Investigation of Hydrogenerator Vulnerability Regarding Shaft Voltage and Bearing Current

Joël Pedneault-Desroches, ing., M.Sc.A.

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Hydro-Québec

More than

99%

OF OUR ELECTRICITY IS PRODUCED USING WATER

Hydro-Québec in figures | 2022

Hydroelectric power plants

62

Transport lines

34 678 km

Generating units

352

Distribution lines

227 796 km

Installed capacity

36,882 MW

Sales volumes

216.2 TWh

Including 35.6 TWh in net exports

Presentation Outline

I. Introduction

II. Origins and vulnerability

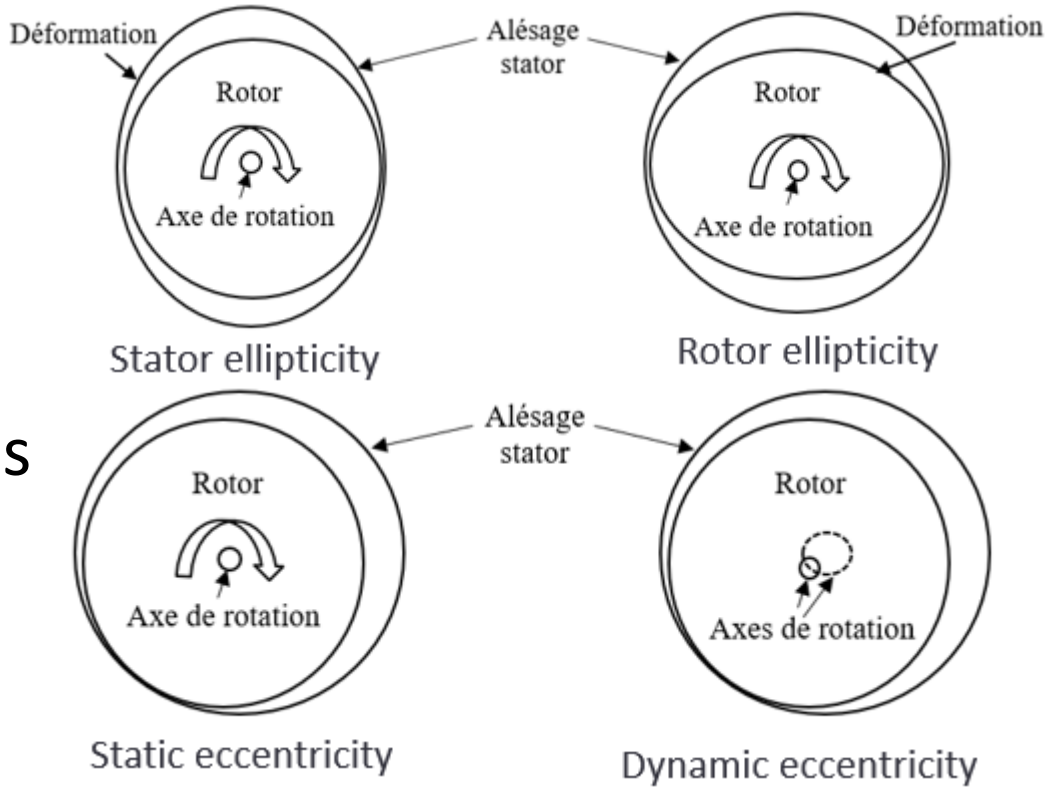
III. Case study

IV. Conclusion

I. Introduction

Why shaft voltage & current is interesting in hydro?

- They could damage the bearings
  - Unpredicted outage…
- Source of inadequate maintenance
  - Repetitive outages…
- Influenced by magnetic perturbations
  - Input for diagnosis…



The challenge

- Lack of standards
- Few data and statistics
- Hidden failures?
- Source of skepticism
- Use the measure!

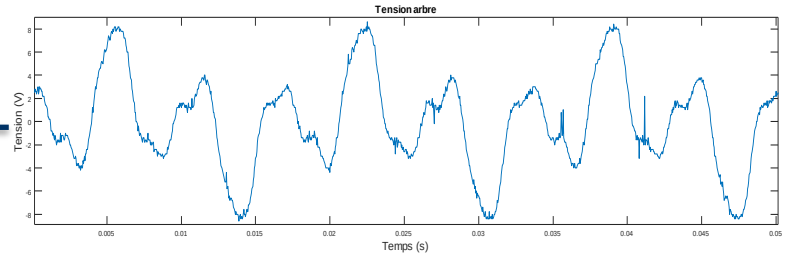
IEEE Std 1129-2014 :

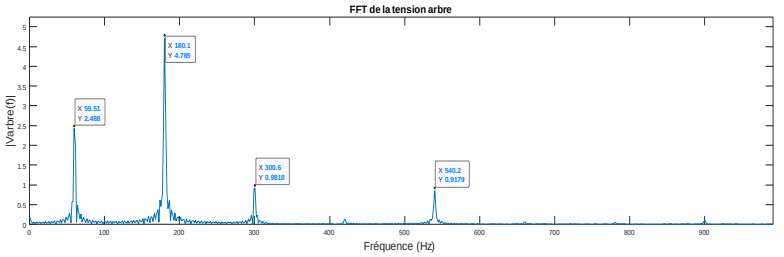
Instrumentation: Continuous shaft voltage (and current) monitoring with a dedicated monitor, or frequent measurement with an oscilloscope, may be desirable to verify proper operation of the shaft grounding system. The basic purpose of the shaft monitoring circuit is to alert the operator that grounding brush performance might be deteriorating and/or voltages on the shaft may reach abnormally high levels, indicating that other failure mechanism may be happening.

Mechanical faults of electrical origin...

(4 V rms)

Good? Bad? Why?



