Integration of variable speed hydropower generation and VSC HVDC

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Abstract

This paper presents the study results on integration of VSC HVDC and variable speed hydropower generation. Different types of variable speed hydropower generation solutions have been reviewed. Refined calculation on annually additional power generated and reliability assessment have been illustrated for the proposed solution based on real hydropower plant parameters. Advantages and challenges for this promising integration technology are presented.

Introduction

Nowadays, the focus of attention in the renewable energy filed is usually on wind power, solar power, geothermal and bioenergy, while hydroelectric resources are often overlooked. Hydropower generation is a long-standing, mature and reliable technology. While because of its maturity, hydropower is sometimes associated with sluggish technology development. The truth could be very different because, power generation is a very competitive business, which requires hydropower industry to take full advantage of the advances in science and engineering. Hydropower is currently the largest renewable source for power generation in the world, producing 3,431TWh and meeting 16% of global electricity needs in 2010. According [1], in the near future, hydropower generation will remain the largest increasing single renewable technology, as shown in Fig. 1.
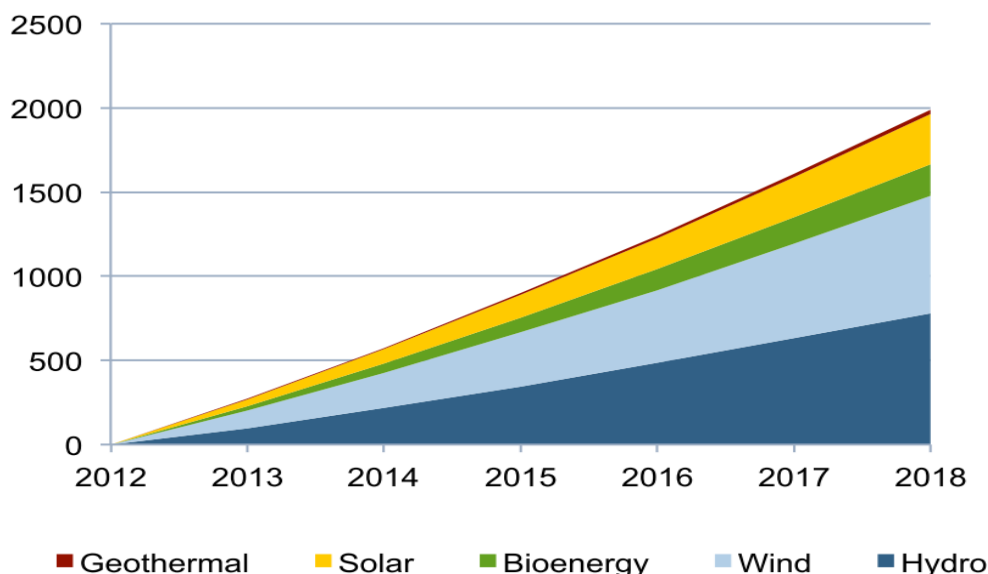

Fig. 1: Forecast cumulative additions of power resources (TWh)

Along with the high speed developing of the hydropower generation, the power conversion and transmission technology, high efficiency and reliability become more and more important for the hydropower industry, which brings the variable speed operation of hydro plants a popular research and development topic.

Benefits from variable speed operation of hydro turbines

By now, all of the large scale conventional hydropower plants adopt fixed turbine speed generation according to the frequency of the integrated AC grid, i.e. 50Hz or 60Hz, which strictly constrained the design and control of the hydropower plant. Any deviations of hydraulic head or change of power order will result in decrease of the efficiency [2].

