APPROACH OF DYNAMIC MODELLING OF A HYDRAULIC SYSTEM

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ABSTRACT

In response to environmental degradation, particularly due to greenhouse gas emissions, renewable energy is increasing significantly today. Their development is also a major concern with regard to the depletion of non-renewable energies. However, their use is limited due to the instability induced in the electrical grid. Energy storage aims to regulate these fluctuations and thus smooth electricity production. Compressed air energy storage (CAES) is a type of high-capacity, low-cost energy storage on the market. REMORA, the storage system studied here is an underwater isothermal CAES system. This innovative system consists of compressing and relaxing the air in a quasi-isothermal way using liquid pistons. This method minimizes overall energy loss by maximizing heat transfer during air compressions and expansions. Compressed air is stored in underwater tanks and takes advantage of the hydrostatic pressure associated with the depth of the water. The architecture and operation of the hydraulic system are specific in order to maximize performance. During the energy storage and restitution processes, the exchange flow become transient due to several valve commutations. It occurs frequently during REMORA hydraulic system operation. Modeling the system become complex. A simple example of a hydroelectric plant, similar to the case study, is modeled using two different software. The results show the most appropriate tool, to model the hydraulic system, with an integrated approach based on dynamic modeling.

1. INTRODUCTION, FIRST HEADINGS

The increase of the need of energy storage is driven by the emergence of energy transition. Indeed, energy storage is necessary in order to integrate the power from renewable energy in the grid. These types of energy sources are generally intermittent. However, the use of energy storage ensures the grid stability. Different types of energy storage are available; the pumped storage power plants are the first type of energy storage used worldwide. It's composed of two water tanks located at different levels. The energy is stored by pumping the water from the lower tank to the higher one during weak electricity demand. When the demand is increasing, the electricity is restored by releasing the water to the higher tank. The water goes through a turbine which drives a generator. The lack of available site limits the development of energy storage stations. They are generally located in a mountainous region in order to install both tanks at different levels. Marine pumped storage projects are also developed to take advantage of the sea as the lower water tank. However, this type of energy storage involves environmental impacts particularly on the landscape and ecosystem around the facility. REMORA, the case study investigated here is an isothermal compressed air energy storage (I-CAES) with an underwater tank with a capacity of few power. The principle is based on the use of liquid piston (Neu, 2017) . It maximizes thermal exchange during air compression and expansion. The system is installed in the sea at 100m depth. Consequently, many sites are available around the world. The optimization of the electrical part of the system is already being studied (Maisonnave et al., 2018). This study is focused on the hydraulic part of

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the UW-I-CAES. Many concerns are discussed to clarify the operation of the system, especially pump performance and flow behaviour during transient period. The flow model through the pump during transient regime is developed in the literature at the pump starting or stopping period as well as during the opening or closing valve. It was shown that quasi steady model was used to described the transient period but is only accurate when the transient is slow (Lefebvre & Barker, 1995; Rizwanuddin, 1994). More complex models have been developed to highlight the inertia and the angular acceleration influence during these periods (Grover & Koranne, 1981; Saito, 1982). A model of the pump flow has been elaborated as a two-dimensional linear cascade unsteady flow (Tsukamoto & Ohashi, 1982). Two distinct periods were identified. In the first period, a high pic pressure is observed. Then, it decreases below the quasi static pressure. This is explained by a delay in the circulation through the impeller vane. A model of a flow along a streamline through a pump is proposed by (Ghelici, 1993) but the simulation result was far from the experimental test result. The pump head was described by means of a pseudo stationary model which decreases the model accuracy. The presence of recirculation has been shown with an experimental study (Picavet, 1996) . He concluded that this phenomenon could explain the difference between the steady and transient flow in the pump. This phenomenon was taken into account in a new model of the pump at starting period (Bolpaire, 2000). A model of the pump based on moment of the quantity momentum equation coupled with the energy equation is proposed (Dazin, Caignaert, & Bois, 2007).It describes the evolution of total head with inertial terms related to the wheel, to the diffuser and the volute. It takes also into account the impeller geometry and blade width variation. The model is compared with experimental head curve results and gives less than 5% difference between both curves. The pump model is included in a hydraulic system on a modelling platform using bond graph method. The simulation is conducted during pump start-up period. Three distinct periods are shown. The effects of angular acceleration are dominant during a first period and then become negligible during the second period with the increase of the effects of hydraulic inertia. Finally during the third period, the viscous effects dominate and the regime becomes almost stationary (Dazin, Caignaert, & Dauphin-Tanguy, 2015).

