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Integration of islanded very large scale onshore wind power with LCC HVDC and a small STATCOM

A novel control method

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***Abstract*—Wind power development is booming globally, and large scale onshore wind power is under development in China, the Americas and India. Compared with AC transmission, HVDC technology can due to lower losses be attractive if the distance from generation to consumption is long. VSC (Voltage Source Converter) HVDC is rapidly maturing as a technology, and offers some significant advantages compared to traditional LCC (Line Commutated Converter) HVDC, such as independent control of active and reactive power. This independent control enables VSC HVDC to operate in very weak/islanded AC systems, however LCC HVDC still has a considerably higher DC current capability than VSC HVDC. Onshore wind conditions require both very high DC current capability, and control flexibility due to very weak/islanded AC systems. Therefore, there is good reason to investigate new solutions to transmit large scale onshore wind power via LCC HVDC, which complements existing VSC and LCC HVDC technology.**

In previous works by the authors, a proof of concept for black start using LCC HVDC was presented [1], which may enable initial startup of an islanded AC network. Once an islanded AC system has been started up, it must be operated in an optimal way. Thus in this paper, a novel control method that enables LCC HVDC combined with a small STATCOM to transmit the rated HVDC power capacity from an islanded large scale PMSG (Permanent Magnet Synchronous Generator) wind farm AC system, is presented. As known from micro grids [2], an islanded AC system with full converter power sources changes the fundamental behavior of the AC system; the AC voltage amplitude depends on the active power balance instead of the reactive power balance; the AC voltage frequency depends on the reactive power balance instead of the active power balance. Considering these non-conventional relations, an LCC HVDC rectifier is used to control the AC voltage amplitude, and a small STATCOM is used to control the AC voltage frequency. A typical ± 800 kV, 8GW bipolar UHVDC system is combined with a large scale onshore PMSG wind farm, and time domain simulations for initial islanding from a supporting AC network, AC faults and DC faults are performed. It is shown that system stability can be achieved with the presented control method. However, the key issue is the AC overvoltage that occurs when the LCC rectifier cannot transmit active power from the islanded AC system, namely DC line faults and LCC inverter AC faults.

Keywords- HVDC transmission; Power system control; Reactive power control; Wind energy integration

I. INTRODUCTION

The introduction of IGBT based VSC (Voltage Source Converter) HVDC [3], [4] brought with it significant advantages compared to the thyristor based LCC HVDC [5], such as independent control of active and reactive power. This independent control enables VSC HVDC to operate in very weak/islanded AC systems and fluctuant power transmission systems [6]. The introduction of MMC (Modular Multilevel Converter) [7], made it relatively easy to scale VSC HVDC upwards in terms of DC voltage, however thyristor based HVDC technology still has a considerably higher DC current capability than VSC technology. Today's highest rated thyristor valves in commercial operation are rated at 5000A, with 6250A shortly coming into operation [8].

Wind power development is booming globally, and large scale onshore wind power is under development in for instance China [9], the Americas [10]-[12] and India [13]. It is also perceivable that the abundant onshore wind resources in for instance Mongolia and Kazakhstan [14], could be utilized in the future by large capacity, long distance HVDC transmission. Feasibility studies regarding arctic wind power has also been performed, where for instance northern Russia is shown to be very rich in arctic wind resources [15]. Onshore wind conditions therefore require both very high DC current capability, and control flexibility due to weak/islanded AC systems with fluctuant power. Therefore, there is good reason to investigate new solutions to complement existing VSC and conventional HVDC technology. In this paper, a novel control method that enables LCC HVDC combined with a relatively small STATCOM (~0.06 p.u of the HVDC) to transmit the rated HVDC power capacity from an islanded large scale PMSG (Permanent Magnet Synchronous Generator) wind farm AC system, is presented.