This operation characteristic can be explained by the so called hill chart curves of a Francis type hydro turbine shown in Fig. 2 [3], in which Q_1' is unit water flow quantity and n_1' is hydraulic turbine speed. For the constant rotating speed operation at certain water head, the efficiency of the turbine will decrease from 89% to 87% (from point A to point B) when unit flow changes from about 0.62 m^3/s to 0.55 m^3/s. In contrast, with variable speed operation, approximately 2% efficiency increase is obtained by adjusting the turbine speed n_1' from 69 r/min to 62 r/min (from point B to point C). Consequently, the adjustable speed of turbine permits a maximum efficiency tracking for a given power command [4].
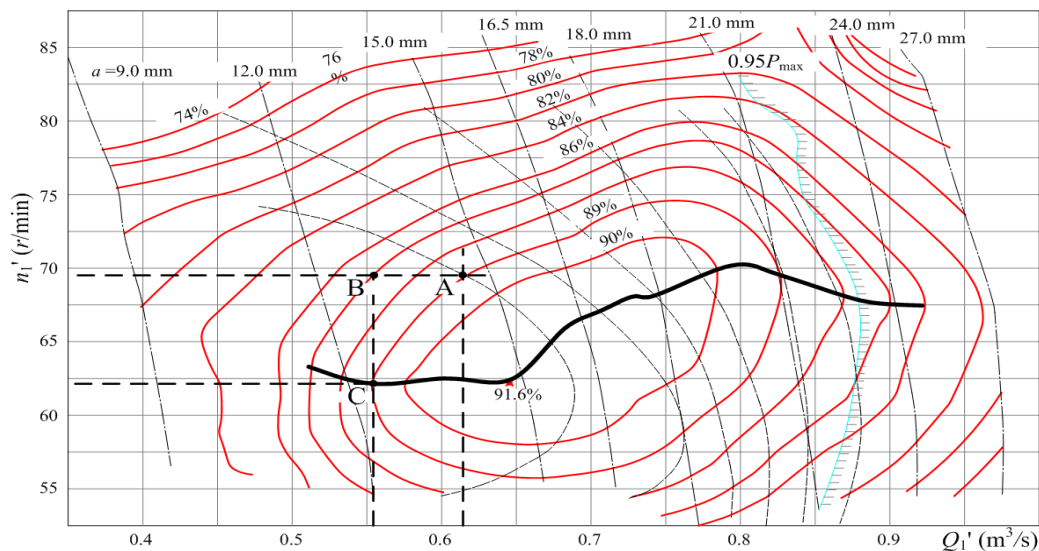

Fig. 2: Hill chart curves of a normalized Francis type hydro turbine (A502-35)

Besides the efficiency increase, the major benefits from variable speed operation of hydropower plant are listed as following:
- Longer service time of turbine thanks to the reduced noise, vibration and cavitation problems;
- New flexibility on the selection of site location and hydro units size;
- Relaxation of parameter requirements on machine design;
- Fast power order response for grid system bundled with wind/solar power ;
- Less environmental impacts.

Variable speed hydropower generation solutions

In recent years, variable speed hydropower generation solutions become very popular for pumped-storage hydropower plants. Mainly two types of solutions have been applied, which are Doubly-Fed Induction Generator (DFIG) and Full Power PWM converter (FPC) back-to-back connection with generator.

The DFIG solution, as shown in Fig. 3, could be counted as a relatively low cost solution because only partial power (depending on the variable speed range) will be transmitted through the PWM converter connected to the generator. However, DFIGs require using expensive wounded-rotor asynchronous machines. Moreover, the detailed analysis on the total cost for higher power application at a conventional hydropower plant is still absent [5].
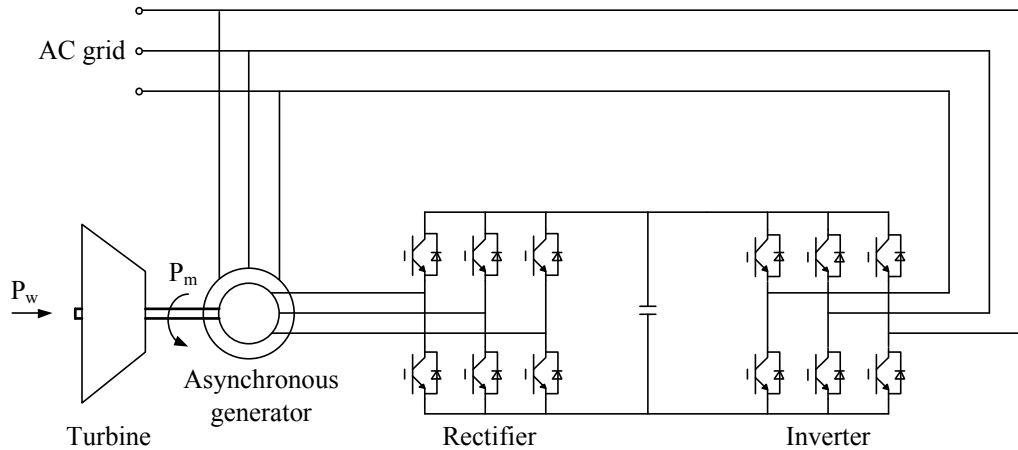