The hydraulic machines in the facility are pump as turbine (PAT). Those are centrifugal pumps which are also used in turbine mode by running the impeller in the opposite direction. This method reduces the platform size and consequently the system cost. It also has the benefits of the pump robustness. Indeed, PAT are generally used in micro hydroelectric power (<1MW), and in water distributions systems. The main difference with a turbine is that they don’t have adjustable guide vanes which decrease its performance in turbine mode. The manufacturer doesn’t usually give the performance curve of the pump in turbine mode. Consequently, different models have been developed to predict this operation. Many researchers developed a coefficient expressing the relation between pump and turbine parameters based from data in pump mode (Alatorre-Frenk, 1994,Childs, 1962, Sharma, 1985, Stepanoff, 1957). The results give 20% error between the calculation with the prediction model and the experimental tests. More complex models are based on the pump design and geometry and give more accurate result (Gülich, 2014; Stefanizzi et al., 2018).But these methods are difficult to use because of the amount of design data needed and non-available. To enhance the PAT performance, variable speed method is used in both modes. The rotational speed of the machine is modified over time according to the system condition. The goal is to reach the best efficient point at each rotational speed. The prediction of PAT performance with variable rotational speeds is realized with the affinity laws. They give three proportional relations to predict pump characteristics at different speeds.

All these challenges have to be addressed and studied to model the UW-I-CAES hydraulic system. A literature review of the different types of compressed air energy is given in the second section. Then, the study case UW-I-CAES is presented. Finally, in order to have a detailed and accurate model of the hydraulic system a comparison study of two modelling tools is conducted on a simple example model to see which one is the most suitable for a complex system. A simple hydraulic structure is chosen because of its basic hydraulic components included also in the future study case model. This work is the first step of modelling the UW-I-CAES hydraulic system.

2. COMPRESSED AIR ENERGY STORAGE HISTORY

Compressed air energy storage (CAES) uses excess energy from the grid to compress and to store air in an underground tank. Only two plants are available in the world because of its low efficiency (54%). The first CAES was installed in Huntorf in Germany in 1978; its capacity is of about 321MW. During peak demands, the air is restored, compressed in the gas compressor and used to burn natural gas in the combustion chambers and then expanded in the gas turbine. This energy is converted to mechanical energy via the gas turbine shaft which operates a generator and produces electricity. The second CAES plant was installed in McIntosh Alabama in 1991 with a capacity of 110 MW and a volume of 538 000 m^3 salt cavern. The capacity has been enhanced to 226MW thanks to two extra generators added. Both have the same operation mode. Their weakness lies in the need for a natural gas supply to warm the air before its expansion. (Budt, Wolf, Span, & Yan, 2016).

Different derivative methods have been developed to avoid energy losses. The Advanced Adiabatic compressed air energy storage (AA-CAES) is based on the CAES system with a thermal energy storage to store the heat during compression and then restore it during expansion. The method allows increasing the efficiency up to 70 %. No mature facility has been implemented yet. However, few projects are currently being developed. The Adele Project is a 290MW AA-CAES plant project in Germany and promise efficiency up to 70%. The main challenge is to develop specialised turbo machines to bear high temperature during compression and high isentropic expansion (Zunft, 2015).

Another technology, called Hydrostor Terra (Hydrostor Inc., 2017) is currently being developed by Hydrostor. Its storage capacity can reach 100MW in 4 hours and the efficiency is estimated up to 60%. Its operation is based on the same principle as energy storage by adiabatic compressed air with heat recovery during compression. This technology uses hydrostatic pressure to maintain constant pressure in the tank. This advantage reduces the tank size relative to traditional CAES tanks. During energy storage, atmospheric air is compressed and transported to the underground tank initially filled with water. The water is then returned to its source. When the energy is returned to the grid, the tank is filled with water from the source; the compressed air is heated and relaxed through the heat regenerator and turbine.

ALACAES is a Swiss AA-CAES project with an efficiency up to 72%, they develop a thermal energy storage more efficient by placing it inside a larger pressure chamber. They used a tunnel in Alpes mountain as a high pressure storage of the cooled air.(ALACAES, 2017) A first pilot plant was built in 2016. TES efficiency cycle was about between 76% to 90% which estimates the efficiency of the pilot plant between 63% to 74%.(Geissbühler et al., 2018).

Isothermal compressed air energy storage (I-CAES) is also a derivative technology of CAES which aims to limit the variation of the air temperature during compression and to avoid using thermal energy storage. Different I-CAES projects are also in development but not mature enough currently. LightSail energy applied for several patents(EP2449259B1, 2016)on an innovation using fine droplets water spray during compression. Sustain X stores the air in a pressure vessel keeping the air at a constant temperature. The technology is a water spray-based heat transfer approach to maintain the water-air exchange surface during compression and expansion. A 1.5MW prototype was going to be develop, however, these project are currently on hold (Technology Performance Report SustainX Smart Grid Program , 2014).

3. STUDY CASE

The energy storage studied here is a specific underwater isothermal compressed air energy storage (UW-I-CAES), using liquid piston. This storage is suitable for any different types of electricity-generating plants, especially offshore energy. The efficiency of this system is estimated about 70% and has a capacity of 15MW for 6 hours. The system is composed of underwater tanks connected to a floating platform where the hydraulic and electric machines and liquid pistons are located. The excess of electricity in the grid is brought into the storage system via the electric machine which operates the pump as turbine. The liquid piston initially filled with air is filled with liquid, raised by the centrifugal pump. The air is compressed and directed to the underwater tank. The reverse process of the energy conversion is realized to restore the compressed air into electricity by using the pump as turbine (PAT) in turbine mode. The energy transfer in the system is shown in Figure **1**.

