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Technology solutions and innovations for developing economies

Overcoming Hydraulic Issues Using Variable Speed Drive in a Hydro Power Scheme

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Summary: In order to access hydraulic energy at economical cost, all means must be sought. This article describes how variable speed generating units can achieve the requested performances of grid code despite an unfavourable hydraulic circuit. Model results computed with SIMSEN software and using in house controls, demonstrate that the desired goals can be achieved; the inverter interfacing the unit to the grid acts plays a key role. The article also shows the influence of the generator inertia in the process.

Keywords: Hydro power, variable speed,

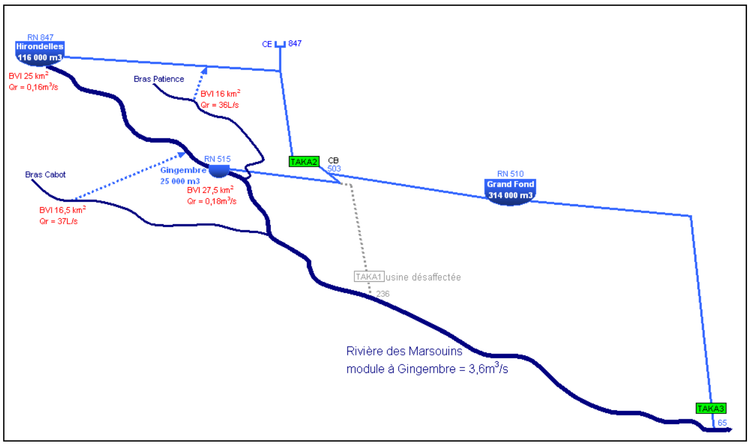
1. Hydro development

Today’s world is requesting more carbon free energy. For many years and still for years to come, hydro power has been and is to remain the largest contributor to green energy generation feeding the world networks. Though hydro potential remains large throughout the world, there are regions where economically viable hydro development is shrinking or has disappeared.

This is especially true on islands where hydro potential is by essence limited.

Part of a hydro cost comes from the dynamic time response required by grid codes; indeed such dynamic behaviour of a generating scheme is quite challenging for hydro units where time response of hydraulic circuit can reach several seconds. This hydraulic time response (T) dawback is sensitive to penstock length (L), since $T = {}^{LV}/_{g\,H}$ (with V water speed, g gravity acceleration, H water head).

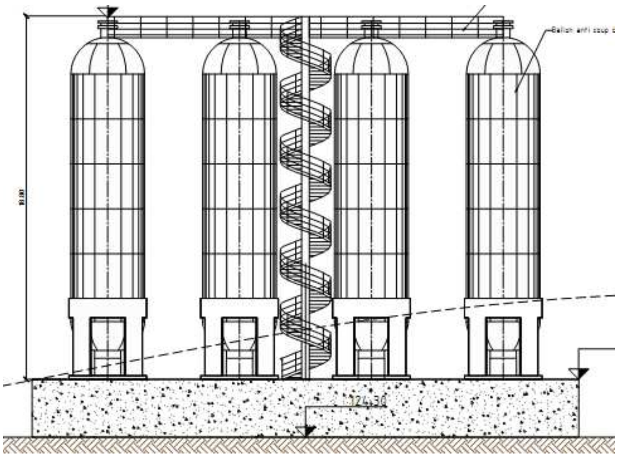
Hydro scheme where reservoir is several kilometres away from the powerhouse require specific device to reduce power time lag. Typically such device is a surge tank located a few hundred meters from the powerhouse. But the soil profile must allow the positioning of such a surge tank at high elevation which is not always the case. The profile below shows an example of a 440m head scheme with a 5000 m long penstock where local topography is not suitable for surge tank erection



General lay out of projected hydro scheme

2. How to overcome hydraulic time response drawback

For specific hydro projects including long penstock on a low slope profile, surge tank is not feasible. Hence other devices have been developed but seldom used; these are pressurized tanks acting as water reservoir and pressure dampers. But these are expensive, bulky and require quite some maintenance.