Fig. 3: Hydropower plant with DFIG solution for variable speed operation

The solution of FPC back-to-back connection with generator, shown in Fig. 4, can be used to fully decouple the speed of the generator from the frequency of AC grid.
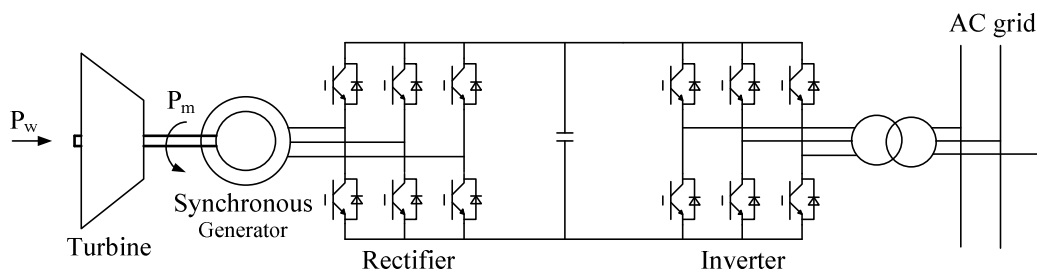

Fig. 4: Hydropower plant with full power PWM converter solution for variable speed operation

While both of the above mentioned two solutions have only been practically applied to low power rating pumped-storage hydropower plants with maximum single generator capacity of 100MW. Relatively high loses and higher cost for the converters, as well as extra space requirement become the bottlenecks for higher power range pumped-storage hydropower plant applications. In order to take the advantages from the technology of variable speed hydropower generation and minimize the loses and cost, to apply this technology to large scale conventional hydropower plant or large power pumped-storage hydropower plants would no doubt be more beneficial.

A comparative calculation on annual generation has been carried out based on Xiaolangdi Hydropower Plant located in Henan Province, China. The main parameters are listed in Table I.

Table I: Main parameters of Xiaolangdi Hydropower Plant

Nominal power of turbines	6×306 MW
Nominal power of generators	6×300 MW
Pole pairs number	28
Generator synchronous speed	107.1 r/min

Efficiency of generators	0.98
Nominal diameter of turbines	6 m
Maximum water head	139.2 m
Weighted average water head	119.9 m
Optimized unit rotating speed	62 r/min