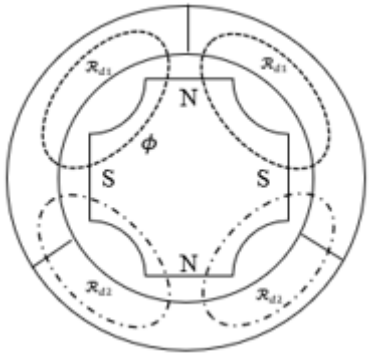


II. Origins and vulnerability

Origins of shaft voltage

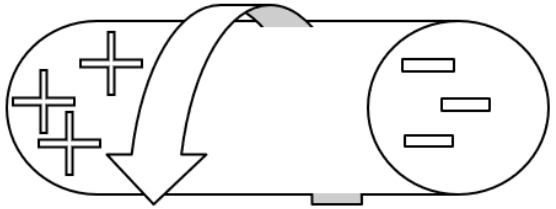
Four categories:

- Induced voltages
- Axial flux
- Electrostatic charges
- Applied potential

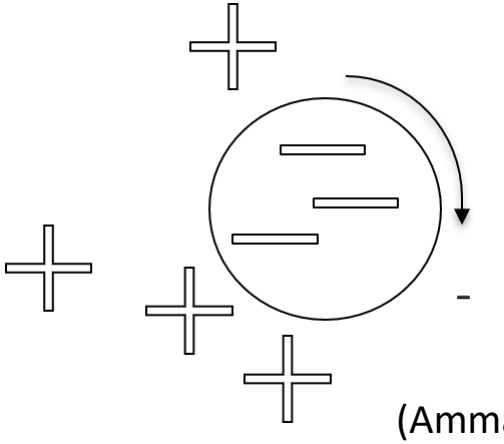


Important sources

- Stator core air gap
- Nonconstant rotor pole air gap
- Eccentricity, ovality…

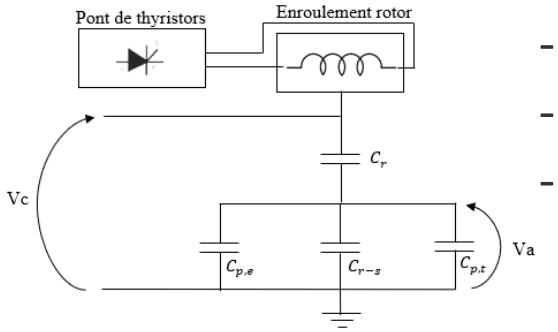


- Solder with poor ground return
- Magnetic inspection
- Ground fault
- Residual magnetism… (Nippes, 2004)



- Friction of a gas or water steam in the turbine

(Ammann, Reichert, Joho, & Posedel, 1988)



- Ground rotor winding
- Measurement systems
- Static excitation (with thyristor bridge)

Induce voltage by stator core air gap

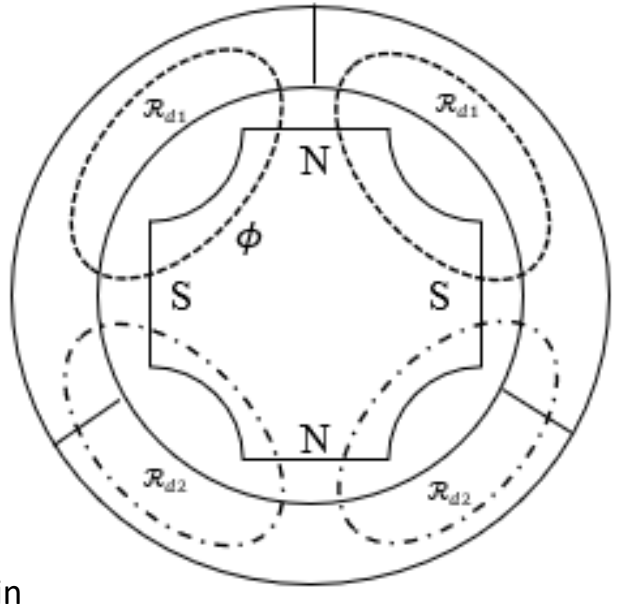
Stator core air gap could create a magnetic asymmetry, i.e., shaft voltage

Prediction rule (Alger & Samson, 1924)

$$\textbf{irrational}: \frac{\boldsymbol{nb\ segments}}{\boldsymbol{nb\ pole\ pairs}} = \frac{\boldsymbol{D}}{\boldsymbol{p}}$$

$$\boldsymbol{if\ D\ is\ odd: asymmetry} = \boldsymbol{D\ x\ f_e\ Hz}\ (\mathbf{1})$$

Where f_e is the grid frequency in Hertz = $\Omega_s P/2$, with Ω_s rotational speed in revolution per second



4-pole; 3-segment

$$\rightarrow \frac{\boldsymbol{D}}{\boldsymbol{p}} = \frac{\mathbf{3}}{\mathbf{2}}$$

Shaft voltage predicted at $3f_e$

Induce voltage by stator core air gap

Hydrogenerator:

- 32-pole (225 rpm)
- 264 slots, *D* = ?

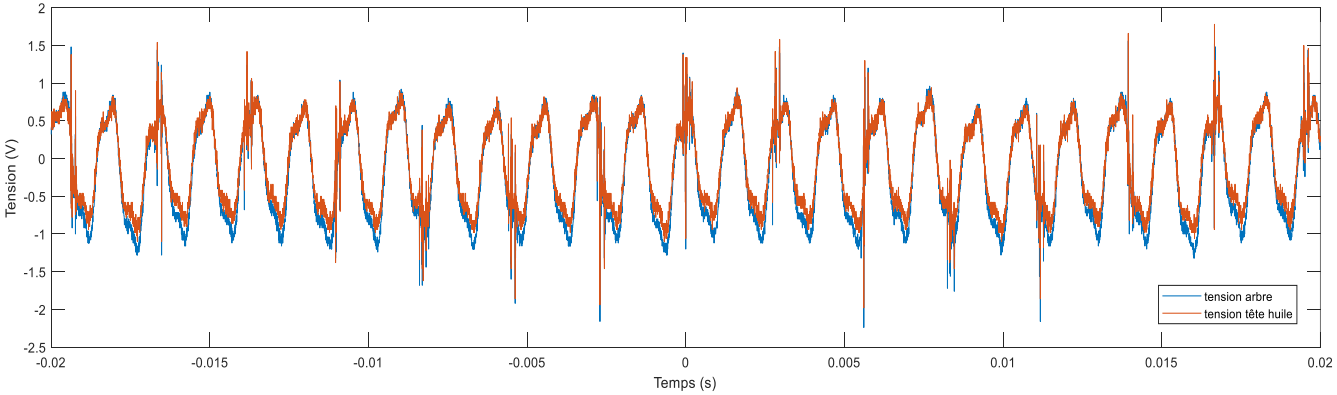
$$\boldsymbol{D = \frac{S_t}{S_s \cdot O} = \frac{264}{12 \cdot 0.5} = 11}$$

