Hydraulic Power Take-Off for Wave Energy Converters

Design, Validation and Control

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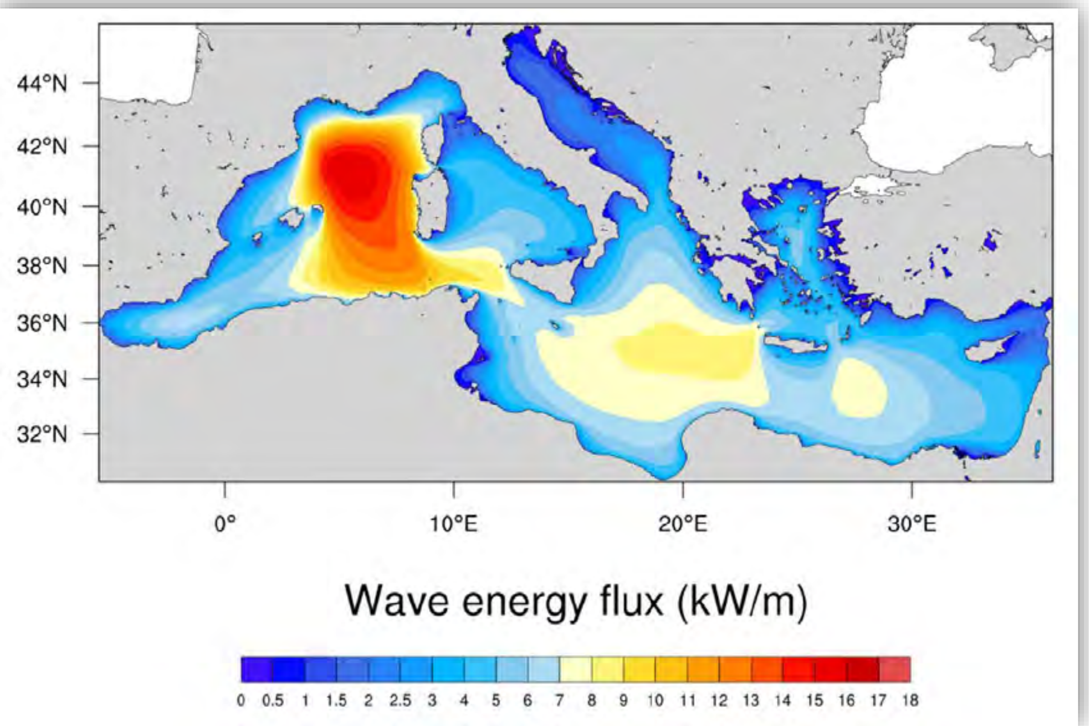
- The Hydraulic Power Take-Off
- Preliminary studies
- Optimal Control
- Design tool
- Test Rig Tests and Experimental Validation
- Conclusions

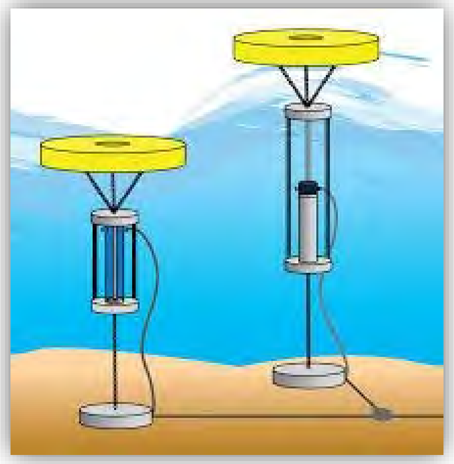
Introduction – Wave Energy Context



The global ocean wave power potential is approximated to be up to 10 TW, and the annual ocean wave energy is approximated to be up to 93,000 TWh [1]

Harness wave energy damping directly the motion of a floating or submerged buoy

Relative motion of mechanical and structural parts constantly in contact with the harsh marine environment

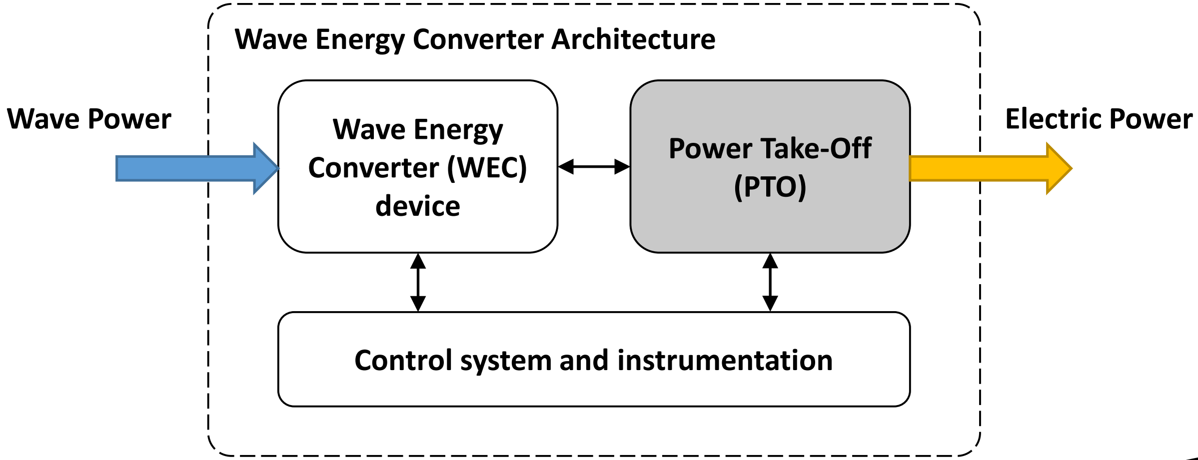


Ocean waves convey power through motions that feature high torques and low speeds

The torques become too high to be handled by electro-mechanical components, up to a level that commercial units are no longer available

[1] Melikoglu, M. Current status and future of ocean energy sources: A global review.

Introduction – Motivation

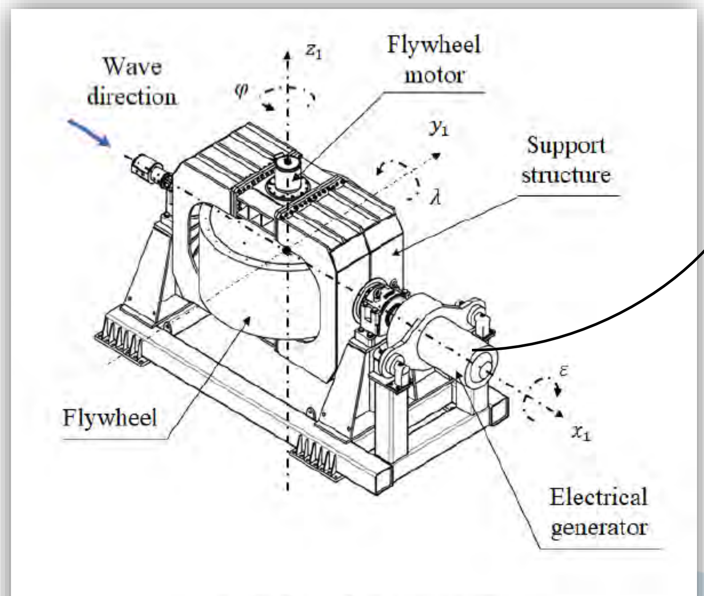


Ocean waves convey power through motions that feature high torques and low speeds

Bidirectional motion and wide range of operational conditions

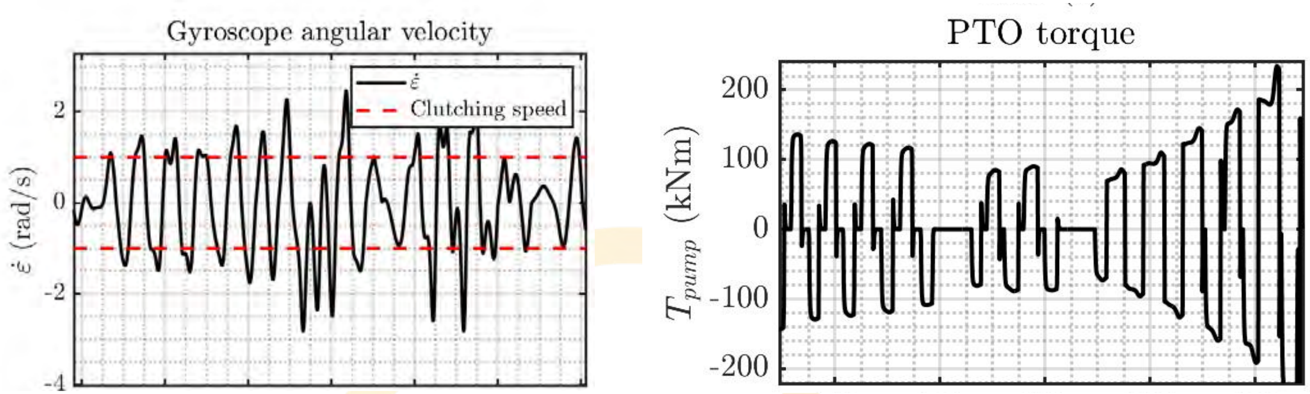
The torques become too high to be handled by electro-mechanical components, up to a level that commercial units are no longer available

Handle power peaks, irregular power generation and Isolated grid management



(b) ISWEC gyroscope

Typical PTO Torque and Speed



Solution?

The Hydraulic Power Take-Off - Advantages

“Hydraulic PTO components are the choice of the vast majority of developers since they offer unmatched force density at low velocities, high controllability and relatively easy rectification (valves) and smothering (accumulators) solutions” [1].

Advantages

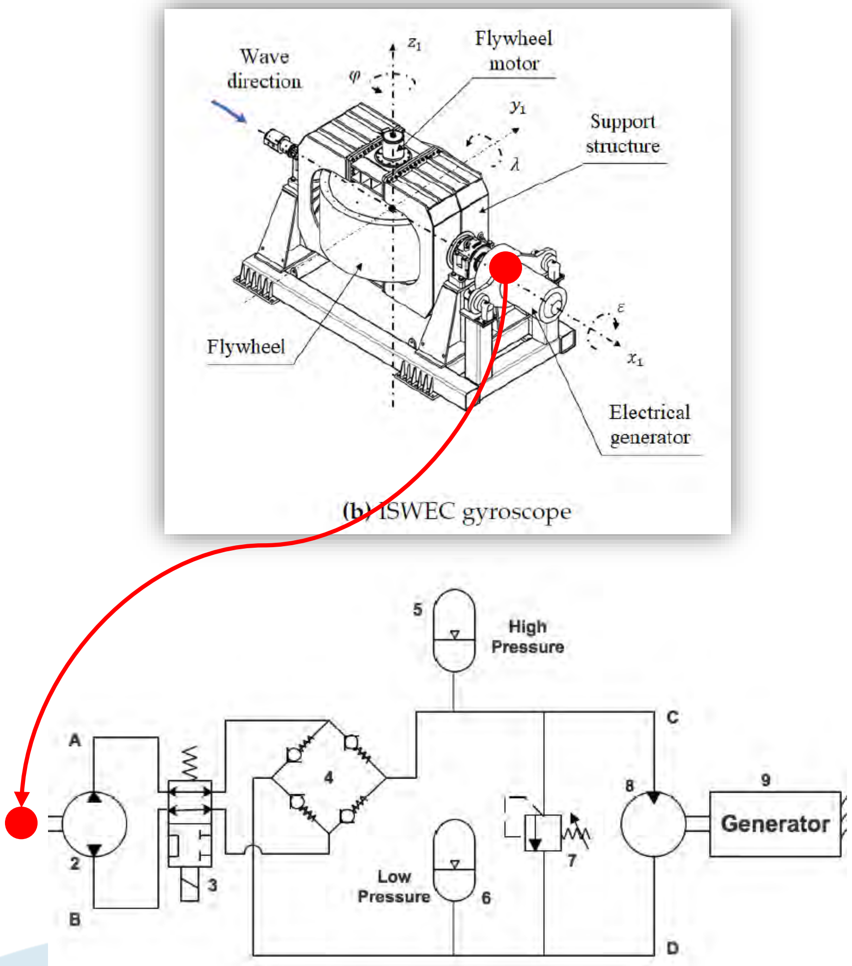
- High torque densities at low velocities with standard components
- High Controllability and relatively easy rectification
- High scalable employing the same technology
- Smothering and storing a large quantity of energy

Elettro-mechanical PTO comparison

- No Gear box and No supercapacitors required
- Downsize of the power electronics and electrical generator

To be assessed

- Efficiency – expected 70-80%
- PTO costs: 25 % of the total device cost



[1] A Review of Wave-to-Wire Models for Wave Energy Converters - Markel Penalba, John V. Ringwood

The Hydraulic Power Take-Off – PhD Timeline

1st Year	2nd Year	3rd Year
Hydraulic PTO preliminary studies HIL test rig design	**Hydraulic PTO advanced non-linear MPC control HIL test rig construction**	**Hydraulic PTO design-tool HIL test rig experimental tests and validation**

Hydraulic PTO preliminary studies → **Hydraulic PTO advanced non-linear MPC control** → **Hydraulic PTO design-tool**

