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VSC HVDC Transmission Supporting Variable Electricity Generation

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SUMMARY

The demand on controlling the global warming is a powerful driver for the deployment of large scale renewable energy sources (RES), such as wind and solar. The transition toward 100% renewable [1] electricity supply is essential in order to be able to manage the goal of preventing the global average temperature from rising more than 2 degree Celsius. However, this transition will pose significant challenge on the grid system operations and planning.

Variable renewable generation, like wind power and solar power technologies, have some very different characteristics than traditional sources based on fossil fuel. The variability and uncertainty of available power from renewable generation, that is inherent in these generation technologies, adds to the variability and uncertainty in the existing electrical energy system. The replacement of traditional thermal turbine generators with distributed generation or offshore wind power will diminish the overall inertia. As a consequence, two new problems have to be solved, that is, dispatchablity and inertia response in order to maintain the same security and controllability as in existing electrical power grids. To solve these problems, the smart grid by using ICT (Information and Communication Technology) [2] is not enough due to that ICT can only provide "monitoring and smart decision based on information obtained. There is an urgent need to have smart "action" instrument which can execute the desired action requested by the smart decision.

The motivation of this paper is to explore the possible multi functions of VSC based HVDC that can effectively support and improve the performance of a grid with large amount of renewable electricity supply. The paper will show that the VSC HVDC converter can provide the necessary primary frequency control even if the inertia in the grid is very low. It will also show that the VSC based HVDC transmission system can accomplish transferring the reserve, including the primary, secondary reserves, from one geographical spot to another place without the constraint of distance. In addition to facilitate trading in deregulated energy market, the interconnection via VSC HVDC will play a vital role in solving the new problems related to dispatchability and inertia response in RES based power grid due to its flexibility in controlling active and reactive power.

KEYWORDS

VSC HVDC, Interconnection, Frequency Control, Dispatchability, RES

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1. INTRODUCTION

The demand on controlling the global warming is a powerful driver for the deployment of large scale renewable energy sources (RES), such as wind, solar. The transition toward 100% renewable electricity supply is essential in order to be able to manage the goal of preventing the global average temperature from rising more than 2 degree Celsius. However, this transition will pose significant challenge on the grid system operations and planning.

Traditionally, the generation of electricity is fully plannable and controllable as the power plants are based on the fossil, or nuclear. The proper schedule together with the controllability makes it possible to maintain the frequency in a specific range in normal operation. In critical events, the inherited kinetic energy storage with rotational inertia in traditional synchronous generators has played a fundamental role in keeping system stability. Due to electro-mechanical coupling, a generator's rotating mass releases the kinetic energy when the connected AC network frequency goes down, and absorbs the electrical energy when the frequency goes up. Thus an instantaneous and automatic frequency control, so-called Primary Frequency Control (PFC), is provided with traditional thermal power plants. Furthermore, the power transmission and distribution system has also been established to facilitate the traditional power generations.

Variable renewable energy source has some very different characteristics than the traditional source, that is, un-predictable and un-controllable. The larger uncertainty is caused by the unexpected change in generation and demand balance from what was anticipated. Power system schedulers often use scheduling techniques throughout the day to match generation and demand. When the total supply of energy is different than the total demand due to variability and/or uncertainty, system operators must deploy operating reserves to correct the energy imbalance. The primary reserve has the capability of automatically detecting frequency fluctuations, and adjusting power production accordingly within 30 seconds, whereas the second reserve can be activated in 30 seconds to 15 minutes to support the power balance control by regulating power generation both upward and downward. It is not possible for the RES based power plant to provide upward power regulation if no curtailment is made during normal operation. It is also very costly for the RES based power plant to give downward regulation in long duration as neither wind nor sunshine can be preserved. To face the challenge of large uncertainty, the requirements and focus on both the primary and secondary reserve become more and more high with the increased penetration of RES based power generation in order to maintain the frequency in normal operation and secure system stability under disturbances. Furthermore, the generated power based on RES is integrated into the grid via converters in most of cases. This means that the rotational inertia is either not directly connected to the grid or completely missing. As a result of low inertia, the rate of change of frequency (ROCOF) will be increased. This can lead to scenarios in which traditional frequency control schemes become too slow with respect to system dynamics for preventing large frequency deviations and series consequences. It is obvious that the increase of renewable energy sources results in an urgent need for new instruments that has fast dynamic response and flexible in control.

