HYPERBOLE

HYdropower plants PERformance and flexiBle Operation towards Lean integration of new renewable Energies

Prof. François Avellan

francois.avellan@epfl.ch

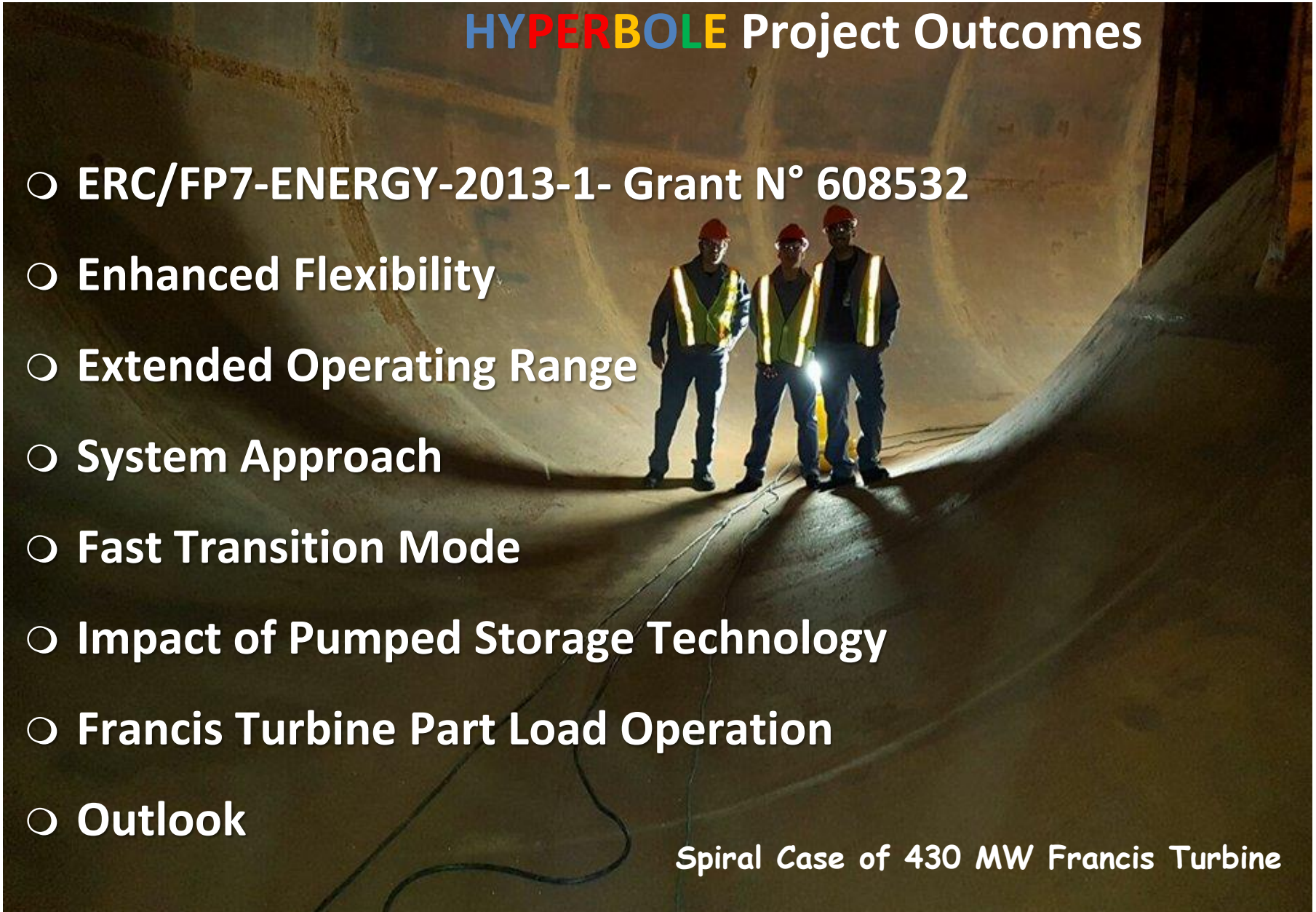
https://hyperbole.epfl.ch/

This project has received funding from the European Union's 7th Framework Programme for research, technological development and demonstration under grant agreement n° 608532

European Commission

HYPERBOLE Project Outcomes

- ERC/FP7-ENERGY-2013-1- Grant N° 608532
- Enhanced Flexibility
- Extended Operating Range
- System Approach
- Fast Transition Mode
- Impact of Pumped Storage Technology
- Francis Turbine Part Load Operation
- Outlook



Spiral Case of 430 MW Francis Turbine

HYPERBOLE

ERC/FP7-ENERGY-2013-1-Grant N° 608532

- HYdropower plants PERformance and flexiBle Operation"towards Lean integration of new renewable Energies
  - ✓ Dynamic Assessment of Francis Turbines & Pump-Turbines
  - ✓ 42 Months, EUR 6.3 Mio
  - ✓ EUR 4.3 Mio Supported by European Commission
  - ✓ 1st Sept. 2013 ÷ 28th Feb. 2017
- Consortium coordinated by EPFL

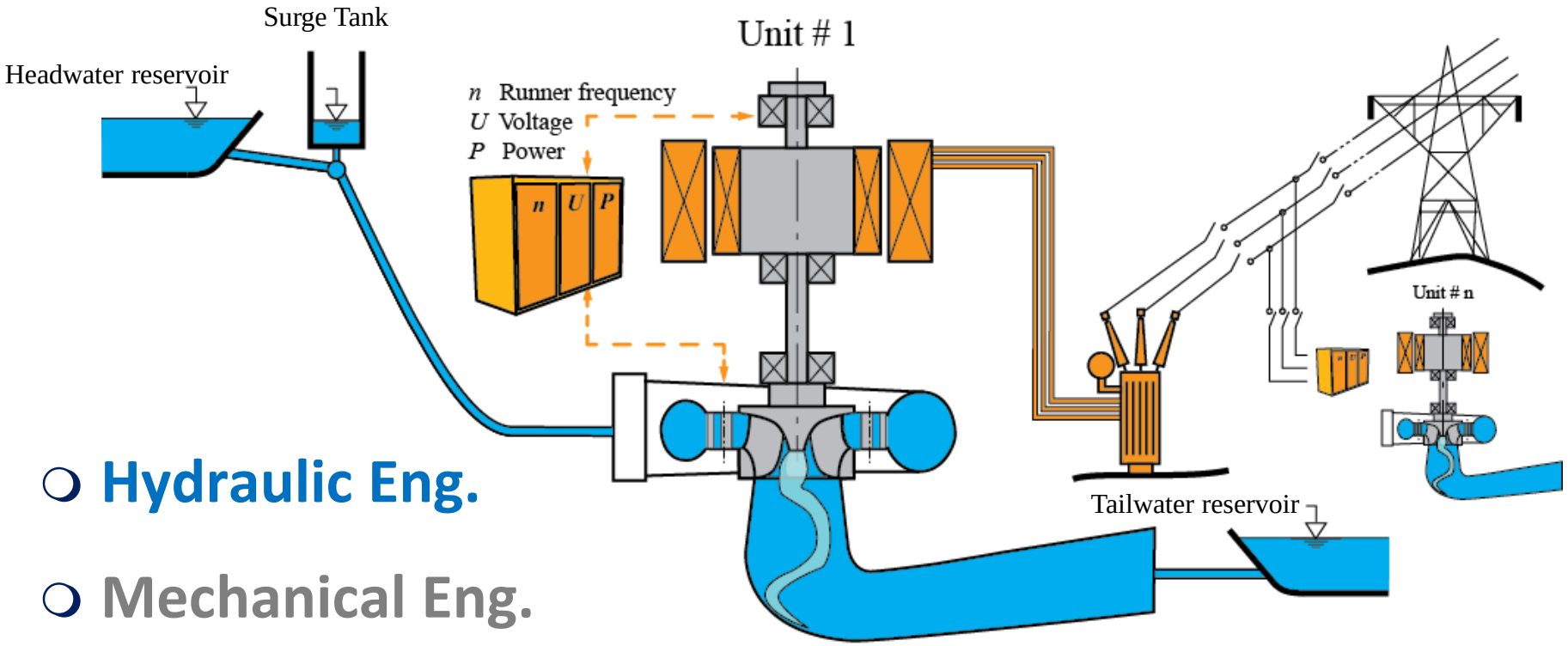
Center Industrial Diagnostics

HYPERBOLE

ERC/FP7-ENERGY-2013-1-Grant N° 608532

SoE	Partner	Country	Costs	EU Funding	Man Year
☑	EPFL Lausanne	CH	2'105'800	1'628'230	11.5
☐	GE Renewable Energy	F	748'357	410'800	4.0
☐	Andritz Hydro GmbH	A	405'400	220'950	1.8
☐	Andritz Hydro AG	CH	314'400	171'500	1.7
☐	Voith Hydro	D	711'700	361'200	3.1
☑	Power Vision Engineering	CH	285'760	217'800	1.7
☐	UPC Barcelona	SP	644'365	489'732	6.8
☐	INESTEC Porto	P	439'128	341'690	4.6
☐	TU Stuttgart	D	458'400	347'600	5.6
☑	HES SO Valais Sion	CH	181'334	136'000	1.3
		Total	**6'294'644**	**4'325'542**	**41.7**
	☑	***SoE***	***2'572'894***	***1'982'030***	***14.5***