The calculation process and calculation result are shown in Fig. 5 and Fig. 6, respectively.
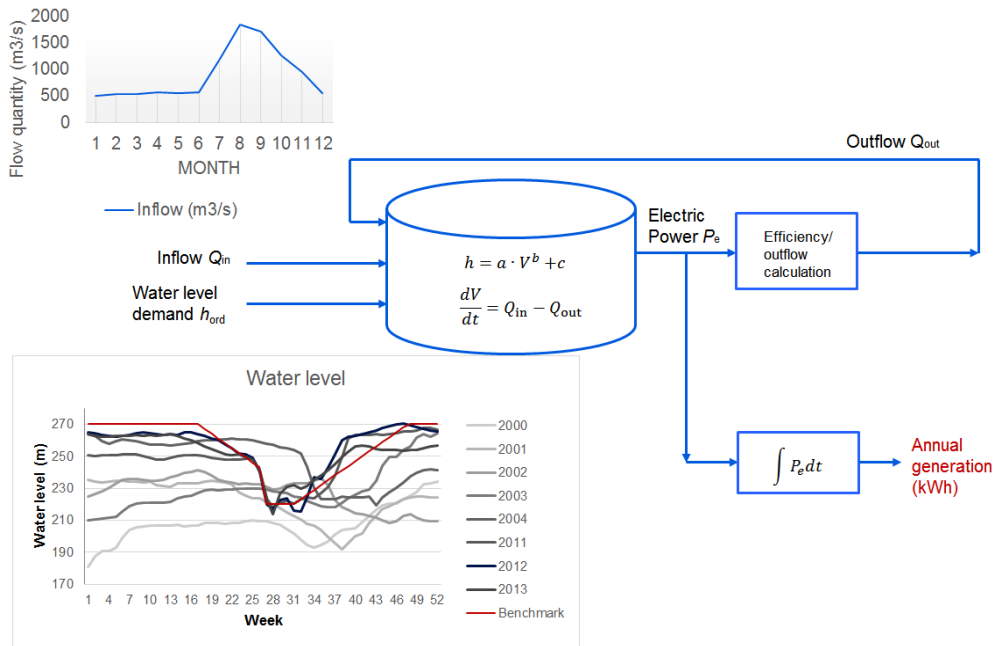

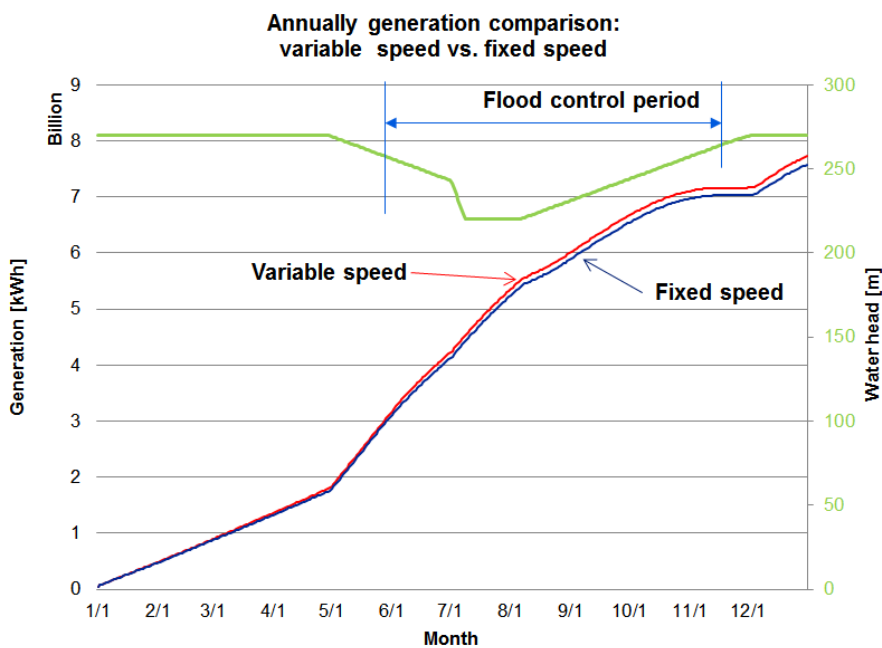Fig. 5: Annual power generation calculation for Xiaolangdi Hydropower Plant

Fig. 6: Comparison of the power generated between fixed speed operation and variable speed operation.

As shown in Fig.5, using the statistical data of annual flow quantity (Q_{in}) and annual water level (h) with Eq. (1) and (2), the flow rate (Q_{out}) can be obtained.

$$h = a \times V^b + c \tag{1}$$

$$\frac{dV}{dt} = Q_{in} - Q_{out} \tag{2}$$

Where:
h = water level [m]
V = water volume [m^3]
Q_{in} = volumetric inlet flow rate [m^3/s]
Q_{out} = volumetric outlet flow rate [m^3/s]
a, b and c are the reservior coefficients

Hence the flow rate and mechanical power of the turbine can be calculated by means of the specific relationships of the turbine as shown in Eq. (3) and (4).

$$q = F(h, x) \tag{3}$$

$$P_m = G(h, q) \tag{4}$$

Where:
x = distributor opening [degree]
P_m = mechnical power [watt]

For a Francis turbine, such relationships can be obtained from the "Hill Chart" in Fig. 2. With variable speed operation, the turbine could always operate around the point with relatively high efficiency. Thereafter, the electrical power can be calculated. The integration of the electrical power brings the result, which is shown in Fig. 6 that, the annually additional power generation could reach 2.66 billion kWh.