Firstly in section II, state of the art for islanded offshore VSC HVDC transmission is discussed, and some issues are highlighted when considering an islanded onshore LCC

HVDC transmission. Then in section III, the special characteristics of a full power converter islanded AC network is shown. In order to be able to control the AC networks amplitude and frequency, a novel control method is derived and presented in section IV. In order to prove the novel control method with a typical ± 800 kV UHVDC transmission, time domain simulations of initial islanding and various system faults are shown in section V. Finally conclusions are drawn in section VI. Section VII lists the main circuit parameters for the AC and DC system.

II. State of the Art for Islanded Offshore VSC HVDC Transmission

In this section, state of the art for islanded offshore VSC HVDC transmission is discussed, and some issues are highlighted when considering an islanded onshore LCC HVDC transmission

A. *Typical islanded offshore VSC HVDC transmissions*

Mostly due to the German energy transition, there have in recent years been a large amount of offshore wind power integrated by VSC HVDC. The offshore station is of special interest since it needs to operate in a completely islanded AC network. By firstly forming an offshore AC voltage that is fixed in amplitude, frequency and phase, the wind generators can relatively easily be started up. Then all power generated by the offshore wind farm is transmitted by the HVDC link. Should the onshore HVDC station temporarily be unable to inject power to the onshore AC network, like for instance during a low impedance AC fault, the DC voltage will increase rapidly. In order to handle this situation a DC Chopper is used, where the onshore DC Chopper can temporarily burn the active power produced by the offshore windfarm. This way the offshore AC network does not have to deal with a sudden and large active power surplus. The onshore placement of the Chopper is purely an economical choice, there is practically nothing preventing placing a Chopper offshore. This is because offshore systems are cable based, hence there is no need to consider temporary DC faults. DC cable faults are not temporary, and in addition they are very costly to repair. Based on this, the whole power transmission must trip immediately should there be a DC fault.

B. *Islanded onshore LCC HVDC transmission*

As discussed in the introduction, there could be large clusters of onshore wind where todays VSC HVDC capacity is not enough, therefore LCC HVDC could be considered an alternative. In order to get a basic understanding of the system, a summary of key issues is shown in Table I.

TABLE I.

Questions	**Basic comparison of offshore VSC HVDC and onshore LCC HVDC, for islanded transmission**		
	Onshore LCC	***Offshore VSC***	***Comment***
Is islanding detection needed?	Maybe, there could be a weak local AC network	No	Offshore system is always islanded
Will the wind turbines be exposed to AC and DC system faults?	Yes, due to OHL	No, AC and DC cables are used, and a DC chopper at inverter side is also used	Offshore system will trip at any DC cable fault. For any AC cable fault, the faulty cable section (and the corresponding wind farm section) will be tripped, but the healthy part will remain in operation
Can the HVDC converter be controlled in a rapid and flexible manner?	No, reactive power is a function of active power. AC filters and shunt capacitors are also necessary	Yes, due to VSC technology	A considerably large STATCOM can work around the LCC HVDC limitations, but the STATCOM size should preferably be small

III. Special Characteristics of a Full Power Converter Islanded AC Network

In this section, a comparison between traditional voltage source generators (like hydro, thermal, nuclear) and current source generators (like PMSG wind turbines) is made.

A. *Current source generators*

A typical PMSG wind turbine has a generator side converter, and a grid side converter. The grid side converter is a voltage source converter, which interfaces the AC grid via an inductance. Based on the voltage difference between the AC grid voltage and the controlled converter AC voltage, there will be a controlled current injection from the generator. Therefore with a typical control scheme, a PMSG wind turbine will appear as a current source generator in the AC power system.

B. *Comparison between voltage source generators and current source generators*

In order to later put the two different generator types into an islanded wind power context, two fundamental AC circuits are firstly compared with each other. Both circuits have a resistance R. There is also one capacitor C with the resulting impedance X_c, and an inductance L with the resulting impedance X_l connected in parallel. For the fundamental AC frequency, the impedances X_c and X_l are equal but with different signs. Thus they cancel out, leaving the AC circuit purely resistive.

