Application of Power Electronics on Hydropower Generation

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Abstract. The developments in power electronics are offering new opportunities in operation of hydropower generating units. The applied load in pump and turbine operation cannot be changed easily. By using of frequency converters, the speed of the units can be changed in a defined range, without losing much efficiency. An additional benefit of such kind of concept is the improved transient performance of the entire system. In the presented paper the advantage of speed variable power generating system equipped with frequency converters are shown.

1. Classical concepts in Hydro power Generation

Electrical Power Systems are operating with a 3-phase alternating current (AC) system with 50Hz or 60Hz. The synchronous speed is defined by the system frequency and the number of poles of the motor/generator. In most of the generation applications the prime mover is direct coupled with the generator. For very high or very low rotational speed of the turbine a gear box will be used. So the size of the generator can be reduced, but on the other hand the efficiency will be reduced and maintenance costs of the unit are increased. In general, AC generating units have to provide active power for balancing of production and consumption and reactive power for voltage stability.

1.1. Electric Machine concepts

Depending on the application different types of electrical machines are used in hydro power generation. For all machines the active power flow only can be controlled by the turbine.

The electrical machine concepts are also different in the amount of provided Inertia. This can be important when special requirements from the Network Code (NC) must be fulfilled.

1.1.1. Synchronous machines
This type of machine in used in 99% of all the power generating systems. In the classical concept the reactive power can be controlled by variation of the excitation voltage. The excitation current can be transferred by slip-rings to the rotor or brushless exciters can be used.

For transient system stabilization a Power System Stabilizer (PSS) can be used. By measuring speed and electrical power, and additional damping torque will be provided for an active stabilization of the units. In most of the Network Codes this additional control function is mandatory.

For small units in special applications permanent excited machines can be used. Because of missing control of reactive power flow, the application of this option must be confirmed by the Transmission System Operator (TSO).
1.1.2. Asynchronous Machines
This type of machine is characterized by a very simple and robust design. On the other hand, these units cannot supply reactive power to the grid. For that purpose, additional electrical components (reactive power compensation) must be installed.

1.1.3. Asynchronous Machines with slip-rings
For special applications, the rotor of the machine can be equipped with a 3-phase winding system which is connected to 3 slip-rings. This type of machines, together with a converter in the rotor circuit, nowadays is used for variable speed hydro power generation. A detailed description of this system can be found in chapter 3.1 below.

1.2. Requirements for Grid Connection
For grid connection, each generating unit has to fulfill different requirements defined in the Network Code of the TSO.

All the parameters of the generating units (voltage and frequency variation) are defined on the network connection point – Point of Common Coupling (PCC). The main requirements are: voltage and frequency variation, reactive power capability, frequency regulation capability, and transient stability. The last point is most critical, especially for units with low inertia (e.g., Bulb type Hydro units, or gas-turbine driven units). In Figure 1 below, the rotor-angle as a function of the inertia constant $H$ following a 150ms grid disturbance is shown.

![Figure 1: Diagrams showing transient stability on a grid fault with clearing time of 150ms and different Inertia $H$](image)

The normalized energy of the rotating mass is expressed in the Inertia constant $H$ measured in MWs/MVA. Units with low inertia are not able to fulfill the transient stability requirements.

The maximal fault clearing time will be defined by the TSO and is in Central Europe 150ms. This time can be different in other regions of the world.

2. Power Electronics
The ongoing development in power electronic switching devices enables now to design and build converters in the multi-Megawatt range. Devices like IGBT, IGCT, and IEGT from different suppliers are available for voltages up to 8000 Volts and 4000 Amps. The used converter topologies are different depending on supplier. All the offered solutions have an excellent transient performance and a high efficiency.

The principal diagram of a frequency converter is shown in Figure 2. The converter itself cannot store energy, so the active power $P$ on both ends must be the same at any time. The reactive power $(Q_1, Q_2)$ can be controlled independently and can be different.

By means of a power electronic circuit, a voltage phasor is generated which is used for control the power flow between the AC and the DC terminals (Figure 3). The very short response time of the voltage control allows very accurate and fast power control of the converter.
2.1. Classical Three-Level converter
This type of converter is mainly used in drive application for low voltage as well as in medium voltage applications. The shape of the phase voltage of such kind of converter is shown in Figure 4 on the left diagram.

