Hydro Power Integration with DC Power Plant Technology

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Abstract:

Given the continuous development of hydropower generation and significant progress of HVDC technologies, the variable speed operation of hydropower plant with HVDC station (unit connection) becomes technically and commercially feasible. It results in a substantial improvement in system efficiency, performance and design flexibility. Further, if the hydro power plant is connected to a DC grid, a DC power plant with DC Power generation and DC voltage control is formed essentially. The DC power plant will play an important role similar to the conventional AC power plant in an AC grid system. A DC power plant can employ either HVDC Classic station or VSC HVDC station. VSC connection provides more control flexibility such as decoupled AC and DC voltage controls and fast electrical emergency braking. In this review paper, the characteristics and control principles of the hydropower plant unit connection with HVDC station are introduced. Based on the unit connect, ion, the DC power plant concept is proposed for hydropower integration into DC grid. The configurations of DC power plant are presented. The advantages of DC power plant and challenges for a practical system are analyzed. It concluded that the DC power plant will have a very attractive prospect for hydropower integration and DC grid application.

Keywords:

DC Power Plant, Unit Connection, Hydropower, HVDC, DC grid, Efficiency, Variable Speed

1. Introduction

Renewable energy generation is continuously growing in the past decades. Among various renewable sources, hydropower is attractive in countries with abundant resources and is still the largest contributor to total renewable power generation globally. According to the estimation of International Energy Agency, hydro power accounted for 80% of total renewable generation in 2011. Over 2011-2017, hydro power generation should grow on average 120 TWh per year (or + 3.1%) as capacity rises from 1070 GW to 1300 GW. China is the world's largest hydro power market and the total installation capacity will reach to 340 GW in 2017. World and China hydropower capacity from 2010 to 2017 is shown in Figure 1[1].

Today there are 3 types of hydro power: conventional hydro with dam, pumped hydro storage and run-of-the-river. Besides, tidal power can be also regarded as hydropower. The conventional hydro with dam is still the main method to generate hydroelectric power, by using the potential energy of water at reservoirs. Turbines placed in water flow extract energy and convert it into mechanical energy and then electricity.

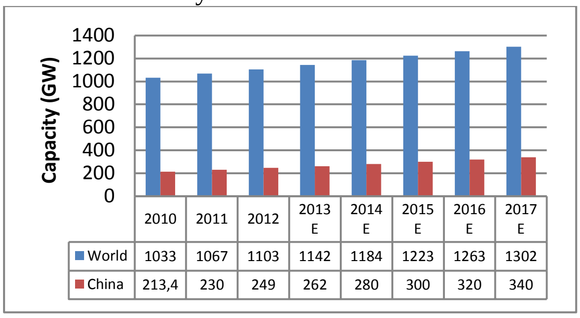


Figure 1 World and China Hydro Power Capacity

Hydropower has been thought as a fully commercial and mature technology for many years. However, as most of new hydro power plants are located at remote areas, high voltage direct current (HVDC) transmission has been preferred for bulk energy and long distance transmission. The coordination of hydro power plant and HVDC system brings possibility to develop new technologies for higher efficiency and lower cost of hydro power generation system. One remarkable technology is adjustable speed operation of hydro power plant by providing an asynchronous tie between the hydro site and main AC grid with HVDC system, which is referred to "Unit connection" in some HVDC literatures. Variable speed operation of hydropower plant results in a substantial improvement in system efficiency and performance, as well as control flexibility, hydro power plant siting and machine design[2, 3].

While the hydro power generation technology develops, the HVDC transmission system is making significant progress in recent years. The most remarkable technology of HVDC today is the DC grid system. A DC grid would be a multi-terminal dc-system (MTDC), which consists of several converter terminals connected in parallel with the dc-buses. Each terminal usually consists of forced commutated voltage source converter (VSC), since VSC is very compact it is easy to site and has the potential to be built as a large multi-terminal system. It is also possible to use thyristor based converter as a part of a VSC-HVDC grid. The voltage control in the DC grid may be realized through droop control, which is similar to the control of the frequency in an AC system. The first vision of a DC grid overlaying

Europe was created during the mid-1990s [4]. Today, the required components for building a regional multi-terminal HVDC (MTDC) grid are available [5]. DC grid will enable the efficient integration and exchange of renewable technology, including wind, solar and hydro power. A unit connected hydropower plant to DC grid will give fully advantages of variable speed operation of turbines and brings additional commercial interests.