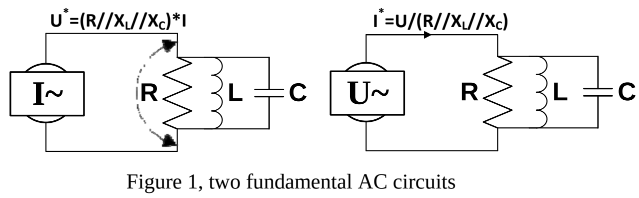

Figure 1, two fundamental AC circuits

For the current source generator circuit on the left hand, the following applies:

- The resistance R decides the voltage amplitude across the circuit, due to the current which the current source drives
- The higher the resistance, the higher the voltage U

For the voltage source generator circuit on the right hand, the following applies:

- The resistance R decides the amplitude of the current flowing in the circuit, which the voltage source drives
- The higher the resistance, the lower the current I

IV. A NOVEL CONTROL METHOD FOR ISLANDED ONSHORE LCC HVDC TRANSMISSION

This section is the key contribution of this paper. Based on the circuits in previous section, the non-conventional relations between active and reactive power in an islanded system is derived. Then based on these relations, a novel control method is suggested.

A. Simplified view of an onshore wind power transmission

In Figure 2 it is assumed that there are three main components in the onshore AC network, namely the PMSG based wind farm, the LCC HVDC rectifier, and a supporting AC network consisting of conventional voltage source generators. The LCC HVDC rectifier is modelled as a variable apparent resistance R and variable apparent inductance L, with a variable apparent capacitance C in parallel. At fundamental AC frequency, the reactive power consumption of the inductance L is cancelled by the reactive power generation of capacitance C.

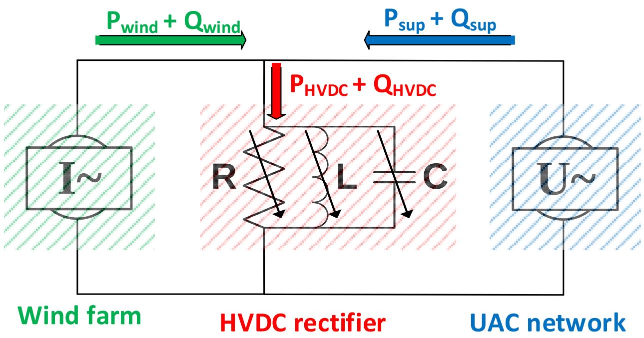

Figure 2, simplified onshore wind power transmission

The active and reactive power that is consumed by the HVDC rectifier, is hence the sum of the two sources:

$$P_{HVDC} = P_{wind} + P_{sup} \qquad (1)$$

Where,

- P_{HVDC} is the active power consumed by the HVDC
- P_{wind} is the active power supplied by the wind farm
- P_{sup} is the active power supplied by the supporting AC network

$$Q_{HVDC}=Q_{wind} + Q_{sup} \qquad (2)$$

Where,

- Q_{HVDC} is the reactive power consumed by the HVDC
- Q_{wind} is the reactive power supplied by the wind farm
- Q_{sup} is the reactive power supplied by the supporting AC network

B. Islanding of the onshore wind power transmission

An islanding of this system means that the supporting AC network is disconnected, as shown in Figure 3.

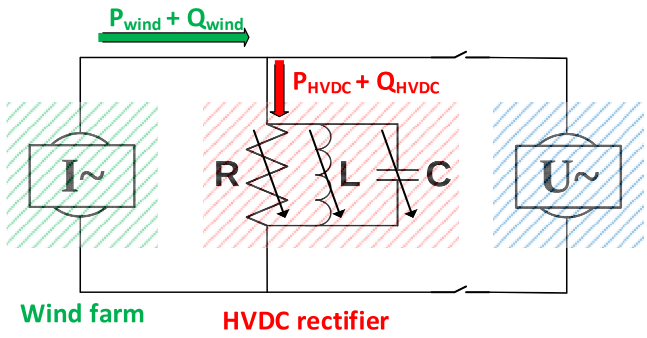

Figure 3, islanding of the system

Hence after islanding, the new voltage level U_{Isl} then becomes:

$$U_{Isl} = \sqrt{P_{wind} * R} \qquad (2)$$

Hence in an AC network with only current sources, the amplitude of the AC voltage can be controlled, by controlling the active power order of the LCC HVDC system (resulting in a change of the apparent resistance R). This is completely opposite to a typical case with voltage sources, such as conventional generators.