It is well known that the VSC based HVDC is a convenient instrument for power trading [3]. Nowadays, it is also commonly recognized that VSC based HVDC can provide black-start function [4]. The motivation of this paper is to explore some new functions of VSC based HVDC that can effectively support the grid with large amount of renewable electricity supply. The paper will show that the VSC HVDC converter can provide the necessary primary frequency control even if the inertia in the grid is very low. It will also show that the VSC based HVDC transmission system can accomplish transferring the reserve, including the primary, secondary reserves, from one geographical spot to another place without the constraint of distance. Thus it is not necessary that the control reserve should be geographically located within the control area, and different types of control reserves can be effectively shared within the inter-connected regions with the new technology of interconnection based on VSC HVDC system. Furthermore, in the emergency situation, the VSC HVDC can function as a last defense to prevent the grid from black out. Finally, it is also discussed that it is essential to build inter-connections with VSC HVDC so that the available natural reserves can be utilized in maximum, and that the challenge of operating the grid can be relieved due to the flexibility and the multiple functions in a 100% renewable electricity supply grid.

2. FUNCTIONS OF VSC HVDC SUPPORTING VARIABLE ELECTRICITY GENERATION

2.1 Review Basic Control Function

The basic control function of a VSC HVDC converter station is that it can provide independent active and reactive power control. The rate of change in active and reactive power can be controlled in a wide range with high rate that is not achievable for conventional synchronous generators. Figure 1 shows as an example how active power and reactive power can be varied.

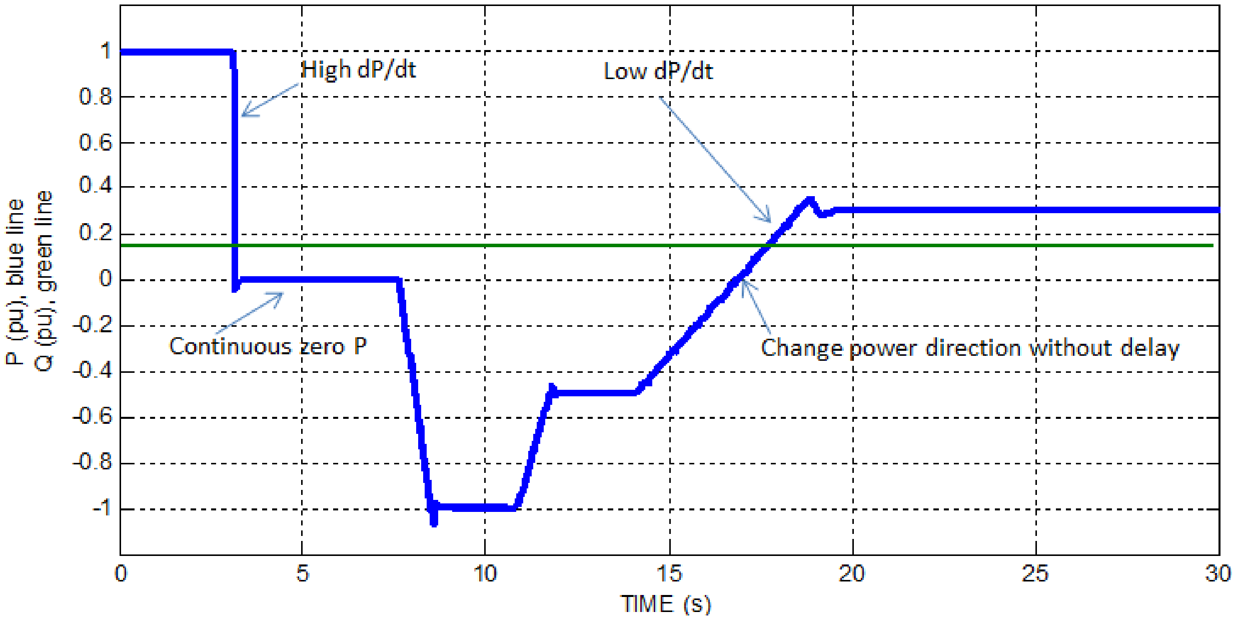

Fig. 1. Example of operating active and reactive power

Comparing with the most installed classic HVDC, which is based on Current source converter (CSC), there are three supreme features:

