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Simplified Modeling of VSC-HVDC in Power System Stability Studies

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Abstract: This paper presents a simplified modeling approach for a voltage source converter based high voltage DC transmission line (VSC-HVDC) for use in power system dynamic studies. In the AC grid sending-end and receiving-end converters (SEC and REC) of the HVDC system are represented by controlled Thévenin sources. The controllers act on the two voltage sources to provide the prescribed terminal conditions by adjusting the magnitude and frequency of the source voltage. The DC link model is incorporated into the controller description and not explicitly represented. Based on this assumption and the typical control objectives in VSC-HVDC the simplified control structures have been systematically derived. The models then were implemented on DIGSILENT software. The simulation results using an open source data of an HVDC installation have demonstrated the feasibility of the approach and the validity of the models developed.

Keywords: VSC-HVDC modeling; offshore link; voltage source converter; wind farm; simplified control.

1. INTRODUCTION

The past two decades have seen the emergence of wind power as an important part of the overall generation capacity in many parts of the world. During the course of the ensuing "wind rush" in countries with large wind installations, most suitable sites onshore and also offshore sites near the coast have largely been used up. The next generation of offshore wind farms is to be located out in the sea at a significant distance from the shore. The transmission distance that needs to be bridged for connection of the wind farms to the grid onshore is a challenge yet to be solved conclusively. AC submarine cable at 50 Hz (or 60 Hz) is a mature and proven technology, but the distance that can be covered is constrained by the charging current. A rule of thumb for the reach of AC submarine cables is a distance of about 100 km. It is possible that the AC cable transmission technology will re-invent itself in the future and extend its reach and thus expand the scope of its application. One recently proposed solution in this direction is the use of lower frequency, for example 16 2/3 Hz frequency (Erlich, 2013) for transmission. Using the current technology and the 50 Hz frequency, however, the charging current (which is directly proportional to the transmission range) will preclude the use of AC cables for linking-up the new generation of offshore wind farms to the grid.

When the limit of AC transmission is reached, the alternative obviously is the use of HVDC transmission. The basic difference between the two currently available HVDC alternatives is the type of converter technology they employ. Conventional HVDC transmission with line-commutated thyristor valves as a converter is available for up to extra high voltage transmission levels and high power ratings. It is characterized by relatively low conversion losses, and there exists decades of operational experience with the technology. But the low degree of controllability, the need for reactive power compensation and the fact that passive or even weak networks cannot be connected to this system make it less attractive. As a result, an increasing number of offshore WFs opt nowadays for VSC based HVDC lines. The outputs of VSC-HVDC transmission lines employing self-commutated valves (IGBTs, IGCTs and GTOs) are determined solely by rating of the equipment and its control system. This gives total flexibility regarding the location of the converters in the AC system since short circuit capacity (SCR) is no longer a limiting factor (Cole, 2011). However, VSC HVDC technology at this point is still in its infancy and is available only for the lower end of high voltage transmission systems. It is more expensive and causes more conversion losses (switching losses) compared to classical HVDC, although new soft-switching methods and more complex topologies significantly reduce the converter losses.

On the other hand, VSC-HVDC comes with some significant operational advantages, including independent and fast control of active and reactive power, capability to contribute to voltage stability and transient stability of the connected AC networks through AC voltage control, black start capability, possibility of connection to weak or even passive networks, ability to change power flow direction almost instantaneously, smaller converter station footprint due to smaller offshore platforms, the possibility of variable frequency operation in the wind farm grid opening up additional control options for the connected wind turbines. Since its inception in 1997 VSC HVDC has made steady progress. The current transmission capacity stands at 400 MW (with ±200 kV DC voltage). But one currently on-going project when completed will have a capacity of 1000 MW at ±320 kV. Voltage levels of up to ±500 kV and power rating of 2000 MW are considered possible by 2017 (ENTSOE, 2012).These facts together with the mutually reinforcing activities of more operational experience and on-going research and innovation make it very likely that VSC-HVDC will feature prominently in future offshore links and grid expansions.

This paper focuses on the simplified modelling of VSC-HVDC in large system studies. Based on general relationships governing the operation of a VSC-HVDC system, first models of the sending-end converter (SEC), receiving-end converter (REC) and the DC circuit derived, with the objective of obtaining a representation which is simple enough for easy incorporation into the overall system simulation model yet capable of reproducing the dynamic response of the VSC-HVDC and its impact on the rest of the system. For validation of the model thus developed, simulations were performed using the data of the ABB open-access benchmark model (ABB, 2007).