Hydraulic PTO preliminary studies
- → **Configurations analysis**
- → **Controllability**
- → **Performance evaluation**

Hydraulic PTO advanced non-linear MPC control
- → **MPC control framework**
- → **Efficiency aware optimal control**
- → **Performance evaluation**

Hydraulic PTO design-tool
- → **Genetic algorithm**
- → **Tecno-economic optimization**
- → **Multi-objective performance evaluation**

Existing numerical model supported the test rig design

Advanced control techniques call for a performing hardware for the test rig

HIL test rig design → **HIL test rig construction** → **HIL test rig tests and validation**

HIL test rig design
- → **Circuit configuration**
- → **Hydraulic components**
- → **Sensors and acquisition system**

HIL test rig construction
- → **Test rig construction**
- → **Hardware design**
- → **Preliminary tests**

HIL test rig tests and validation
- → **Efficiency evaluation**
- → **Numerical model validation**
- → **Test rig performances**

Hydraulic PTO model validation supported the numerical design-tool

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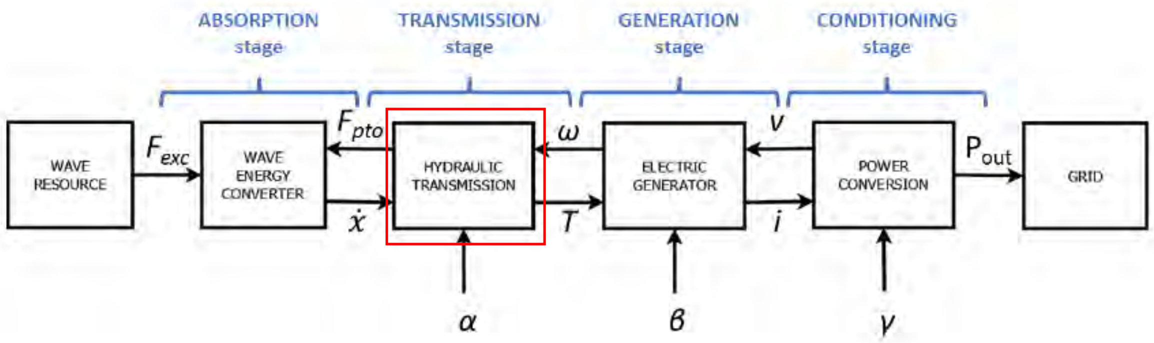
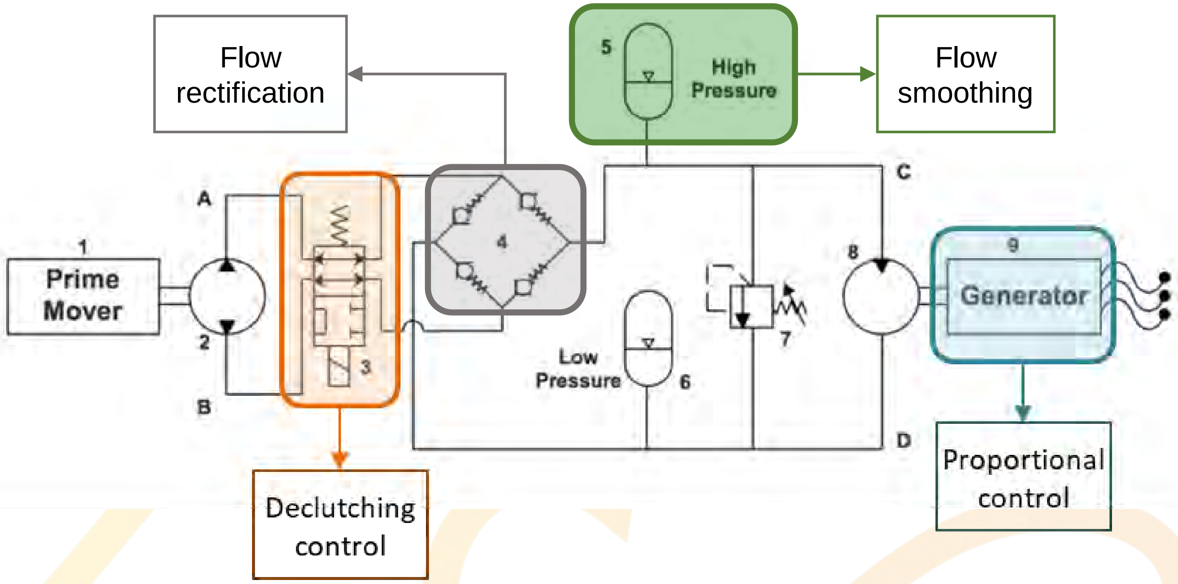
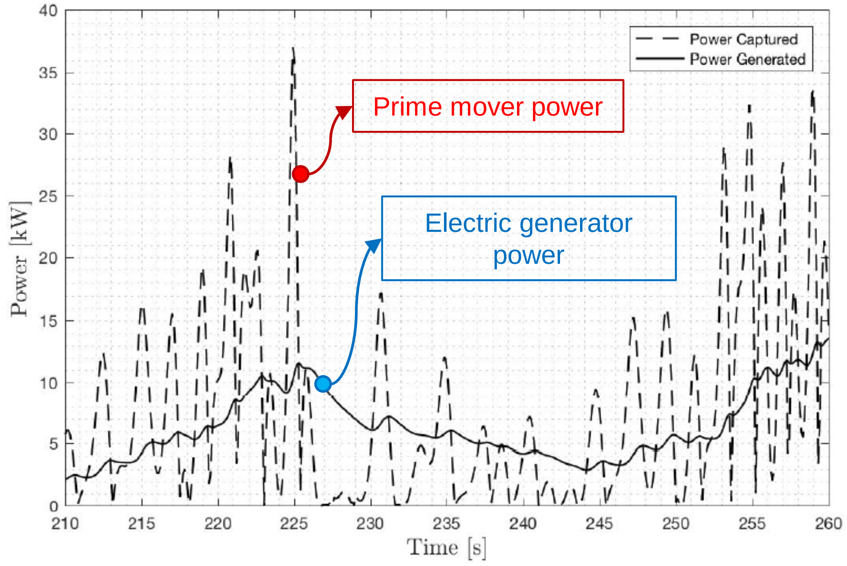
Ongoing activities

Preliminary studies - Architecture







Relatively simple configuration – low components

Possibility to handle more than one gyroscopic unit with one electrical generator

Smothering and control properties to improve the extracted power

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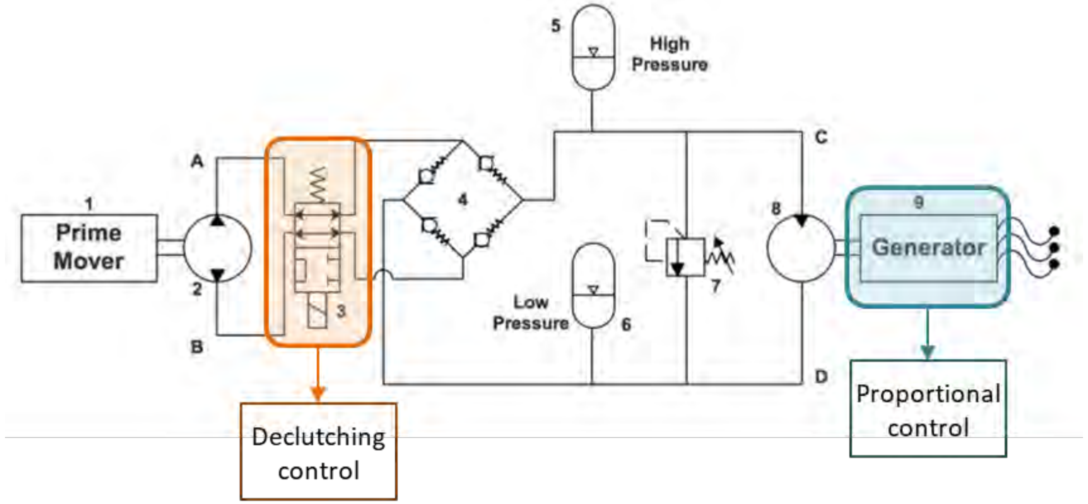
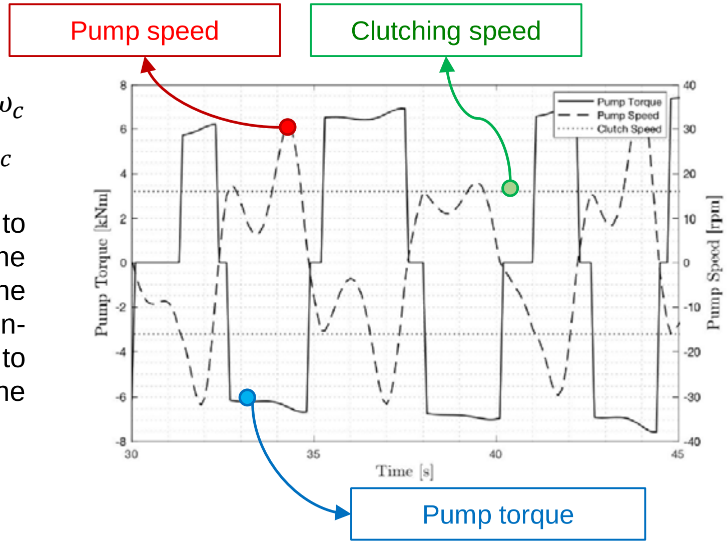
Preliminary studies - Controllability



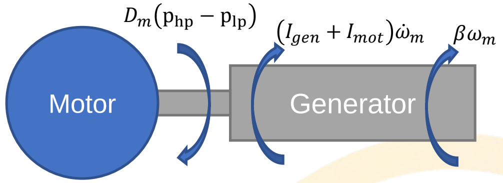
Declutching control

$$\begin{cases} \Delta_{p_{pump}} = \Delta_p \quad if \quad \omega_p > \omega_c \\ \Delta_{p_{pump}} = 0 \quad if \quad \omega_p < \omega_c \end{cases}$$

Declutching control is used to decouple the pump (and the prime mover) from the accumulator action. This on-off modulation allows to 'regulate' the torque on the prime mover.



Proportional control

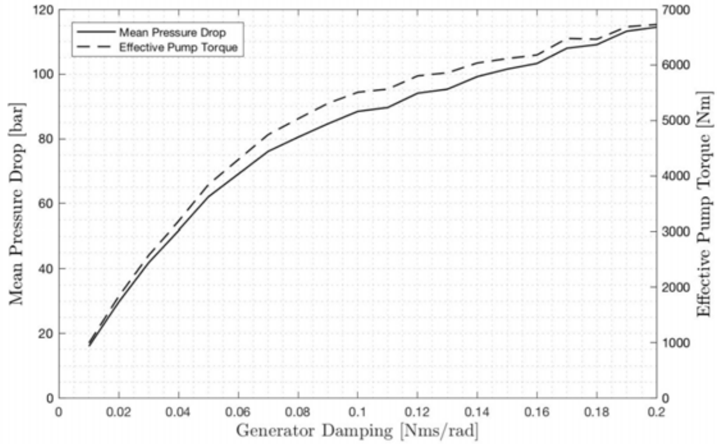


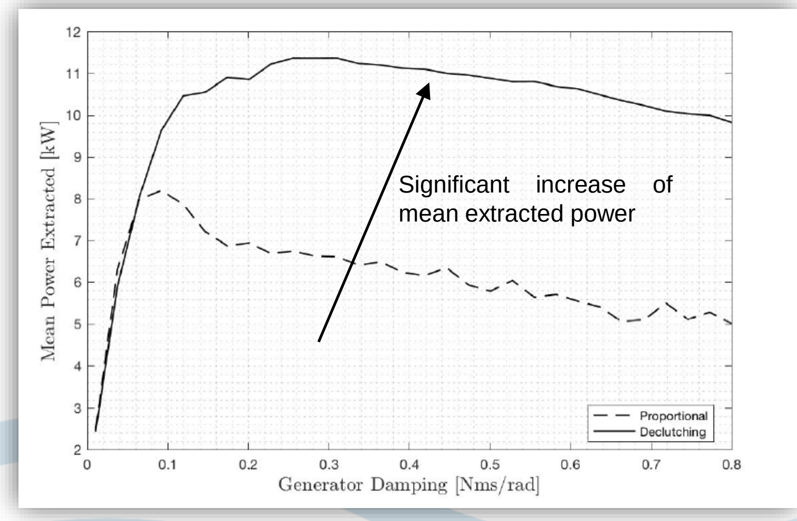
$$D_m(p_{hp} - p_{lp}) = (I_{gen} + I_{mot})\dot{\omega}_m + \beta\omega_m$$

$$D_m(p_{hp} - p_{lp}) \cong \beta\omega_m \rightarrow \frac{D_m^2}{\beta}(p_{hp} - p_l) \cong Q_m$$

$$Equilibrium\ state: \overline{\Delta_p} \cong \frac{\beta}{D_m^2}\overline{Q_m}$$

Proportional control ends up being a control on the pressure values, such in a way that their difference is kept around the mean value