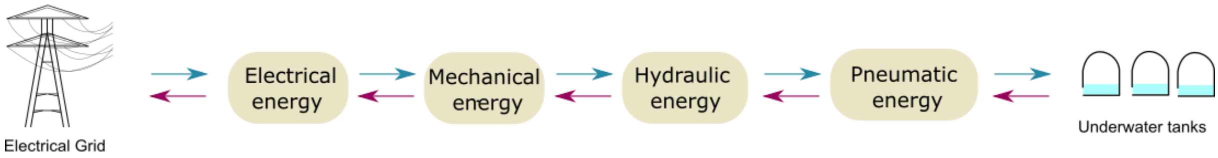


Figure 1: Energy exchange in the system

Its architecture is particular in order to minimize energy losses between each part. Two pumps with different operating range take turns to fill each liquid piston to ensure that they are used at their nominal operating. In addition, variable speed is also used to maximize the pump efficiency. An example of a conversion module with 4 liquid pistons is given in

Figure **2**. Here, each pump is connected to each liquid piston with a main pipe branching into 4 secondary pipes. A valve is placed in each secondary pipe to ensure the direction of the flow to the right liquid piston.

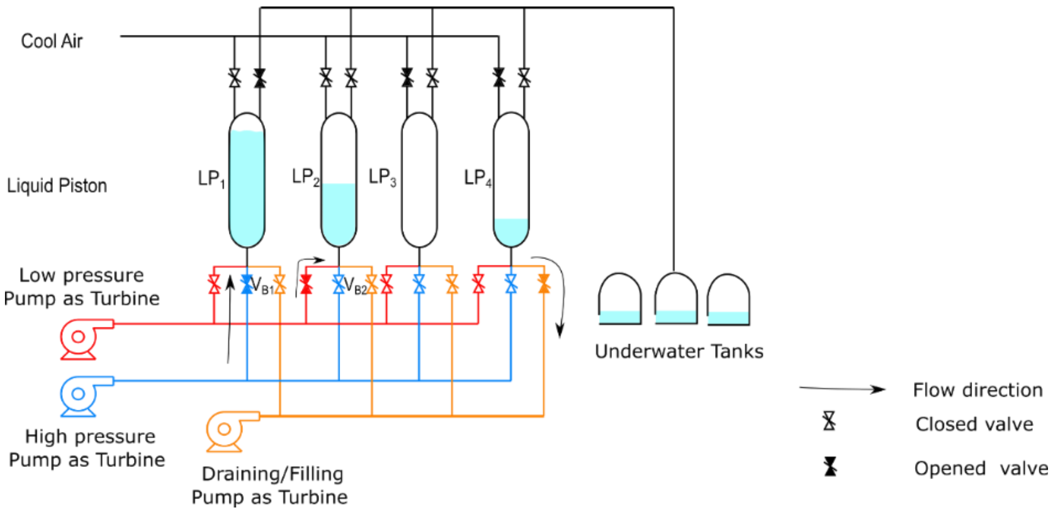


Figure 2: Scheme of the system

During this storage scenario the high-pressure PAT is operating in the first liquid piston. The associate valve (V_{B1}) is already fully opened while the others are fully closed. When the liquid piston LP_1 is fully filled with liquid, the valve V_{B1} is closing while V_{B2} is opening in order to let the high-pressure pump to fill the second liquid piston. The same process is repeated with each piston and each pump. The flow behaviour is uncertain due to the inertial effects in the T-junction and the opening and closing valve process. Variable speeds operating are used in the system. A centrifugal pump curve is given by the manufacturer which defines its operating range for one given speed. The best efficient point is the point where the efficiency of the pump is the highest on the curve. To maximize the efficiency of the pump the method of variable speeds is used to approach the best efficient point (BEP) for each given running speed.

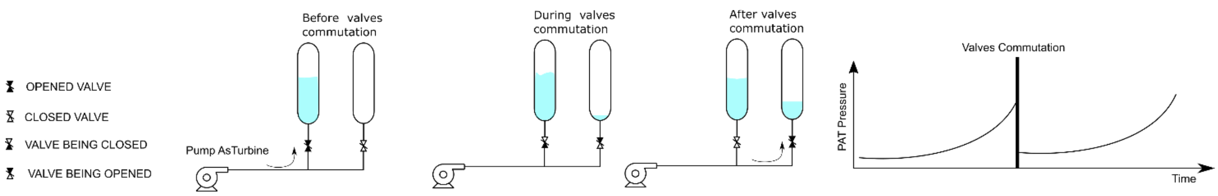


Figure 3: operation of valve switching

The transient periods are observed when the valves/pistons are commutating. The PAT pressure varies considerably (