2. VSC-HVDC CONTROL FUNCTIONS: AN OVERVIEW

To re-state the obvious, both converters of VSC-HVDC - one operating as a rectifier and the other as an inverter - are connected to AC networks at both ends of the line. The list of operational variables that may be controlled includes the AC voltages at the connection points, the DC voltage as well as active and reactive power flows. Additionally, the various physical limitations, such as current output and internal converter voltage limitation, need to be incorporated into the model. Functions designed to improve the dynamic performance of the overall system and to fulfil grid code requirements may be included as required. Fig. 1 summarizes the most basic control functions (Li, 2010).

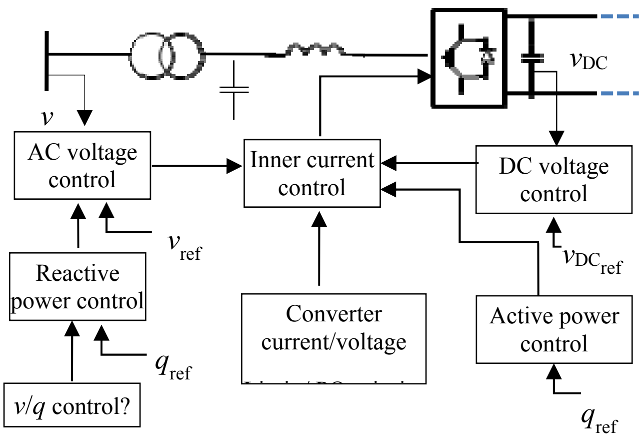

Fig. 1 Overview of major VSC-HVDC control tasks.

For a two-terminal HVDC-VSC system, one of the converters controls the DC voltage and the other the active power. Additionally, each of the converters can optionally be set in either AC voltage or reactive power control mode. The inner current control loop derives its reference values from the outputs of the outer loops. The following section deals with the details of the modelling procedure.

3. VSC-HVDC MODELLING IN LARGE SYSTEM STUDIES

The simplified modelling approach is based on the basic and well-known assumption that the two converters, connected to one another by the HVDC line, can be represented by their respective Thévenin or Norton equivalent circuits, with the control system acting on the two voltage (current) sources to provide the prescribed terminal conditions by adjusting the magnitude, phase angle and frequency of the source voltage (current). In other words, regardless of the converter topology or complexity, the terminals of the VSC can be considered as voltage (current) sources, which are connected to the rest of the network via reactors as shown in Fig. 2 in the simplest form (ABB, a).

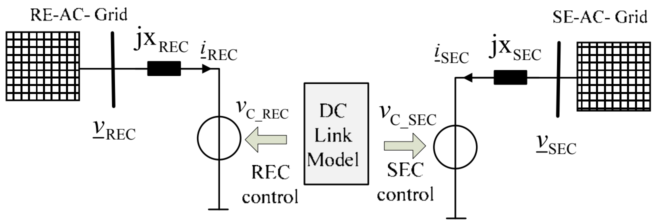

Fig. 2 The Thevenin equivalent circuit of VSC HVDC.

The acronyms used in Fig. 2 are as follows:

- x_{REC}, $\underline{v}_{REC}$, $\underline{v}_{C\_REC}$: Receiving end: reactor, terminal voltage, converter voltage, respectively.
- x_{SEC}, $\underline{v}_{SEC}$, $\underline{v}_{C\_SEC}$: Sending end: reactor, terminal voltage, converter voltage, respectively.

Each of the converter stations is connected to the AC system via the impedances, labelled in Fig. 2 as x_{REC} resp. x_{SEC} (with resistances neglected) representing the converter transformer and reactor between the VSC and the AC system. However, if the filter or any other element of the station are required to be represented explicitly, the circuit can be modified accordingly (Li, 2010). The dynamic response of the capacitor banks connected on the DC side of each station, and the DC line itself are not represented explicitly, and only their effect is considered in the control system.