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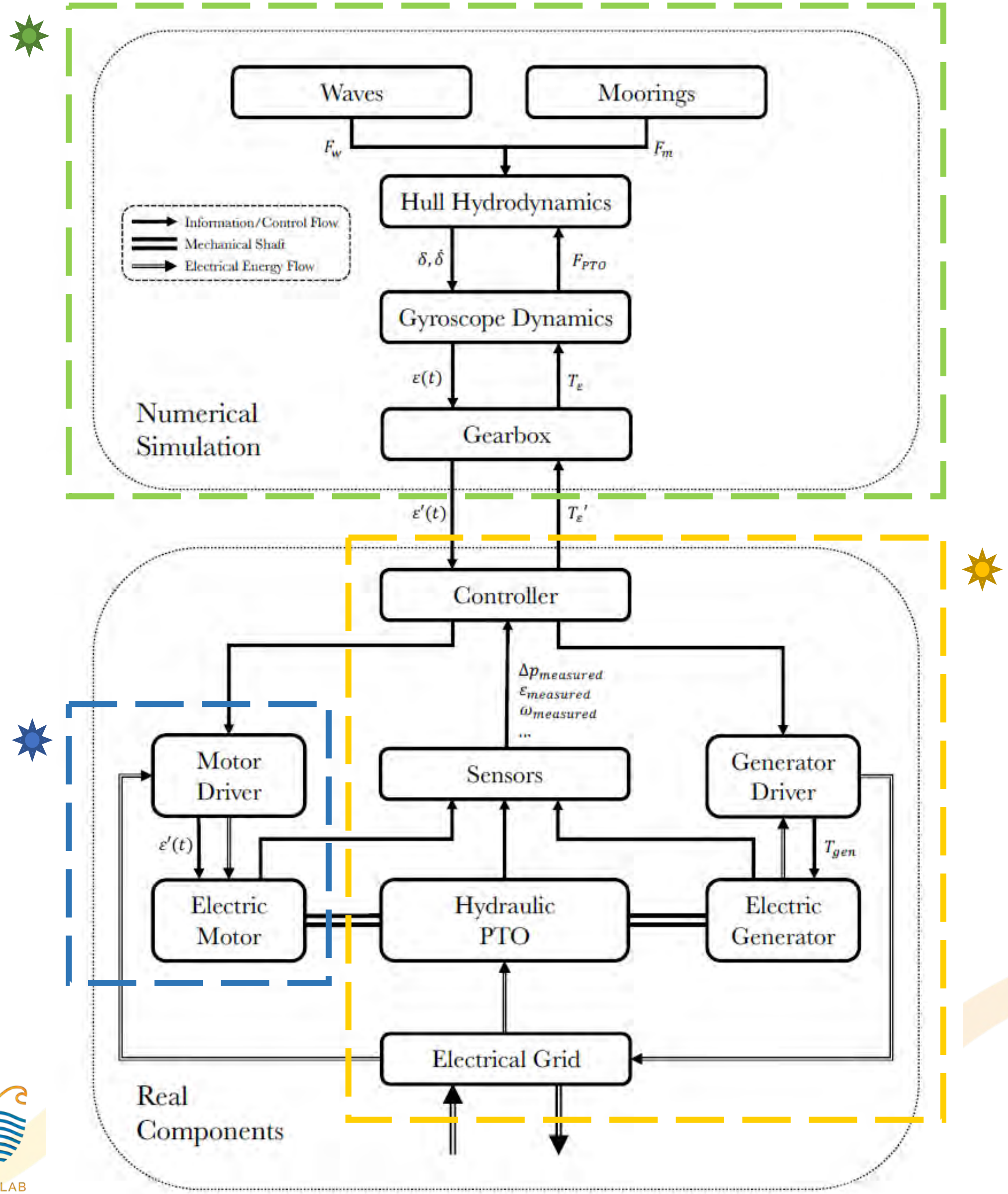
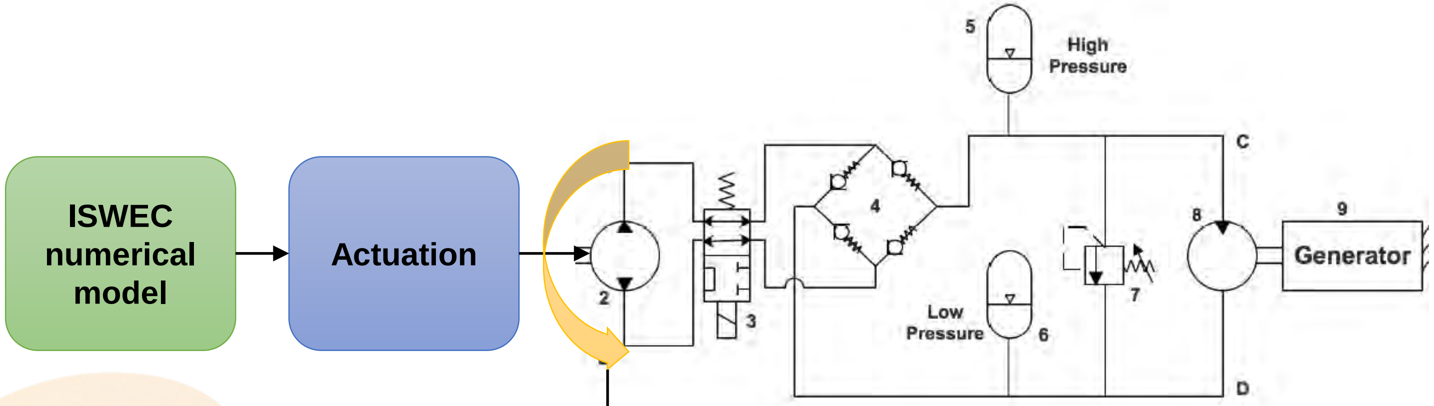
Preliminary studies – HIL test rig



- Numerical model (validated in previous works)
- Actuation part (not used in real device)
- Hydraulic PTO, control and power electronics (part to test)

Hardware In the Loop (HIL) simulations



Hydraulic Pump Speed controlled

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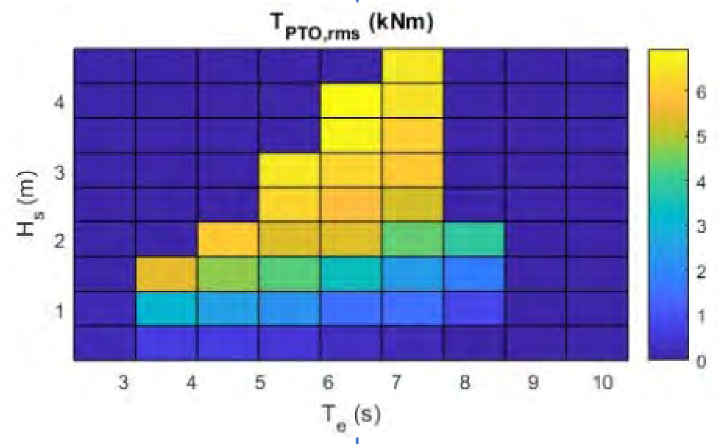
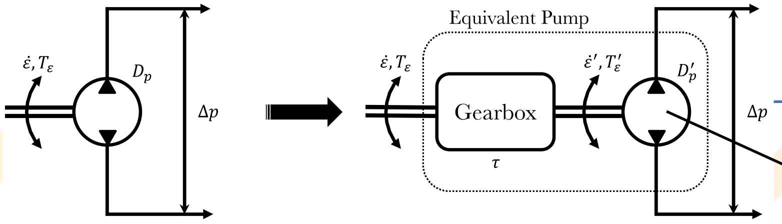
Preliminary studies - Test rig design

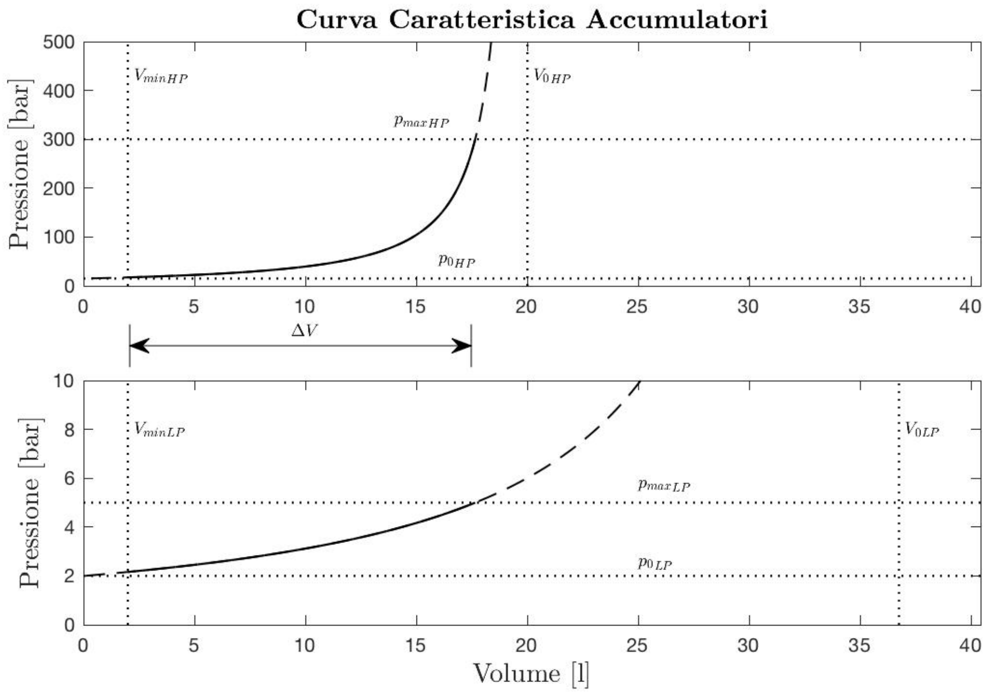
Mechanical Power Take-Off → Simulations and Power Optimization → Rms torque values



Maximum rms torque → Maximum pressure 300 bar → $D'_p > \frac{6936\ Nm}{300\ bar} = 1340\ cm^3$