In this paper, a DC power plant concept is proposed based on the hydropower unit connection and DC grid technology. Firstly, the progress of hydropower unit connection is summarized and the configurations of DC power plant with both HVDC Classic Station and VSC HVDC station are presented. Secondly, the advantages of employing DC power plant technology are researched; the design considerations of DC Power plant are outlined. Finally, the challenges to realize DC power plant are discussed.

2. Hydropower unit connection and DC power plant concept

A typical hydro power unit connection scheme with HVDC Classic is shown in Figure 2, in which *a* is the guide van opening and *n* is the turbine speed, .

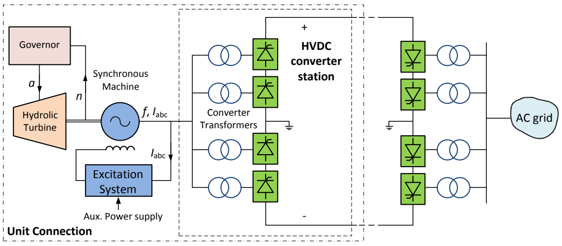


Figure 2 Hydro Power Unit Connected with HVDC Classic

The hydro power unit connection with HVDC connection was firstly presented by Brown Boveri&Cie (BBC) in 1973[6], but the turbine was assumed to operate at a fixed speed. Since 1980s, many literatures had proposed HVDC converter station for adjustable speed operation of hydro power plant [2, 3, 7-11], including variable speed pumped hydro power application [2, 3], harmonic measurement and analysis of generator [11, 12], and unit connection system design [8, 10]. In all these papers, the HVDC systems were thyristor converter based HVDC or HVDC Classic. The applications of VSC HVDC were rarely discussed, because the capacity and voltage rating of VSC HVDC had been thought as a major limitation for transmission level application and the first commercial VSC HVDC was introduced until 1999[13]. However, in recent years, the VSC HVDC technology has been in evaluation and made significant progress. The global trend shows VSC projects with continuously increased capacities up to 1,200 MW while the voltage rating reaches ±500kV. Due to the development of new VSC topologies, the power losses of VSC converter station has reduced from about 3% to approximately 1%. All the progresses lift the VSC HVDC application from sub-transmission and distribution to transmission level.

It is natural way to extend the unit connection concept from HVDC classic to VSC HVDC. The VSC converter station can allow current in both directions and decoupled control of active power and reactive power, which will maximize the advantages of HVDC unit connection. A hydro power unit connection scheme with HVDC Classic is proposed in Figure 3.

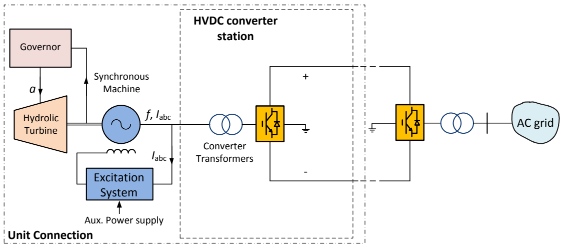
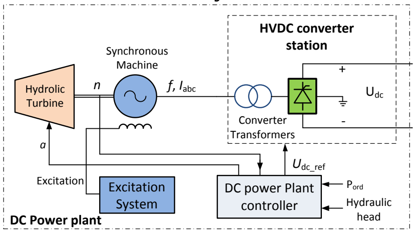


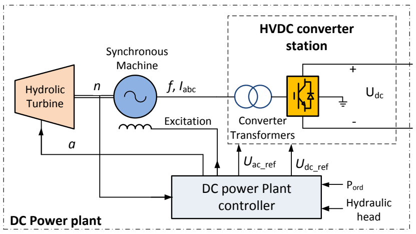
Figure 3 Hydro Power Unit Connected with VSC HVDC

Further, it can be foreseen that DC grid would be formed in the future, which consists of several terminals connected in parallel with DC buses. Therefore it's possible to connect several HVDC based (either HVDC Classic or VSC HVDC) hydropower units into one DC grid. This is particularly profitable when several hydro power plant are cascaded located at one river. For this case, the hydropower unit connection becomes a DC Power plant, which DC voltage and power will be adjusted according to the orders from dispatch center of the DC grid. The major difference between the DC power plant and unit connection is that the DC voltage control should be considered to fulfill a drooping control characteristic for DC grid power flow control, with the input of power order and hydraulic head. The HVDC converter control, turbine governor and excitation system will be integrated into a DC power plant controller. Such a DC power plant is illustrated in Figure 4.