Figure **3**). At the beginning of this specific period the PAT pressure is at his maximum value (during compression) and has to decrease rapidly at its initial state at the end of the process. The same operation, including parameters variation in short time, happens during expansion mode. This period is similar to a stopping pump period then a starting pump period with valve opening and closing. In order to obtain a suitable model of this future work, two multi-domain physical system simulation tools are compared to show the advantages of each one. The study is developed in the next section. A simple hydraulic system including a Pelton turbine is chosen as example. Firstly, the platform Simulink is introduced where the hydraulic system model is simulated. Each part of the system is described by differential equations. They are organized by block diagram in the software. Secondly, the same hydraulic system model is simulated in the platform 20sim using bond graph method. Then, their results are presented and compared.

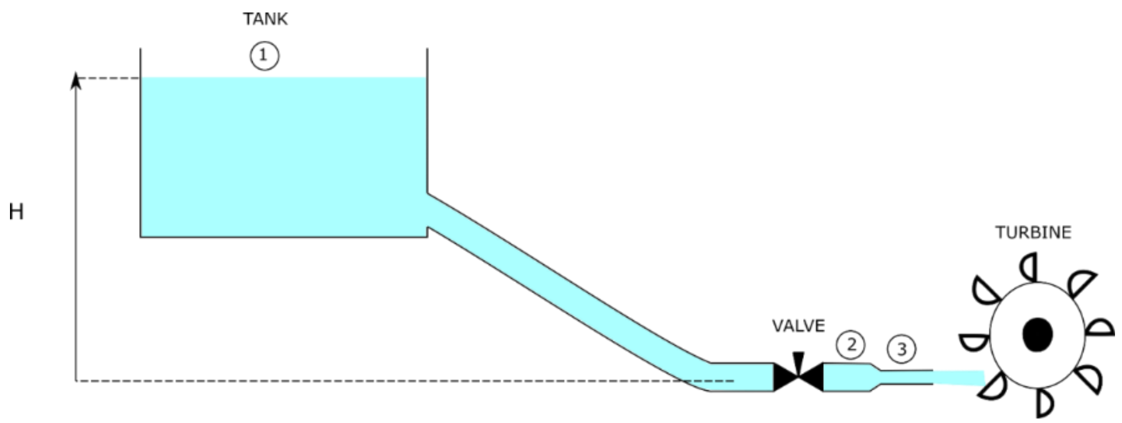
4. HYDRAULIC SYSTEM MODEL

The aim of this paragraph is to become familiar with the 0D tools applied to the hydraulic system, especially Simulink with block diagram method and 20sim with bond graph method. The methods and results will be compared in order to decide which one is the most appropriate for the study case presented.

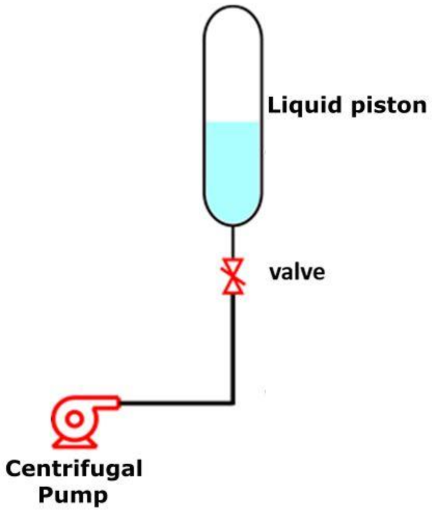
4.1 Description

A hydroelectric system with a Pelton turbine is modelled on MATLAB Simulink and 20sim. It is composed by an opened tank linked to a pipe, a needle valve, a nozzle, a Pelton turbine and a DC generator. The flow at the tank outlet is directed in the pipe, it goes through the needle valve and it is accelerated in the nozzle. The water jet is out of the nozzle at the atmospheric pressure level. The energy from the water jet exerts a force on the Pelton impeller bucket and starts spinning the impeller. A generator coupled with the turbine is driven rotationally to convert the mechanical energy into electrical energy.

The system can be related to the study case previously presented to the extend that an hydraulic circuit including tank and valve are found in both systems. In addition, hydraulic energy transformation into another sort of energy occurs in both situations. Figure 4 shows the hydroelectric system and a part of the Remora hydraulic system.



(a)



(b)

Figure 4: The hydroelectric system schematic (a) and a part of remora hydraulic system schematic (b)

Moreover, the flow behavior is decribed by Bernoulli equation in both cases. The hydroelectric system equations are detailed in the following part.