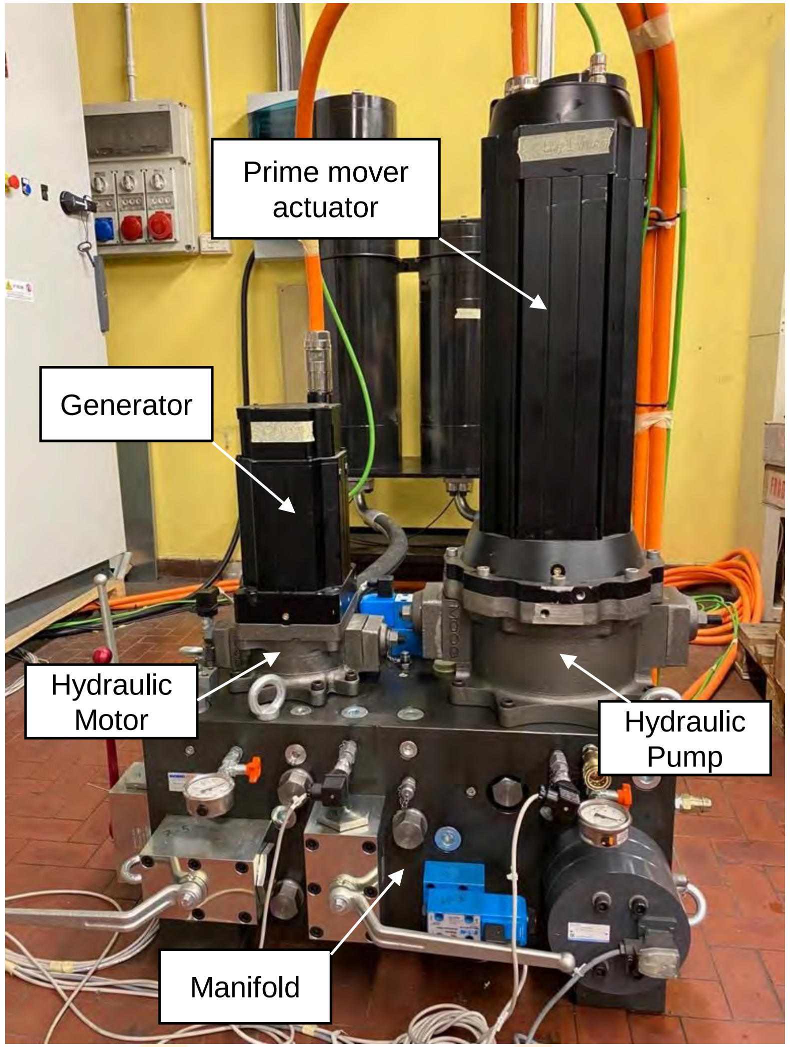


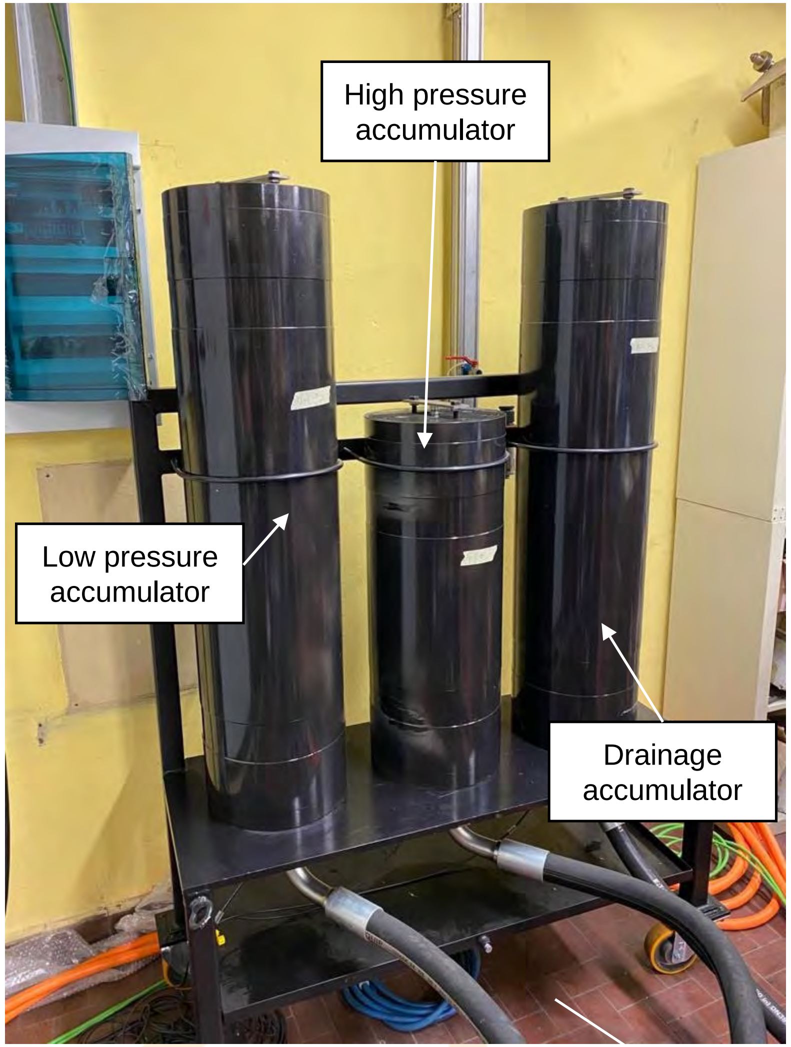
Minimum pressure 2 bar → Maximum pressure 300 bar → Maximize flow damping without power losses

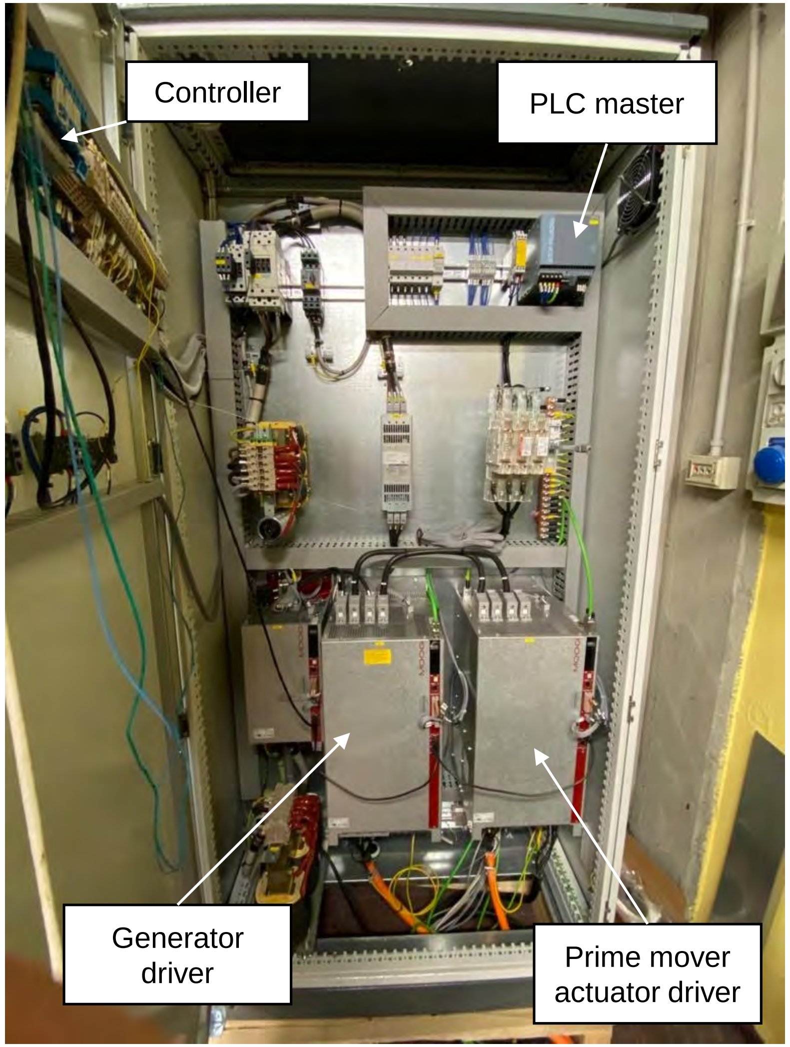


Real Pump → $80\ cm^3$

Preliminary studies – Test rig Construction

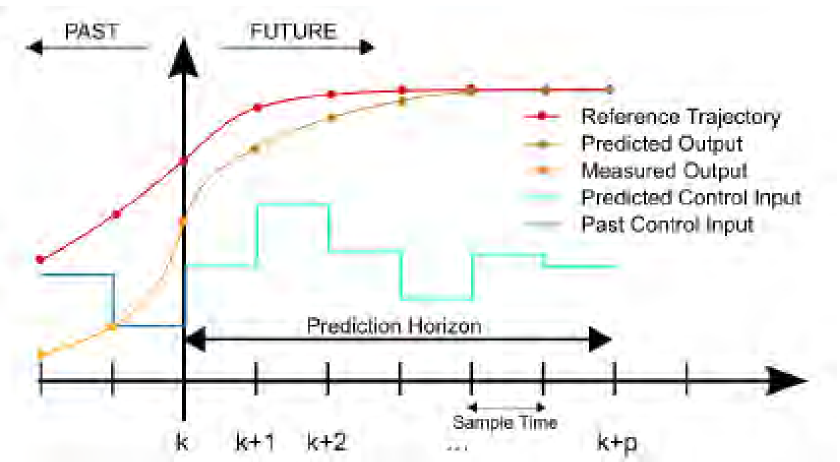






Optimal control – Control framework

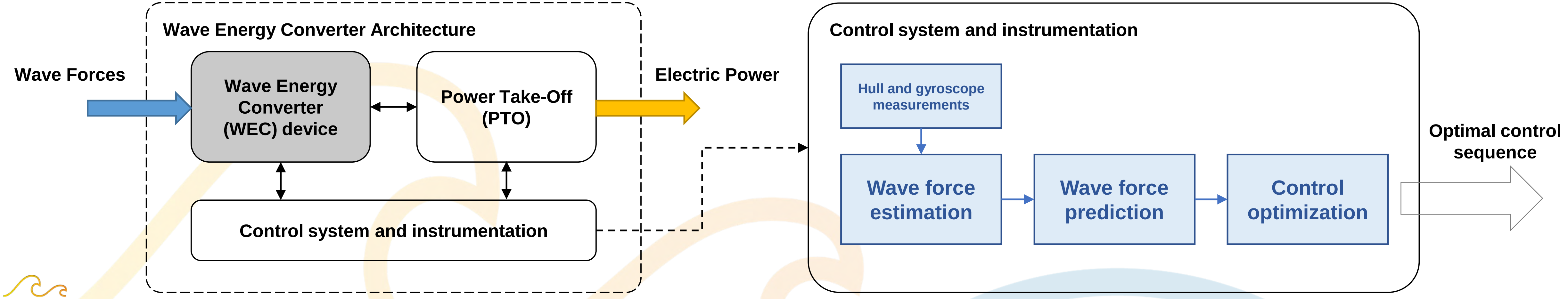
Model Predictive Control (MPC) logic:



Model based control:

- The underlying model is used to build the cost function to optimize and to forecast the system behaviour
- The control action is computed step-by-step basing on an on-line optimization of a system performance. The system behaviour is predicted and the control action is computed each instant k.
- No gain scheduling required, the control action is computed by the controller

$$\mathit{Control\ Objective}: \quad E(t) = -\int_0^t \langle u(t) | y(t) \rangle dt \ \rightarrow \ \mathit{Extracted\ power}$$



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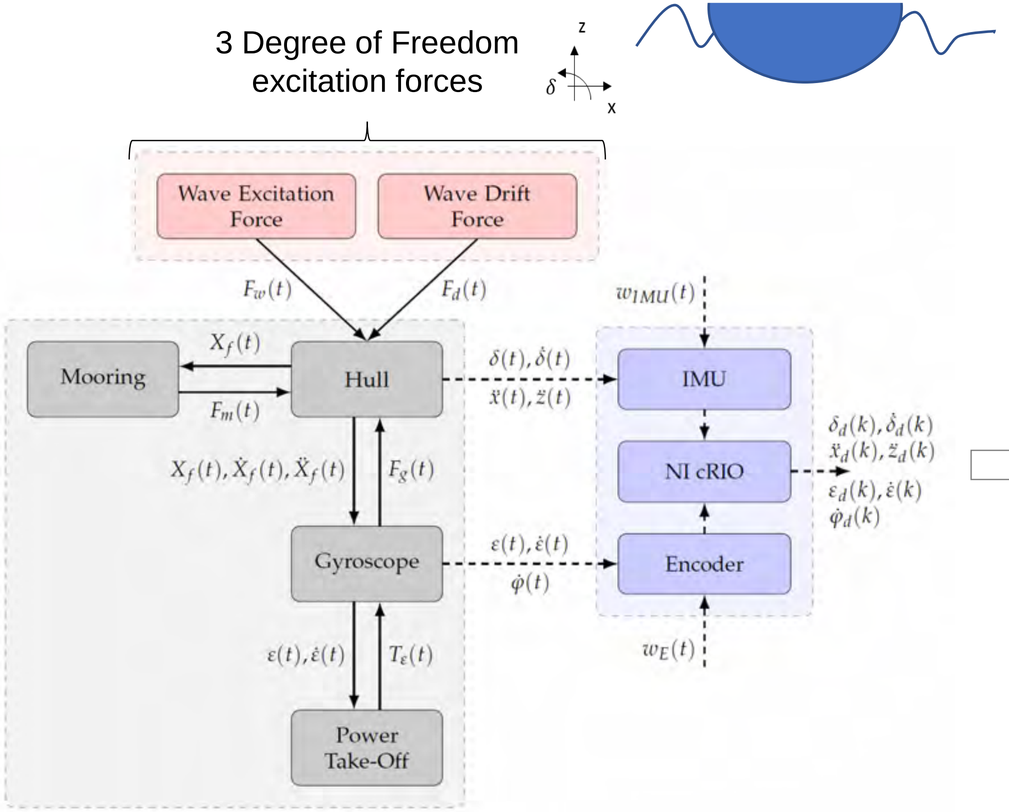
Optimal control – Wave Forces estimation problem



Measurement frameworks available. Four cases are considered: Full Measurement (FM), Motion Reference Unit (MRU), Inertial Measurement Unit with Differencial GPS (IMU+DGPS) and Inertial Measurement Unit (IMU)

	Measures	FM Data	MRU Data	MRU σ	IMU+DGPS Data	IMU+DGPS σ	IMU Data	IMU σ
Hull motion	$x(m)$	•	∘	0.05	∘	0.5	–	–
	$\dot{x}(m/s)$	•	∘	0.03	–	–	–	–
	$\ddot{x}(m/s^2)$	•	∘	0.001	∘	0.01	∘	0.01
	$z(m)$	•	∘	0.05	∘	0.5	–	–
	$\dot{z}(m/s)$	•	∘	0.03	–	–	–	–
	$\ddot{z}(m/s^2)$	•	∘	0.001	∘	0.01	∘	0.01
	$\delta(rad)$	•	∘	$5 \cdot 10^{-4}$	∘	0.01	∘	0.01
	$\dot{\delta}(rad/s)$	•	∘	10^{-4}	∘	0.002	∘	0.002
Gyroscope motion	$\varepsilon(rad)$	•	∘	0.02	∘	0.02	∘	0.02
	$\dot{\varepsilon}(rad/s)$	•	∘	0.001	∘	0.001	∘	0.001
Flywheel motion	$\dot{\varphi}(rad/s)$	•	∘	0.001	∘	0.001	∘	0.001

The estimation problem is addressed basing on the avaiable measurements from **different sensor frameworks**

The estimation problem is addressed with two techniques: **Kalman Filter Observer** and **Neural Network Model**