The physical analogy and thus the adequacy of the circuit in Fig. 2 to represent the behaviour of a VSC-HVDC system can be easily explained. Both the amplitude and the phase angle of the converter fundamental voltages ($\underline{v}_{C\_REC}$ and $\underline{v}_{C\_SEC}$) are controlled (in magnitude and phase angle) with respect to the (respective) terminal voltages by the pulse sequence of the converter bridge. Making the reasonable simplifying assumption that $\underline{v}_{REC}$ and $\underline{v}_{SEC}$ are approximately constant during normal operation, it can easily be seen that active power flow between the converter and the respective

AC network can be controlled by changing the phase angle of the $\underline{v}_{C\_REC}$ resp. $\underline{v}_{C\_SEC}$, and the reactive power flow by the amplitudes of the voltages (Cole, 2011). Just like in any transmission link between two points in an AC network, the voltage drop across the reactors x_{REC} resp. x_{SEC} determines the power flow between the grid connection points and the respective converter voltages, thus the DC side.

In the following sections the control system which determines the operational behaviour of VSC-HVDC vis-à-vis the AC grids connected to it are described. Depending on the direction of active power flow one station functions as a rectifier while the other operates as an inverter. Each VSC station has two degrees of control freedom, of which one is used for reactive power (or voltage) control, while the other is dedicated to active power or DC voltage control.

3.1 Sending-end converter (SEC) model

The reactive power (or alternatively its voltage at the respective network connection point) control of each station occurs independently of the other station. Additionally, one or both stations typically contain functions for voltage support control of the AC system, to which the VSC is connected. The control objective in this case is to maintain voltage at the point of common coupling (PCC) or any other bus in the circuit at the desired value. But when it comes to active power, the power balance relationship requires that the injected power at the SEC must be delivered to the network connected to the REC, which means that the active power entering the HVDC system must be equal to the active power leaving at REC plus the losses in the DC transmission system. This fact necessitates that one of the VSC-stations has to control the active power and the other the DC voltage.

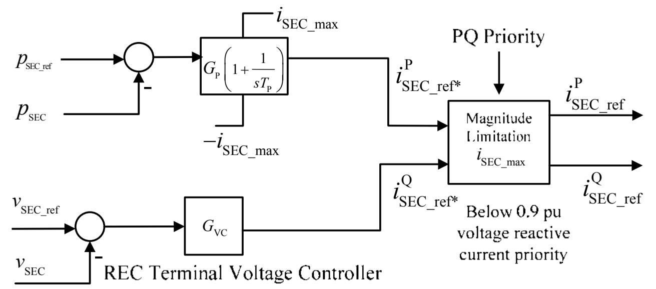

Fig. 3 Sending-end converter model.

The control functions at the SEC are summarized in Fig. 3, in which the following three core functions are depicted:

- The PI-controller maintaining the active power at the specified value with the active converter current as a control variable.
- The AC voltage control block (or alternatively the power factor control) to control the voltage at PCC or elsewhere.
- The current magnitude limitation block with active current priority during normal operation and with conditions for the reactive current priority being defined to match the grid code requirements.

For an HVDC line connected to an offshore wind farm, the active power injected into the line is a function of the settings in the wind farm. In this case the PI controller may be tasked with for frequency control. Accordingly, the active current reference can be calculated directly on the basis of the active power measured at the SEC.

3.2 Receiving-end converter (REC) model

The task of the REC is to transfer the active power to the AC grid by maintaining the DC voltage level at the prescribed value, with the active current as the control variable. The reactive current control loop can optionally be used to control the REC terminal voltage on the AC side or to guarantee a constant power factor, and also to support the grid voltage during faults. Fig. 4 summarizes the control tasks, which include:

- The PI-controller maintaining the DC voltage with the active converter current as a control variable
- The current magnitude limitation block with active current priority during normal operation
- The AC voltage control block (or alternatively the power factor controller).

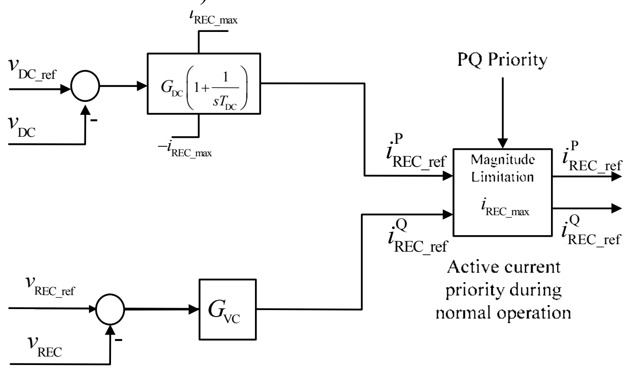

Fig. 4 Receiving-end converter control.

This block is also responsible for grid voltage support during faults. In steady-state operation the DC voltage control and by implication the d-axis component of the REC current has priority. In case of grid fault, however, the priority is switched to reactive current to provide fast voltage support.