I) The active power can be changed in both directions without any time delay
II) The active power can be settled to any levels within the power rating without hindering of minimum power of zero
III) The reactive power is also seamlessly controlled and independent of active power level.

These features together with the wide range of rates of change of power make the VSC HVDC a powerful instrument in supporting grid with substantial large amount of RES based power supply.

2.2 Steady-state Power Imbalance Control

In any electrical system, total supply and demand must be balanced constantly in order to maintain the system frequency within the acceptable range. It becomes very difficult to operate the system when the source of supply is difficult to predict and the demand of loads is changing continuously, especially when the exchanges of power across borders of a country is not controllable since they are using AC connections. Thus, it is vital to eliminate at least one uncertainty by having controlled exchange across the borders with VSC HVDC. When there is high energy production from the wind and solar, the surplus electricity generated from RES can be imported to the countries where the electricity energy can be stored in one or another form, such as reservoirs in Norwegian. When there is low energy production from solar and wind, the necessary power consumption may be compensated by the hydra-power. Give a 2000 MW HVDC Link as an example, the total controllable power range is 4000 MW with 2000 MW equivalent to the generation and 2000 MW equivalent to the consumption. Thus, a VSC HVDC link plays the double role in power balance control with high flexibility.

2.3 Congestion Remission

With the increasing of a large amount of wind power in certain geographically limited area, local overloads appear even during steady-state operation. At the disturbance of outage of a line connecting to large amount of generation or loads, the overloads can reach unacceptable levels which can threaten the stability and synchronous operation of the grid [5] due to the interconnection between countries based on AC technology. The congestion in some national markets, most significantly the German and Danish systems, has repeatedly led to negative electricity prices during high wind and weak load. Thanks to fully control on active power flow in both directions, it is possible for the VSC HVDC to relief the congestion in three different ways.

One way could be installing a back-to-back VSC HVDC in the existing AC lines [6]. The power transmission capacity would be increased to double and the power flow will be also in fully control without the difficulty encountered in obtaining the approval of rights of way required for building new transmission. Furthermore, the site for the converter station is reduced to one location.

The other way would be installing a new VSC HVDC which is allocated in parallel with the congested AC line. The parallel VSC HVDC will not only increase the power transmission capability, but also provide power flow control on the parallel AC line. A similar control strategy has been implemented in Gotland HVDC Light project [7], where the power flow control on the parallel AC line is targeted for minimizing total losses in the AC grid.

The third way would be converting the existing congestion AC line to VSC HVDC transmission. There are a number of studies that show that the conversion from AC to DC transmission will significantly increase the transmission capacity [8].

2.4 Primary and Secondary Frequency Control

Due to that active power can be controlled in a wide range with different rates of change, it is possible for the VSC HVDC converter to provide inertial response as the primary and secondary frequency control. The advanced control strategies result in that the HVDC converter will behave in a way similar to synchronous generators. There are two possible ways to deliver frequency support control.

Firstly, the HVDC converter can use a power dispatch mode, the power order may be adjusted in according to the frequency deviation. As shown in Fig. 2, with the system frequency as control input and the power deviation as control output, the control emulates both the inertial response (virtual inertia) and the primary control (droop) of a synchronous generator.