4.2 Mathematical description and analytical solving

Parameters and variables are described in the nomenclature table at the end of the paper. In order to describe the physical system some classical analytical equations can be written. It is possible to solve them, only in some very particular cases since many equations are nonlinear.
The flow of an incompressible fluid through the pipe is described by the unsteady Bernoulli equation along a streamline between points 1 and 3 neglecting flow velocity in the tank.

$$\rho g H = \rho L \frac{dv_2}{dt} + \frac{1}{2}\rho v_3^2 + \lambda \frac{L}{D_c}\rho \frac{v_2^2}{2} + H_l \qquad (1)$$

The term H_l represents the sum of head losses due to the singularities through the pipe and the valve.

This equations are analytically soved to determine the expression of the jet velocity v_3 by applying equation of continuity (equation (2)).

$$v_2 = v_3 \frac{S_3}{S_2} \qquad (2)$$

The equation (1) is rewritten in the following manner:

$$\frac{dv_3}{dt} = \frac{gHS_2}{LS_3} - v_3^2 \left(\frac{1 + \left(\frac{S_3}{S_2}\right)^2 \left(\lambda \frac{L}{D_c} + K_l\right)}{2L\frac{S_3}{S_2}} \right) \qquad (3)$$

Where K_l represents the sum of head losses coefficients

The expression of jet velocity is written below :

$$v_3 = \sqrt{\frac{b}{a}} \left(\frac{e^{2\sqrt{ab}t} - 1}{1 + e^{2\sqrt{ab}t}} \right) \qquad (4)$$

With $a = \left(\frac{1+\left(\frac{S_3}{S_2}\right)^2 \left(\lambda \frac{L}{D} + K_l\right)}{2L\frac{S_3}{S_2}} \right)$ and $b = \frac{gHS_2}{LS_3}$

The relative force of the jet on the Pelton turbine wheel is obtained from the Newton's second law:

$$F_r = \rho Q_v(v_3 - \omega R)(1 - cos\beta_2) \quad (5)$$

The mechanical and the electrical parts of the system are described by the equations (6) and (7) respectively:

$$I\frac{d\omega}{dt} + B\omega = T_{turbine} - T_{generator} \quad (6)$$

$$L_a \frac{di_a(t)}{dt} + R_a i_a + k\omega(t) = U_s(t) \quad (7)$$

In the next section, graphical approaches are proposed in order to analyse the dynamical behaviour of this system. Then, some simulations can be performed.

5 MODEL DESCRIPTION

Simulink and bond graph simulation tools were used. Simulink is a Matlab software for modeling and simulation of dynamic systems in Universities and in industry. It uses the graphical user interface to build models like block diagrams and adopts click-and-drag mouse operations. Today, many toolkits are available in Simulink. Bond graph represents the power interactions between model components whose basic concept is the graphic link approach. The connection lines between the different components, carry both power variables and causalities between power variables.

5.1 Simulink

The MATLAB Simulink tool is already known for modelling and simulating dynamic systems such as a hydroelectric plant. It provides a friendly graphical modelling interface including a large library to build different systems. Block diagrams are connected together to create each different components of the system according to mathematical equations. In the literature, most of the 0D hydroelectric plants modelling on SIMULINK are focused on the electrical part of the system (Acakpovi, Hagan, & Fifatin, 2014; Sattouf, 2014)

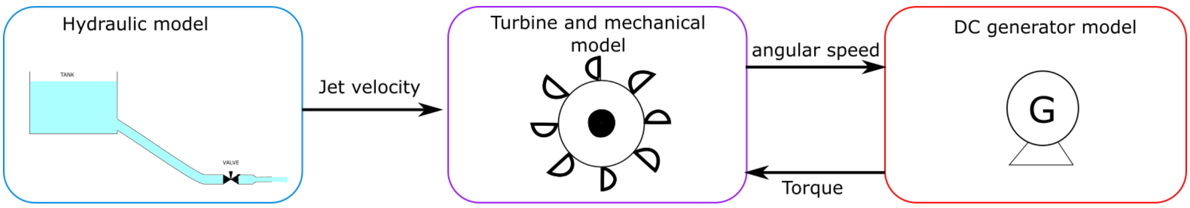


Figure 5: schematic model of the hydroelectric system

The entire system is divided into three different subsystems and is presented in

Figure . The first subsystem represents the hydraulic part including the tank, pipe, valve and injector. It is modelled by equation (1).

The output are the jet velocity and flow rate, they are transferred to the Pelton wheel which is modelled in the second subsystem. This part is described by equations (3) and (4). It takes also into account the mechanical part of the system. And finally, the generator is represented in the third subsystem thanks to the equation (5). It receives the angular speed from the turbine and delivers the electric current and voltage. A full description of each subsystem is given in **Erreur ! Source du renvoi introuvable.**.