HYdropower plants PERformance and flexiBle Operation towards Lean integration of new renewable Energies



- Hydraulic Eng.
- Mechanical Eng.
- Electrical Eng.
- System Approach

HYPERBOLE

ERC/FP7-ENERGY-2013-1-Grant 608532

Methodology

CDIF UPC
Center Industrial Diagnostics

INESCTEC
TECHNOLOGY & SCIENCE
ASSOCIATE LABORATORY
PORTUGAL

WP5
Field Test Based Validation

WP6
Powerplant Network Integration

WP4
Hydroelectric System Modelling

ANDRITZ Hydro

WP2
Mechanical Structure
Dynamics

WP3
Electrical Machine
and Power Electronics

WP1
Hydraulic Excitation Sources
Induced by Off-Design Operations

VOITH

Experimental
Investigations using
Reduced-Scale Physical Model

SIMSEN:System
Dynamics Numerical
Simulation Software

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

SIMSEN

HYPERBOLE Objective: Enhanced Flexibility Extended Operating Range

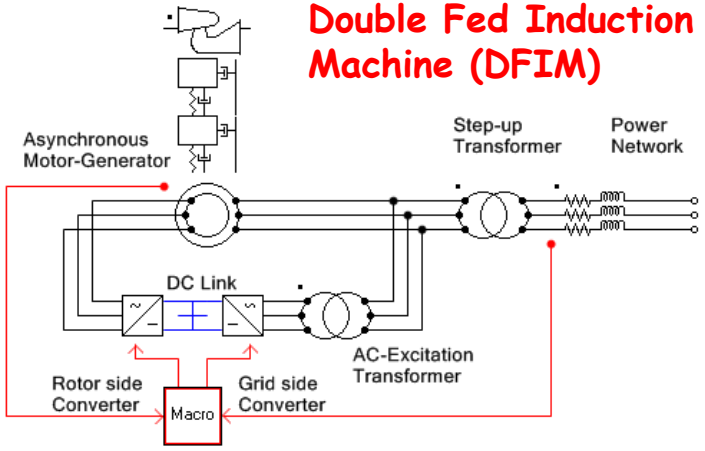
- Understanding the root causes of the operating range limitations (WP1, WP2, WP3)
  - ✓ Reduced Scale Physical Model Testing
  - ✓ Flow and Structure Numerical Simulations
  - ✓ 430 MW Francis Turbine Case Study
  - ✓ 220 MW Pump-Turbine Case Study
- Modeling and simulation of the hydropower plants dynamics over the full range of operation (WP4, WP5)
  - ✓ Transient Simulation
  - ✓ Hydro-acoustic Parameters
  - ✓ Francis Turbine Extensive Monitoring and Field Tests
- Enabling NRE(s) development (WP6)
  - ✓ Portugese Transmission System Case Study
  - ✓ Impact of Pumped Storage Plant

HYPERBOLE

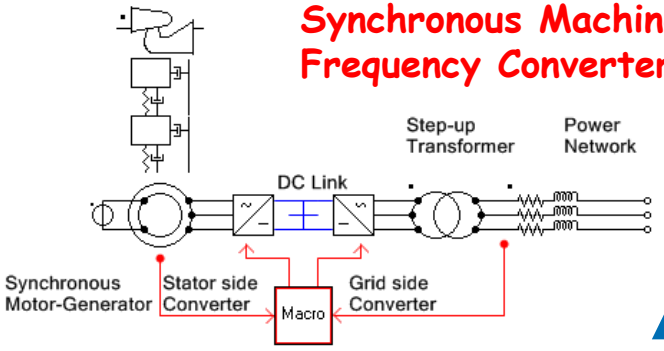
Fast Transition Mode

- **Variable Speed Technology**
  - ✓ Active power control in pumping mode
  - ✓ Fast active power injection/absorption in pump and turbine mode thanks to "Flywheel" effect
  - ✓ Extended operating range in turbine and pumping mode
  - ✓ Pump start-up without supplementary equipment
  - ✓ Suitability for large head variations in pump mode
  - ✓ Reactive power control (Static Var Compensator) at standstill

Double Fed Induction Machine (DFIM)



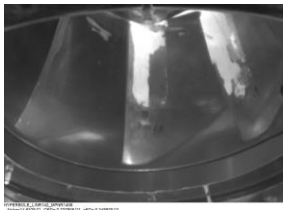
Synchronous Machine & Full Size Frequency Converter (FSFC)



ANDRITZ Hydro

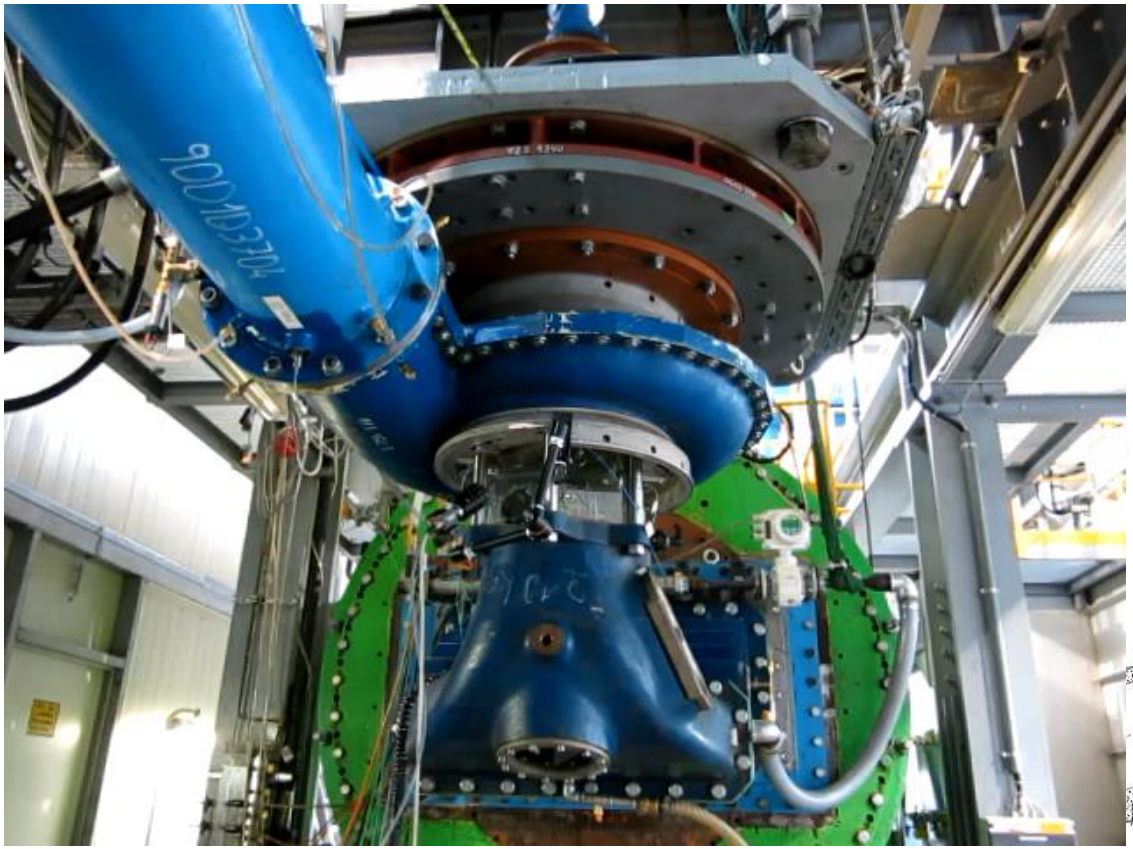
Power Vision Engineering

HYPERBOLE WP3 Reversible Pump-Turbine Reduced Scale Physical Model



- **Prototype**
  - ✓ 2 x 210 MW
  - ✓ H = 133.5 m
  - ✓ N = 200 min^{-1}
  - ✓ D_{ref} = 3.86 m
  - ✓ N_{QE} = 0.17
- **Model**
  - ✓ D_{ref} = 0.244 m
  - ✓ N_{QE} = 0.17