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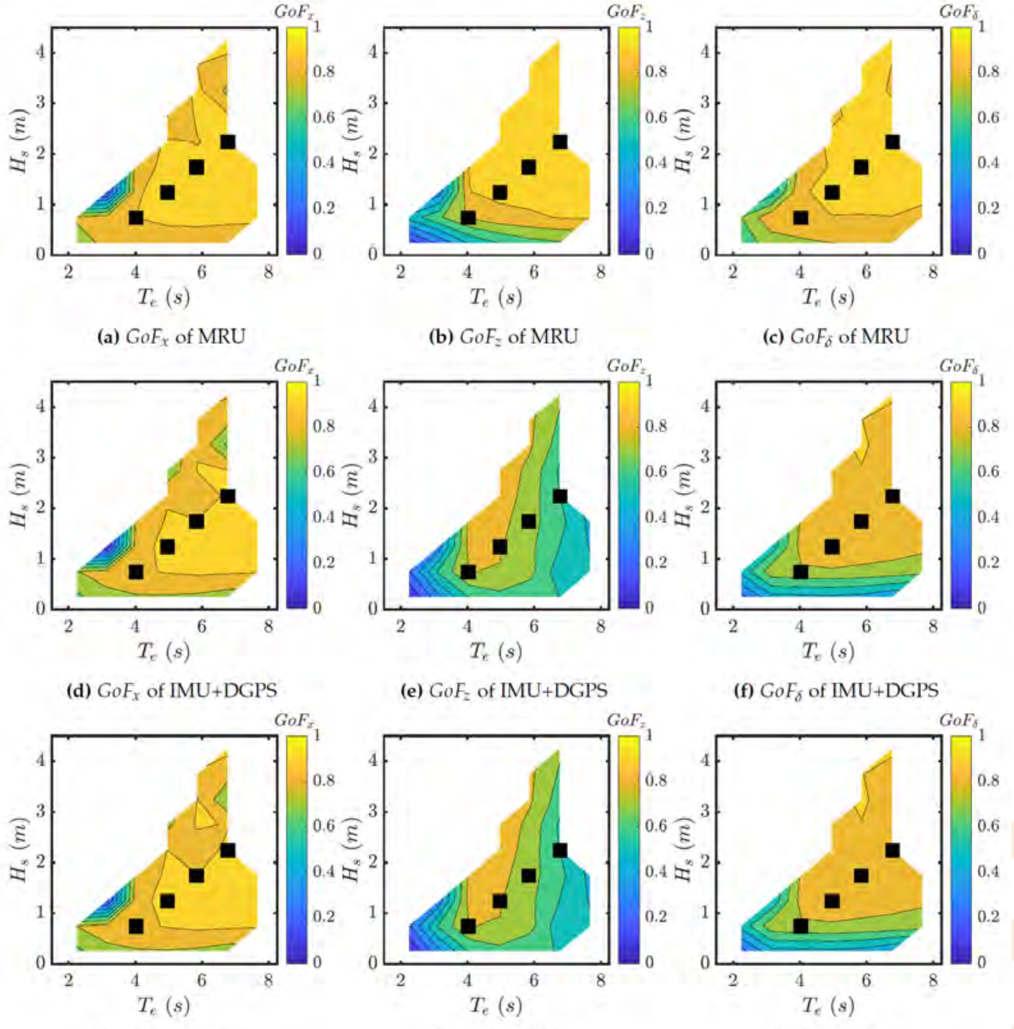
Optimal control – Estimation results comparison

$$GoF_j = 1 - \frac{\sqrt{\sum_{k=1}^{T_s} \left(F_{wj}(k) - \hat{F}_{wj}(k)\right)^2}}{\sqrt{\sum_{k=1}^{T_s} F_{wj}(k)^2}}$$

Kalman Filter

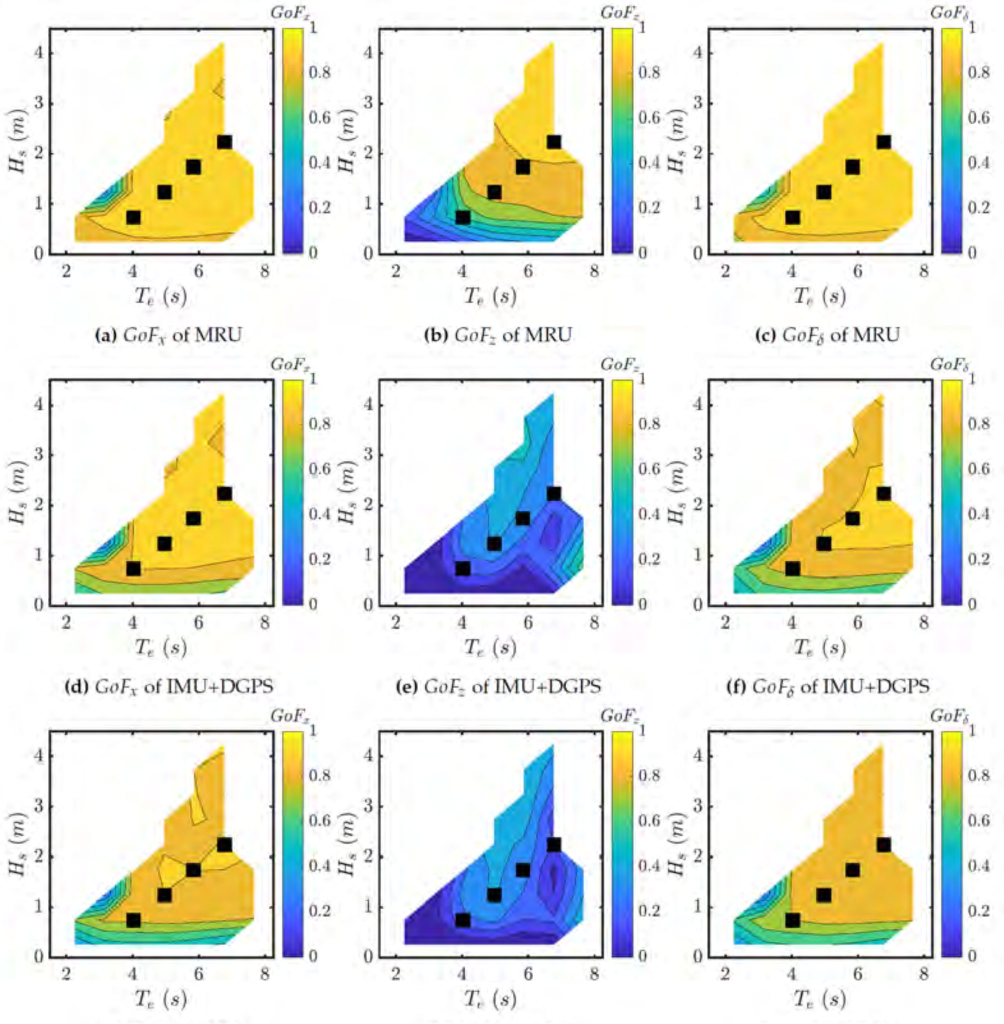


(a) GoF_x of MRU (b) GoF_z of MRU (c) GoF_δ of MRU

(d) GoF_x of IMU+DGPS (e) GoF_z of IMU+DGPS (f) GoF_δ of IMU+DGPS

(g) GoF_x of IMU (h) GoF_z of IMU (i) GoF_δ of IMU

Neural Network



(a) GoF_x of MRU (b) GoF_z of MRU (c) GoF_δ of MRU

(d) GoF_x of IMU+DGPS (e) GoF_z of IMU+DGPS (f) GoF_δ of IMU+DGPS

(g) GoF_x of IMU (h) GoF_z of IMU (i) GoF_δ of IMU

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Optimal control – Estimation results comparison

$$\overline{GoF_j} = \frac{\sum_{v=1}^{V} GoF_j(v)E(v)}{\sum_{v=1}^{V} E(v)}$$

$$\Delta\overline{GoF_j} = \frac{\overline{GoF_j}|_{NN} - \overline{GoF_j}|_{KF}}{\overline{GoF_j}|_{KF}} 100$$

Framework	Noise	Kalman Filter			Neural Network					
		$\overline{GoF_x}$	$\overline{GoF_z}$	$\overline{GoF_\delta}$	$\overline{GoF_x}$	$\overline{GoF_z}$	$\overline{GoF_\delta}$	$\Delta\overline{GoF}_x(\%)$	$\Delta\overline{GoF}_z(\%)$	$\Delta\overline{GoF}_\delta(\%)$
MRU*	×	0.910	0.971	0.901	0.951	0.941	0.961	**4.50**	**-3.08**	**6.65**
IMU+DGPS*	×	0.910	0.967	0.902	0.950	0.939	0.959	**4.39**	**-2.89**	**6.31**
IMU*	×	0.893	0.758	0.889	0.913	0.542	0.940	**2.23**	**-28.5**	**5.73**
MRU	✓	0.898	0.873	0.895	0.950	0.771	0.955	**5.79**	**-11.6**	**6.70**
IMU+DGPS	✓	0.875	0.744	0.824	0.912	0.327	0.863	**4.22**	**-56.1**	**4.73**
IMU	✓	0.878	0.744	0.819	0.854	0.322	0.839	**-2.73**	**-56.7**	**1.82**

The Neural Network framework has been chosen in the MPC application.

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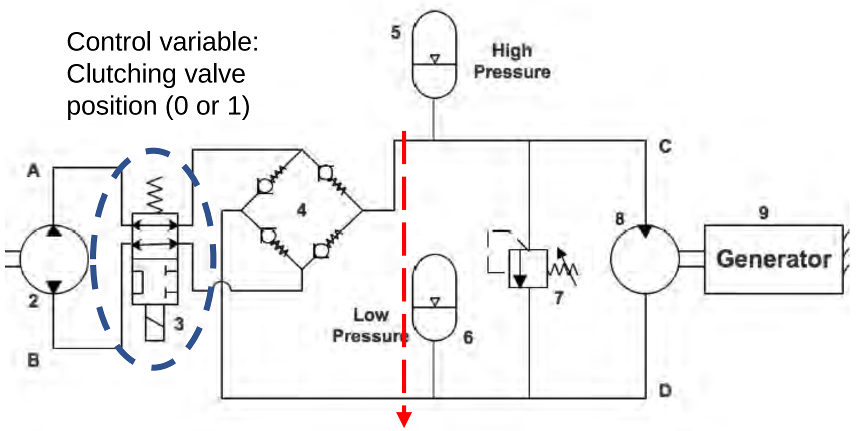
Optimal control – Optimization problem

Control variable:
Clutching valve
position (0 or 1)



$$maxE_u = \int_0^{tf} q_p(p - p_0)\, dt$$

$$X = \left[X_f\ \dot{X}_f\ \varepsilon\ \dot{\varepsilon}\ \omega\ V\ p\ \zeta_r\right]^t$$

$$\dot{X} = \begin{bmatrix} \dot{X}_f \\ M_f^{-1}\left(\tau_w + F_g - K_f X_f - C_r\zeta_r - D_r\dot{X}_f\right) \\ \dot{\varepsilon} \\ \frac{1}{I_g}\left(-J\dot{\varphi}\dot{\delta}\cos(\varepsilon) - \frac{D_p\left(sign\dot{\varepsilon}\right)}{\eta_{mp}}\Delta P_p - mgd\,sin(\varepsilon)\right) \\ \frac{1}{\left(I_{gen} + I_m + I_{added}\right)} D_m\left(\Delta P_m \eta_{mm}\eta_{mgen} - \beta\omega\right) \\ -D_p\dot{\varepsilon}\eta_{vp}u + \frac{D_m\omega}{\eta_{vm}} + q_{rv} \\ -\frac{\gamma p}{V}\left(-D_p\dot{\varepsilon}\eta_{vp}u + \frac{D_m\omega}{\eta_{vm}} + q_{rv}\right) \\ A_r\zeta_r + B_r\dot{X}_f \end{bmatrix}$$

Hull

Gyroscope - Pump

Motor - Generator

Accumulator

Radiation states

Pontryagin's minimum principle

$$\boldsymbol{H = q_p(p - p_0) + \Lambda^t \dot{X}} \longrightarrow \text{Co-states trajectories}$$

Cost function

$$H(X, u, \Lambda, t) = \Phi u + \Theta$$

$$X(0) = X_0\,, \lambda(t_f) = 0$$

$$\frac{\partial\lambda}{\partial X} = \dot{\lambda}\,,\ \frac{\partial \text{H}}{\partial u} = \Phi\,, u = \begin{cases} u_{max} & if\ \Phi < 0 \\ u_{sing} & if\ \Phi = 0 \\ u_{min} & if\ \Phi > 0 \end{cases}$$

$$\begin{aligned} \text{H} = {} & q_p(p - p_0) + \\ & + \vec{\lambda_1}^T \dot{X}_f + \vec{\lambda_2}^T M_f^{-1}\left(\tau_w + F_g - K_f X_f - C_r\zeta_r - D_r\dot{X}_f\right) + \lambda_3\dot{\varepsilon} + \\ & + \lambda_4 \frac{1}{I_g}\left(-J\dot{\varphi}\dot{\delta}\cos(\varepsilon) - \frac{D_p\left(sign\dot{\varepsilon}\right)}{\eta_{mp}}\Delta P_p - mgd\,sin(\varepsilon)\right) \\ & + \lambda_5 \frac{1}{\left(I_{gen} + I_m + I_{added}\right)} D_m\left((p - p_0) i_{svv}\, \eta_{mm}\eta_{mgen} - \beta\omega\right) + \lambda_6\left(-D_p\dot{\varepsilon}\eta_{vp}u + \frac{D_m\omega}{\eta_{vm}} + q_{rv}\right) + \\ & + \lambda_7\left(-\frac{\gamma p}{V}\left(-D_p\dot{\varepsilon}\eta_{vp}u + \frac{D_m\omega}{\eta_{vm}} + q_{rv}\right)\right) + \vec{\lambda_8}^T\left(A_r\zeta_r + B_r\dot{X}_f\right) \end{aligned}$$