Integration of variable speed hydropower generation with VSC HVDC

As an advanced and popular technology, VSC HVDC is currently employed in the field of power collection from the offshore wind farm and power transmission to the islanding location, such as the oil-drilling platform. The direct connection of hydro generator with VSC HVDC converter, referred as VSC Hydro here after, opens a new door for variable speed hydropower generation and transmission. Meanwhile, it also enriches the portfolio of VSC HVDC application.
Compared with the DFIG and FPC solutions of variable speed hydropower generation for pumped-storage hydropower plants, the VSC Hydro solution has following advantages:
- Can be connected with large capacity synchronous generators;
- Reduced converter losses;
- The converter and inverter station can be located in different physical locations, which means less space will be required than the FPC and DFIG solutions.

As demonstrated in Fig. 7, the hydro generator(s) can be connected directly to the VSC HVDC converter station through a converter transformer without access to any AC grid. Thereafter the generated power can be transmitted to the remote VSC HVDC inverter station via HVDC overhead line or cable. The VSC HVDC system fully decoupled the hydro turbine speed and the frequency of

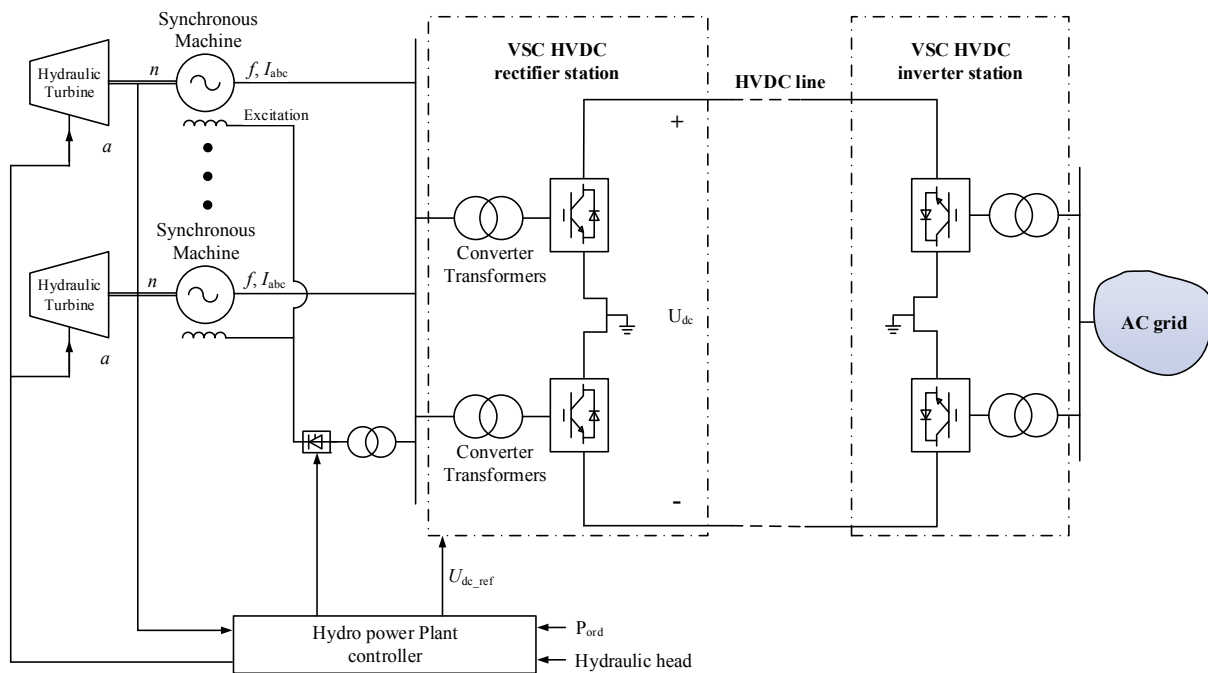the AC grid, which allows the hydropower plant generation with variable speed at the maximum efficiency.