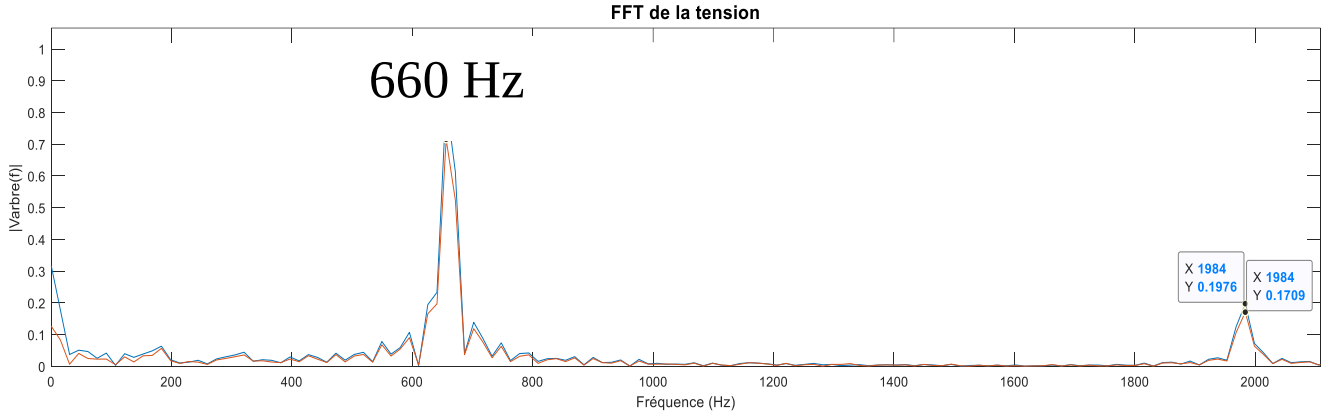
Where S_t is the total stator slots, S_s the slots per sheet and *O* the overlap of the sheets

$$\frac{\boldsymbol{D}}{\boldsymbol{p}} = \frac{\boxed{\boldsymbol{11}}}{\boldsymbol{16}} \textit{(odd)} \boldsymbol{(irrational)}$$

$$\boldsymbol{\rightarrow D\ x\ f_e = 660\ Hz}$$

Shaft voltage





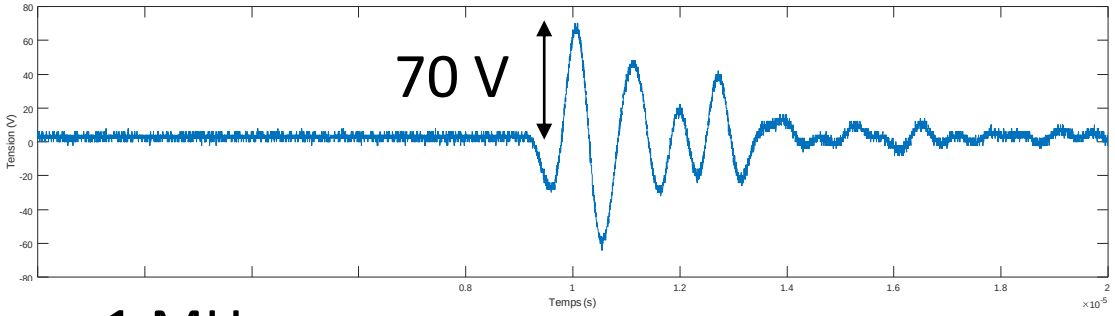
Static excitation system

The use of thyristor rectifiers…

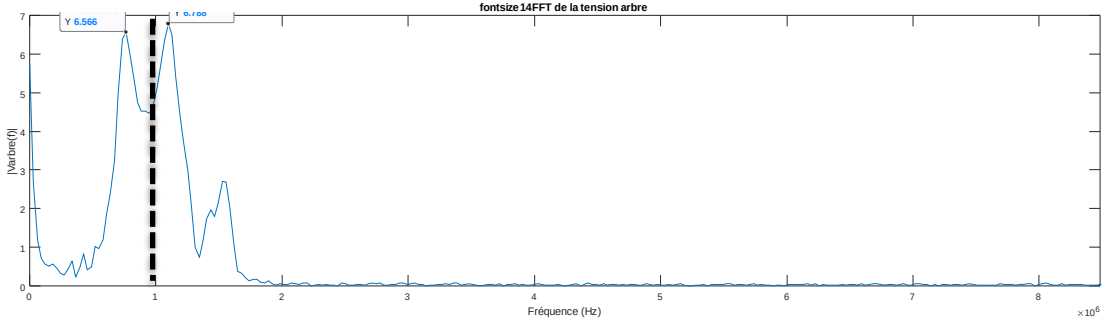
- Capacitance current
- Electric discharge machining (EDM)
- High frequency current
- Ground fault current

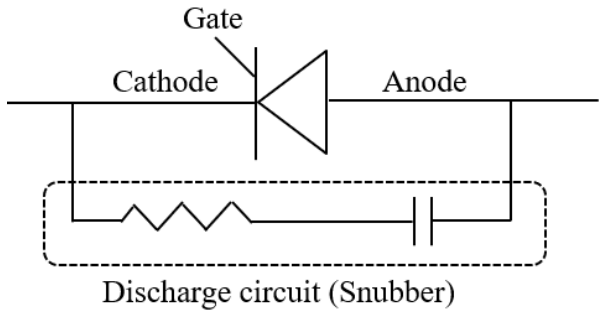
(Muetze & Binder, 2007)