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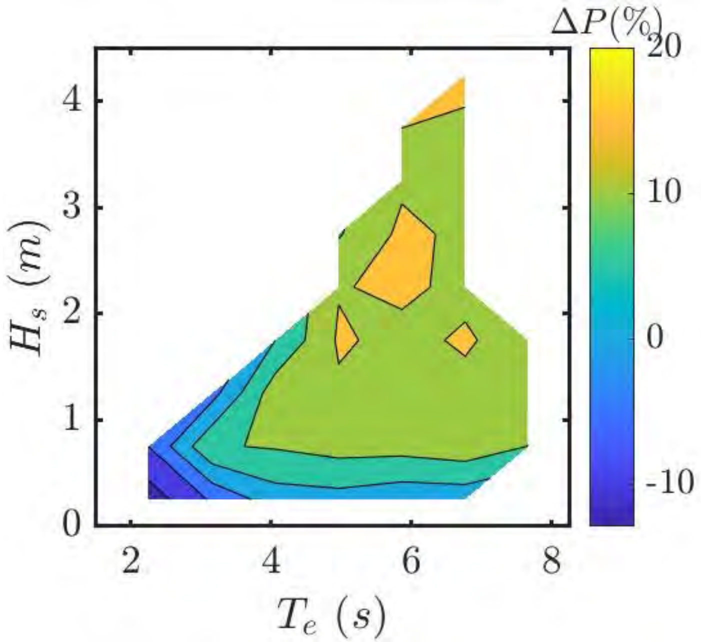
Optimal control – Results

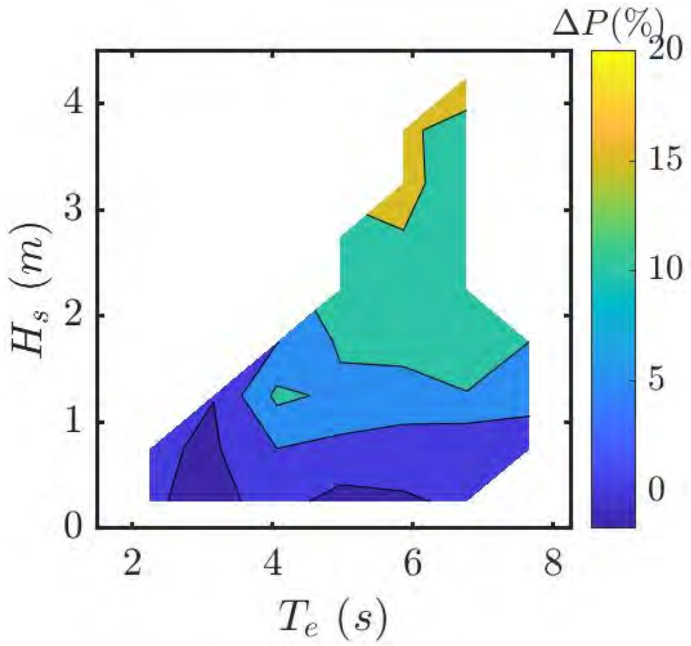
Mean energy increase / decrease:

MRU unit



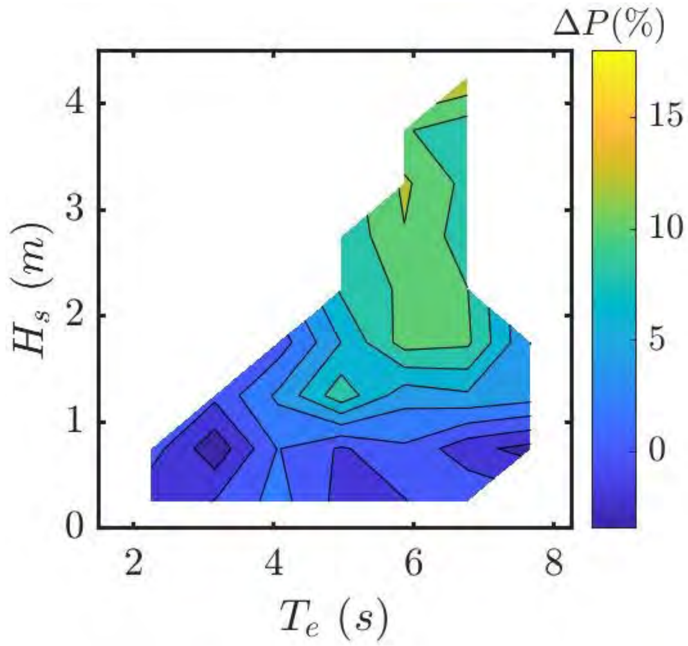
$\Delta \mathbf{P_w} = \mathbf{12\%}$

IMUDGPS unit



$\Delta \mathbf{P_w} = \mathbf{9\%}$

IMU unit



$\Delta \mathbf{P_w} = \mathbf{6\%}$

The MPC application results in a increase of the mean net annual power extracted equal to 12% for the MRU framework, 9% with the IMU+DGPS framework and 6% with the IMU framework. The Neural Network has been considered for the estimation process.

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Design tool – Aim

1. **Scope**

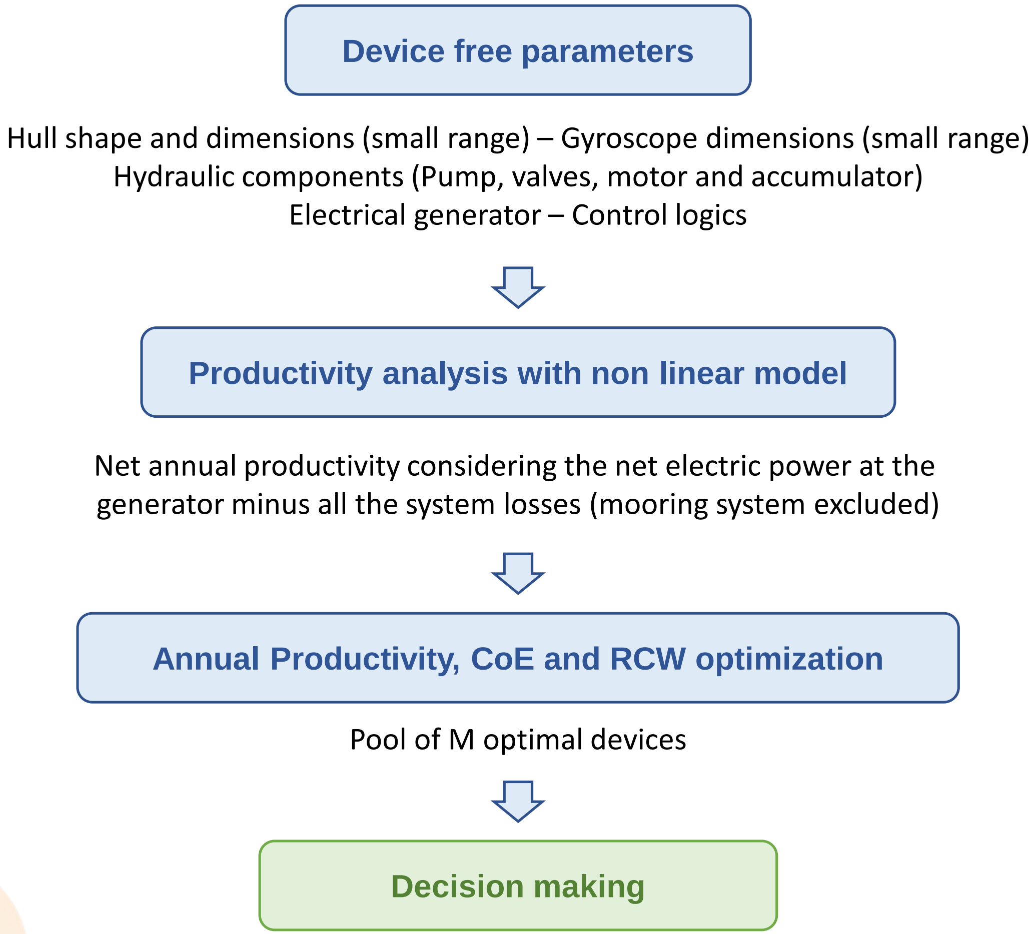
   Perform the second optimization considering all the hydraulic PTO free parameters and a small range of gyroscope and hull free parameters. The aim is to obtain the optimal device with the hydraulic PTO, the overrall cost including all the hydraulic components and a more accurate performance evaluation.

2. **Numerical model**

   Non linear time domain model with the hydraulic PTO. The performance evaluation is done in the time domain considering only one long realization for each input wave to avoid long computational time. The power losses considered are the flywheel losses, base loads, volumetric losses, pressure losses, valve losses, and generator losses.

3. **Expected results**

   1. Device dimensions, gyroscope and hydraulic PTO components (pump, control logics, accumulator, valves, motor and generator)
   2. A serie of ISWEC devices collected by power size
   3. Optimization on Cost of Energy (CoE), Relative Capture Width (RCW) and Annual Productivity
   4. Decision making for Phase 2



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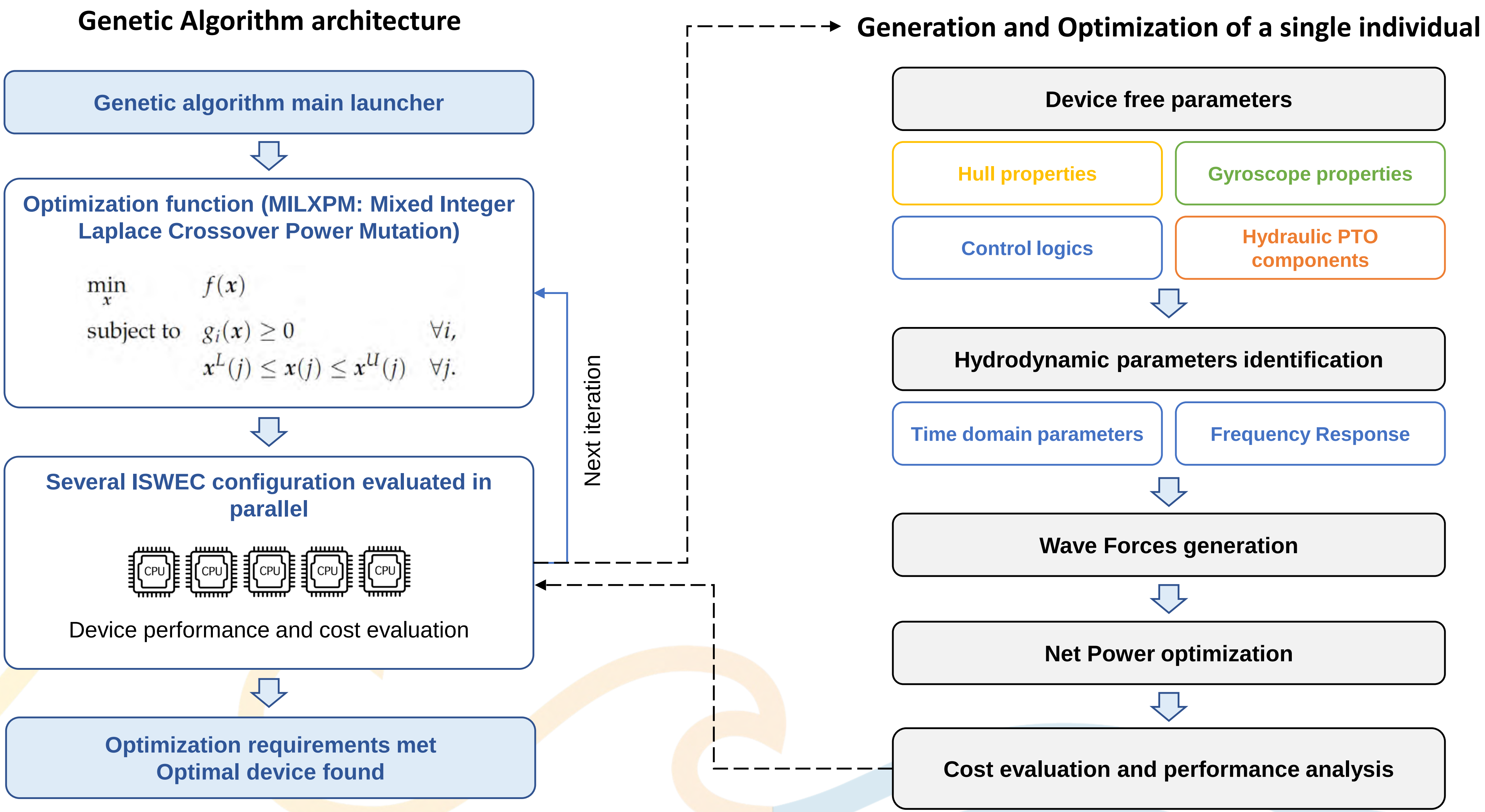
Design tool – Architecture



Design tool – Optimization parameters

1 - Pump id: The pump id represents an hydraulic pump model in the catalogue. 20/30 different solution and tandem configuration are collected together with their properties and costs.