Fig. 7: Direct connection of hydro generator with VSC HVDC

Reliability assessment with the consideration of the economic losses due to failure

Considering the possibility of practical application of the variable speed hydropower generation with VSC HVDC, it is meaningful to make a reliability assessment. Based on the statistical data of the components from real projects, the reliability assessment has been performed, in which the economic losses due to failure have been calculated and compared between the conventional LCC HVDC transmitted hydropower with the VSC Hydro, the topologies are shown in Fig. 8.
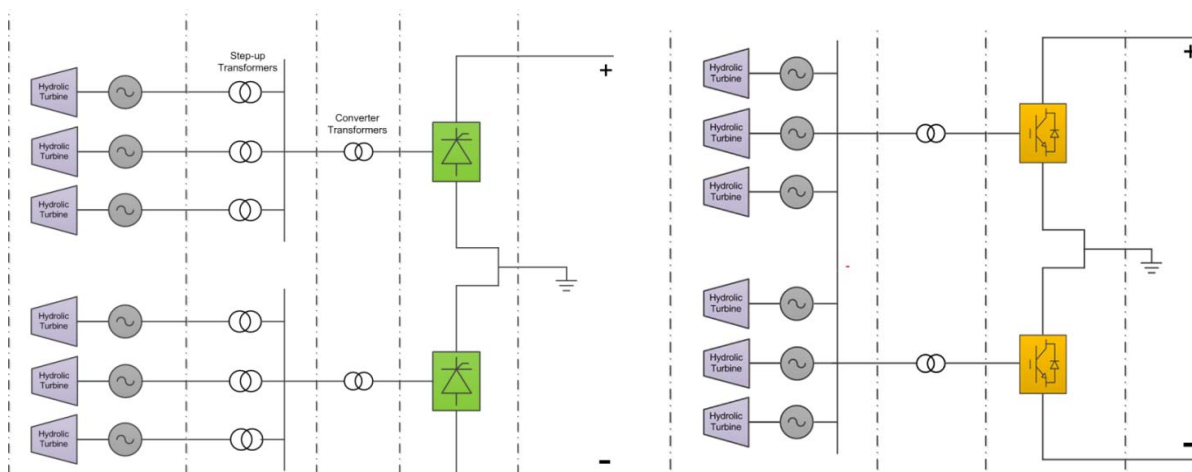

Fig. 8: Topologies for conventional LCC HVDC transmitted hydropower (left) and VSC HVDC (right)

The Series-parallel network analysis method has been adopted. By using this method, the whole system can be divided into the following modules:

- Hydro turbine and generator (including step-up transformer)
- HVDC LCC / VSC Converter (including converter transformer)

Hydro turbine and generator reliability

As a very mature technology, many statistic data for the reliability of hydro turbines and generators can be found from different references, such as published papers and textbooks. In order to verifying the accuracy of the data, a cross reference check with the data from different sources have been carried out, finally the data shown in Table II is selected [6, 7, 8]. The annual failure rate and repair time for the hydro turbine and generator are based on the statistical data of 600MW hydro generation unit. For the step-up transformer, the failure rate and repair time are obtained from the reliability statistical results on above 500kV transformers from Russian, Canada and CIGRE.

Table II Annual Failure Rate and Repair Time for Hydro Turbine and Generator

Components	Failure Rate (/year)	Repair Time (h)
One set of hydro turbines & generator	3.5	73
Step-up transformer	0.0262	585.58[1]

(1) The redudancy transformer is not considered

HVDC Reliability

In the past three decades, many LCC HVDC transmission projects have been accomplished all over the world, hence plenty of the reliability data for LCC HVDC are available. On the contrary, very few data for the VSC HVDC reliability can be found from the open source due to the reason that this technology has not been commercialized very long. Furthermore, very rare papers can be found regarding to the reliability comparison between LCC HVDC and VSC HVDC.