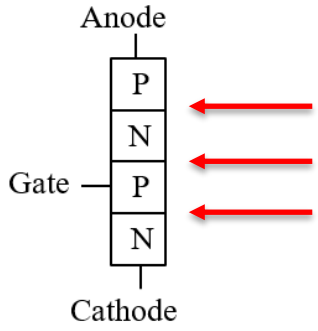
Shaft voltage



1 MHz







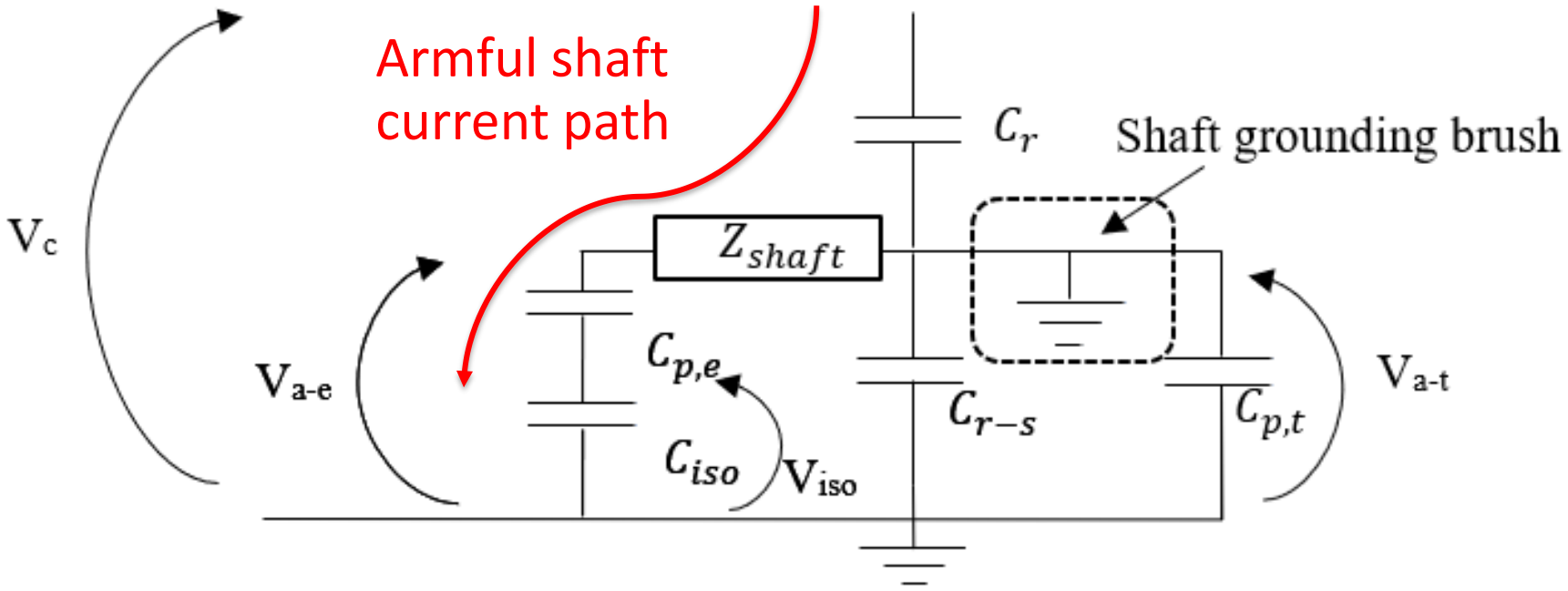
Accumulation of charges at the junctions

→ Charges return to equilibrium during off mode creating a reverse current (µs)

→ HF reverse current pushing in a high inductive load = <u>overvoltage</u>

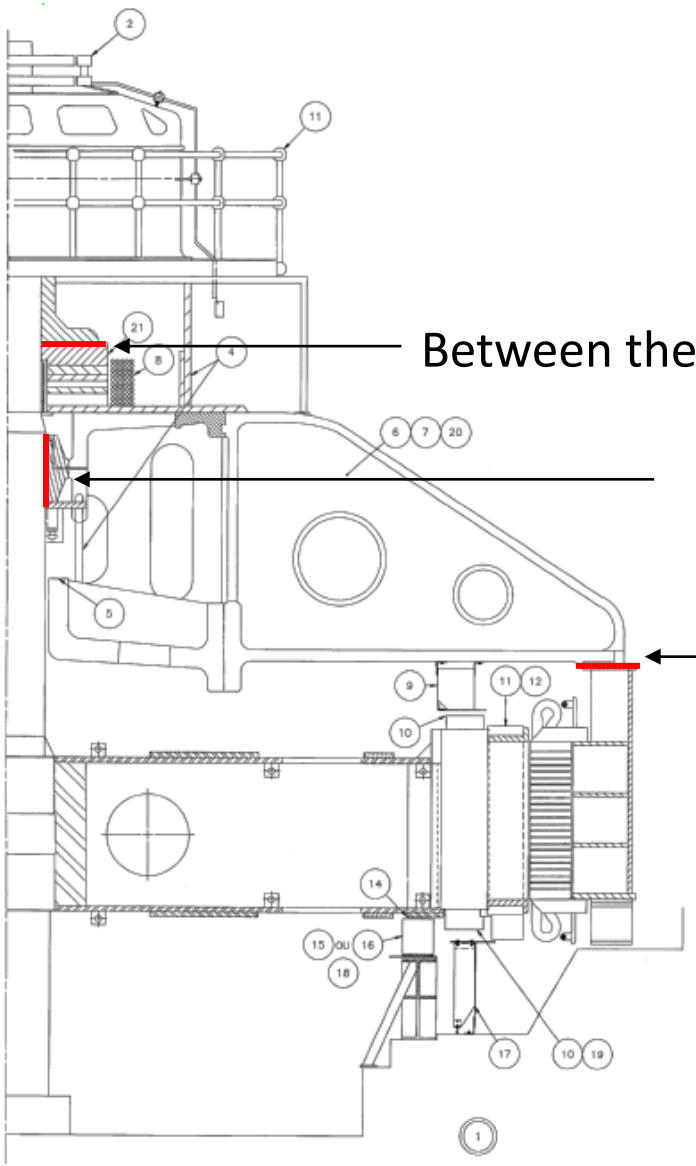
Shaft voltage… harmful?