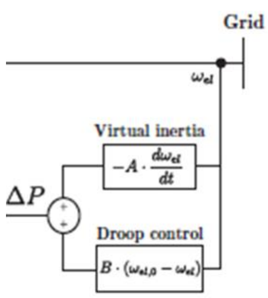

Fig. 2. VSC Converter Supporting Frequency Control by power dispatch mode

An alternative method uses that the HVDC converter is in frequency control mode and there is no direct active power control. Instead, the active power delivered or absorbed by the converter is naturally determined by the grid for maintaining the target system frequency. As will be shown in next section, this method of controlling frequency is exellent for the grid with very low overall inertia.

Since the HVDC transmission system itself has little inertia or stored energy, the demanded power for performing the frequency support control is delivered by the grid connected to the other station. This station is in the DC voltage control mode via keeping the total power on the DC side in balance. In this way, inertia resources as well as the primary and secondary reserve is determined by the grid connected to the other station. The strength of this grid will determine the level of frequency support that can be delivered.

2.5 Site Operating Experiences in Supporting Frequency Control

The Caprivi Link Interconnector HVDC Light® transmission (-350 kV/0, 300 MW) interconnects the Namibian and Zambian/Zimbabwean a.c. systems. The length of overhead DC line between the converter stations is 952 km [9]. During the commissioning, the AC networks at both sides have very low overall inertia, and are extremely weak with the short-circuit power ratio (SCR) less than 1.0. Any disturbances like tripping a substation transformer or a line can lead to large frequency deviation in short time.

As one example, Fig. 3 shows a recording by the automatic triggering during an event of frequency collapse caused by tripping a line due to the over load protection in the grid of Zambezi. It can be seen that the frequency dip is more than 5 Hz, refer to the first plot, during this event. The frequency starts increasing as soon as the HVDC converter is changed to frequency control mode (FV_CTRL) from the normal DC voltage control mode (UDC_CTRL), refer to the last plot in Fig. 3. Within 600 ms the system frequency recovers to the normal operating frequency, thereafter, the system maintains a stable operation. In the process from eliminating the frequency dip to maintaining the system frequency around 50 Hz with near zero frequency deviation, the Zambezi station has injected maximum 150 MW dynamic peak power to the grid, and increased the steady state power from about 9 MW to 50 MW, refer to the second plot. This demonstrates that both the primary and secondary frequency control has been automatically realized seamlessly. The third plot shows the AC grid voltage measured at the point of common coupling (blue line) and the DC side voltage (green line). Due to extremely long distance and very weak grid in the other station, a transient DC voltage dip is observed when large amount of power is injected into Zambezi grid. As a result, a transient AC voltage dip appears since the injected reactive power is temporarily limited by the DC voltage.

It may be worth of noting that before the event, the Zambezi station was in DC voltage control mode, which maintained the DC voltage to the nominal level, and the Gerus station (in Namibian) was in the power control mode, which tracked the power order. The sudden outage of the line led to frequency collapse in Zambezi grid which is detected by HVDC converter control. As a consequence, the Zambezi station automatically gave up the DC voltage control mode and switched to frequency control. Via the tele-communication the Gerus station was informed that something emergent occurred in the other station. Consequently, Gerus station gave up tracking the power order, instead it took over the DC voltage control.

