappear at lower speed	May act like a rub.
Oil Film Instability (Oil Whirl)	Approx. (.43-.48)*rotational	Unstable	Steady		
Anti-Friction Bearing Problems	Various Frequencies dependent on bearing design	Unstable	Steady		Four basic frequencies.
Resonant Parts	At forcing Frequency or Multiples	N/A	Steady♣	Drops rapidly	May be adjacent parts
Top Cover Fit	120 Hz. Radial	N/A	Steady.	Disappears immediately.	⊙ Magnification of 120 Hz electrical. ⊙ Top cover rests on basic core support.

Source: W. R. Finley, M. M. Hodowanec, and W. G. Holter, "An analytical approach to solving motor vibration problems," IEEE Trans. Ind. Appl., vol. 36, no. 5, pp. 1467–1480, 2000.

Thank you

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