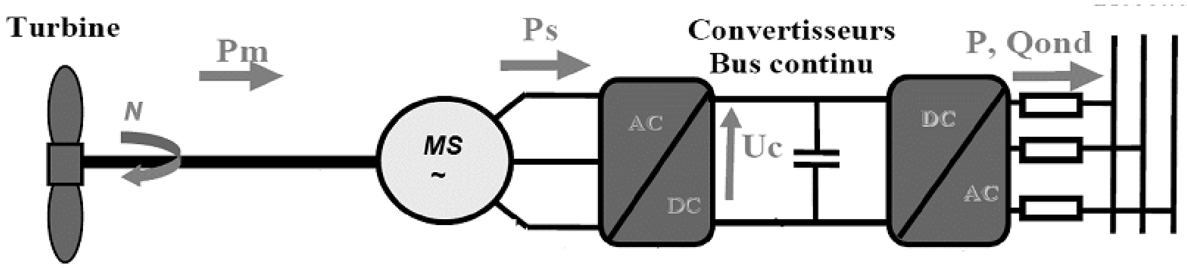
Example of 18m high pressurized tank

Looking for an alternative to cumbersome pressurized tanks, proposal was made to use variable speed in order to make use of the rotor kinetic energy during the hydraulic time response.

The basics behind this proposal is to interface the hydro generator to the network using a voltage source inverter (VSI) and to make use of the stored rotating energy through the inverter to generate electric power. Obviously, in the process, the turbine speed is to decrease in case of power demand. The challenge sits in the time matching between the release of the stored rotating energy and the hydraulic time response.

To assess the ability of such an energy management strategy on a hydro unit, EDF has computed a full model (hydraulic and electric) in order to run several transient scenarios and check the behaviour of the rotating unit, the power delivered to grid, the hydraulic parameters (water head variation mainly).

The basic diagram is as follow:



Schematic diagram of a hydro generator linked to grid through an inverter drive

3. Using a full hydro electrical model with SIMSEN software

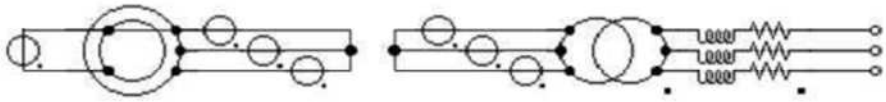
In order to compute all interactions between hydraulic circuit, turbine, generator, excitation system, VSI and grid, EDF Hydro engineering uses an off the shelf software developed by Ecole Polytechnique de Lausanne in Switzerland. This software has been developed since 1996 and upgraded ever since. It features pre modelled objects (turbine, generator, pipes, regulators, thyristors ,…) whose parameters are to be customized to the actual hydro scheme components (turbine torque vs opening; generator impedances; pipe sizes; regulators settings,…). The software also features control and logic components that enable to design in house control laws.

To compute the model, the expected design of the hydro scheme was entirely translated into SIMSEN components.

These included:

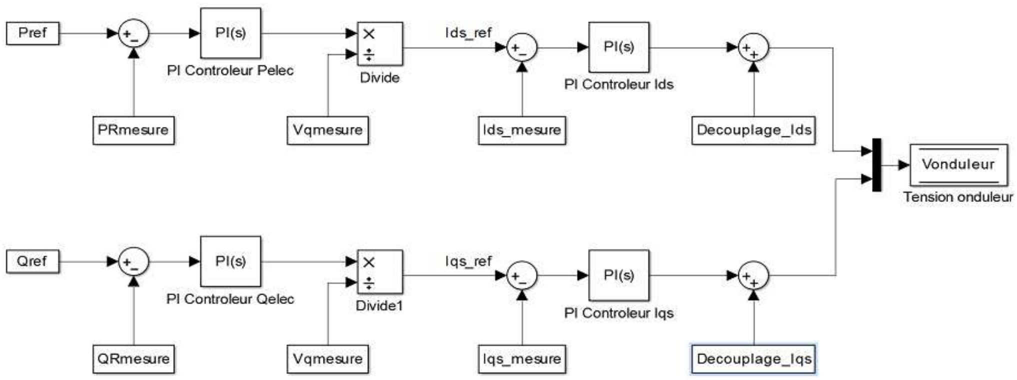
- 2 generating sets, each equipped with a Pelton runner, and a generator
- Each runner is equipped with a speed regulator adjusting the needle opening; the deflector is considered fully open and serves no purpose for the speed adjustment
- Each generator includes a static excitation system with AVR
- Each generator stator is connected to a VSI
- 2 transformers
- The turbines are fed with a penstock 5km long with a 440m gross head

Modeling the VSI is not an issue but can become very computing time consuming. In previous models using VSI, EDF has demonstrated that a quasi continuous model of the VSI shows same result as a full discrete element model. Hence, for this model, VSI was also modelled using continuous voltage sources driven by the VSI control and power regulators.