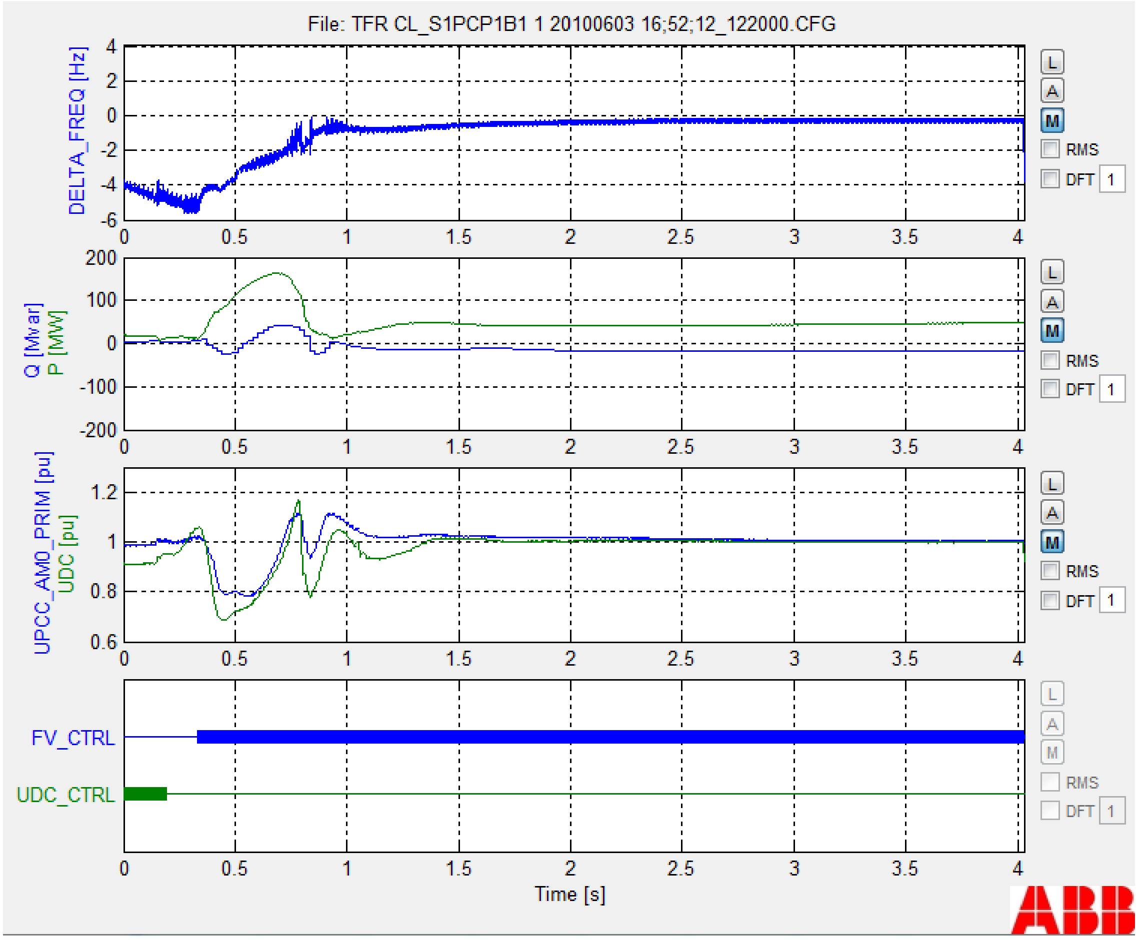

Fig. 3. Preformance of VSC HVDC in providing primary and secondary control – control under frequency

Plot 1: Frequency deviation from the nominal frequency (50 Hz)

Plot 2: Active power (green), Reactive power (blue)

Plot 3: AC voltage magnitude at PCC (point of common connection) (blue), DC voltage (green)

Plot 4: Indication of activating the voltage and frequency stabilizing control (blue), Indication of disabling the DC voltage control (green)

As another example, Fig. 4 shows a recorded event of over frequency caused by tripping a substation transformer which led to the disconnection of some loads in the grid of Zambezi. It can be seen that the frequency increases up to 2 Hz, refer to the first plot. The frequency starts decreasing as soon as the HVDC converter is transferred to the frequency control mode (FV_CTRL), refer to the last plot in Fig. 4. Within 600 ms the system frequency recovers to the normal operating frequency, thereafter, the system maintains a stable operation. In the process of controlling over frequency and to maintain the system frequency around 50 Hz with near zero deviation, the Zambezi station has absorbed maximum 50 MW dynamic peak power from the grid, and decreased the steady state power from about - 9 MW to -17 MW, refer to green line in the second plot of Fig. 4. This also shows that both the primary and secondary frequency control has been automatically realized without any action of operator. The third plot shows the AC grid voltage which is well controlled by automatically adjusting the reactive power, refer to blue curve in the second plot. The reactive power has been increased transiently when the active power absorption is increased.

