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Control strategy of the MGR Wave Energy Converter (WEC)

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Abstract. This paper presents the control strategy proposed for a new wave energy converter (WEC) design, the MGR. The control aims to maximise the energy absorption from waves, adapting converter's resistance to the incoming wave size. The MGR is a near shore submerged converter that takes advantage of the oscillating water column created by the wave when it passes on the converter's platform. The wave column moves the platform, transmitting the force to a single acting cylinder, that pumps sea water to the coast, where is turbined generating electricity.

The control strategy is based on adjusting the system pressure to the coming wave size to create the optimal resistance, absorbing the maximum energy from it. The pressure is controlled by the aperture of turbine jet, positioning jet needle. In addition, the PLC implements the synchronous generator's load (torque) in order to maintain the turbine working at the maximum efficiency rotation speed.

Key words

wave energy, control strategy, PI algorithm, near shore device, resonance with waves

1. Introduction

This paper derives from an initial design approach for a new concept of Wave Energy Converter (WEC): the MGR. The proposed WEC is a small-medium power facility that uses well-known and reliable technologies, as Pelton turbine, synchronous generator and hydraulic components. This system is only able to profit the potential energy portion of the wave. Its common components and the use of accessible technologies compensate its inefficiency.

The proposed WEC is based on 'Up and down' working principle, and can be classified as 'second generation' WEC, 'near shore' device [1]. The converter is placed on the seabed, 7 – 8m depth and 50 – 100 m offshore. It takes advantage of the oscillating water column created by the waves when they pass over the submerged platform. The platform pushes a single-act cylinder that pumps high pressure sea water. To damp cylinder pulses and obtain constant flow, each module includes accumulators, that pump the pressurised water to the coast by a pipe, where a Pelton turbine generates electricity. The characteristics that differs the to the coast by a pipe. This water at high pressure impulses the turbine and electricity is generated.

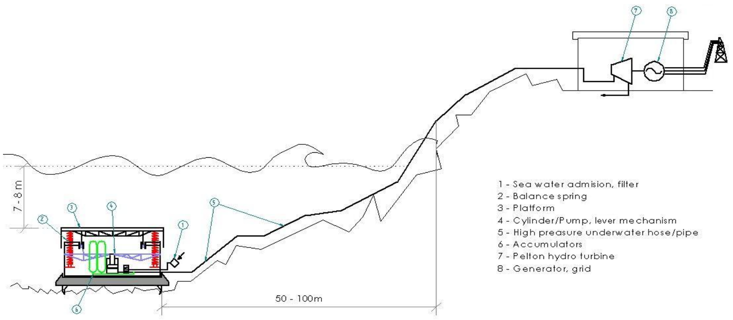

Fig. 1 Proposed WEC diagram

The design can be also modified for reverse osmosis application, obtaining fresh water from the pressurised sea water. Instead massive energy production big power plants, this facility is thought for stand alone settlements, or connected to the grid.

There are hundreds of proposals of different WECs, therefore it is almost impossible to propose a completely new and revolutionary design. The proposed design shares the intermediate the intermediate energy phase (high pressure sea water), transport and electric energy generation with UFRJ, CETO II and WaveBob. The working principle, submerged and profiting oscillating water column, is similar to AWS. The main innovations introduced by the MGR are the arrangement in modules, the variable working pressure and the use of springs to recover the original position.

2. MGR operation

The normal operation steps are listed in the following paragraph,

1. The waves come, each one has different height H and period T
2. The buoy sends these information to the PLC
3. The PLC uses these information to calculate the appropriate working pressure and estimates the generated electrical energy
4. The optimal pressure is achieved through closed-loop acting on the jet needle

   And to adapt the load to the actual energy, the PLC set the generator load torque according to the turbine's optimal speed
5. Using the optimal parameters set by the PLC in real time, the energy chain works as follows,
   - the platform moves up and down due the weight of the waves, overcoming the resistance of the lever-cylinder
   - the PLC synchronises the admission and pumping of sea water acting on the 3-way valve
   - the water is pumped to the coast, storing some energy in accumulators to damp cylinder pulses, obtaining constant flow at the turbine
   - the water pushes turbine blades trough the jet
   - the turbine transmits the torque to the generator
   - the generator, after rectify the energy sends the energy to the grid
6. If the wave height is not enough and the accumulators' pressure is under the minimum, the system stops