Model of the electrical components, the VSI is represented with 6 single phase voltage source

The generator active and reactive powers are controlled through the VSI using a vector control algorithm. The regulation diagram uses four PI regulators: Let’s note that on the generator side there's no need for reactive power, hence its reference will always be set to zero. This feature shows that with an inverter interfacing the network, the generator can be smaller than if directly connected to the grid. With an inverter interfacing the grid, it will be the inverter task to supply the reactive power.

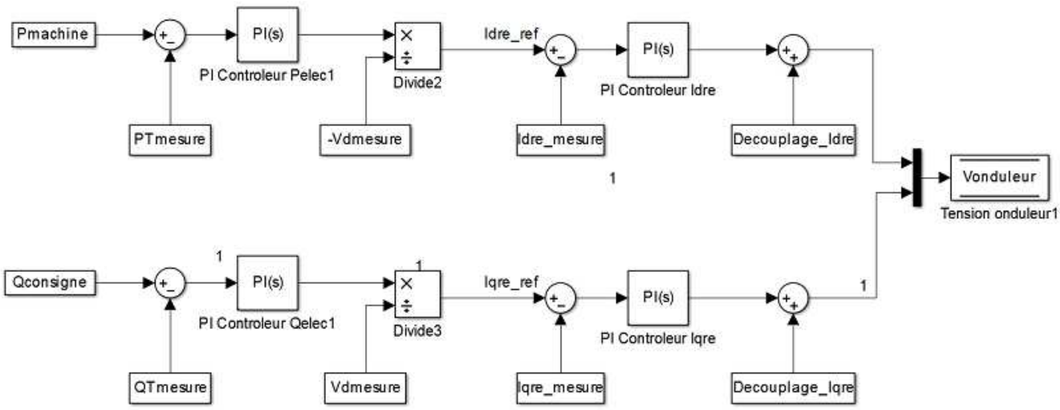


Regulation diagram of the generator side inverter

The inverter connected to the stator draws the power as requested by the grid set point. Hence, the stator side inverter acts on the airgap torque. As a consequence, the rotor will vary and the speed regulator will counter act accordingly. Therefore, two regulating loops are also necessary on the generator side, one to adjust the speed using the turbine control, and one to keep the stator voltage constant using the automatic voltage regulator and excitation system.

On the grid side, the inverter must supply the exact active power coming from the generator side inverter. Also, as explained above, the inverter shall also supply grid voltage with reactive power.

The grid inverter voltage sources are also controlled using vector control, with the following diagram: The control loops also use four PI regulators.



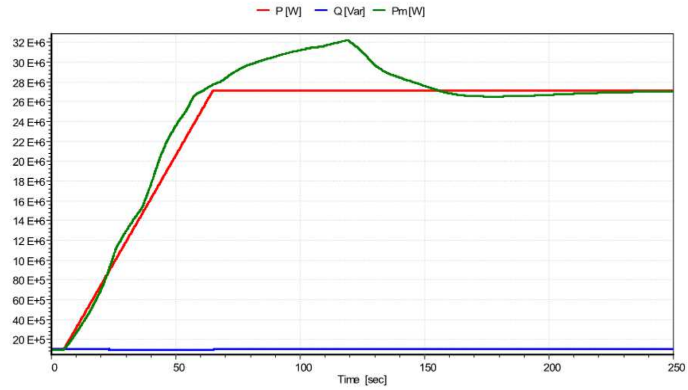
Regulation diagram of the grid side inverter

The grid side inverter is in charge of reactive power delivered to grid. And on the active power side, the grid side inverter transfers the entire power drawn from the unit by the generator side inverter. The inverter time response is so quick (10 mille seconds) that its time lag is negligible in comparison to the generator and turbine.

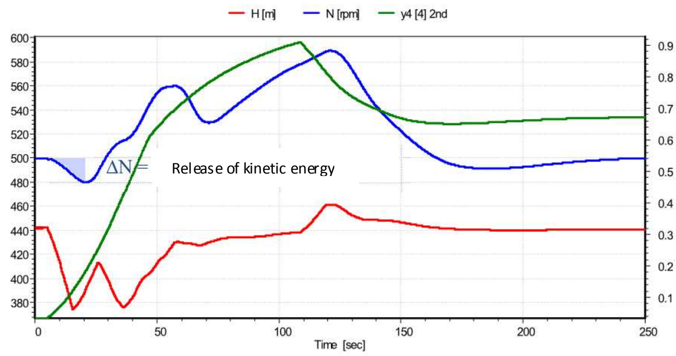
4. Modelling results

To validate the model and to validate the proposed concept 3 operation sequence were simulated as requested in the grid code. These included load increase from zero to 100% in