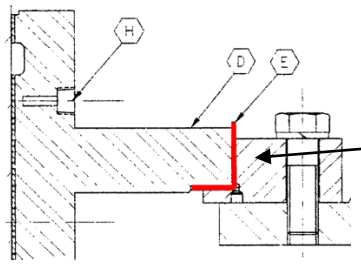
No if there's **sufficient impedance** from the bearing or in the insulation



with: C_r Rotor capacitance, $C_{p,e}$ Exciter-end bearing capacitance, C_{r-s} Rotor to stator capacitance, $C_{p,t}$ Turbine-end bearing capacitance, and C_{iso} Insulation capacitance

Bearing insulation systems in hydro





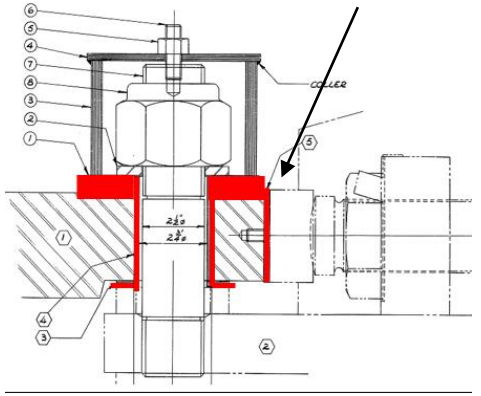
Between the bearing shell and the hoop

Between the shaft and the rotating ring

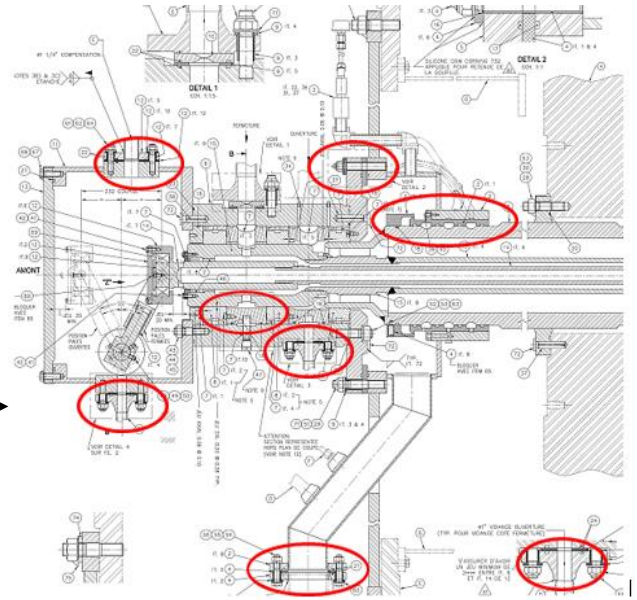
Between the shaft and the rotating skirt

Complete upper bracket

Between the bearing and the upper bracket



Oil head of a Kaplan turbine

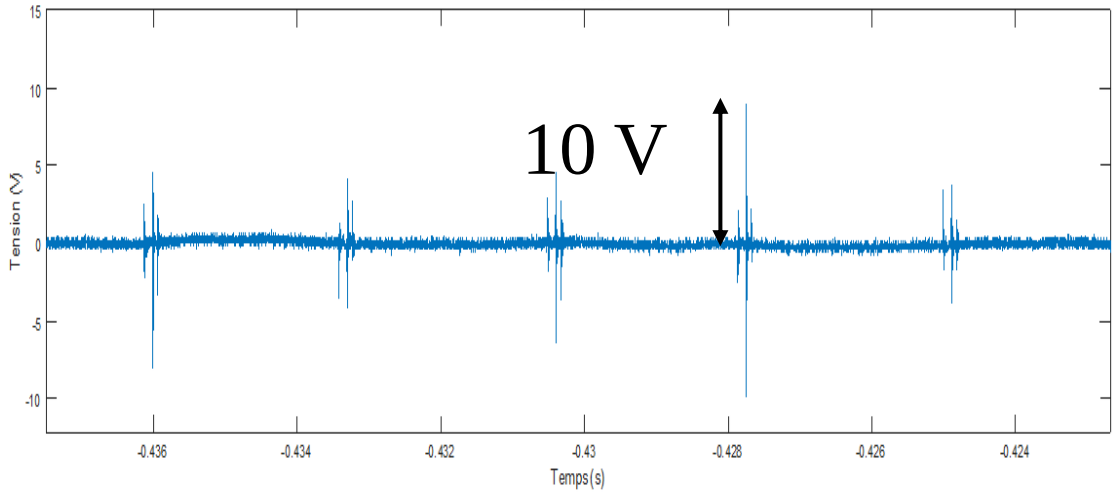


III. Case study

Unit A: 50 MVA, 52-pole (138.5 rpm)

Exciter-end guide bearing show trace of “pitting”

HF applied shaft voltage is near 750 kHz



→*D* is pair from (1)

→*Static excitation is present*

Bearing current?