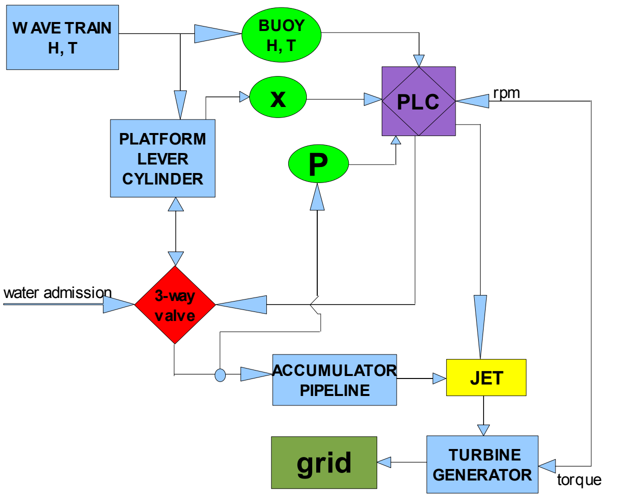

Fig. 2 Operation flow chart

3. Control strategies and algorithm

The power that the WEC can absorb from the waves is maximum when platform's movement is tuned to the waves: its natural frequency of oscillation is close to the incident wave frequency [2]. Resonance is then said to occur. It is not easy to match both frequencies, because of device constructional problems, and real waves are irregular with no well-defined frequency. There are two features to be controlled to achieve resonance condition:

- System pressure must create the appropriate resistance in the cylinder to match the wave energy. Working pressure varies acting on turbine jet aperture, controlling its needle position, according to the wave size signal sent by the measuring buoy
- The generator's load must be tuned according to the incoming wave energy. Knowing the actual working pressure and flow, and turbine's optimal rotation speed (that depends on the pressure), the PLC sets the generator's load torque in order to achieve the optimal rotation speed

In other words, wave energy is divided in two: the absorbed by the springs (fixed), and the absorbed by the cylinder (adaptable). The measuring buoy's wave size data (H, T) is used to foresee the optimal system pressure. If the pressure is bigger than the adequate, the piston cannot reach to cylinder bottom, and if it is smaller, not all the available wave energy is absorbed after the piston reach cylinder bottom. In other hand, to get the maximum efficiency, the turbine must work in a determined rotation speed, that depends on net height (system pressure) and generator's load.

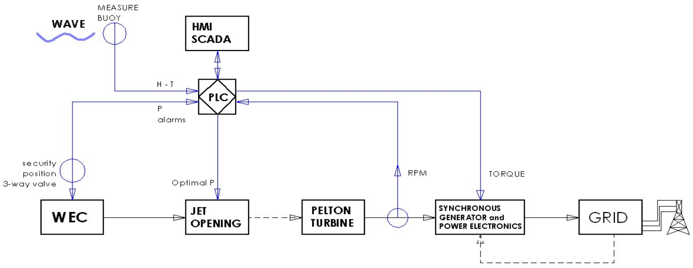

Fig. 3 Control schema of the system

To achieve these aims, there are two control algorithms (both based in system's pressure): the pressure control algorithm and the generator's load algorithm.

4. Pressure control algoritm

As explained before, the optimum pressure control is made adjusting the flow, acting in jet needle position. The following figures show how the position of the needle can vary the flow,

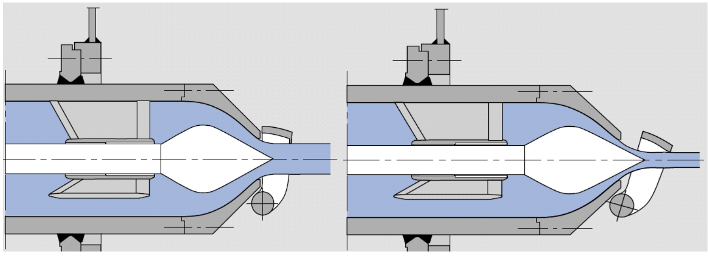

Fig. 4 Turbine regulation by the jet needle

The PLC calculates in real time the adequate system pressure in function of wave size (H, T), $P_J = P_J(H, T)$, and achieve it positioning the jet needle. Studying the energy balance and flow, the equation that defines this relationship is developed. To estimate the water pressure in the turbine jet, the pressure drop produced in the circuit has to be taken into account when sending the pressurised water to the coast.

