High flexible Hydropower Generation concepts for future grids

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Abstract. The ongoing changes in electric power generation are resulting in new requirements for the classical generating units. In consequence a paradigm change in operation of power systems is necessary and a new approach in finding solutions is needed. The presented paper is dealing with the new requirements on current and future energy systems with the focus on hydro power generation. A power generation landscape for some European regions is shown and generation and operational flexibility is explained. Based on the requirements from the Transmission System Operator in UK, the transient performance of a Pumped Storage installation is discussed.

1. Flexibility in power system operation
All the impacts of high penetration of RES in the production mix were already discussed in the last years with the conclusion that all remaining classical generating units in grid must be more flexible in the future. The current power generation and consumption is nowadays characterized by the following features:

- **Steeper Ramping**: The rate of increase and decrease of dispatchable capacity of generation
- **Lower Turn downs**: To operate units at part or minimal load
- **Shorter peaks**: The peaks of generated power from RES are shorter in duration

As a consequence the whole power system including all different sources is faced to new challenges. The overall Power System has to provide in the future more Flexibility in Generation, Transmission, Demand side management and System operation.

1.1. The Impact of inflexibility to power system operation
Missing flexibility is resulting in operational limitations and can also reduce the system stability. In case of a severe system fault, the system can become unstable and this could result - under worst case condition - in a system black out.

Indications of reduced or missing electrical system flexibility are:

- **Problems to balance demand and supply**: As a result the grid frequency deviates from the nominal value and exceed the defined limits under worst case conditions
- **Curtailment of RES**: Due to restrictions in transmission capacity the available generated power from RES cannot be transferred to the consumers
- **Violations of area balancing**: These are deviation from schedule in power area balance
- **Negative market prices**: This can be a consequence of any kind of inflexibility. E.g. power plants cannot reduce the output or load cannot absorb the generated power
- **High Price volatility**: Any kind of inflexibility can result changes the energy price
1.2. Graphical representation of Flexibility
The power generation mix in different regions of Europe is quite different. In the following diagrams 5 different power sources are considered. This representation was first introduced by Yasuda in [4] and is shown in Figure 1 below. Significant is the power generation in Denmark, with a high contribution of wind power and interconnection. Nordic countries having a high contribution of Hydro Power in the generation mix. The power generation in Portugal is characterized by hydro and thermal generation.

![Figure 1: Diagrams showing the power generation mix in Europe in 2013 [4]](image)

1.3. Definition of operational Flexibility in Power Systems
The term “Flexibility” is frequently used in power system discussions but not clearly defined. This can result in misunderstanding and differences in expectations in communication about system stability and future grid topologies. Below a physical/mathematical approach is shown [1].

For measurement of operational flexibility of the different power generating units in the grid, the following methodology is established.

- **Power Capacity [MW]**: which is the dispatchable range of generation power output of a unit
- **Power ramp rate [MW/min]**: the rate for increase and decrease of the unit generation power
- **Storage Energy [MWh]**: The energy must be stored needed for power area balancing

1.4. Modelling of operational Flexibility
Operational flexibility can be defined as the interaction of the flexibility needed by the system and the generation available flexibility. For successful operation of an electric power system, the needed flexibility must be fulfilled by the Flexibility offered by the generating units.

1.4.1. Available generation Flexibility
In Figure 2 below, the Flexibility of different power generation technologies is shown.

![Figure 2: Flexibility chart for different power generation technologies](image)
1.4.2. Needed operational Flexibility
For the needed operational Flexibility no general rules exists. Basically the influencing factors are: contribution of RES in the power generation mix, the stored energy in the grid (inertia) and the degree of interconnection to other systems.

2. Requirements from the Grid
The European electrical grid comprised different Transmission System Operators (TSO) between Portugal and Poland and between Greece and Norway. The installed generation capacity in the entso-e grid is about 994 GW (2015 - Data provided by ENTSO-E) with an increasing penetration of renewable power generation, like wind and solar. The ongoing phase out of nuclear power generation in Germany is resulting in new challenges for the TSO’s because of reduction of system inertia as well as reduction of system damping.

3. The role of Hydropower generation in the power system
There is no need to explain the importance of Hydro Power generation in the total electrical energy production in the world. In the following sections, the technical features in terms of flexibility of hydro power will be discussed.

3.1. Existing installations
Most of the units currently in commercial operation are running with a constant rotational speed. New installations in Portugal and Switzerland with variable speed concepts are currently in the commissioning phase. Depending on the type of installed turbine, the concepts are offering the following features:

- Units equipped with KAPLAN turbines are not so flexible in transient operation and currently are not used for Primary Control.
- PELTON units are very flexible and can operate in a wide range. The ramping time must be coordinated with the permissible pressure rise and drop in the often long penstock.
- FRANCIS Turbines are used for high power application up to 1000MW, with a limitation in the operating range
- Reversible Pump Turbines are more specific designed, because of operation in two directions of rotational speed with different signs of output
- TERNARY sets are combination of a Pelton or Francis turbine and a Pump with only one direction of rotational speed. The hydraulic machines can be mechanically separated by a clutch. This solution is showing the highest transient performance.