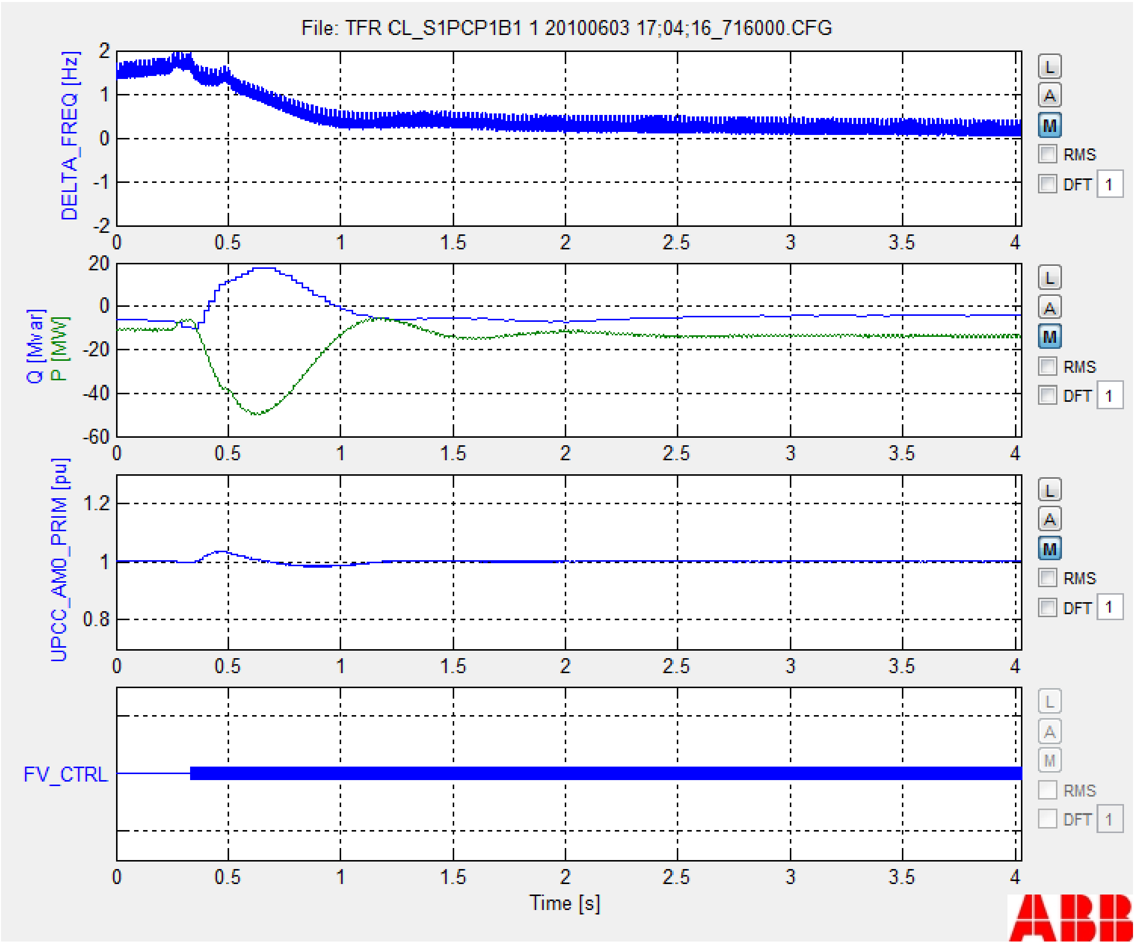

Fig. 4. Performance of VSC HVDC in providing primary and secondary control – control over frequency

Plot 1: Frequency deviation from the nominal frequency (50 Hz)

Plot 2: Active power (green), Reactive power (blue)

Plot 3: AC voltage magnitude at PCC (point of common connection) (blue), DC voltage (green)

Plot 4: Indication of activating the voltage and frequency stabilizing control (blue)