$$N_{QE} = n \cdot Q^{0.5} / E^{0.75}$$



Andritz Hydro Hydraulic Laboratory, Linz, Austria

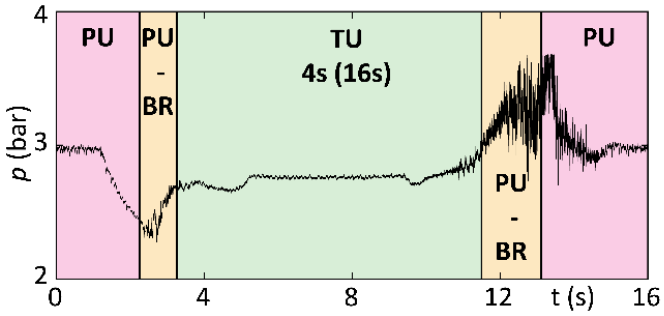
HYPERBOLE WP3

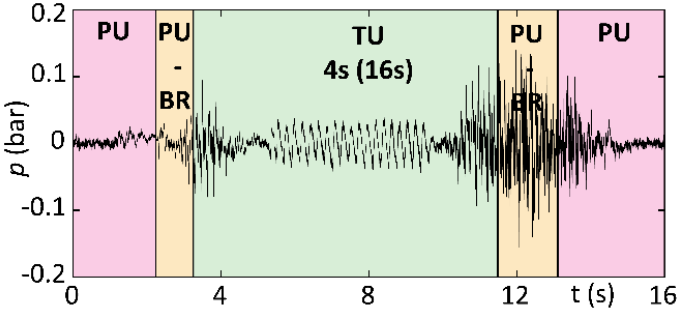
Pump-Turbine Fast Transition Mode

- ***p* Fluctuations Time History**

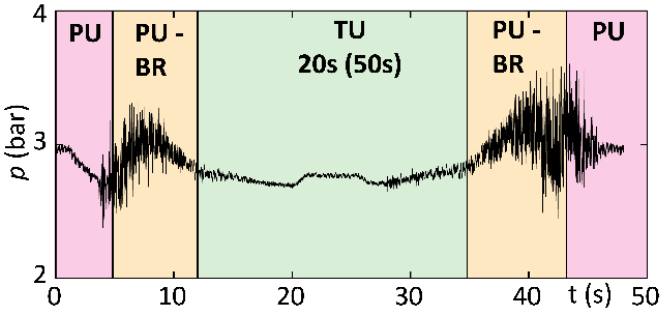
Blade less Gap | *Draft Tube Cone*

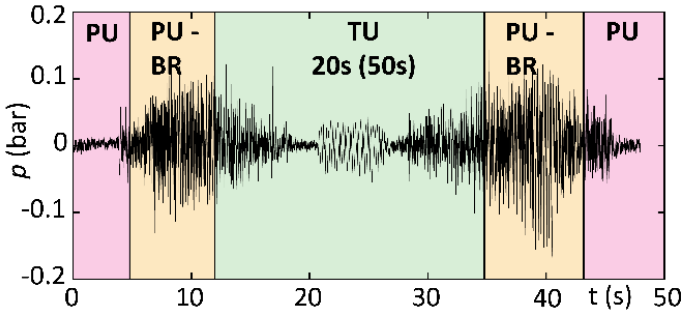
✓ ***Fast !***





✓ ***Slow !***



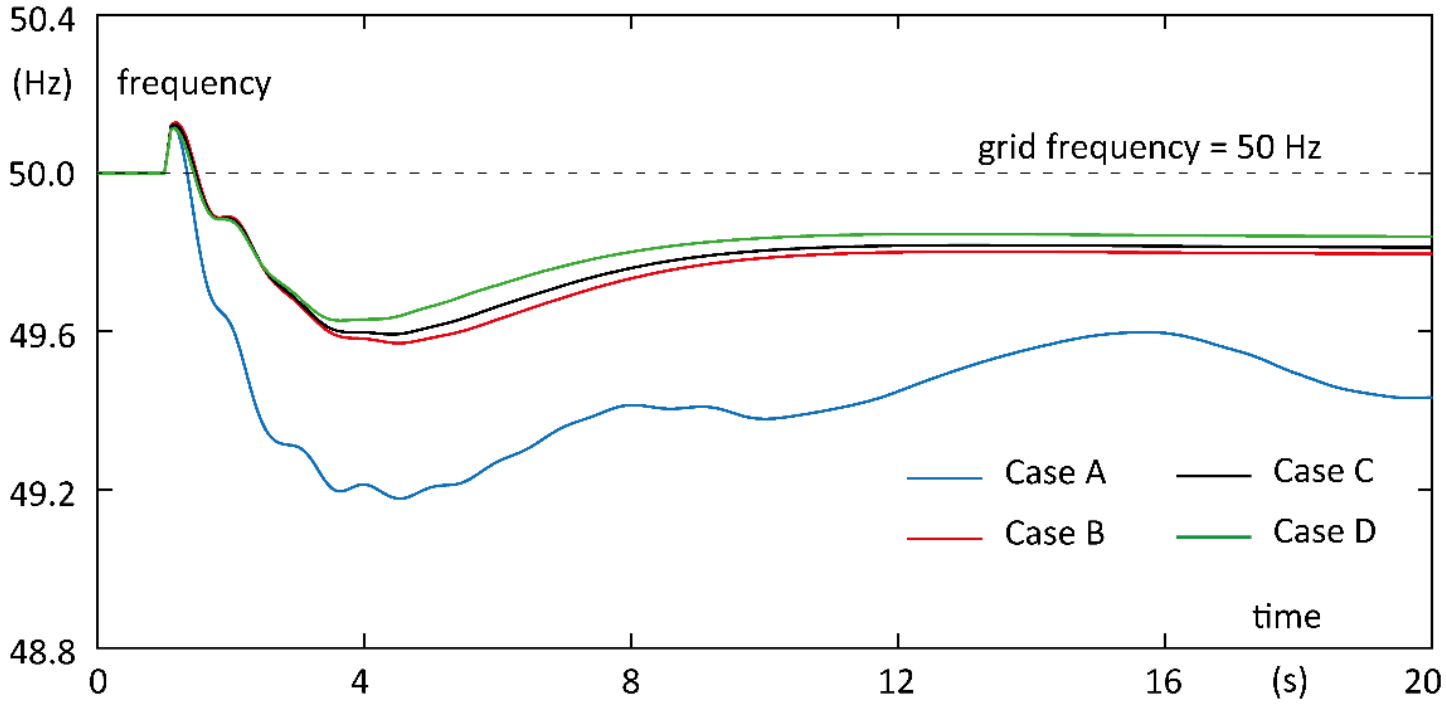


ANDRITZ Hydro

HYPERBOLE WP6

Impact of Pumped Storage Technology

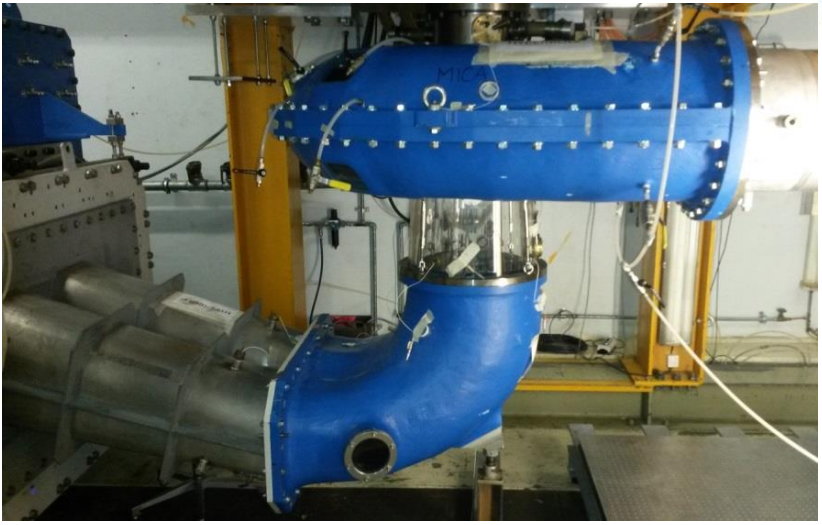
- **Portuguese Transmission System Test Case:**
  Fault leading the disconnection of non-FRT compliant wind farms