Another thing that needs to be controlled is the AC voltage frequency, called f_{Isl}. Assuming that there is no change in reactive power consumption of the HVDC system (L and C are both fixed), the following applies:

$$Q_{wind} = \frac{U_{Isl}^2}{\left(2\pi * f_{Isl} * L - \frac{1}{2\pi * f_{Isl} * C}\right)} \qquad (3)$$

Where,

- f_{Isl} is the AC network frequency.
- L is the inductance, which the HVDC appears as for fundamental AC frequency.
- C is the total capacitance from AC filters and shunt capacitors.

The frequency f_{Isl} can then be expressed as an ordinary quadratic equation:

$$(f_{Isl})^2 - f_{Isl}\frac{U_{Isl}^2}{2\pi * Q_{wind} * L} - \frac{1}{4\pi^2 * L * C} = 0 \qquad (4)$$

Which has two solutions, out of which only the positive has physical meaning:

$$f_{Isl} = \frac{U_{Isl}^2}{4\pi * Q_{wind} * L} \pm \sqrt{\left(\frac{U_{Isl}^2}{4\pi * Q_{wind} * L}\right)^2 + \frac{1}{4\pi^2 * L * C}} \quad (5)$$

The frequency in the current source AC network will hence depend on the AC voltage amplitude, and the reactive power balance. As previously derived, the voltage amplitude can be controlled by controlling the active power order of the HVDC system (resulting in a change of the apparent resistance R). This means that the frequency can then in turn be controlled, by controlling the reactive power drawn. This is once again completely opposite to a typical case with voltage sources, such as conventional generators.

C. *Novel control method*

Hence the AC voltage amplitude can be controlled, by controlling the LCC HVDC active power order. An overview is shown in Figure 4. The difference between measured and ordered AC voltage amplitude is firstly sent to a dead band, and then to a normal PI regulator. Finally the output delta power order is added to the existing power order.

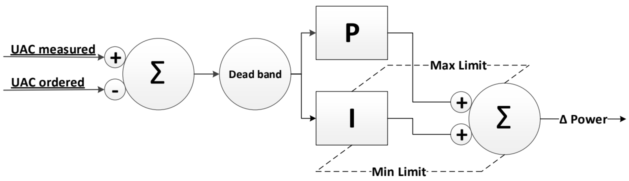

Figure 4, AC voltage amplitude controller

Since reactive power consumption is a function of active power for LCC HVDC, it is not possible to control the reactive power independent of active power. Therefore a STATCOM is used to balance out the relatively small difference between the reactive power consumed by the LCC HVDC, and the reactive power generated by the related AC filters and shunt capacitors. This way the frequency can be controlled in the islanded system. An overview is shown in Figure 5. The difference between measured and ordered AC voltage frequency is firstly sent through a low pass filter, and then a dead band. The output then forms the STATCOM reactive power reference.

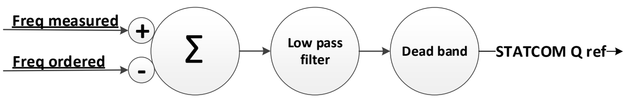

Figure 5, AC voltage frequency controller

V. TIME DOMAIN SIMULATIONS

In order to verify the regulator design in previous section, time domain simulations for initial islanding from a supporting AC network, DC faults and AC faults are performed in this section.

A. *Initial islanding from a supporting AC network*

Referring to Figure 6, the HVDC system is initially operating at ~1.1 p.u active power, with ~1.0 p.u coming from the wind farm (AC Grid 1), and the remaining ~0.1 p.u coming from the supporting AC network (AC Grid 2). There is also some reactive power support of ~0.08 p.u from the supporting AC network, which is typical for a lightly loaded high voltage AC line.