3.2. New Technologies – Power Electronics / Speed variation
By means of Power Electronics the generator can be separated from the grid and operate with a speed different from the synchronous speed. The specific size of the converter varies on supplier and is in the range of 3-4 m³/MW. The losses are in the range of 1.5% - 2% for a 100MW converter.

These drawbacks are compensated by additional features of the entire system which makes the unit now much more flexible in operation.

3.2.1. Controlled Power flow
So-called Full Size Frequency Converter (FSFC) is connecting two systems with different voltages and frequency by using power electronics. Reactive power can be controlled independently on both sides. By control of the speed of the generating unit, the hydraulic turbine or pump can operate on the best efficiency point depending on applied load and hydraulic head.

The main advantage of such a concept is the fast control of the power flow between the grid and the electrical machine. For that reason disturbances in the grid (in voltage and frequency) are not influencing the generator.
3.2.2. Synthetic Inertia
Due to decoupling of grid and generating unit, the system is insensitive for frequency excursions in the
grid. This behavior can be observed in solar power applications and is not welcome by the TSO.
On the other hand by means of control now units equipped with FSFC can provide additional
power depending on frequency gradient. The energy stored in the rotating mass will be used for the
fast power response. This feature is called “Synthetic Inertia”, when the power is higher than the
natural reaction of a synchronous machine with the same size.

4. Ongoing developments in Electrical Power Systems

4.1. Current situation in the Great Britain grid
The electrical grid in GB is characterized by a high penetration of RES and low system inertia. At the
moment the frequency control in the grid is provided by primary control with a response time of
9 seconds (compared to a response time of 30 seconds in Continental Europe).

![Figure 3: Grid-Frequency in GB record from November 2015](image)
Frequency measurements with a sampling rate of 1 second for the years 2014 and 2015 are provided
by nationalgrid [6]. In the diagram left an example of a period of 1000 secs, from November 2015 is
shown. The drop of the frequency is a result of loss of generation. The following overswing is caused
by activation of primary and secondary control.

4.2. Enhanced Frequency Response (EFR)
For fast dynamic grid stabilization nationalgrid is asking for new service called “Enhanced Frequency
Response” EFR. In Figure 4 three power output curves depending on frequency deviation are defined.
The actual value of control power should be within the RED and BLUE boundary curve.
With this new fast responding service the grid can be stabilized much better and as a consequence
the amount of primary and secondary control reserve can be reduced.

![Figure 4: nationalgrid definition for Enhanced Frequency Response EFR](image)
The service must be provided symmetrical for a duration of 15 minutes.
The requested response time should be less than 1 second.
4.3. **FIXED speed system response**

Figure 5: investigated concepts – FIXED speed (upper part) – VARIABLE speed with FSFC (lower part)

Due the requested short response time for the EFR service and the wide operating range classical Pumped Hydro Storage concepts with Synchronous machines and FIXED speed are not in the position to fulfill the requirements. Especially in Pump operation control of the power of the unit is not possible. The simulation results are shown in Figure 6 below.

![Transmit simulation for EFR request of a FIXED speed installation with variable grid frequency](image)

Figure 6: Transient simulation for EFR request of a FIXED speed installation with variable grid frequency (as shown in Figure 3) LEFT: Turbine operation; RIGHT: Pump operation

4.4. **VARIABLE speed system response**

One of the options to fulfil the requirements is to use a system, which allows a very fast and accurate power control. This can be done by using a variable speed power generation system, equipped with a Full Size Frequency Converter (FSFC). The fast power response now can be provided by using the flywheel effect of the generator (Synthetic Inertia) and for static response the ability of the hydraulic pump-turbine of power variation by changing the rotational speed. The results of the simulation of a variable speed system are presented below in Figure 7. The requirements can be fulfilled with any restrictions. The simulation results showed below based on an example for 300MW Pumped Storage installation.

![Transient simulation of a VARIABLE speed installation and variable grid frequency](image)

Figure 7: Transient simulation of a VARIABLE speed installation and variable grid frequency

As already mentioned above, with a VARIABLE speed system the requested performance can be achieved easily. The control power is inside the defined range for the considered case.
5. Summary & Conclusion
In the presented paper the current and future situation in electric power grids in terms of Flexibility was discussed. In section 4.1, an example based on the requirements for “Enhanced Frequency Response” published by the TSO of UK – national grid was given.

![Comparison of the EFR requirements for a FIXED speed unit (left), and a VARIABLE speed unit (right) in pump operation](image)

Figure 8: Comparison of the EFR requirements for a FIXED speed unit (left), and a VARIABLE speed unit (right) in pump operation

The results of the simulation for a FIXED and VARIABLE speed Pumped Storage unit can be summarized for the different features as follows:

- To provide a fast responding service with hydro power generating units, variable speed solutions must be used. By using the stored energy of the rotating mass of the rotor, power can be supplied or consumed from the grid within parts of seconds (see Figure 8)
- In combination with the flywheel effect, the variable speed concept also allows to operate the unit in an extended range of output
- Especially in pump operation mode, the power can be controlled by speed variation
- Due to decoupling of grid and generating unit, the system allows a wide operating range for grid frequency and voltage. So the new requirements for grid connection from the Transmission System Operator can be fulfilled easily
- In most of the cases the drawback of a needed converter will be compensated by the additional new features described above

6. References
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