3.3 Simplified inner current control loop

The inner current control is the same in both SEC and REC. Active current reference is calculated from the desired active power to be transmitted through the HVDC line or the DC voltage order, which are determined by system-wide objectives such as power flow control, congestion management, etc. and as a result, during normal operation these settings are determined by the system operator. The converter control is based on a vector control approach with its rotating reference frame aligned with the respective terminal voltages. As a result, a PLL for acquiring the voltage phase angle would be needed. However, in RMS type simplified simulations, there is no need to model the PLL as it can be obtained directly from the simulation.

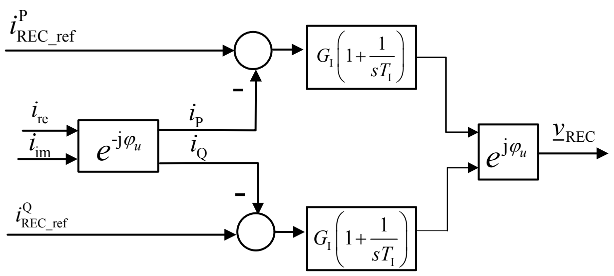

Fig. 5 Current controller in terminal voltage reference frame.

Once the transformation into terminal voltage reference is performed active power is controlled through d- axis and reactive power through q- axis component of the converter current, both independently of one another. A reference voltage, equal in phase and magnitude to the fundamental frequency component of the desired output voltage to be generated by the converter bridge is calculated. However, the converted is not represented explicitly in the simplified simulation, and the controller output voltage is directly passed to the voltage source. The control scheme for the current controller is given in Fig. 5, in which only the REC current control is shown. It should be noted that in this simplified representation the feed forward terms included in real applications have been neglected and the model is composed of merely the PI controller, in addition to coordinate transformations.

As stated above, it is necessary in the modelling to consider the converter-current limitation, which is imposed by the current carrying capability of the VSC valves.

3.4 The Model of the DC Capacitors and the HVDC Line

In the simplified model the link between the SEC and the REC is established, as shown in Fig. 6 without explicitly including the HVDC line in the network diagram. When the power balance is maintained, the input into the model (Fig. 6) remains zero, the chopper is deactivated and the DC voltage remains constant. Any power imbalance between the two stations causes the DC voltage to change and (depending on the level of the voltage rise) leads to the DC chopper activation which is required to guarantee Fault Ride-Through (FRT) capability. The model also accounts for the power dissipated by the resistance of the chopper if and when it is activated.

The chopper is ignited when the DC voltages exceeds a pre-set threshold and de-activated when the voltage drops well below the activation value. In the DIgSILENT implementation of the model the available special functions can be used to model the voltage hysteresis for chopper activation and de-activation.

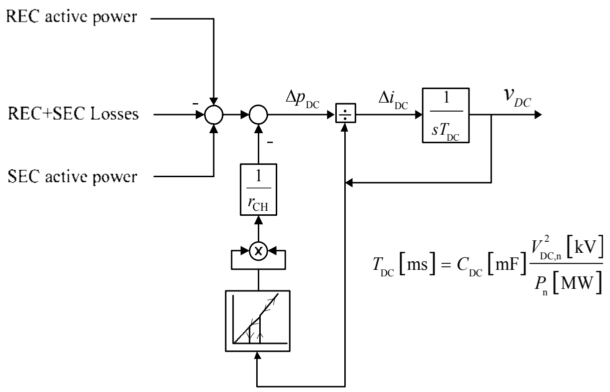

Fig. 6 HVDC link model.

4. IMPLEMENTATION OF THE VSC HVDC MODEL ON DIGSILENT

For the demonstration of the feasibility of the approach described above, the REC, SEC and the DC link models were implemented on the simulation software DIgSILENT. Additionally, the results obtained were compared with those of the ABB HVDC Light open access model. The DIgSILENT version of the ABB model itself uses the DIgSILENT standard elements for modeling of the primary equipment. But the control system is composed of a set of Fortran external subroutines linked to DIgSILENT as a dynamic linked library (DLL). For ease of comparison the topology and parameters of the primary circuit elements were the same as those of the ABB model "M5" (Bjorklund, 2006). The standard DIgSILENT element voltage source offers only the possibility of steady state power flow control. For this reason the element "static generator" defined as a voltage source was used instead. The resulting overall primary circuit is given in Fig. 7 Important parameters of the circuit elements are summarized in Table 1.