The DC power plant technology would have a very attractive prospect in the countries which have good potential hydro power resources such as China, India, Brazil and Norway. In China, the energy resources and productivities are distributed reversely. Most of the large hydropower bases to be constructed are far from the load centers. Existing studies show that during the end of "12th five years plan" or within the "13th five years plan", the Jinsha River hydropower project and the Tibet hydropower transmission project have requirement of MTDC/ DC Grid technology[14]. As matter of fact that the scale of single hydropower of the upstream of the rivers is relatively small and far away from the back bone AC grid, MTDC/ DC grid connected with several DC power plants can be employed to transfer power cost effectively.



(a) DC power plant with HVDC Classic station



(a) DC power plant with VSC HVDC station

Figure 4 DC Power Plant schemes for Hydropower connected to DC grid

3. Advantages of DC power plant

The major advantages of DC power plant come from variable speed operation of hydro turbines, and unit connection. Besides, the application of DC power plants brings commercial benefits for both generation companies and transmission system operators.

3.1 Benefits from variable speed operation of hydro turbines

Today, all the synchronous generators used in conventional hydropower plants are designed to match the rated frequency of integrated AC grid, i.e. 50Hz or 60Hz. The turbines are also designed to run at the speed specified by frequency of AC grid, under rated hydraulic head and guide vane opening. This means that the design and control of hydropower plant are strictly constrained. Any deviations of hydraulic head will result in decrease of efficiency.

This operation characteristic can be explained by the so called hill chart curves shown in Figure 5[8], in which AA' defines the fixed speed operation range for a normalized flow (and output power) change. The efficiency of the turbine system decreases from 89% to 88% when unit flow changes from about 0.72 to 0.68. In contrast, with variable speed operation, higher efficiency can be obtained: Adjusting the operating speed to move from point P_f to P_a increases the power output by 1% in the case in Figure 5. Finally, the adjustable speed of turbine permits a maximum efficiency tracking for a given power command.

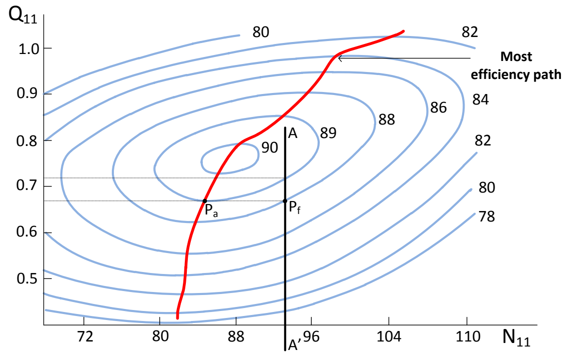


Figure 5 Hill chart curves of a normalized hydro turbine

In addition to the significant energy savings, a number of other important benefit will be realized if the speed of the turbine can be adjusted[2], such as:

1) Longer life time of turbine thanks to reduced noise, vibration and cavitation problems;

2) New flexibility in site selection and sizing of hydro units;

3) Fast response during load changes and emergency braking function;

4) Relaxation of parameter requirements on machine design.

3.2 Benefits from unit connection

Large power plants are usually installed far away from load centers. In this situation, HVDC transmission is preferred. Traditionally, an AC transmission system, which connects the large power plant, local AC grid and HVDC converter station, is constructed. Considering the high investment of new AC line and the limited capacity of local AC grid, power conversion located at power plant side could be a convictive choice. Besides the new AC line, generator transformer can also be saved as only one voltage transmission step is needed with the direct connection of generator and HVDC converter station.