- Block diagram of the hydraulic part in case A
- Block diagram of the mechanical part in case B
- Block diagram of the electrical part in case C

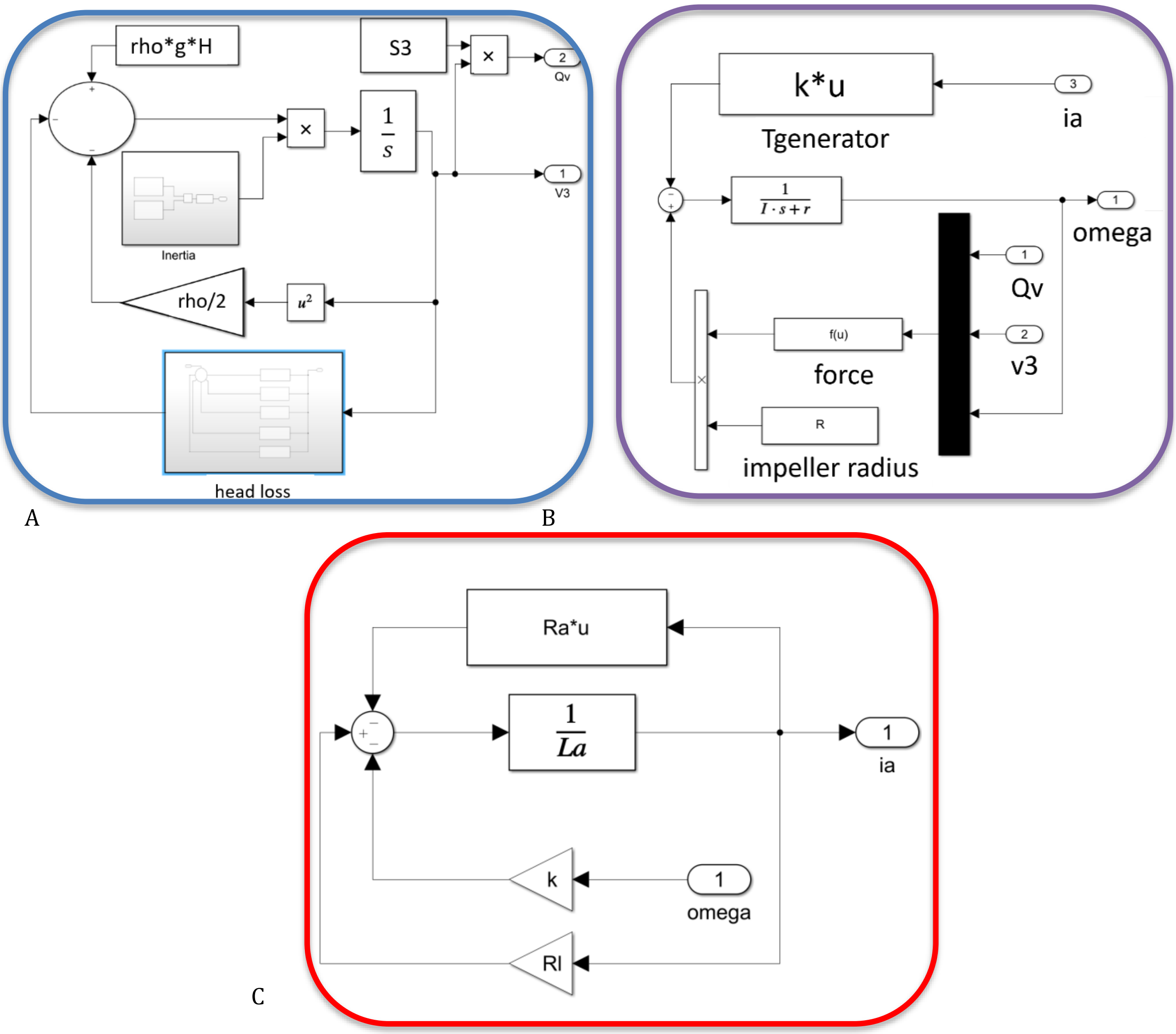


Figure 6: Block diagrams for each subsystem

5.2 Bond Graph description

Nowadays, bond graph approach is used for many research fields in many places around the world. The bond graph methodology is based on the analysis and description of the power flow that takes place in the system (Dauphin-Tanguy G., 2000.), as well as the causality. The energy can be stored, dissipated or interchanged in a physical system. When two systems are connected, the interchange of power appears between them. This is achieved in bond graph modelling by adding a so-called half arrow to each bond indicating the positive reference direction of the energy flow. A half arrow is chosen to distinguish between energy flows and signal flows. Signal flows are commonly represented by edges with a full arrow (Merzouki Rochdi et al., 2013), (Borutzky, 2010). Power variables are generally referred to as effort and flow; additional qualifications pertaining to the domain under consideration may also be included in the model. Table 1 gives effort and flow variables for some of the physical domains. The power P(t) exchanged at the port is the product effort and flow:

$$P(t) = e(t)f(t) \tag{6}$$

Domain	effort e(t)	flow f(t)
Electrical	Voltage (Volt)	Current (A)
Mechanical rotation	Torque (N.m)	Angular velocity (rad/s)
Hydraulics	Pressure (Pa)	Volume Flow rate (m^3/s)

Table 1: Bond graph variables used in various energy domains.