Table 1. Parameters of the primary circuit.

Reactors	373 MVA, 400 kV/195 kV
Filters	55.95 Mvar, 195 kV
Transformers	396 MVA, 12%, 400kV/195kV

Once the topology is put together and element parameter definitions completed the control structures described in the previous section were incorporated into the respective voltage sources. Measurement points for power and voltage are chosen to be PCC1 and PCC2. The filter is defined only as a capacitor since in any series LC circuit tuned for higher order harmonics the capacitance is the predominating element at fundamental frequency.

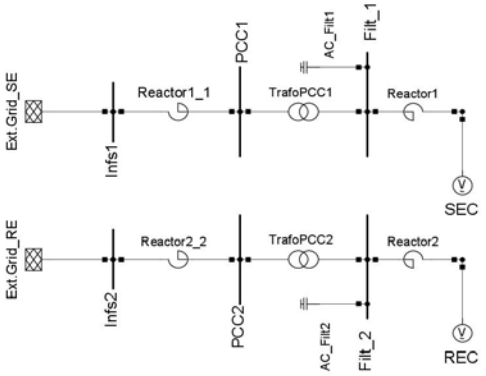

Fig. 7 HVDC model - primary equipment.

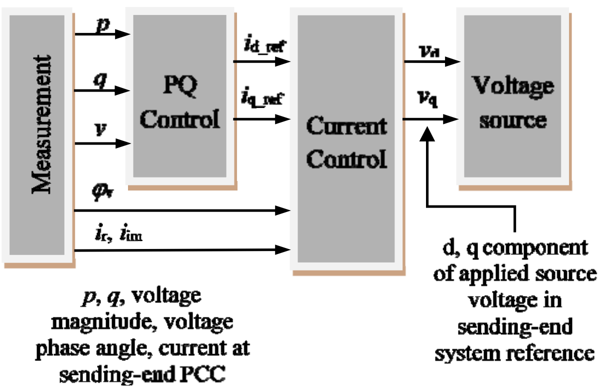

Fig. 8 Sending-end converter frame

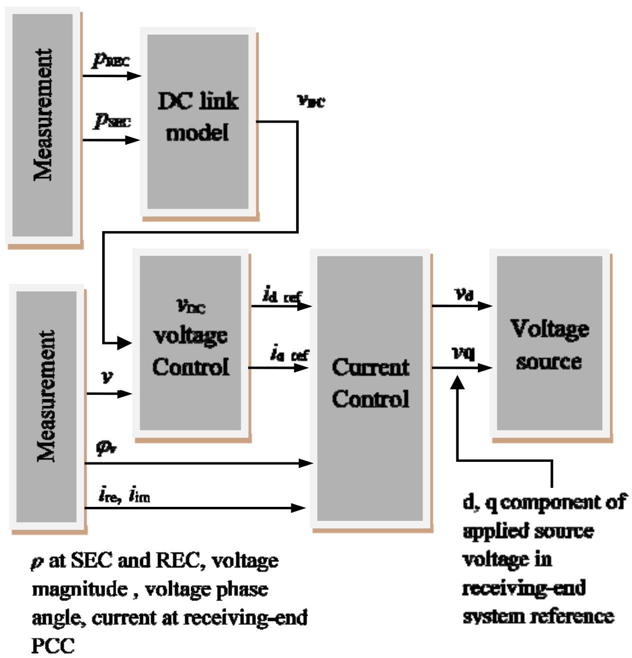

Fig. 9. Sending-end converter frame.

8 and 9 show the "frames" (in DIFSILENT parlance) which define the overall structure of the model and specify access points to the primary circuit by the controllers. Similar in both cases is the current controller, which – on the basis of reference values provided by the higher order controller - acts on the respective voltage sources. The core elements, which provide these references, are the active/reactive power (PQ) and the DC and AC voltage (v_{DC} / voltage) controllers described above. They may also include any additional functions required for voltage support or improving the system performance.

5. SIMULATION RESULTS

For the conceptual validation and testing the functionality of the control approach alternating three-phase faults were introduced in the sending- and receiving-end converter side of the circuit. The results obtained are shown Gig. 10 and Fig.11, which will be discussed briefly.