2 – Pump control id: The pump control id identifies which control type is considered on the on the pump units. Four different logics are considered:

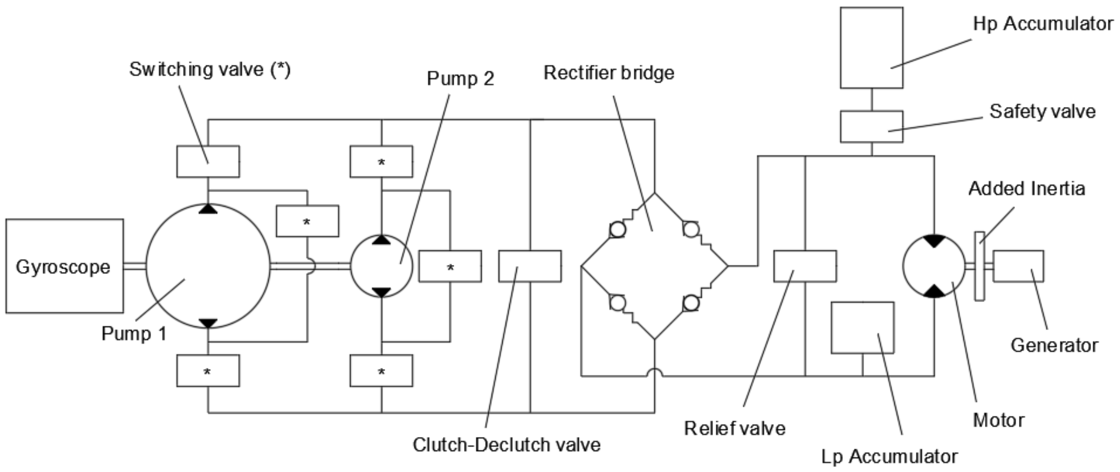
1. NO clutch-declutch valve, NO switching of the pumps
2. YES clutch-declutch valve, NO switching of the pumps
3. NO clutch-declutch valve, YES switching of the pumps
4. YES clutch-declutch valve, YES switching of the pumps

When a single pump is considered, logics 3 and 4 are not avaiable

3 – Accumulator volume: The accumulator volume represents the capacity of the system to filter the flow peaks and store energy to continuos feed the electrical generator.

4 – Accumulator pre-charge pressure: The accumulator pre-charge represents the capacity of the system to filter the flow peaks and fix the lowest level of torque avaiable on the motor and the pump. Remember that the torque acting on the pump – motor is computed form the pressure difference on them.

5 – Motor – Generator id: The motor-generator id represents an hydraulic motor coupled with an electrical generator in the catalogue. 10/12 different solution are collected together with their properties and costs.

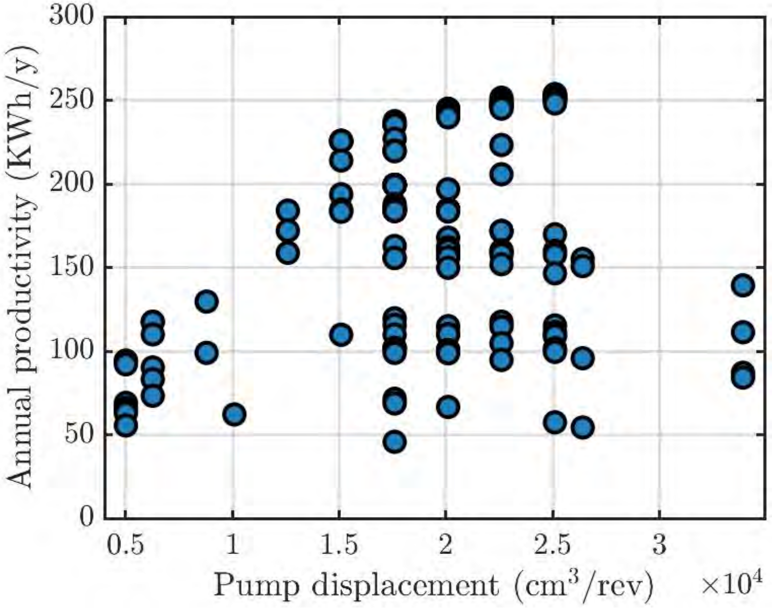


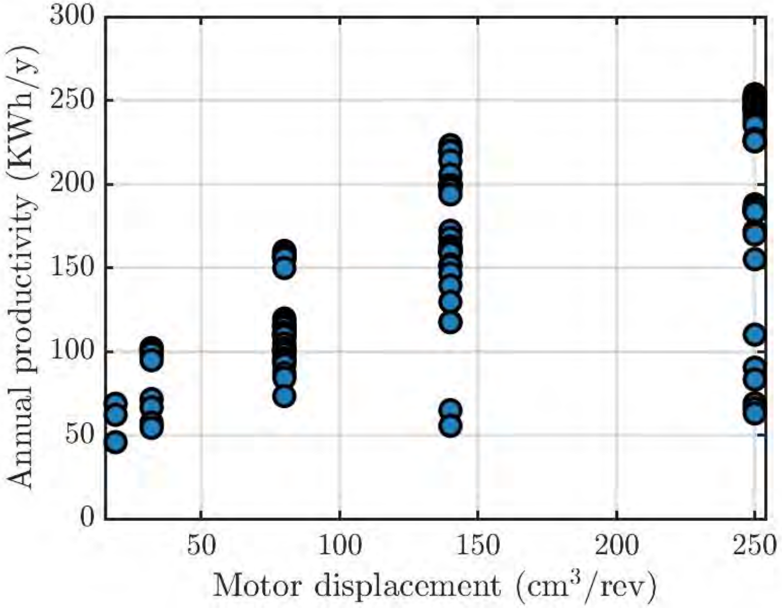
6 – Generator control id: The generator control id identifies which control type is considered on the on the generator. Two different logics are considered:

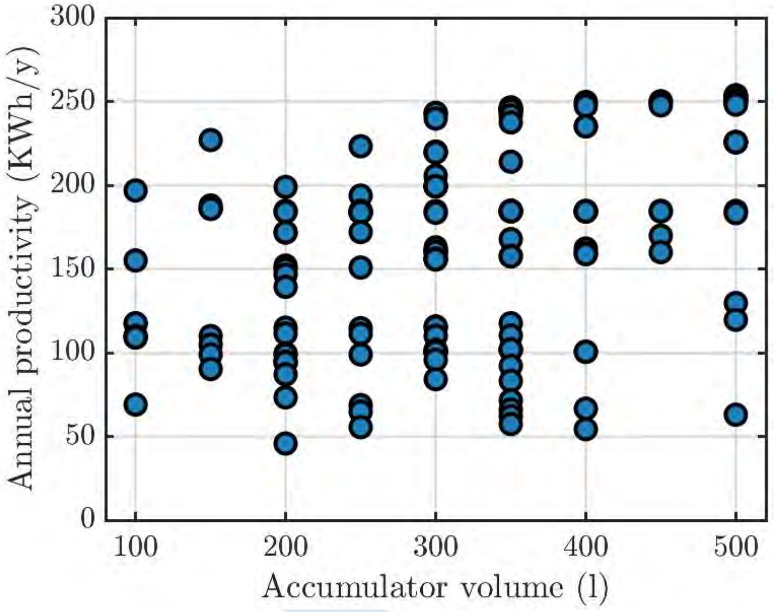
1. Torque control, with a proportional law in respect to the generator angular speed
2. Speed control, in respect to a fixed speed reference (PI)

7 – Added inertia: The low inertia of the motor-generator units is increased to avoid rapid accelerations when there are pressure peaks in the accumulator. Moreover, when the generator is speed controlled, the inertia helps to keep the generator speed around its reference value.

Design tool – Results







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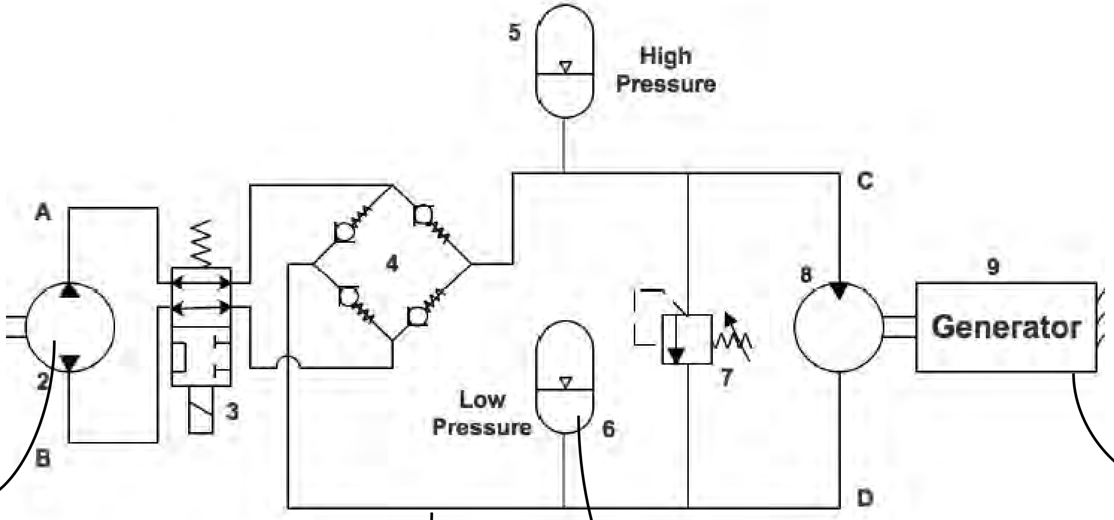
Test rig tests – Operating modes and sensing

- Sinusoidal speed
- Constant speed
- Load speed time serie
- HIL

Speed control →



← Proportional Torque control

Pump: Speed, Torque, Voltage, Current, Power and Temperature

Oil: Pressure, Flow and Temperature

Oil: Volume level and pressure

Motor-Generator: Speed, Torque, Voltage, Current, Power and Temperature

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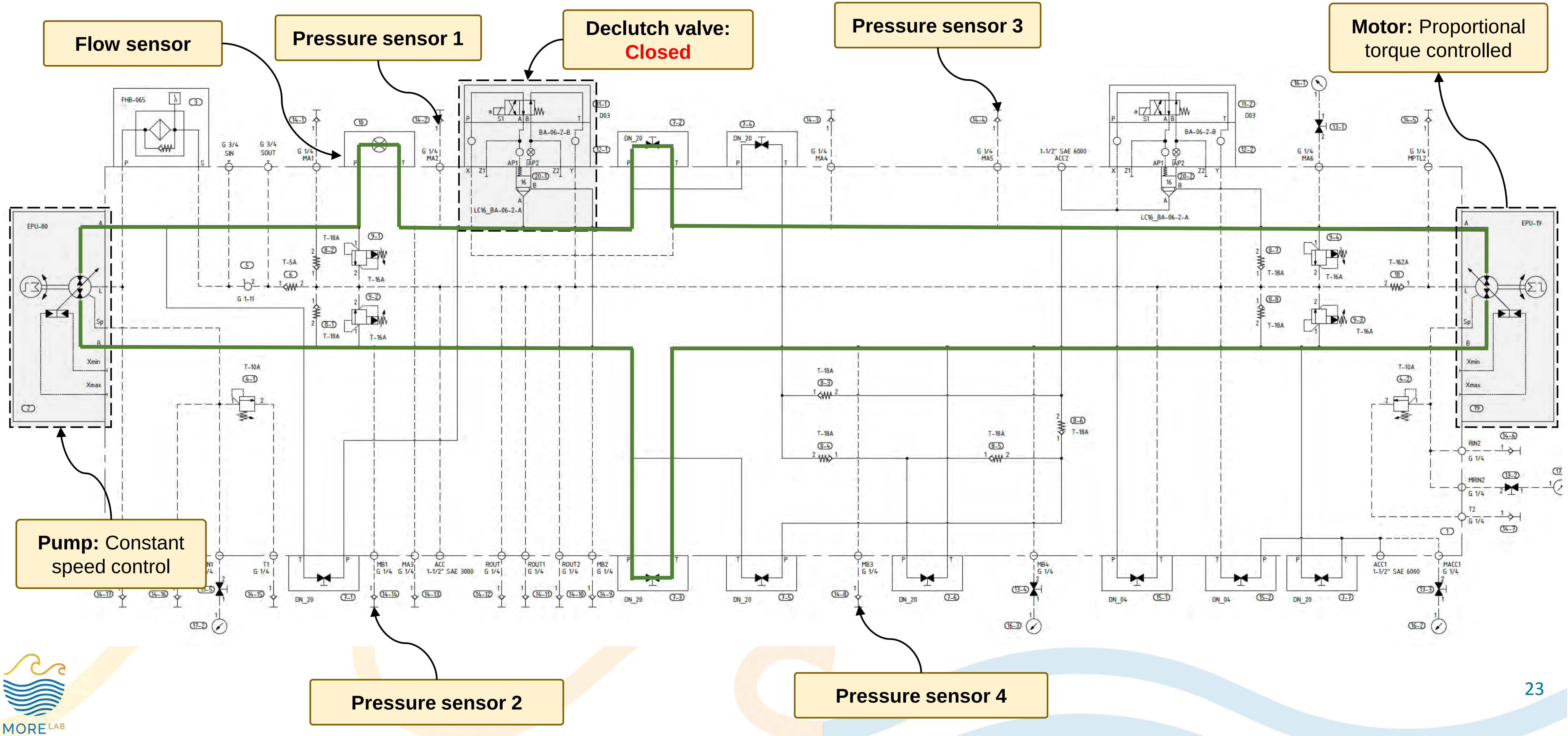
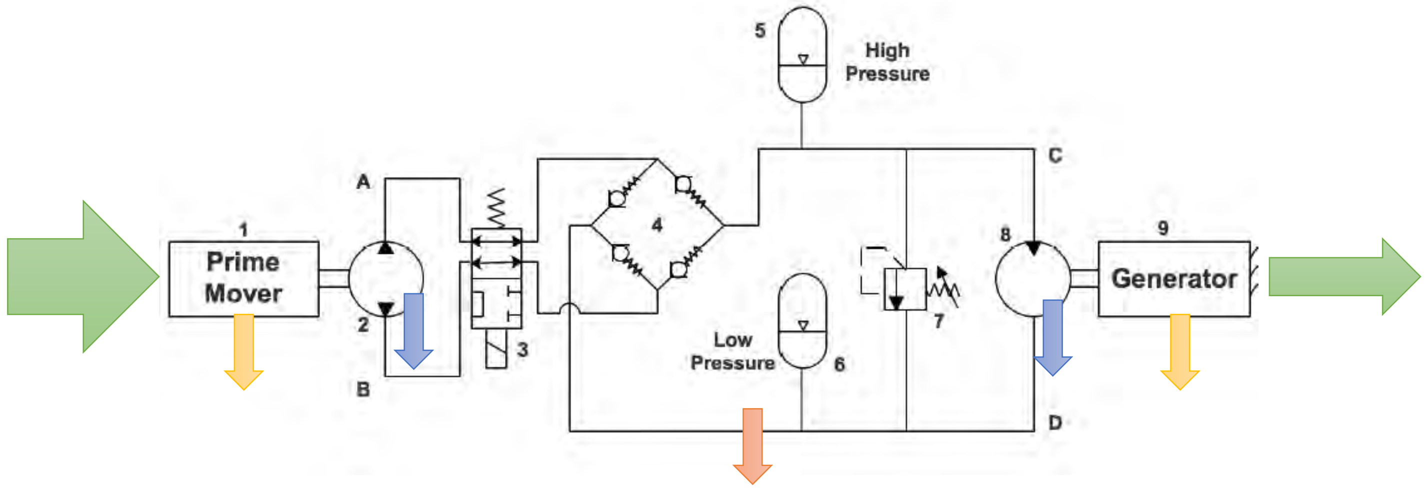
Test rig tests – Efficiency tests, full circuit