Unit A: Guide bearing HF current

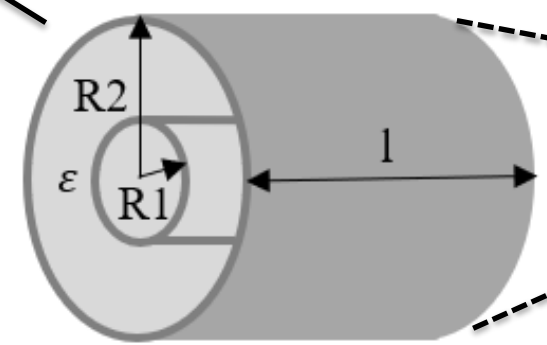
$$C = 2\pi\varepsilon_0\varepsilon_r \frac{l}{\ln\left(\frac{R_2}{R_1}\right)} = 162{,}4 \text{ nF}$$

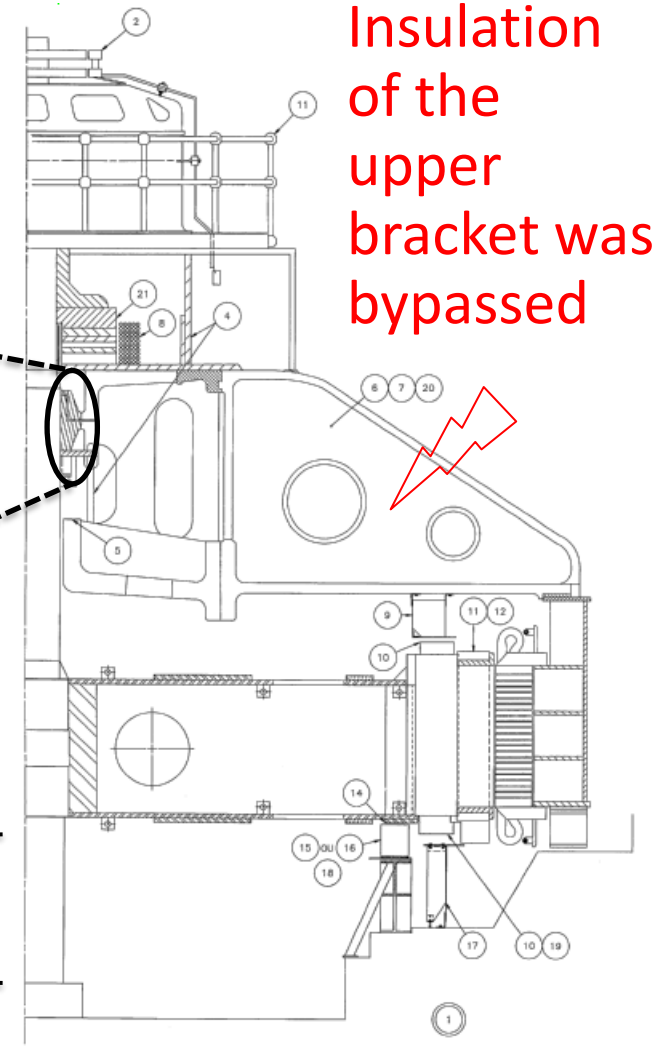
(≈750 kHz)

$$Z_c = \frac{1}{2\pi f C} = \frac{1}{2\pi \cdot 750\times10^3 \cdot 162{,}4\times10^{-9}} = 1{,}31\ \Omega$$

(10 V peak)

$$I_{bearing} = \frac{\hat{V}}{Z_C} = 7.6 \text{ A peak}$$



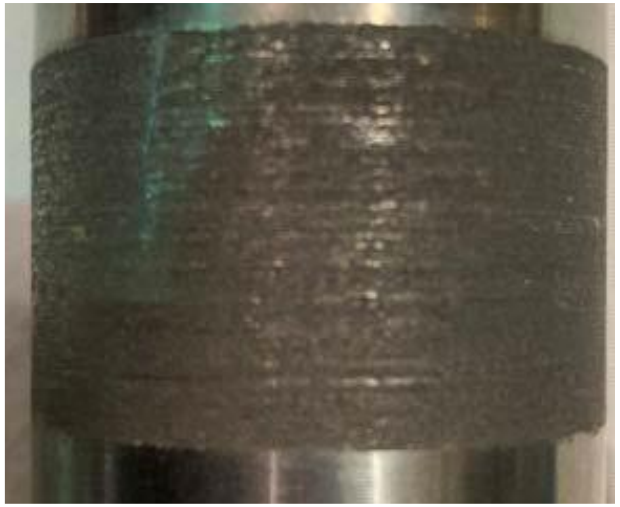


Insulation of the upper bracket was bypassed

(I_{shaft} measured at = 15 A peak)

Unit B: 11,5 MVA, 36-pole (200 rpm)

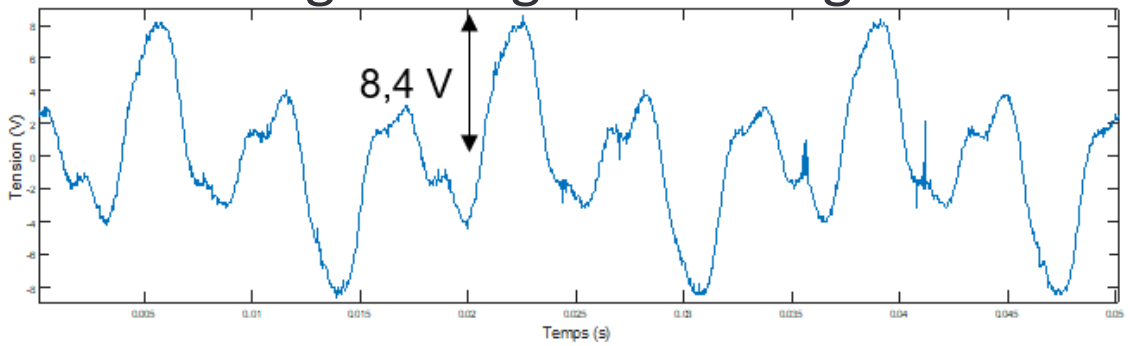
Exciter-end shaft show trace of “pitting”