CIGRÉ Study Committee B4, Advisory Group B4.04 has assembled and published data on the reliability and operational experience of LCC HVDC systems in service around the world since 1968. Reference [9] calculates the frequency and duration values of forced and scheduled outages by component by specific percentiles from all reports received by CIGRÉ from 1983 through to 2004 for thyristor valve systems. Table III shows the calculated values for Forced Energy Unavailability (FEU) and Scheduled Energy Unavailability (SEU) for the 50% percentile and 80% percentile for monopole and bipole schemes on an annual basis [10].

Table III FEU and SEU for Monopole and Bipole Systems

	50% Percentile (Median%)		80% Percentile	
	FEU [%]	SEU [%]	FEU [%]	SEU [%]
Monopole	0.45	2.7	0.17	2.3
Bipole	0.83	4.9	0.24	3.3

While VSC HVDC system has not reported reliability performance data to AG B4.04 to date. Reference [11] provides some data on the operation of the Cross Sound Cable project. Table IV shows the average and median FEU and SEU for the system for seven years operation from 2003 through to 2009.

Table IV Reliability performance of Cross Sound VSC-HVDC System

	FEU		SEU	
	Average%	Median%	Average%	Median%
Cross Sound (330 MW)	1.16	0.93	1.92	1.17

In the CIGRÉ report [10], HVDC System Energy Unavailability has been considered as the key factor for analyzing HVDC performance. Energy Unavailability is the sum of Forced Energy Unavailability (FEU) and Scheduled Energy Unavailability (SEU).

Due to lack of VSC reliability information, the data from CIGRÉ report are chosen, and regarded as trustworthy. In order to simply the calculation, for the bipole LCC HVDC system, take the median FEU 0.83% in Table III and for VSC HVDC system the Media FEU 0.93% is selected for one converter station.

Assessment result

As listed in Table V, VSC HVDC is slightly more reliable than the conventional LCC HVDC for transmitting the hydropower, mainly due to the reason that the step-up transformer can be removed. Furthermore, in this assessment, only considered the fixed speed operation failure rate of the hydro, which should be improved when running with variable speed to avoid the operation point with severe vibration and cavitation, etc.

Table V: Annual losses comparison between LCC + Hydro and VSC + Hydro

	Turbine & Generator (MUSD/year)	HVDC (MUSD/year)	Total loss (MUSD/year)
LCC + Hydro	24.38 (with Step-up Transformer)	6.54	30.92
VSC + Hydro	23.00 (without Step-up Transformer)	7.33	30.33

Conclusion

This paper presents a novel application of VSC HVDC, especially for the next generation VSC HVDC with higher capacity and lower loss, to transmit the hydropower by means of the directly connected hydro generator(s) and the VSC HVDC converter. Proved by the refined calculation of the additional generated power annually, employing this application, the efficiency and performance of the hydropower generation system can be greatly increased by using variable speed, at the same time the overall cost, construction time and footprint of the whole system can be reduced. Considering the possibility of practical application in the future, a reliability assessment has been performed during the study, which shows that the proposed solution has lower annul loses due to failure than the conventional solution.

So far, it is only the first step study of the VSC hydro. From the system design optimization, control and protection points of view, the proposed VSC Hydro is more complex than the conventional fixed-speed hydropower plant, mainly due to the following challenges:

- During the variable speed generation, the governor controller of the turbine need to be modified according to the generator speed and the maximum efficiency tracking mechanism;
- The excitation system of the generator needed to be updated to control the intermediate AC voltage inside the hydropower station;
- The coordination between the controllers of the turbine-generator set and VSC HVDC converter need to be established.

Hence, the above mentioned topics and issues need to be continually studied and finally solved before this new technology could be put into reality in the future.

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