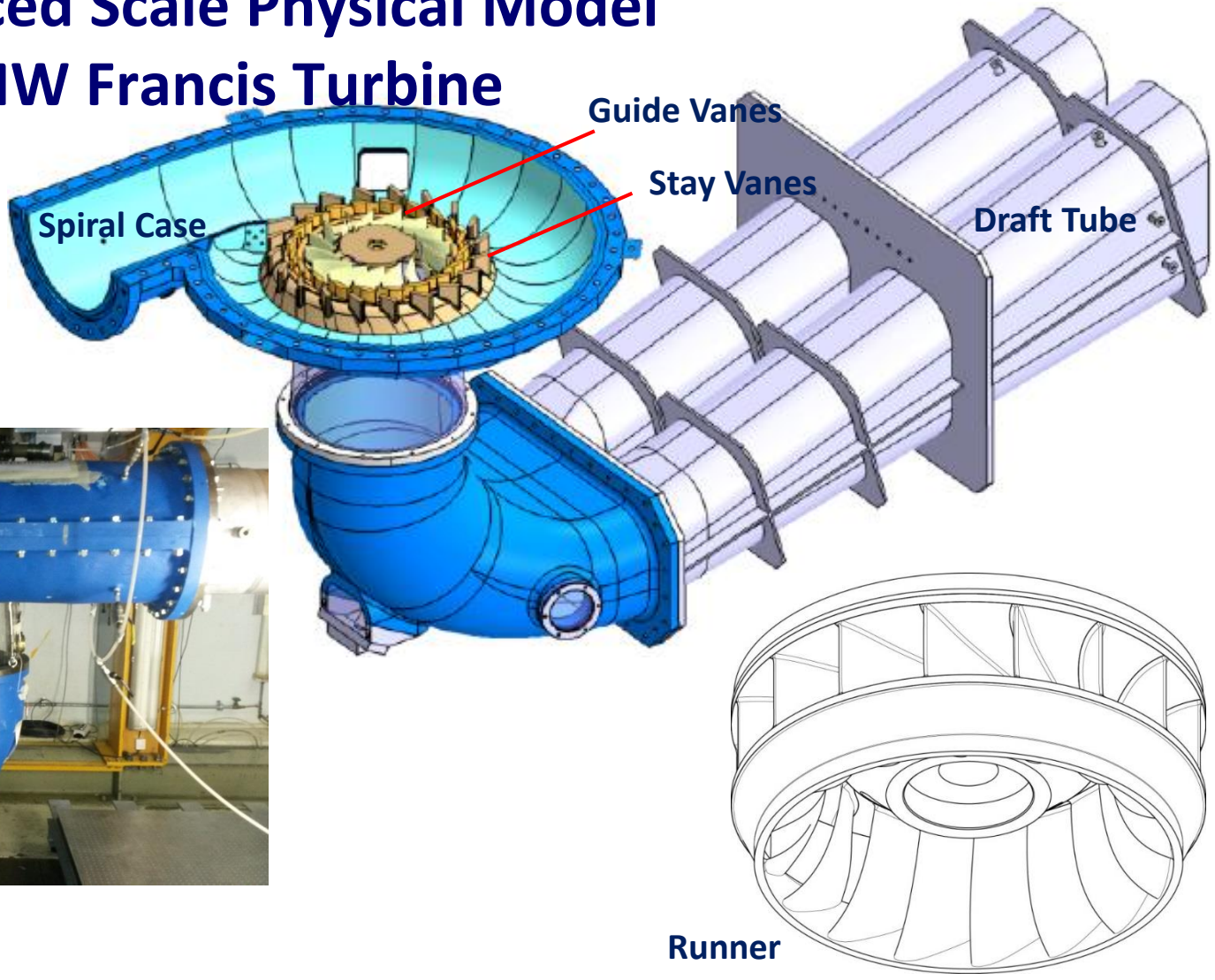


✓ **e.g. frequency restoration reserve (FRR) markets**

INESCTEC TECHNOLOGY & SCIENCE | ASSOCIATE LABORATORY PORTUGAL

1:16 Reduced Scale Physical Model of a 430 MW Francis Turbine

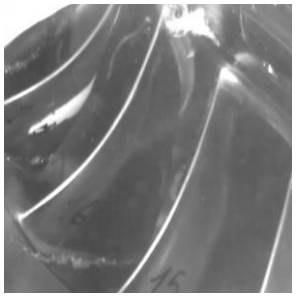


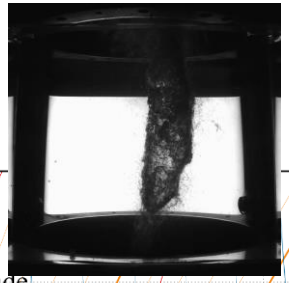


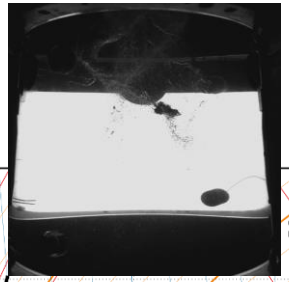
Experimental Set-Up: Francis Turbine Reduced Scale Model installed on EPFL PF3 Test Rig