the prescribed time frame (60 s), load reduction and increase of 20% also within the prescribed time (15 s).
The load increase are quite challenging for this hydraulic set up since the pipe is 5km long and has no surge tank. Its launching time is 6 seconds, meaning a rather slow rate of load variation.
On the other hand, load reduction leads to a pressure rise in the penstock, and an oscillation of pressure which damping has to be watched carefully. Indeed, one of the mechanical constraint is to avoid penstock oversizing in two aspects : steel fatigue and therefore avoid pressure oscillation and steel stress and therefore maximum over pressure. Head variation must therefore remain +/- 15% of static head.
Nevertheless, the simulation shows that the unit controls can achieve the desired scenario in terms of power delivered to the grid still complying with the maximum admissible head variation.



100% power ram up ; (red) Power delivered to the grid; (green) Mechanical power on shaft.



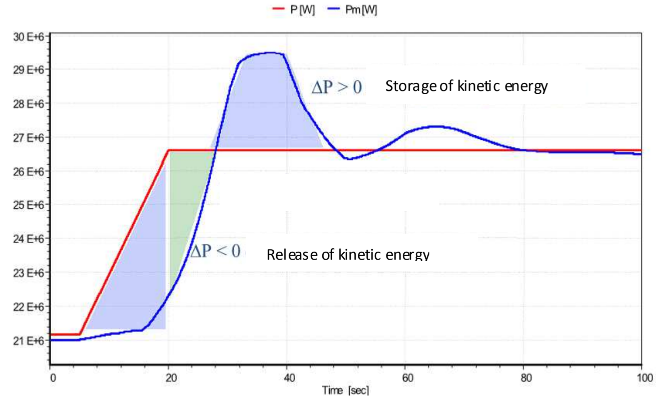
100% power ram up ; (red) water head; (green) turbine opening; (blue) shaft speed

Ultimately, it can be noticed that the bothering time lag of hydraulic turbine is completely cancelled thanks to the availability of the rotating kinetic energy, which is drawn as soon as the active power set point increases.

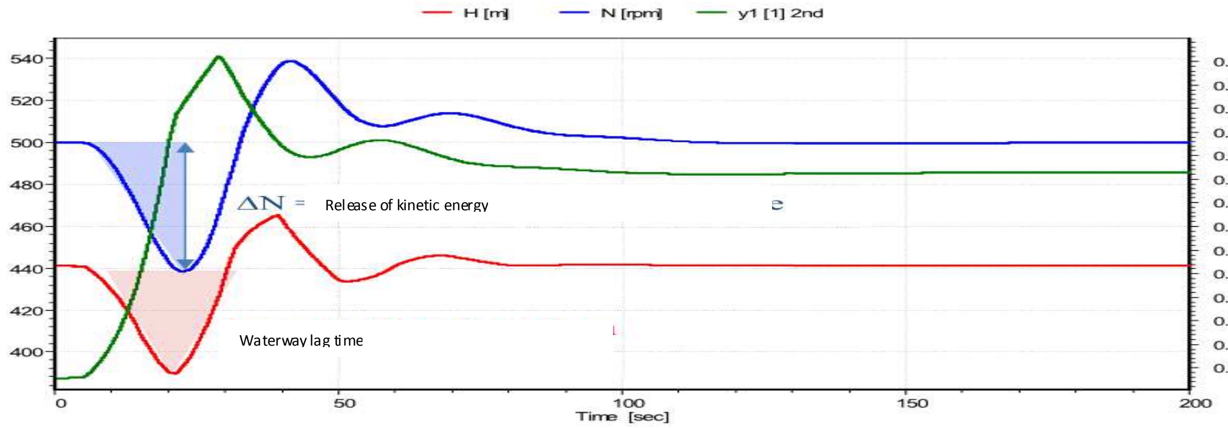
Similarly, with the same constraints for maximum admissible water head variation, modelling the 20% load increase in 15 sec shows the following results :

The power delivered to grid is extremely stable and follows the set point, whereas the mechanical power on shaft shows several seconds lag time.

The speed and power oscillations are dampened in less than 100 seconds while the water head variation remains within the 15% admissible variation.