Moreover, in the bond graph modelling framework, the physical system or component is divided into Active, Passive, and Multi-port elements (Merzouki Rochdi et al., 2013, Wolfang Borutzky, 2010).

5.2.1 Basic Elements

Active Elements: Sources that supply power to the system as sources of effort (Se) give effort to the system, and sources of flow (Sf) give flow to the system. The bond orientation always goes out of the source.

Passive elements: There are three types of basic passive elements: Inertial element (I) defined by the constitutive equation $\Phi_I(f(t), \int e(t)\,dt) = 0$ (electrical inductance, mass, inertial components, etc.), Capacitor element (C) defined by the constitutive equation as $\Phi_C(e(t), \int f(t)\,dt) = 0$ (spring, hydraulic tank, electrical capacitance) and Resistor element (R) defined by the constitutive equation $\Phi_R\big(e(t), f(t)\big) = 0$ (electrical resistance, mechanical friction, dissipative forces).

The representation of either of them is done by directing the bond onto these elements as shown in Figure 7.

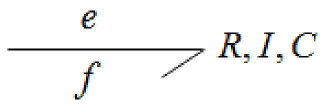


Figure 7: Graphic representation of passive elements

5.2.3 20-sim Description

20-sim® is a modelling and simulation software for dynamical systems. The models can be created graphically or using equations. 20-sim is software that supports bond graph modelling and facilitate drawing the bond graph model. These models can be analyzed, and control systems can be designed. 20-sim can export the model developed as C-code to be used in hardware. Also, 20-sim can create a 3D animated representation for the model. Any Bond graph built in 20-sim can be changed automatically to a linear state space model and the results can be shown as Bode Plot or export the state space model as a Matlab M-file.

Bond graph modelling process of the hydroelectric system is shown in Figure 8 where the transmission of energy between each block is observed. This representation is called "word bond graph". There is an electric part (red) that represents the generator and electric load, a mechanical part (purple) representing the Pelton turbine and shaft and finally a hydraulic section (blue). Besides, the bond graph representation is developed in accordance with the equation (1) for the hydraulic part, the equation (3) for the Pelton turbine and equations (4) and (5) for the electromechanical part.

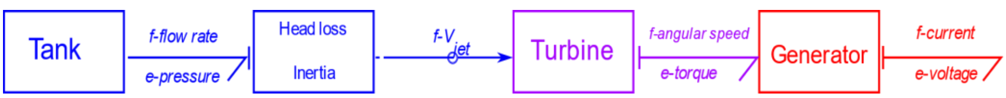


Figure 8: Word Bond graph of the hydroelectric system

The detailed model is given in Figure 9. Bond graph allows representing the power transfer between each element where the energy direction is shown explicitly. The model is realized step by step by adding each element of the system respecting energy exchange and conservation. The behaviour of each component can be verified individually over time.

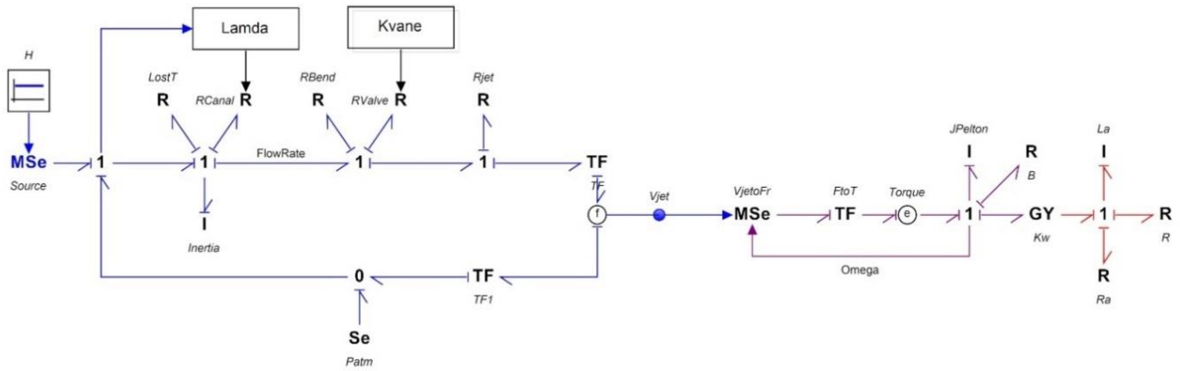


Figure 9: Bond graph representation of the hydroelectric system

5.3 Simulations

Simulations are launched under the same conditions in both software with runge-kutta 4 integration method and with 0.0001 step size. The results in **Erreur ! Source du renvoi introuvable.**show the evolution of the jet velocity simulated in 20-sim®, Simulink and calculated analytically. This figure confirms the accuracy of both models. The simplicity of the system and of its elements doesn't highlight the difference between both tools. The two methods describe precisely the system.