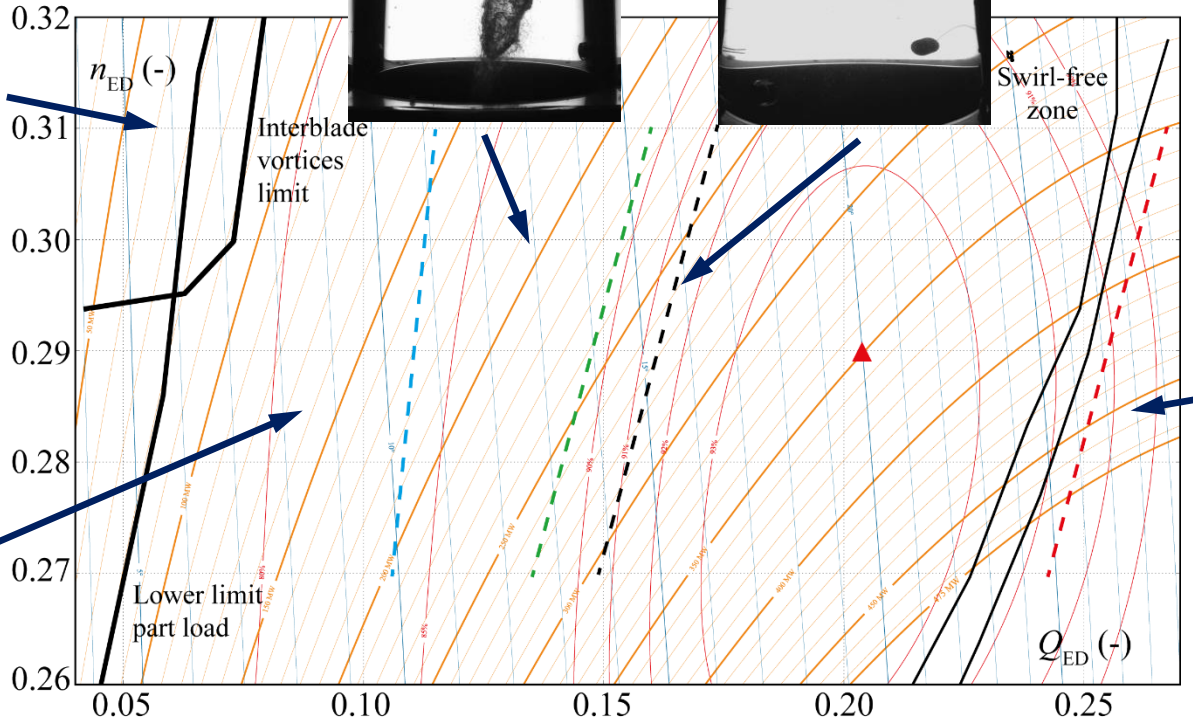
HYPERBOLE WP1 - WP4

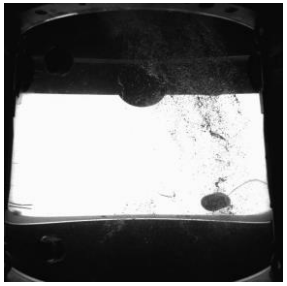
Vortex Cavitation Visualization

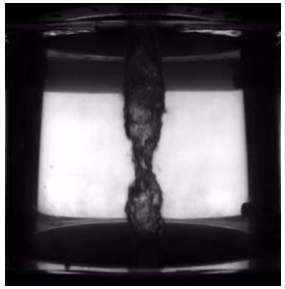








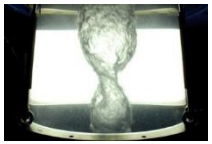


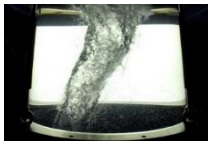


- - - - limit of full load stability
- - - - 1st limit at part load: development of vortex rope
- - - - 2nd limit at part load: development of high coherent vortex rope
- - - - 3rd limit at part load: transition between high coherent and no-coherent vortex rope

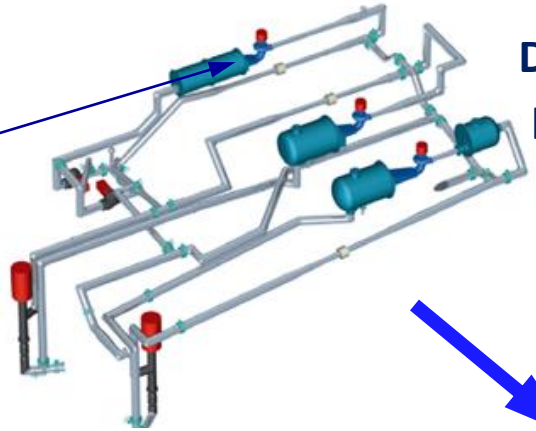
HYPERBOLE WP4: How to Transpose Generating Unit Dynamics from Model Tests to Prototype ?