20% power increase: (red) power delivered to grid; (blue) mechanical power on shaft



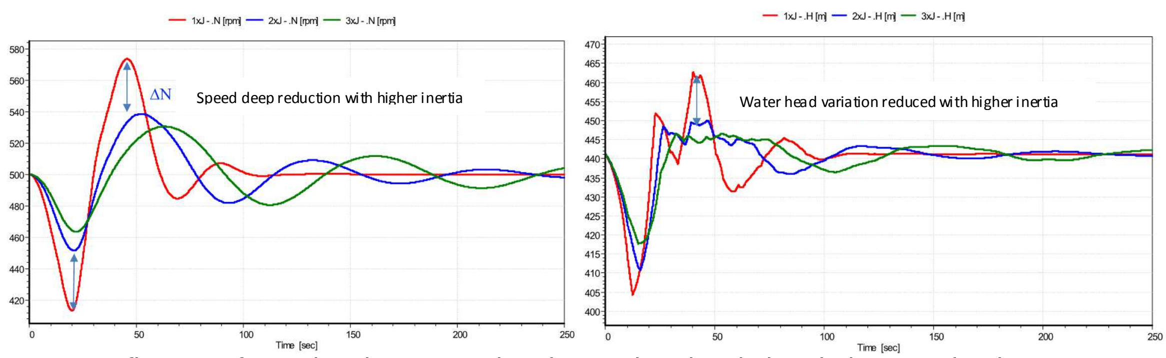
20% power increase: (red) water head; (blue) shaft speed; (green) turbine opening

As a consequence, the simulation demonstrate that island grid code criteria can be fulfilled with an inverter interfaced generator despite the long penstock and the water inertia.

5. Influence of rotor inertia

As seen above, using kinetic energy stored in the rotor to supply the grid during the hydraulic transient works and achieves the desired goals. However, it could be expected that with a greater rotor inertia, and thus a greater stored kinetic energy, the unit dynamic behaviour would be improved.

The model was used and the regulators were tuned in order to test higher inertia values. 3 inertia values were compared : a/ the natural inertia (red), b/ twice the natural inertia (blue) , c/ three times the natural inertia (green). A load increase of 20% in 15 sec was tested.



Influence of rotor inertia on speed and water head variation during 20% load ramp up

As expected the speed deeps are less important with larger inertia: doubling the inertia, reduces speed variation almost by half but triple rotor inertia only reduces speed variation by an extra 5%. However the speed oscillations last longer since the damping remains the same. Hence the turbine governor keeps adjusting the turbine opening to counter act the speed oscillation which is detrimental to head fluctuation in the penstock and metal fatigue.

As a consequence, it can concluded that an optimum inertia is to be sought between one and two times the natural inertia both economically and technically.

6. Other benefits of variable speed drive

Using a variable speed drive to connect the generator to the grid includes several other benefits on top of the enhanced dynamic frequency/power response.

One of the benefit of the power inverter is to be able to deal with the reactive power – and thus voltage support – on a larger scale than the generator. The P/Q capacity curve or an inverter is a circle, hence avoiding the generator usual limits that are rotor maximum excitation current, and power factor leading stability limit.

Also, since the reactive load is handled through the inverter, the generator can be specified with power factor = 1, making it smaller and thus cheaper, even though the rotor inertia has to be greater than the natural one (steel remains cheaper than copper).

Another benefit of the inverter is that it can remain connected to the grid even when the hydro unit is not generating then acting as a static VAR compensator. This extra benefit for voltage support can be of interest to the grid managers and, since such grid services are paid for, it brings an extra income to the plan owners.

On a mechanical point of view, the inverter being 4 quadrants type, it can be used to help launching the unit up to speed together with the turbine and thus reducing ramp up time and water consumption. This feature can be very useful on Francis type turbine where zero speed water flow generates high vibration and wear.

7. To conclude

Using stores kinetic energy as a mean to increase the transient capability of a hydro unit is an old idea, however it had to wait for the inverter technology to improve and become able to handle tens of megawatt before being feasible.

As part of EDF innovation seeking, it has been demonstrated that long waterway lag time can be overcome thanks to the use of stored kinetic energy, but that regulation has to be properly set in order to avoid high head variation that could be detrimental to penstock ageing.

Moreover, the study showed that, contrary to common belief, higher inertia does not lead to improved unit behaviour since the stabilisation time of the rotating part also increases and leads to long lasting water head oscillations.

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