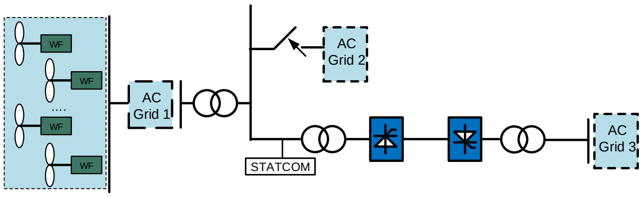

Figure 6, overview of the tested system

At 0.1s in Figure 7, the supporting AC network is disconnected. In order to represent an islanding detection delay, the combined HVDC and STATCOM system receives an islanding indication at 0.15s, and activates the novel controls described in previous section. As can be seen from the simulation result, both the AC voltage amplitude and frequency can successfully be controlled. Graphs from top to bottom: Graph 1: Active power flowing out from the supporting network (blue); Reactive power flowing out from the supporting network (green). Graph 2: Active power transmitted by the HVDC rectifier. Graph 3: AC voltage amplitude. Graph 4: STATCOM reactive power output. Graph 5: AC voltage frequency.

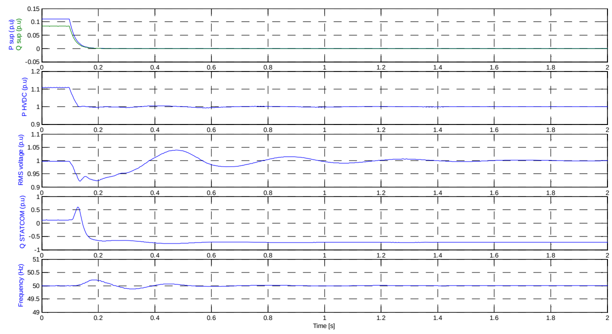

Figure 7, initial islanding of the system

B. *Impact of DC and AC faults*

As shown in Figure 3, the only remaining resistance in the AC system after islanding is the HVDC rectifier. Should the HVDC rectifier be unable to transmit all generated power, the resistance R would effectively become very large, i.e. there would be a very high AC voltage due to the current still driven by the current source generators (PMSG wind farm).

In order to deal with this very difficult problem, a DC Chopper was introduced at the rectifier. An overview of the DC Chopper is shown in Figure 8.

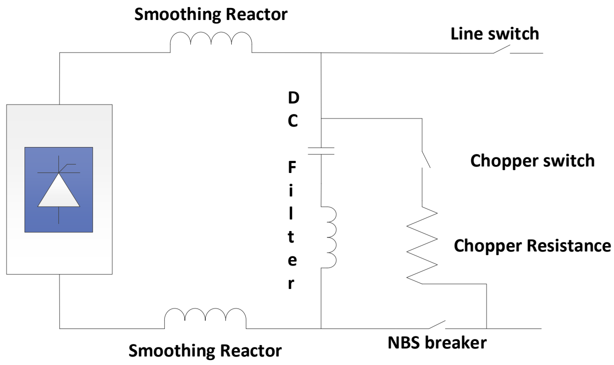

Figure 8, rectifier DC chopper

A flowchart describing the operation of the DC Chopper is shown in Figure 9.