Draft Tube Flow Instabilities



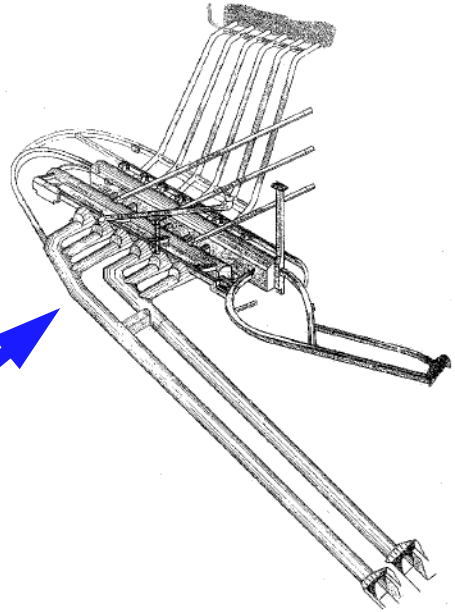


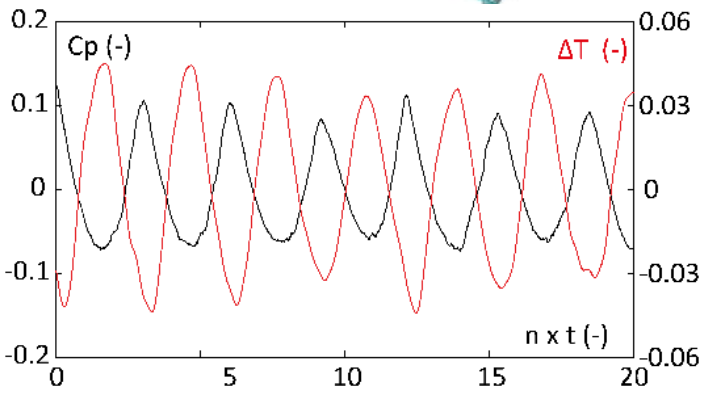
Reduced Scale Physical Model



Direct transposition of pressure fluctuations

Hydropower Plant



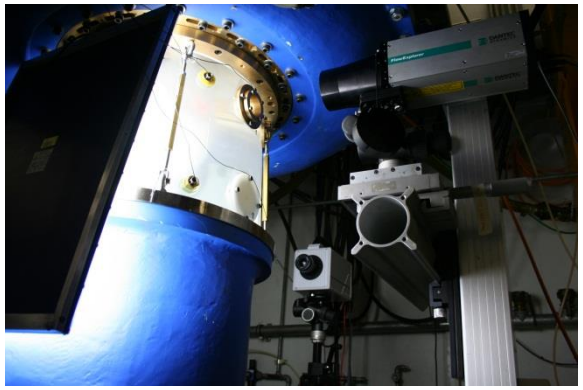


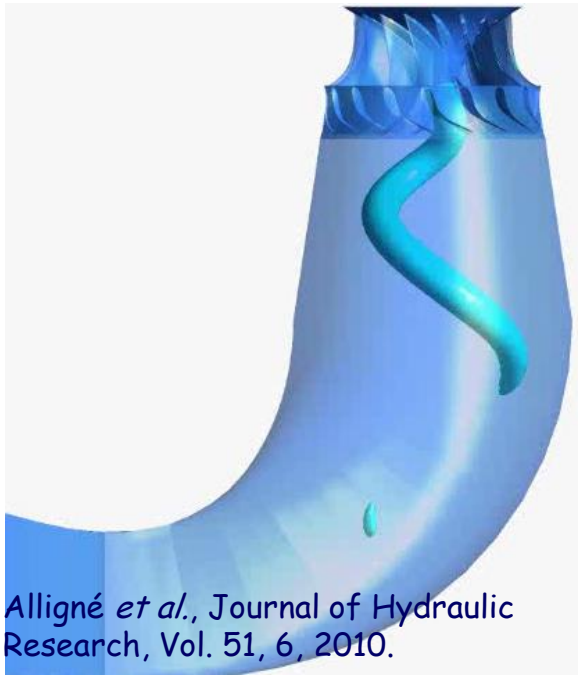
1D Transient Simulations

SIMSEN
http://simsen.epfl.ch/

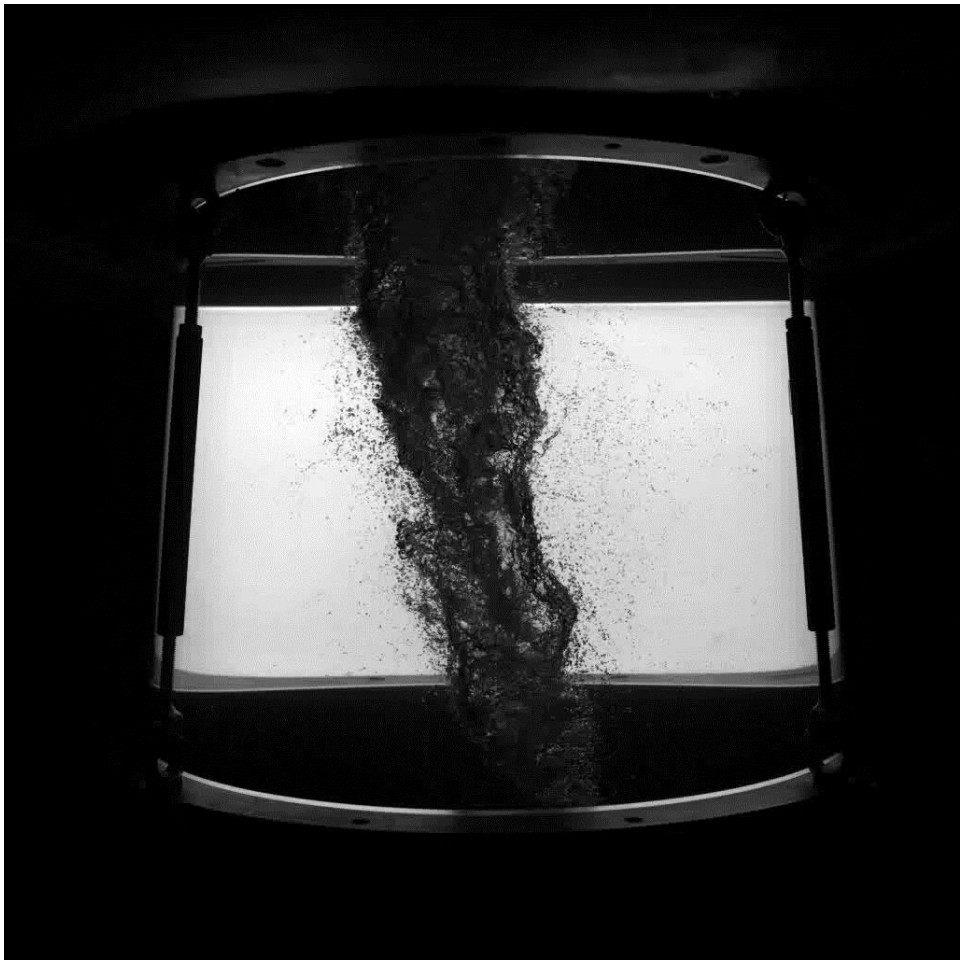
Power Vision Engineering

Francis Turbine: Unsteady Flow in Draft Tube





Alligné *et al.*, Journal of Hydraulic Research, Vol. 51, 6, 2010.

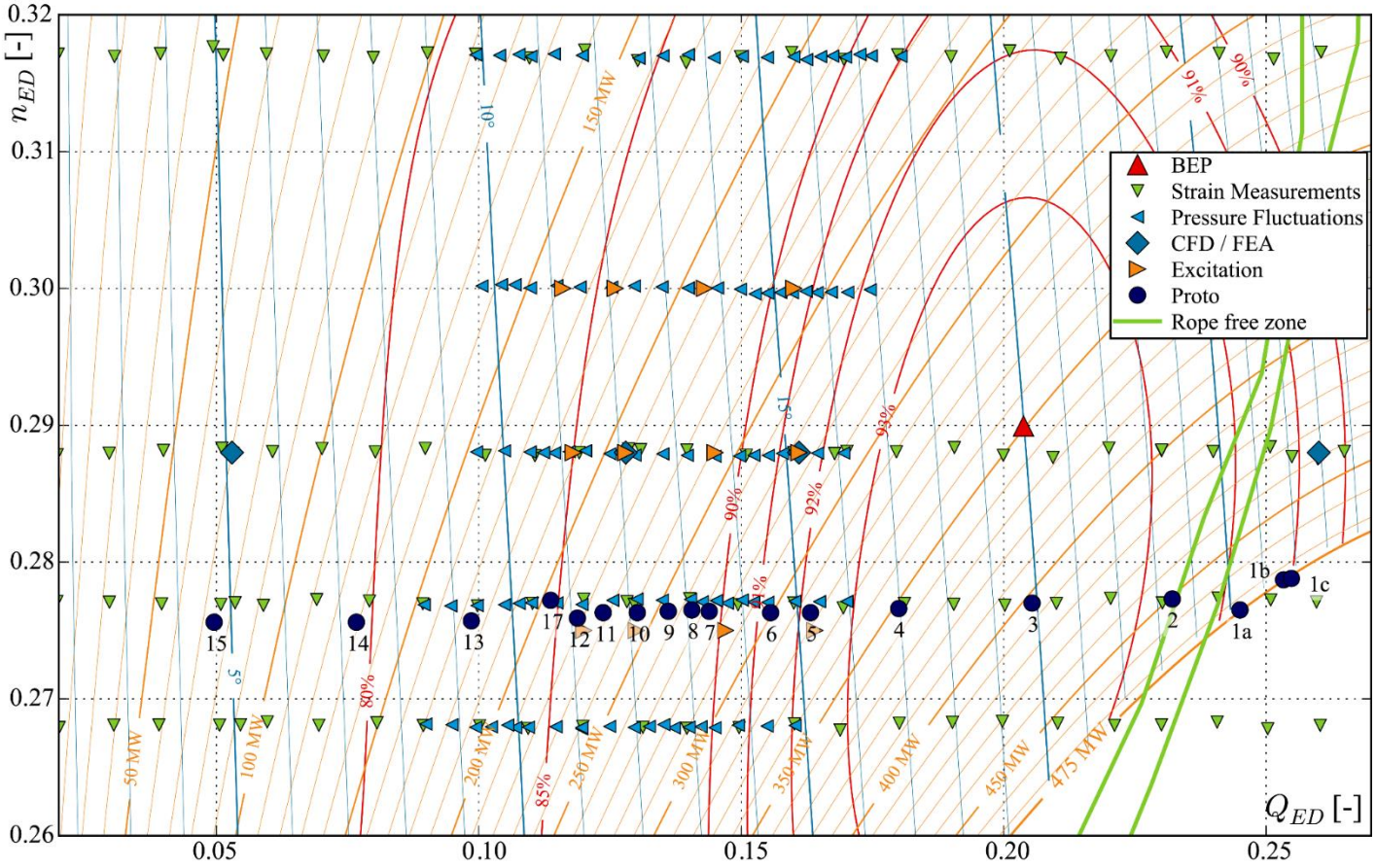


Simon Pasche Doctoral Work, SNF GRANT N° 200021_149818

Pasche et al. (2017) "Part Load Vortex Rope as a Global Unstable Mode", Journal of Fluids Engineering, Vol.139 (5).