Further, the AC filters, reactive power compensation devices on-load tap changers and most of the AC switch gears and busbars at the HVDC converter station can be removed. The capital cost and maintenance cost of converter station will be reduced greatly. Elimination of AC filter also avoids the risk of low order harmonic resonances[7].

3.3 Benefits from potential business mode

The application of DC power plants brings commercial interests, not only from the energy saving and lower capital and maintenance costs, but also benefits generated from new business mode, for both generation companies and transmission system operators.

A) For generation companies:

With variable speed operation of DC power plant, high efficiency operations at either low head or high head are available. Thus the adjustable stored volume of reservoir becomes significantly larger. It results in greater flexibility in the dispatch and more opportunities for allocating the produced energy in the electric system. Alternatively, for the same regulation capacity, the reservoir area could be reduced with the consequent benefits in the environmental impact [15, 16].

Other benefits for generation side also include updating of old stations with DC power plant, cost reduction in civil works and etc.

B) For Transmission system operators

New business mode for HVDC construction becomes possible during the development of DC Power plant. The HVDC line for hydro power plant connection could be "rented" by generation companies to share the profit obtained by variable frequency operation of DC power plant, with rental yields or get cheaper feed-in tariff.

Besides, faster response of hydro power plant and better performance during AC faults also increase the system stability, and facilitate wind/solar power integration in the same grid system.

4. Challenges and Design considerations of DC power plant

Attracted by the significant technical and commercial advantages of variable speed operation of hydropower stations, many researchers and institutes had studied the design issue of unit connection with HVDC Classic[8, 10, 17], whereas few study performed for unit connection with VSC HVDC, much less DC power plant. Anyhow, the plant optimizing design, control& protection, modeling and calculation are more complex than a conventional hydropower plant with a self-governed HVDC converter station.

4.1 Harmonic currents in the generator

Due to the elimination of the AC filter in the HVDC converter station, the harmonic currents will flow into the generator windings. The ratings of the generators thus should be recalculated. Besides, the generator will also provide all the reactive power for the converter, in particular for HVDC Classic converter station. However, a study on a unit connection scenario case for a HVDC link in New Zealand had shown an optimistic result that the harmonic current levels are well below the specified maximum ratings of the generators[11, 12].

4.2 Excitation system

The conventional excitation systems for hydropower generators are designed to operate at constant frequency. The performance of excitation systems and the stability of the whole system under variable speed need to be re-evaluated.

Besides, due to the variable frequency of the AC system inside the plant, the auxiliary power supply for excitation system needs special design consideration. This disadvantage may not a serious problem as a small capacity static frequency converter can be installed to provide auxiliary power to the whole plant.

4.3 DC Power plant with VSC HVDC station

Operation characteristics of unit connection with HVDC Classic and even diode valve based converter were studied [8, 10, 17]. For HVDC Classic connection, the AC voltage amplitude of generators will decrease during low frequency operation to avoid flux saturation. This will result in decreased rectifier DC voltage and may limit the power transmission capacity. This issue can be resolved by using VSC HVDC station connection. VSC employs insulated gate bipolar transistors (IGBTs), which brings significant advantages such as small size of converter station, independent reactive power control capability and islanding power supply. With VSC converter station connection, the DC voltage output of DC power plant is directly controlled by converter itself with faster speed. The AC voltage and DC voltage control are decoupled to a great extent. Besides, the electrical emergency baking is of generators is easy to be implemented as the VSC station can realized power flow reverse quickly.

As the VSC converter has independent AC voltage/reactive power control capability, the coordination control between VSC and generator excitation system is needed, which may bring simplicity to the whole control system.

5. Conclusion

The DC power plant has significant profits due to its variable speed operation, unit connection and additional commercial interests. It would have a very attractive prospect in the countries with good potential hydro power resources, where most of the large hydropower bases to be constructed are far from the load centers. The HVDC Classic based unit connection technology had been well developed in the pass decades. Based on the existing studies, DC power plant is more complex than a conventional hydropower plant with a self-governed HVDC converter station, while there is no big technical obstacle for a practical system. With the VSC HVDC connection, additional advantages can be obtained such as decoupled AC and DC voltage control and fast electrical emergency braking. Although the authors are optimistic on the DC power plant technology, intensive studies and refinement design are needed to realize commercial application.

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