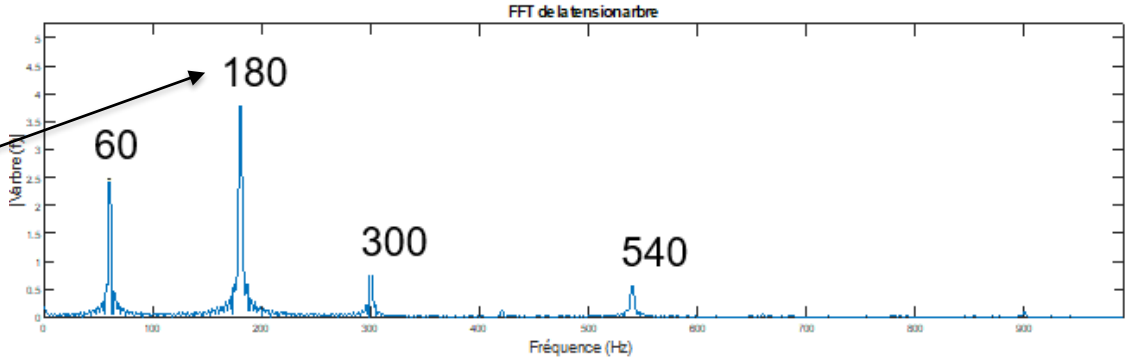


→*D = 3* odd: 180 Hz from (1)

→*Static excitation is present*

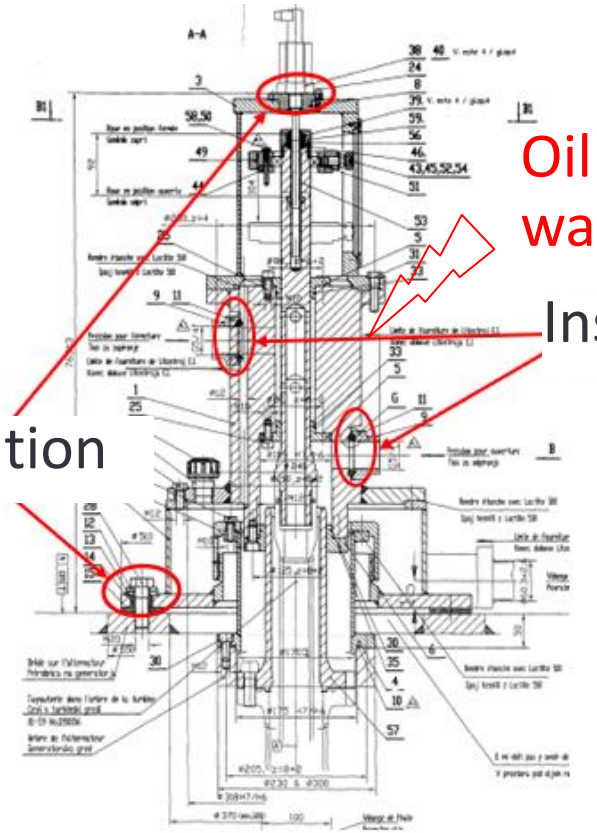
Shaft voltage with good bearing insulation



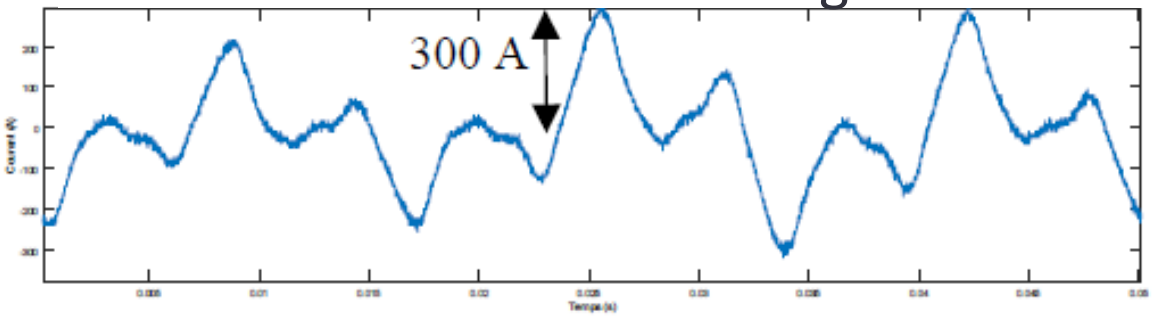


Bearing current?

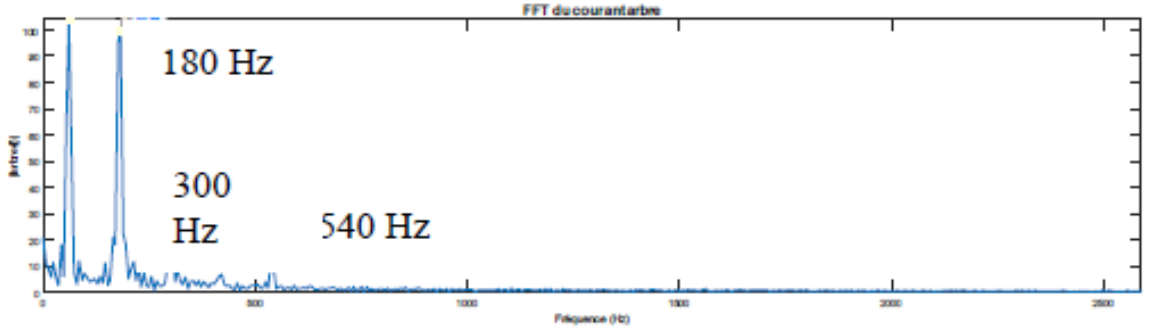
Unit B: Guide bearing current



Shaft currant with bad bearing insulation



60 Hz



Bearing current ≈ shaft current ≈ 150 A rms

IV. Conclusion

Conclusion

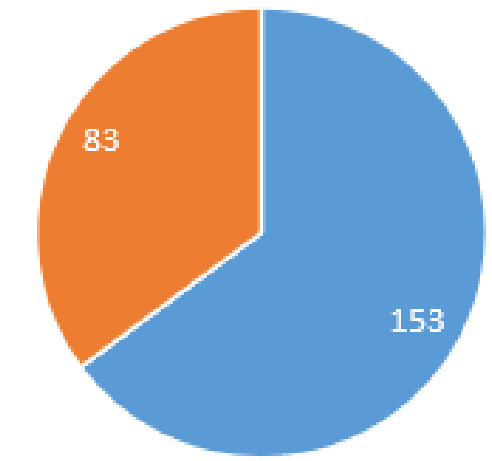
- The vulnerability of hydrogenerators has been demonstrated in several ways:
  - Induced voltage by stator core air gap
  - HF voltage of the static excitation (thyristors bridge)
  - The insulation system vulnerability to bypass
- Shaft current in hydro (even if rare) could lead to rapid bearing failure and inadequate maintenance.