HYPERBOLE WP4 Francis turbine test-case

Investigated operating conditions



HYPERBOLE WP5 Field Tests

- Spiral Case

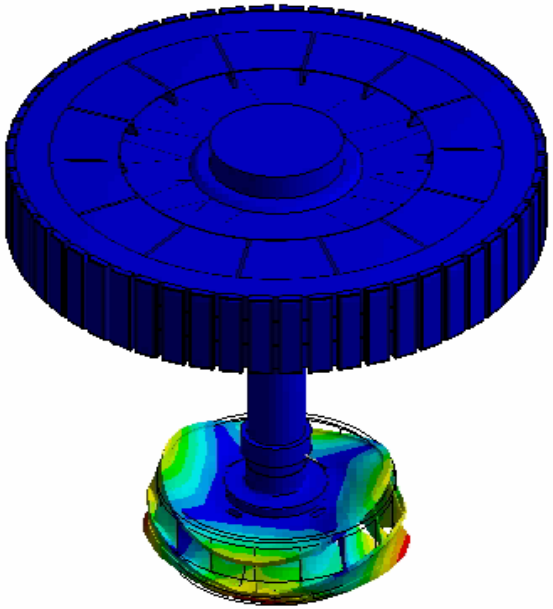
- Control Room

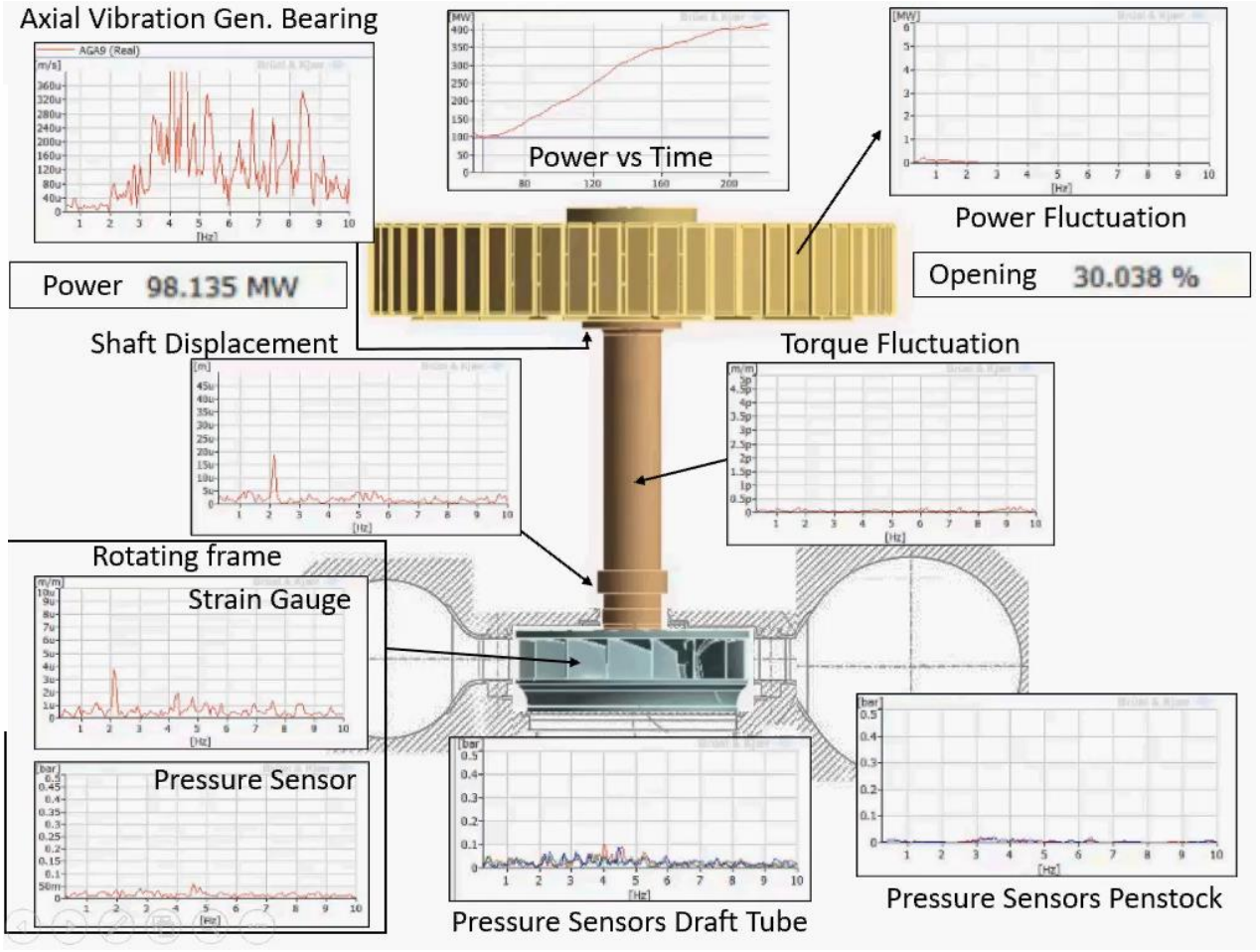
CDIF UPC Center Industrial Diagnostics

VOITH

HYPERBOLE WP5 Field Tests

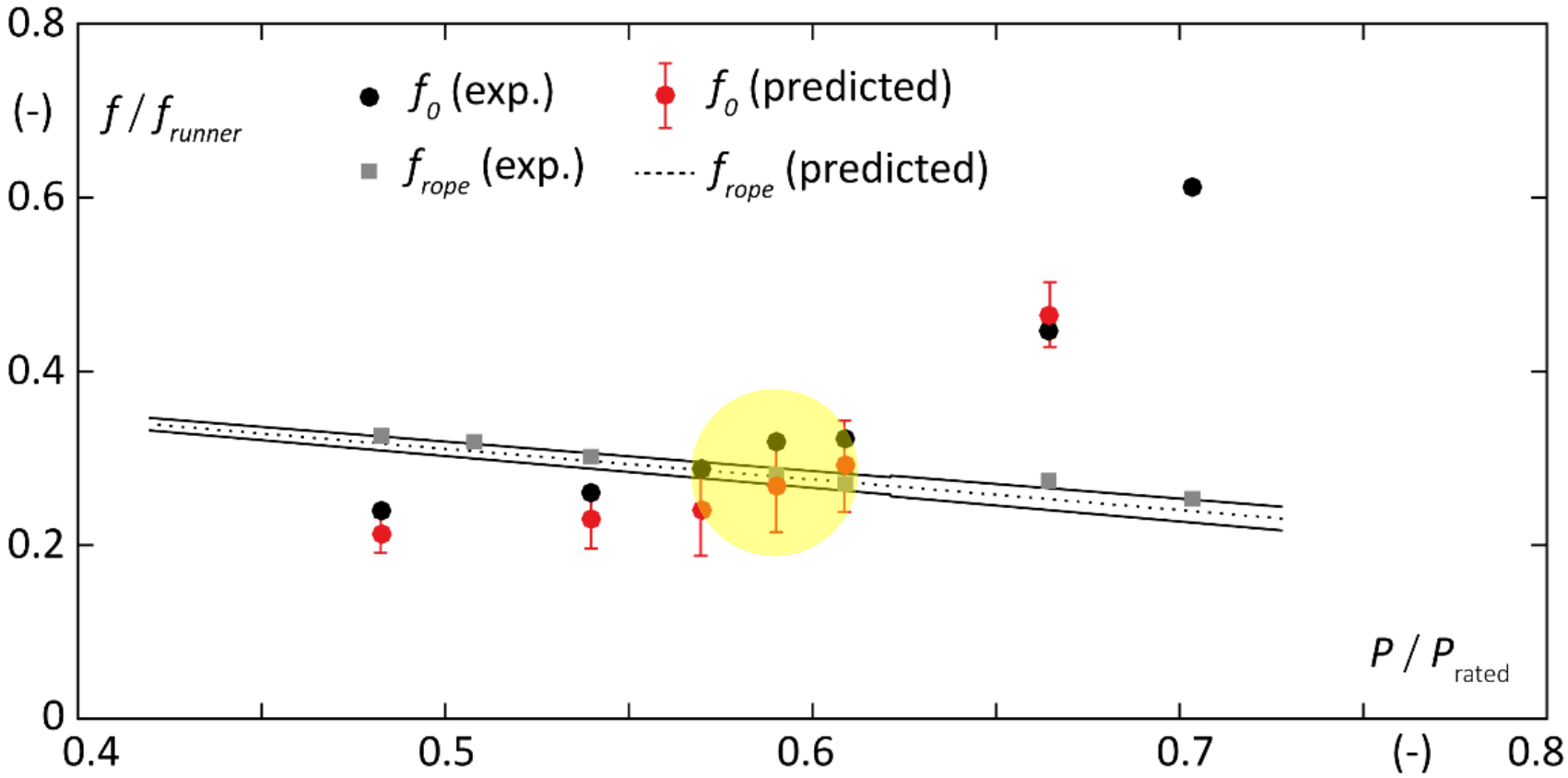
Power Ramp Up





CDIF UPC
Center Industrial Diagnostics

Delivery D4.4: Prediction of Resonance Onset for Part Load Operating Conditions



HYPERBOLE Papers & EPFL Theses

- **Full load:**
  - ✓ Müller et al. (2017), *"Fluid-structure interaction mechanisms leading to dangerous power swings in Francis turbines at full load"*, Journal of Fluids and Structures, vol. 69.
  - ✓ Müller et al. (2016), *"Measurement of the self-oscillating vortex rope dynamics for hydroacoustic stability analysis"*, Journal of Fluids Engineering, vol. 138.
  - ✓ Müller A. (2014), *"Physical Mechanisms governing self-excited pressure oscillations in Francis turbines"*, EPFL Doctoral Thesis n°6206.
  - ✓ Müller et al. (2013), *"Draft tube discharge fluctuation during self-sustained pressure surge: fluorescent particle image velocimetry in two-phase flow"*, Experiments in Fluids, vol. 54.
- **Part load:**
  - ✓ Favrel et al. (2017), *"New insight in Francis turbine cavitation vortex rope: Role of the runner outlet flow swirl number"*, Journal of Hydraulic Research, In Press.
  - ✓ Pasche et al. (2017), "Part Load Vortex Rope as a Global Unstable Mode", Transactions of the ASME, Journal of Fluids Engineering, Vol.139 (5), https://doi.org/10.1115/1.4035640.
  - ✓ Favrel et al. (2016), *"LDV survey of cavitation and resonance effect on the precessing vortex rope dynamics in the draft tube of Francis turbines"*, Experiment in Fluids, vol. 57(11)
  - ✓ Favrel A. (2016), *"Dynamics of the cavitation precessing vortex rope for Francis turbine at part load operating conditions"*, EPFL Doctoral Thesis n°6880.
  - ✓ Favrel et al. (2015), *"Study of vortex-induced pressure excitation source in a Francis turbine draft tube by particle image velocimetry"*, Experiment in Fluids, vol. 56 (12).