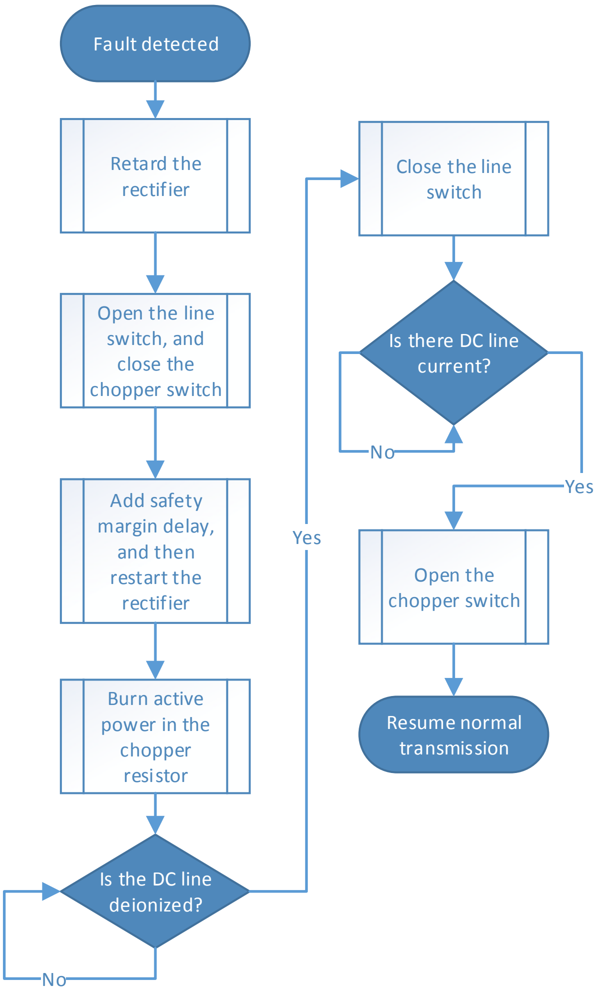

Figure 9, flowchart for DC Chopper operation

Since the only mature technology that currently could work as Line switch and Chopper switch is resonant mechanical DC breakers, the maneuvering times were selected accordingly, i.e. closing time of 65ms and opening time of 33ms [16].

In Figure 10, a DC fault is applied in pole 1 at 0.1s, while pole 2 still transmits power. Before the DC Chopper can be connected at ~0.17s, the AC voltage amplitude goes very high, peaking at ~2.4 p.u. As soon as the DC Chopper is connected, the AC voltage amplitude can be controlled down to its nominal value. Finally the DC Chopper is disconnected at ~0.47s, and power transmission is resumed. Graphs from top to bottom: Graph 1: AC voltages. Graph 2: DC voltage. Graph 3: DC line current. Graph 4: HVDC firing angle (alpha).

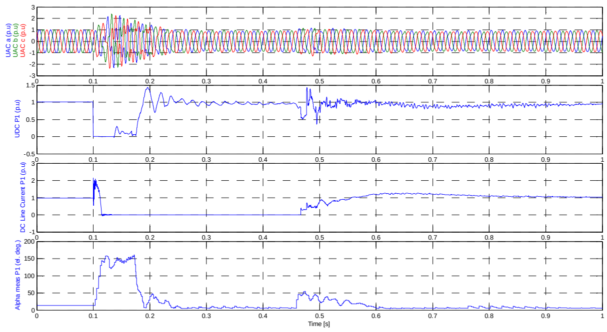

Figure 10, DC fault in pole 1, while pole 2 transmits power

To test an even worse case, a low impedance three phase to ground inverter AC fault is applied at 0.1s in Figure 11. Since the HVDC system is unable to transmit any active power on either pole, the AC voltage amplitude quickly becomes extremely high, peaking at ~3.4 p.u. As soon as both DC Choppers are connected, the AC voltage amplitude can be controlled down to its nominal value. In order to avoid causing a large active power unbalance again, the two poles resumes power transmission at different times. Pole 1 hence resumes at ~0.37s, while pole 2 resumes power transmission at ~0.67s. The graph legend is the same as Figure 10.

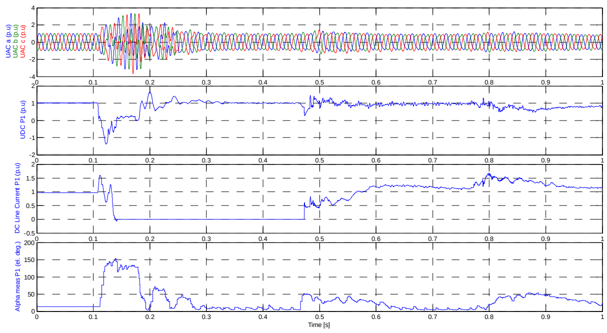

Figure 11, low impedance three phase AC fault at the inverter

VI. Conclusions

In this paper, a novel control method for islanded wind power transmission was presented. By identifying and using the special characteristics of an islanded AC network consisting of only PMSG wind generators, both the AC voltage amplitude and frequency can be controlled by a LCC HVDC rectifier combined with a relatively small STATCOM. The key issue in the islanded system is the extremely high transient AC overvoltage that occurs when limited, or no DC power can be transmitted, i.e. inverter DC faults and AC faults. In order to improve the AC overvoltage, a DC Chopper was introduced. But since it takes considerable time to connect the DC Chopper, the initial AC voltage peaks are extremely high.