A Energy study

Once defined the minimum wave size, the extra energy of larger waves is used to increase the pressure, absorbing the maximum energy according to the wave size. The treatment given to estimate the wave energy is assuming the linear wave theory [3].

Energy balance

$$E_{WAVE} = E_{CYLINDER} + E_{SPRING} \qquad (1)$$

System optimal pressure

$$\frac{1000}{2}\ \frac{g\,H_s^{\,2}\,T}{8}\cdot b = h_A\,c\,\frac{\pi\,D_c^{\,2}}{4} + K\,(x_2^{\,2} - x_1^{\,2}) \qquad (2)$$

$$P_A = \frac{4}{\pi\,D_c^{\,2}\,c}\ (62{,}5\ H^2\ T\ b - K\cdot(x_2^{\,2} - x_1^{\,2}))\quad (\mathrm{Pa}) \qquad (3)$$

$$h_A = \frac{P_A}{10^4}\quad (\mathrm{wcm}) \qquad (4)$$

This formula relates the wave size parameters (H, T) with the optimal system pressure (P_A, h_A).

B Pressure drop

The proposed WEC is a hydraulic circuit indeed, that uses pressurised sea water as intermediate medium to transform wave energy into electric energy. To obtain the needed pressure in the turbine´s nozzle, the pressure drop in the circuit must be taken into account. It is very important to minimise the hydraulic losses in the circuit in order to optimise the energy output. There are three types of losses [4],

- pressure losses due the height difference between the platform and the turbine jet, $h_{fz} = f(z)$
- pressure drop in the pipeline, $h_{fp} = f(Q, D, L, \varepsilon)$
- energy losses caused by conduction elements, $h_{pe} = f(Q, D, \Sigma Cv_i)$ where Cv_i is the pass factor of each element

The cylinder pumps against system pressure (P_A, pressure in accumulators). once the sea water arrives to to jet it has lost part of its energy (h_f) due its transit in the circuit (h_J),

Net height, pressure in the nozzle

$$h_J = h_A - h_f \qquad (5)$$

where the pressure drop is

$$h_f = \Delta z + f\,\frac{L}{D}\cdot\frac{v_p^{\,2}}{2g} + \Sigma\,C_v\,\frac{v_p^{\,2}}{2g} \qquad (6)$$

The PLC must calculate in real time the optimal pressure to adapt the system to the optimal conditions. The control loop will compare the optimal calculated value with the actual accumulators pressure, trying to cancel the error.

5. Generator's load algorithm

At the same time, the PLC must vary generator's load, adapting it to the actual water energy. The characteristics needed are: relatively high speed (1000 – 1500 rpm, the smaller Pelton turbine, the faster rotation speed), variable speed, high efficiency and simple control. The generator may work in isolate mode or network operation. The selected generator is the permanent magnets single feed synchronous generator [5], and these are its advantages,

- Use of permanent magnets (no excitation losses)
- The contactors electronic control is simpler and cheaper than wound induction generator
- It can work in isolate or connected to the grid
- Without slip rings, require less maintenance
- High power-volume ratio, compact
- The control loop acts on the torque or speed
- Speed range 1000 – 2000 rpm

The double feed generator could be suitable too. Both are widely used in wind energy industry. The double feed asynchronous generator is a newly developed technology. It uses cheaper power electronics, but its control algorithm complexity, and deep dynamical behaviour knowing makes it no adequate for this application.

The synchronous singly-fed generator uses the torque as setpoint. The PLC can estimate it with the actual system pressure and available flow. Turbine optimal speed is used as reference to set the the torque. Figure 6. shows single-fed synchronous generator's diagram.