HYPERBOLE Papers Papers & EPFL Doctoral Theses

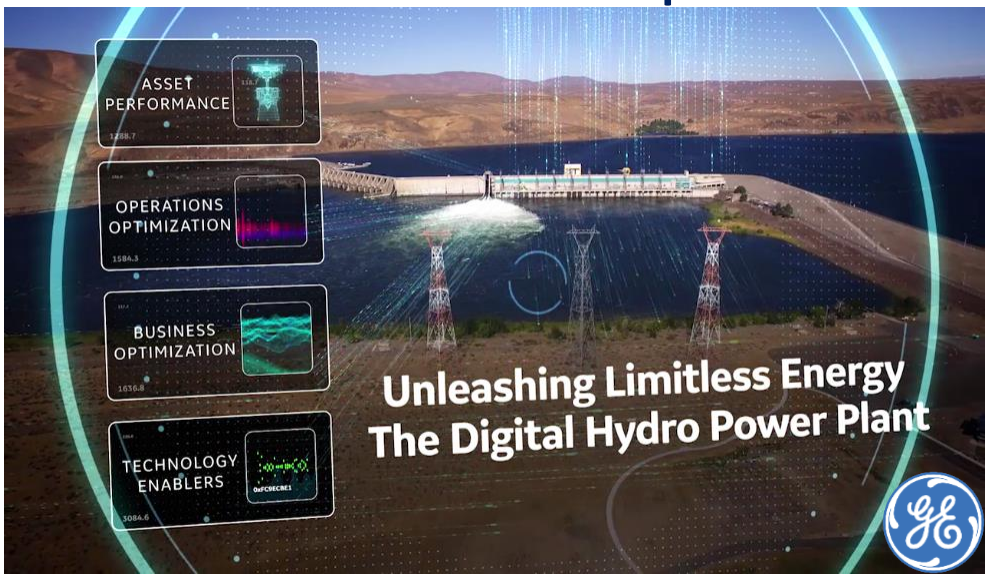
- **Deep part load:**
  - ✓ Yamamoto et al. (2017), *"Experimental evidence of inter-blade cavitation vortex development in Francis turbines at deep part load condition"*, Experiments in Fluids, in press.
  - ✓ Yamamoto K. (2017), *"Hydrodynamics of Francis turbine operation at deep part load condition"*, EPFL Doctoral Thesis n° 7730.
  - ✓ Yamamoto et al. (2015); *"Experimental method for the evaluation of the dynamic transfer matrix using pressure transducers"*, in Journal of Hydraulic Research, vol. 53.
- **Turbine Dynamics Modeling and Hydro-Acoustic Parameters Identification:**
  - ✓ Landry et al. (2016), *"Local wave speed and bulk flow viscosity in Francis turbines at part load operation"*, Journal of Hydraulic Research, vol. 52.
  - ✓ Landry C. (2015), *"Hydro-acoustic Modeling of a Cavitation Vortex Rope for a Francis Turbine"*, EPFL Doctoral Thesis n°6547.
  - ✓ Alligné et al. (2014), *"Cavitation surge modelling in Francis turbine draft tube"*, Journal of Hydraulic Research, vol. 52.

Outlook

- Unprecedented set of experimental and numerical simulation results
- Digital Avatar of Generating Unit Dynamics
- Enhanced Condition of Operation
- Advanced Maintenance

Conclusion & Outlook
Scientific Challenges and Engineering Education

- **Digital Disruption**
  - ✓ 17% of the World Electricity
  - ✓ 1'100 GW to be modernized
  - ✓ 1'000 GW to install up to 2050



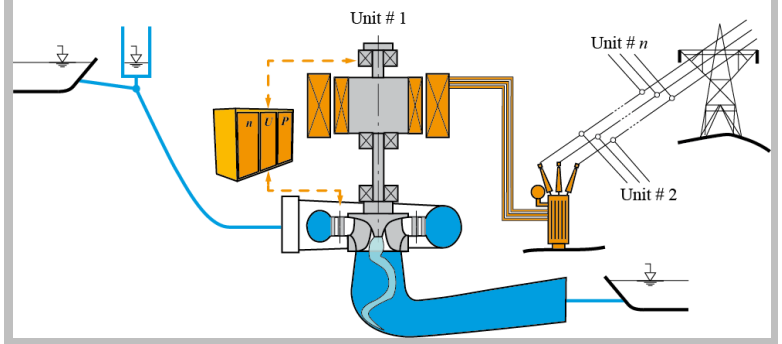
- **2050 CH Energy Strategy**
  - ✓ 59.9% of the Swiss Electricity
  - ✓ Water Protection Act
  - ✓ Ending Concessions
  - ✓ 11 GW to be Modernized

Outlook: Digital Turbine

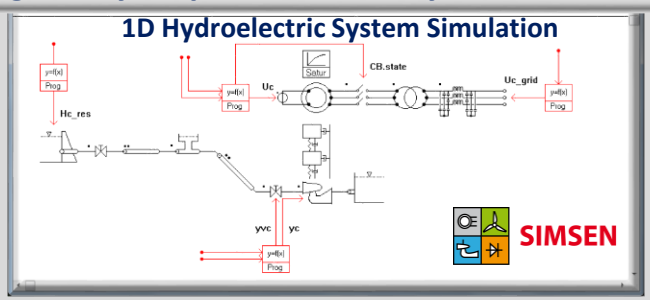
HPP Operating Conditions: Z_{up}, Z_{down}, P_{set1}, P_{set2}, etc.

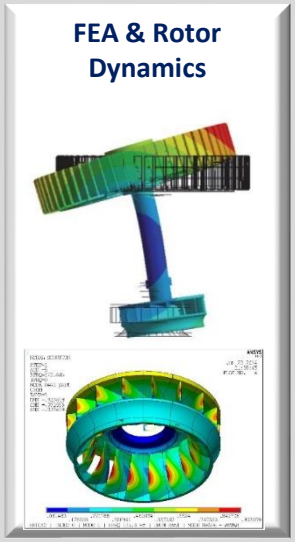
Off-Line Simulations for Specific Scenarios and Conditions

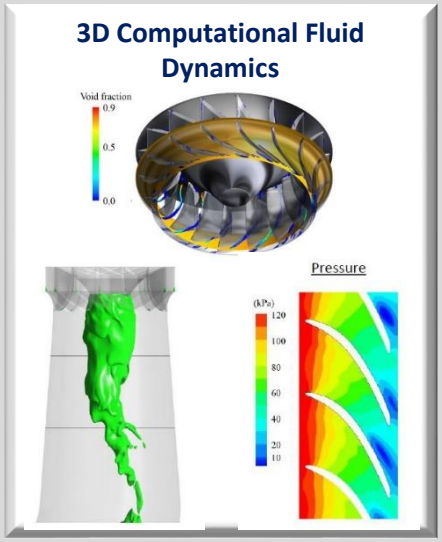
Actual Hydropower Plant



Digital Hydropower Plant Dynamics Avatar







Real-Time Condition Monitoring

Comparison, Upgrading

Reaction to Abnormal Operation

Calculated Parameters

Management Recommendations, Maintenance

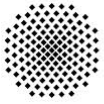
Lifetime Prediction, Failure Forecast

Digital Avatar of Hydropower Plant Dynamics for Enabling Enhanced Services to the European Grid

THANK YOU FOR YOUR ATTENTION




Center Industrial Diagnostics



Universität Stuttgart


Special thanks to the HYPERBOLE Consortium

This project has received funding from the European Union's 7th Framework Programme for research, technological development and demonstration under grant agreement n° 608532

HYPERBOLE

ERC/FP7-ENERGY-2013-1-Grant N° 608532

- February 2017: 2 Days Conf. in Porto (125 attendees)
- 23 Deliverables
- 52 Peer reviewed papers
- 7 Doctoral theses

Model Testing by the Numbers @ EPFL

- Since 10 Years …..
  - ✓ 80'000 MW Installed Capacity
  - ✓ 85 Hydropower Projects for 23 Countries
  - ✓ 19'594 MW in PR China
  - ✓ 19'316 MW in Brazil
  - ✓ 16'205 MW in Canada
  - ✓ 19 Reduced Scale Physical Models