VII. AC AND DC SYSTEM MAIN CIRCUIT PARAMETERS

In this section, the key data of the AC and DC system used for the time domain simulations is presented.

TABLE II.

Name	Rectifier	Inverter
Nominal AC voltage UacN (kV)	750	500
AC network short circuit capacity (MVA)	24000	40000
Frequency (Hz)	50	50
STATCOM capacity (MVAr)	500	-
Nominal DC voltage UdcN (kV)	800	756.8
Nominal DC current IdN (kA)	5.0	
Length of transmission line (km)	2300	
DC line resistance (ohm)	8.6	
Udi0 at nominal operation point (kV)	236.2	218.8
Nominal alpha (degree)	15	-
Nominal gamma (degree)	-	17
QfiltN/PdN (pu)	0.571	0.49
DC smoothing reactor (H)	0.1334	0.1334
Converter transformer dxN (%)	11.5	9
Converter transformer drN (%)	0.3	0.3

REFERENCES

[1] M. Andersson, R. Cai, C. Yang, "Round Power Black start method for passive AC Network using bipolar LCC HVDC system", Southern Power System Technology Journal, 9(6):6-14, 2015

[2] C.K. Sao, P.W. Lehn, “Intentional Islanded Operation of Converter Fed Microgrids”, IEEE Power Engineering Society General Meeting, Montreal, Canada, June 18-22, 2006

[3] G. Asplund , K. Eriksson, H. Jiang, J. Lindberg, R. Pålsson, K. Svensson, "DC transmission based on voltage source converters", Cigré Conference, Paris, France, 1998

[4] U. Axelsson, A. Holm, C. Liljegren, K. Eriksson, L. Weimers, "Gotland HVDC Light transmission - worlds first commercial small scale DC transmission", Cired Conference, Nice, France, May 1999

[5] L. Carlsson, G. Flisberg, L. Weimers, "Recent Evolution in Classic HVDC", The 4th International Conference on Power Transmission & Distribution Technology, Changsha, China, 2003

[6] A. Skytt, P. Holmberg, L. Juhlin, "HVDC Light for connection of wind farms", Second International Workshop on Transmission Networks for Off shore Wind Farms, Royal Institute of Technology, Stockholm, Sweden, March 29-30, 2001

[7] A. Lesnicar, R. Marquardt, “An innovative modular multilevel converter topology suitable for a wide power range” in Proc. IEEE Power Tech Conf., Bologna, Italy, 2003, vol. 3, p. 6.

[8] J. Vobecky, T. Stiasny, V. Botan, K. Stiegler, U. Meier, M. Bellini, "New Thyristor Platform for UHVDC (>1 MV) Transmission", International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nuremberg, Germany, 20-22 May 2014

[9] IEC white paper, "Grid integration of large-capacity Renewable Energy sources and use of large-capacity Electrical Energy Storage”, P69, Oct. 2011

[10] http://www.cleanlineenergy.com/projects

[11] http://www.transwestexpress.net/

[12] http://www.datcllc.com/projects/zephyr/

[13] Power Grid Corporation of India Ltd., "Transmission Plan for Envisaged Renewable Capacity, Vol-I", P102 and P213, July 2012

[14] J. Shah, "Quantum Leap in Wind Power in Asia: Context, Barriers and Objectives", Clean Energy Expo Asia, Singapore, November 2-4, 2010

[15] State Grid Corporation of China, “A Study on Wind Power Resources in the Arctic Region and Their Development”, Global Energy Interconnection international conference, Beijing, China, March 30-31, 2016

[16] ABB, “Live Tank Circuit Breakers Buyer’s Guide”, available online

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