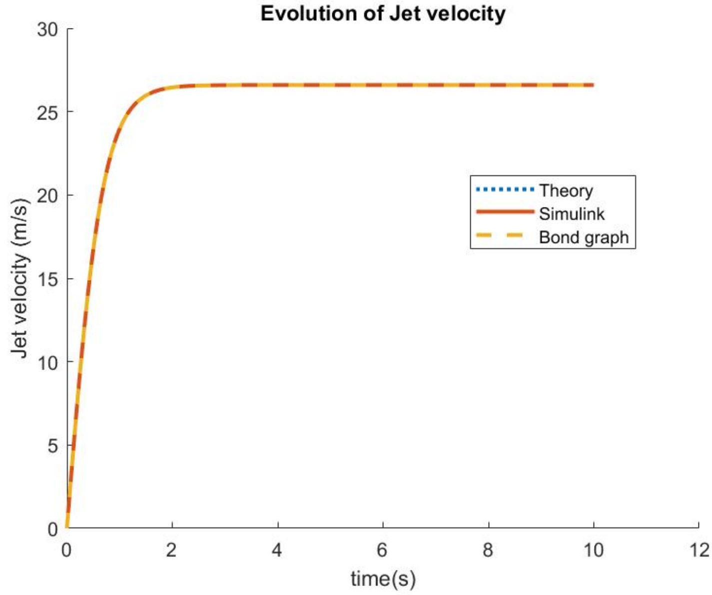


Figure 10: Evolution of the jet velocity resulting from analytical calculation, Simulink and 20 sim simulation

The comparison is then based on the modelling method and the graphic interface of both tools. The mathematical equations are explicitly written in Simulink in the form of block diagrams which allows a better understanding of the physical behaviour of the system. On the other hand, equations are modelled naturally in bond graph models respecting the power exchange and causality between each element. The Bond graph modelling is based on energy transfer between elements of the system. It offers another approach. The main advantage is that it allows reduction of the graph by regrouping the same type of elements with the junction whereas the Simulink model can be very complex depending on the circuits number of the system. The addition of an inertial element or a pipe circuit for example induces to rewrite the equations in the Simulink model. This is not the case in the bond graph model. This basic hydraulic modelling is similar to a simple circuit of the new system presented. However, the UW-I-CAES hydraulic system is composed of many parallel circuits where the flow is governed by the transient regime. The possible fluctuations during the operating system induced by the switching of valves, the presence of many junctions and the rotational speeds variation of the

PAT impeller imply the addition of inertia elements in the pipe, in the valve or in the pump model. The bond graph tool will facilitate the addition of transient elements in more complex structures. It also allows to locate each physical phenomenon that appears during the simulation. In addition, tools are avalaible to convert bond graph model into simulink model if needed.

6. CONCLUSIONS

A new CAES project has been presented. The purpose of this project is to optimize the operation of the hydraulic part of the system. It is necessary to know the flow behaviour during compression and expansion. The process involves considerable rotational speed variations especially during valves switching. It happens while a pump switches from a liquid piston to another one. This process is poorly described in the literature. The known similar applications are related to pump start up or shut down and opening or closing valves. Transient flow is observed during these operations. Some models of transient pump have been presented. However, in the case of the UW-I-CAES operation, the initial parameters and the operating time are very different. Uncertainty also arises from a lack of awareness of large-scale PATs operation and particularly of turbine mode when rotational speed changes. The application of the laws of similarity is to be studied in particular for radial PATs with variable speeds in order to determine their accuracy. The hydraulic part of the UW-I-CAES presented will be modelled in a subsequent study.
Its complex architecture is delicate, and a study is conducted in order to choose the most suitable software. Simulink and bond graph are used to simulate a simple hydroelectric system.

Both models and methods are compared. It has been shown that both results are accurate, however bond graph modelling gives an easier configuration of the system. Indeed, the study case system involves several PAT supplying many circuits in parallel including opening and closing valves in each circuit. bond graph allows the simulation of complex dynamical systems without generating several equations system. It facilitates the energy conversion among mechanical and hydraulic domains. The main goal is to model the UW-I-CAES system by adding progressively each circuit element to visualize the consequences of the physical phenomena.

NOMENCLATURE

Latin letter

B	friction	N.m.s
D	Diameter	m
g	Gravity	m/s^2
F_r	Force	N
H	Height	m
i_a	Electric current	A
I	Inertia	$Kg.m^2$
k	Back emf constant	Nm/A
K_l	Singular head loss coefficient	
L	Pipe length	m
L_a	Inductance	H
N_f	Final rotational speed	rad/s
Q_v	Flow rate	m^3/s
R	Impeller radius	m
$R_{a,} R_l$	Electric resistance	ohm
S_2	Pipe section	m
S_3	Convergent nozzle section	m
$T_{turbine}, T_{generator}$	Torque	N.m
U_s	Voltage	volt
$v_{3,} v_{2\,,}$	Velocity of flow	m/s

Greek letter

β_2	Vane angle	rad
λ	Pipe frictional coefficient	
ρ	Density	kg/m^3
ω	Impeller or turbine rotational speed	rad/s

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