Test rig tests – Efficiency tests, full circuit



Electric losses

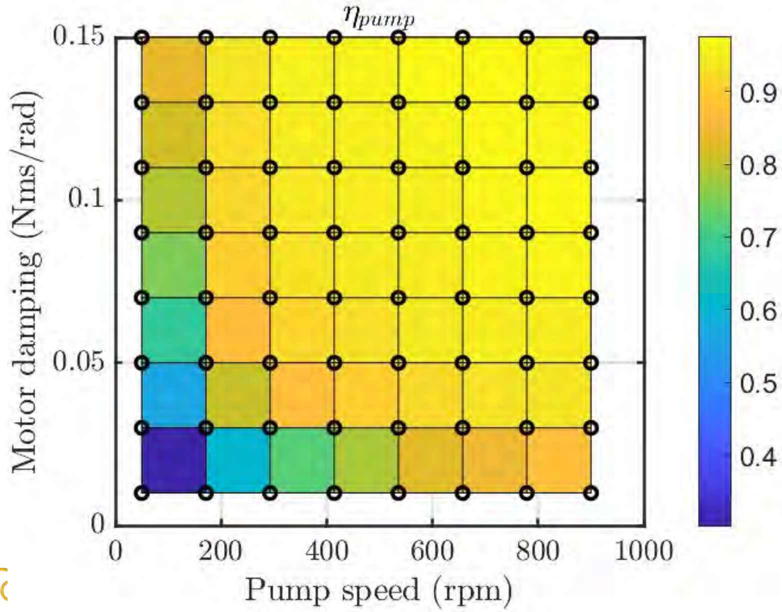
Pump and motor losses

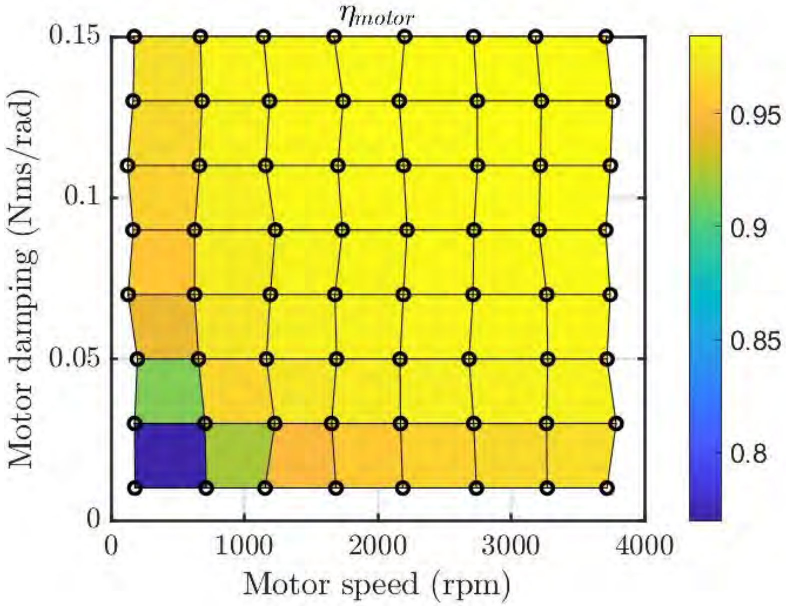
Circuit pressure drop

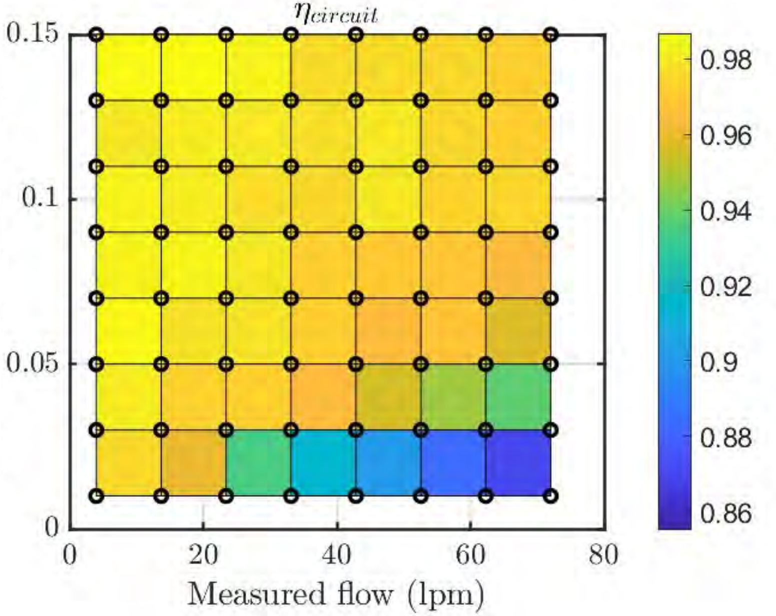
$$\eta_{pump} = \frac{q_{pump} \cdot \Delta P_{pump}}{P_{in}}$$

$$\eta_{motor} = \frac{P_{out}}{q_{motor} \cdot \Delta P_{motor}}$$

$$\eta_{circuit} = \frac{q_{motor} \cdot \Delta P_{motor}}{q_{pump} \cdot \Delta P_{pump}}$$

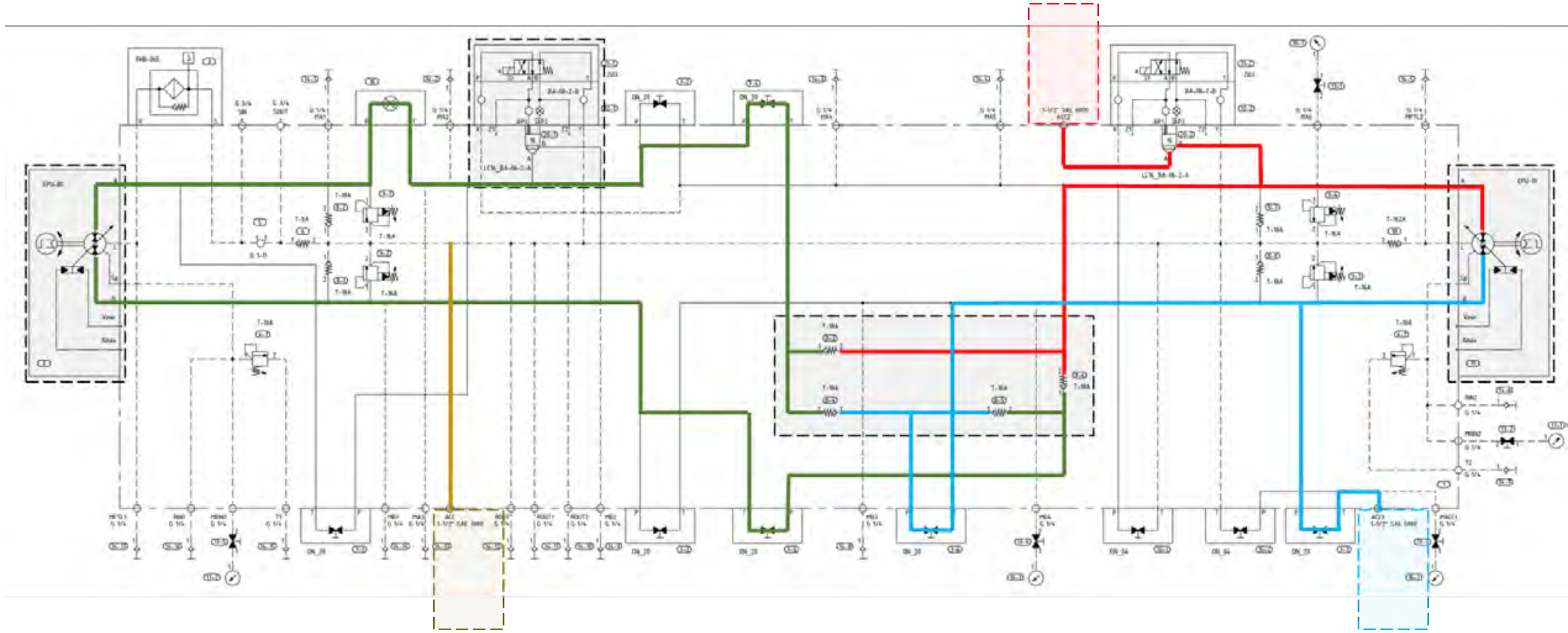




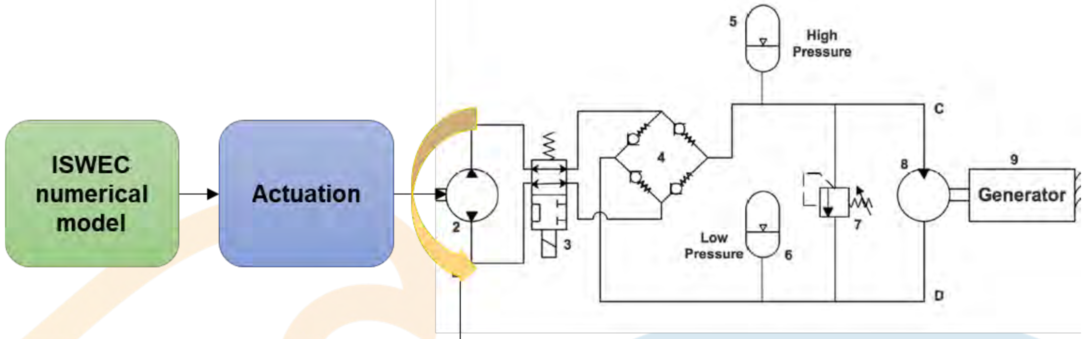


Experimental Validation - WIP

- **Performance of the Hydraulic PTO**
  - Controllability
  - Extracted power
  - Operating conditions efficiency



- **HIL mode**
  - HIL tests
  - Numerical model validation



Hydraulic Pump Speed controlled

Conclusions

1st Year	2nd Year	3rd Year
Hydraulic PTO preliminary studies **HIL test rig design**	**Hydraulic PTO advanced non-linear MPC control** **HIL test rig construction**	**Hydraulic PTO design-tool** **HIL test rig experimental tests and validation**

→ Design of a Full-scale HIL test rig

→Controllability studies

→Increase of ISWEC rated power

→ Advanced control algorithm

→Relevant improvement of ISWEC production

→ Numerical model validation

→ Design tool with hydraulic PTO

→Full scale PTO tests

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Grazie per l'attenzione!

Q&A

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