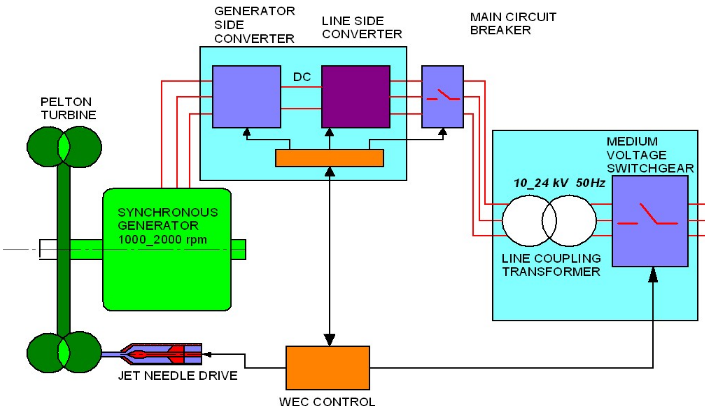

Fig. 5 Singly-fed synchronous generator diagram

The synchronous singly-fed generator uses the torque as setpoint, which is determined by the turbine optimal speed, the actual flow, working pressure, and finally the power obtained by the turbine for the given conditions.

A Flow study

The flow is created by the single-act cylinder when the platform pushes it down. Therefore the cylinder pumps its volume once per period. This justifies the use of accumulators, to store energy and damp pressure peaks in the circuit.

Flow (m^3/s), cylinder volume over period

$$Q=\left(\frac{D_c^{\,2}c}{4}\right)\frac{1}{T} \tag{7}$$

B. Optimal rotation speed

The criterion taken to command the generator, in addition to high pressure water energy (P pressure and Q flow), is the optimal rotation speed of the turbine. Turbine rotation speed depends on system pressure too.

Turbine optimal linear speed (m/s)

$$u=\frac{v_J}{2} \tag{8}$$

Linear speed on the jet (m/s)

$$v_J=\sqrt{2gh_J} \tag{9}$$

Optimal rotation speed (rad/s)

$$\omega=\frac{v_J}{R_t}=\frac{\sqrt{2gh_J}}{R_t} \tag{10}$$

C Torque

Once determined the rotation speed and flow, and system pressure and and flow, and recovering the Formulas that define system pressure (4, 5 and 6), the turbine output power can be estimated. With the expected power and turbine rotation speed, the torque is defined in Formula (12).

Estimated power output

$$Pw=\eta_{mech}\cdot\eta_{turbine}\cdot\rho\cdot g\cdot h_J\cdot Q \tag{11}$$

Torque

$$Tq=\frac{P_W}{\omega}=\eta_m\eta_t g\,h_J\frac{R_t}{\sqrt{2gh_J}}=\eta_m\eta_t R_t\sqrt{2gh_J} \tag{12}$$

Optimal torque stems from optimal pressure and rotation speed, and is defined by coming wave size, H and T. This is the torque signal sent by the PLC to the generator to adapt its load to actual wave regime.

6. PI regulation

As explained before, the control strategy is based on system pressure and generator's load control. Both derive from the measuring buoy data defining the wave size (H, T) start calculating the optimal pressure for current wave conditions in real time. Figure 7. explains the double loop that controls the converter's behaviour.

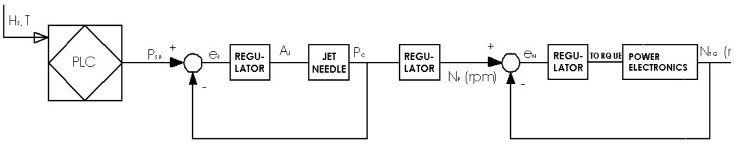

Fig. 6 PI control schema, pressure loop (jet needle) and generator load loop

Present PLCs have integrated the regulator. The regulator receives the optimal system pressure (derived from buoy data), and the actual pressure. The difference between then is the error and the PI regulator commands jet needle position trying to make the error zero.

The second control loop sets turbine's optimal speed according to the optimal pressure. The optimal rotation speed is calculated by the PLC, that compares with the actual speed. To match both speeds controls generator's load with the torque signal.

7. Monitoring and SCADA interface

The PLC needs sensors that asses its objectives are fulfilled. The main sensors needed to track the performance of the system are listed in Table 1, additional may be needed to assure the safety. Figure 8. explains the arrangement of these sensors and transducers.