3. DISCUSSION ON THE ROLE OF VSC HVDC IN FUTURE POWER GRID

The vision of future grid is 100% renewable energy supply [1]. This implies that all traditional power plants based on fossil fuel will be replaced by wind, solar, hydro or biomass power. As a consequence, two new problems have to be solved, that is, dispatchablity and inertia response in order to maintain the same high security and controllability as in traditional power grids. To solve these problems, the smart grid by using ICT (Information and Communication Technology) [2] is not enough due to that ICT can only provide "monitoring and smart decision based on information obtained. There is an urgent need to have smart "action" instrument which can execute the desired action requested in the smart decision. The precondition for this smart acting instrument is that it has the capability to control active and reactive power independently without the limit of power directions, that is, regulating power in both upward and downward and maintaining voltage stability. The VSC based HVDC is the only available power system equipment which can fulfil this precondition, thus it will play a pivotal role in the future power grid. The choice of HVDC or HVAC may be no longer depends on the facts of cost and efficiency, other facts may turn out that VSC HVDC is a must.

In the future, even if one unified grid is built by interconnections over a region or a continent, the operation of power system will be still under the control of a nation or a TSO (Transmission System Operator). The total power of a nation mainly consists of three parts: generation, load and exchange.

In the aspect of load, constant access to affordable energy is a prerequisite for the modern society, thus the supply should be guaranteed albeit with the constant varying without being fully predicated. In the aspect of power generation, it is also fluctuating and difficult to alter since some renewable sources of power, such as solar and wind, are intermittent. In order to be able to operate the system, there must be some power that is controllable. This means that the power exchanges between neighbouring countries or other regions must be fully controlled in order to maintain the system frequency. Therefore, the interconnections via VSC HVDC become essential for operating the power grid.

With the phasing out of all thermal power plants based on fossil fuel, the reduced inertia poses a big challenge on maintaining transient stability. There is a need to access the available and reliable primary reserve such as hydro and biomass power plants. OWP (Offshore Wind Power) or CSP (Concentrated Solar Power) may be not counted as reliable primary reserve even if smart frequency control functions are implemented, since the source itself is intermittent. The hydro power source may be available only in certain areas, for instance in Europe, rich hydro power sources locate in north (e.g., Norway), south (e.g., Portugal) and east (Alps). As has been demonstrated in section 2.5, the VSC HVDC can perform well the primary frequency control. It is essential to connect one converter station to the area which has sufficient primary reserve so that the other station can effectively support the primary frequency control in the connected grid where the overall inertia is low.

4. CONCLUSION

The paper has present different functions of VSC HVDC supporting varies RES based power supply grid with focus on auxiliary services. It has been demonstrated by site experiences that the VSC can perform satisfying primary frequency control, and seamlessly move to secondary frequency control. The capability of 100% active power control in both directions and the independent reactive power control will make VSC HVDC the most smart instrument in the future grid. In the case power trading and power dispatch is aligned, the interconnection by VSC HVDC will largely reduce the challenge of operating the grid even if both loads and generation are variable. In the case power trading is primarily driving by economy, the VSC HVDC will secure the stability of the grid by acting fast in changing power level as well direction. For the future grid, it is important to deploy the interconnection with VSC HVDC in align with the reliable primary reserve such as hydro power or biomass energy.

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Ying Jiang-Häfner received her B. Sc. And M. Sc. Degrees in electrical engineering from Huazhong University of Science and Technology, China, respectively in 1984 and 1987. She received Ph. D. Degree in electrical engineering from Royal Institute of Technology (KTH) of Sweden in 1998. She was a Lecture at Huaihai University in China from 1987 to 1991, and a Research Assistant in KTH from 1991 to 1997. She joined the System Development Department of ABB Power System in Sweden in 1998. She was with the design and commissioning of the first VSC HVDC project in the world. She has been involved in the development and design of control system for HVDC Light as well as in delivering all VSC HVDC projects supplied by ABB. She is now a senior specialist in the technical area of HVDC Light control.

Peter Lundberg recieved his MSc and Licentiate in Electrical Engineering at Chalmers University of Technology, Gothenburg Sweden, 1989 and 1994. He then joined ABB Corporate Research in Västerås and was part of the HVDC Light development. In 2001 he moved to the HVDC business unit and has had a number of R&D, project and manager position. Peter is currently working as Global Product Manager for HVDC Light.

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