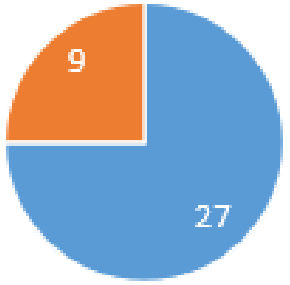
Is shaft V&I in hydro still of interest nowadays?

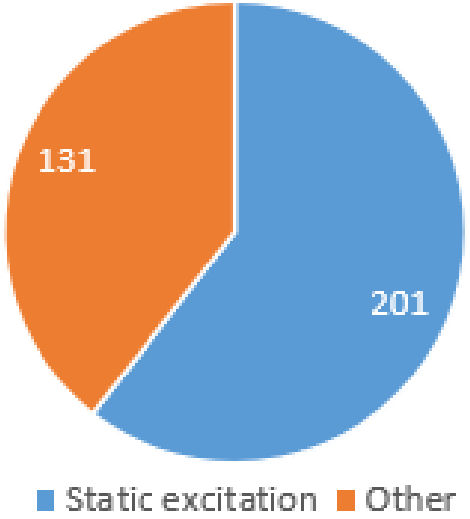
Shaft voltage creating asymmetries from the segmentation of the stator core has increased (20 years)

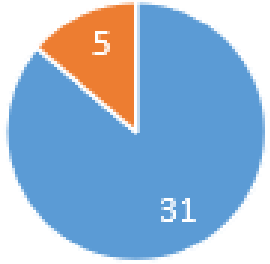
Static excitation (with thyristors) has become a standard

Yes!





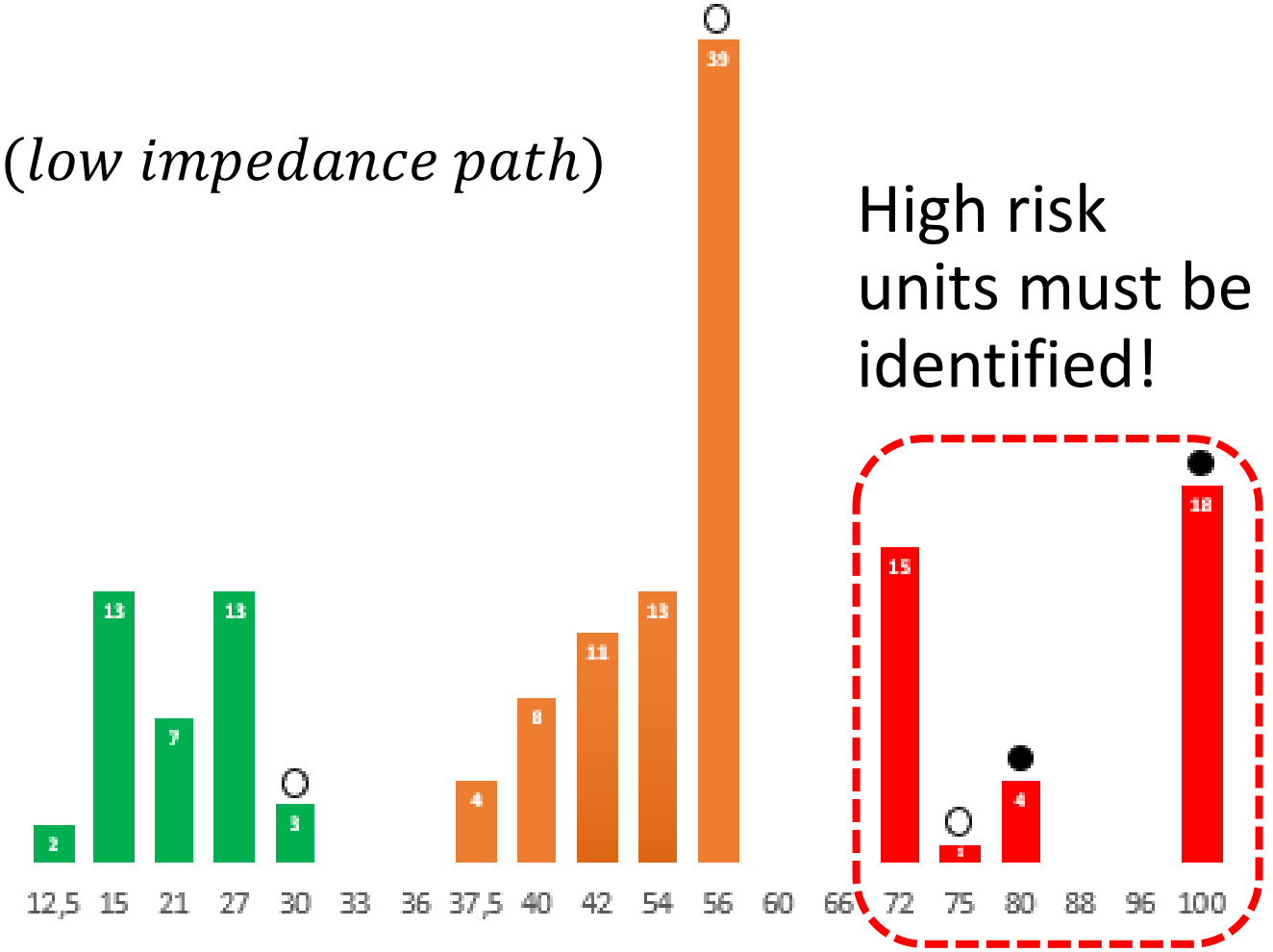




Is shaft V&I in hydro should be always a preoccupation?

Hydrogenerators have varying levels of vulnerability to shaft current:

$$Risk_{unit} = p(shaft\ voltage) \cdot p(low\ impedance\ path)$$



High risk units must be identified!

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Thank you! / Questions?


Hydro
Québec