TABLE I List of monitoring sensors

Measure buoy (H, T) **SA1**	Acquire data to calculate converter´s optimal resistance (pressure)
Generated electricity – Load (kW) **SB1**	Track the good operation of the device, supplying good quality energy to the grid
Turning speed (rpm) **SB2**	Match the load with the discharge variation, maintaining the optimal speed Safety: to activate active the jet deflector in case of over-speeding
Needle position **SB3**	Transducer to command hydraulic actuator that sets jet needle position feed, according to pressure setpoint error
Generator temperature, bearings, ea.	Safety sensors of the generator
System pressure in accumulators (P_P) **SC1**	Track the good operation of the device Re-feed signal to estimate the error Open the relief valve if over pressure
Position of the platform **SC2**	Track if the platform reaches both extremes - Top: the cylinder has been filled - Bottom: adequate resistance (pressure)
Pressure inside the device **SC3**	Check any seepage of water/air
Water in the converter **SC4**	To activate the purge pump

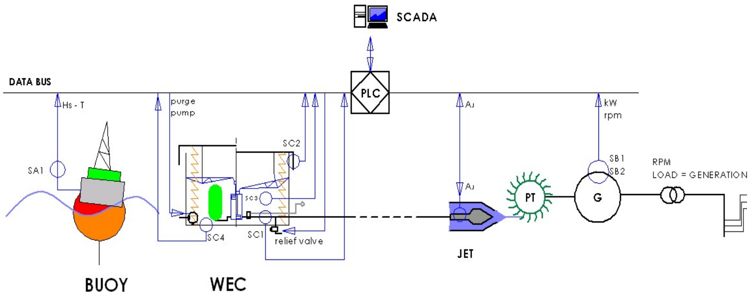

Fig. 7 Simplified control schema including sensors

A SCADA centralised system monitors and controls the power plant. Site control is performed automatically by the PLC. Host control functions are restricted to basic site overriding or supervisory level intervention. For example, a PLC controls the flow of turbine jet, but the SCADA system may allow operators to change the set points for the flow, and enable alarm conditions, such as loss of flow and high pressure, to be displayed and recorded. The feedback control loop passes through the PLC, while the SCADA system monitors the overall performance of the loop.

8. Conclusions

This paper has presented a double loop control that aims to maximise the energy output. The absorbed energy is maximum when the submerged platform movement is tuned with the waves. Real wave trains are aleatory, and as wind energy, the load must be adapted in order to maximise the energy absorption. To follow the wave movement, two control algorithms lead this objective:

- adaptation of the system pressure to the wave size, acting on turbine jet
- the absorbed energy matches generator´s load setting the torque according to turbine's rotation speed

The research is in initial development stage, where MGR characteristics and features are defined roughly.

Acknowledgements

The development of the MGR would not be possible without Margarida Coelho's encouragement.

Nomenclature

H (m) – Wave height
P (Pa) – Water pressure
P_J (Pa) – Pressure before jet
N (rpm) – Rotation speed
u (m/s)– Buckets linear speed
b (m) - Platform width
Q_C (m^3/s) – Flow (cylinder)
D_C (m) – Cylinder diameter
D_P (m) – Pipe diameter
ε – Rugosity of the pipe
L (m) – Pipe length
T (s) – Period
P_A (Pa)– Pressure in accumulators
v_P (m/s) – Water speed in the pipe
R_T (m) – Turbine radius
v_J (m/s) – Water speed on the jet
Q_J (m^3/s) – Jet discharge
Q_P (m^3/s) – Flow in the pipe
c (m) – Cylinder's stroke
Cv – Global pass factor
f – Dimensionless friction factor
E (J) – Energy
Δz (m) – Height between accumulators and jet
h_f (m) – Pressure drop
g (m/s^2) – Gravity
γ (N/m^3) – Specific weight
x (m) – Platform position
Pw (W) – Power output
h_n (m) – Net height, $h_n = P_A/\gamma - h_f$
ρ (kg/m^3) – Sea water density
η - Efficiency
K (N/m) – Spring rate
Tq (Nm) – Torque

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