2.2. Multi-level converter
This converter topology will also be used for High Voltage Direct Current (HVDC) power transmission. Hereby identical power electronic modules are connected in series so high output voltages (some 100kV’s) can be achieved. The same modules can also be used in application for power generation for voltages up 20kV. For operation at frequencies lower than 15Hz, the output current must be reduced.

In Hydro Power generation this restriction does not limit the application of the converter, because of the speed operating range of a hydro turbine is small and the frequency can be defined by choosing the number of poles of the generator.

3. Variable speed concepts for Hydro Power Generation
Based on the machine and the converter technology different concepts for variable speed power generation systems are possible. In the following paragraphs, an example for a variable speed unit with a rated output of 420MVA is presented.
3.1. Double Fed Induction Machine

For the Double Fed Induction Machine concept an asynchronous machine with slip rings is used. The converter is connected between the rotor circuit and the grid for exchange of the “slip-power” (see Figure 5 below). It should be noted, that in generator mode and sub-synchronous operation a circular power flow is generated (left diagram). A detailed description of the electrical model is available in [5]. General transient power system aspects can be found in [6], [8] and [7].

![Turbine (generator) mode](image1)

![Pump (motor) mode](image2)

In the diagrams in Figure 5, the power flow from the mechanical shaft through the generator and converter to the grid for different load cases is shown.

The power flow through the converter depends on load flow and on the sign of slip.

In pumped storage applications the units are usually operating in sub-synchronous mode in turbine operation and in super-synchronous mode in pump operation.

![Figure 5: Power flow diagram for Turbine operation (sub-synchronous) and Pump operation (super-synchronous) of an example case](image3)

This kind of system can operate only in a limited speed range. In the diagrams below (Figure 6) the efficiency for different loads in generator mode and in a defined speed range of +/- 7% is presented.

![Figure 6: Efficiency for a DFIM for different load and speed](image4)
The total losses are calculated as sum of the losses of the involved components with different characteristics. Mechanical losses are depending only on speed, generator losses are more depending on load and some losses are constant.

3.2. Full Size Frequency Converter
For Full Size Frequency Converter application (see Figure 2) the diagrams for efficiency are shown in Figure 7. Due to different loss mechanisms the shape of the losses curves looks different. In general the losses are higher, compared to a DFIM. On the other hand this system offers more flexibility in terms of operating range and transient performance.

Figure 7: Efficiency for a Full Size Frequency Converter concept for different load and speed

4. Comparison & Outlook
In the table below the two proposed concepts are compared on different criteria’s.

Table 1: Comparison of different concepts for variable speed power generation

|                              | Double Fed Induction Machine                                                                 | Full Size Frequency Converter                                |
|------------------------------|------------------------------------------------------------------------------------------------|---------------------------------------------------------------|
| **Electrical Machine**       | 3-phase winding system in the rotor, connected to slip-rings.                                   | Simple electric excited Synchronous machine                   |
| **Speed range**              | Limited: about +/- 7% from synchr. speed in practical hydro application                         | Speed can defined with restriction to fit best to hydraulic conditions |
| **Start/Stop**               | Additional equipment for pump-start needed                                                    | Pump-start in water with converter possible¹                  |
| **Grid Code Compliance:**    | Can be fulfilled with additional equipment or oversized converter                               | Can be simple fulfilled                                       |
| **Fault Ride Through²**      | Must be provided by machine and converter                                                      | Provided by converter only                                    |
| **Reactive Power**           | Generator and connection more complex, Converter small                                         | Generator simple, Converter larger                             |
| **Sizing of equipment**      |                                                                                               |                                                               |

¹ Operation of the unit in the full speed range (FSFC) is reducing the mechanical stresses of the hydraulic equipment during transitions. This is a main advantage when the units are operating with frequent start/stops.

² This is a mandatory requirement from network code and will be defined in detail by the related TSO. A basic definition is provided by entso-e [3]
Both of the proposed concepts are showing major improvements in hydro power generation by:

- Extension of operating range, and
- Improving the transient performance

The drawback of installation of additional power electronic equipment with higher losses will be compensated by higher flexibility which becomes more important in the future. Due to future developments in power electronics reduction in cost and size of the converters can be expected.

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