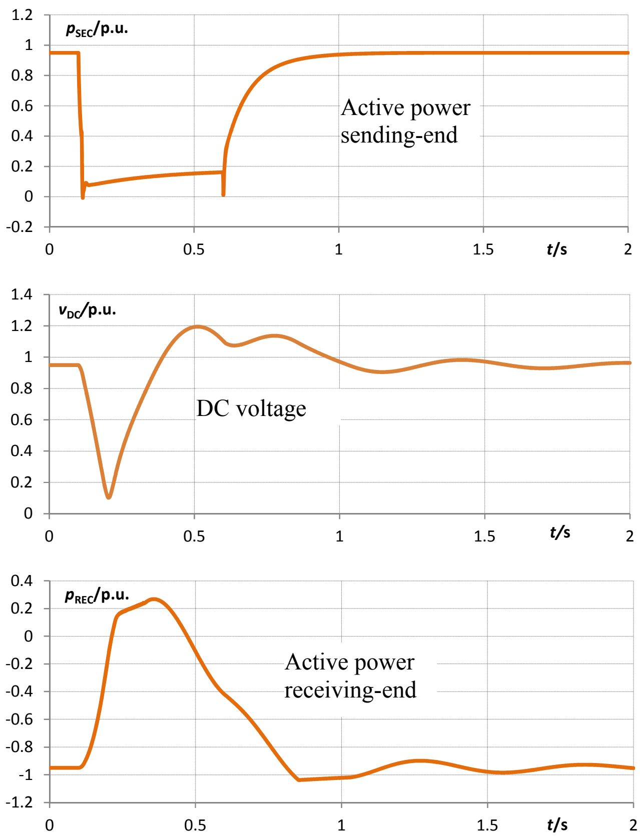

Fig. 10 Power and DC voltage behaviour during a fault on SEC side.

Since the converter is replaced by simple voltage sources the results obviously cannot be expected to represent the physical behaviour of the converter in full. The objective rather is to demonstrate the ability of the algorithm to adequately reproduce some of the salient features of VSC-HVDC such as fast control of the active and reactive power, the capability to support the AC network, particularly during disturbances, etc. Additionally, in phases where the converter is supporting the AC system with reactive power supply/consumption, it has to be ensured that active power is limited to the extent that the valve current remains within limit. Another limitation which determines the reactive power capability of the VSC is the over/under voltage magnitude of the VSC (modulation index limitation). The over- voltage limitation is imposed by the DC voltage level of the VSC, and the under-voltage limit by the main-circuit design and the active-power transfer capability, which requires a minimum voltage magnitude to transmit the active power.

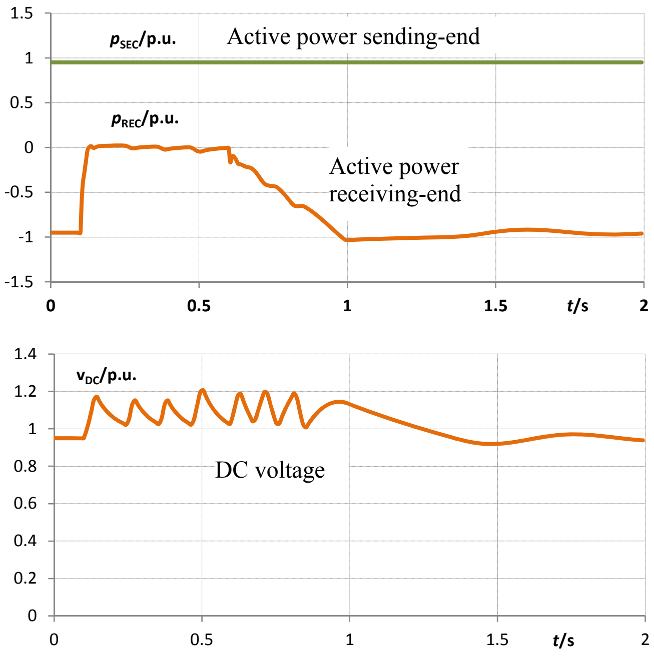

Fig. 11 Power and DC voltage during a fault on REC side.

The results of the simulations performed show that the above-mentioned features of VSC-HVDC can be represented in the control system adequately. Faults of varying severity and location were introduced to observe the response. Fig. 10 shows the time variation of active power on SEC and REC sides as well as the DC voltage for a fault of 500 ms duration on the SEC side. As a result of the fault the power fed into SEC drops to nearly zero. As a result the receiving-end power decreases also slowly. In the process the DC voltage rises, but does not lead to chopper activation, when the threshold voltage for chopper activation was set at 120%. For this same fault location and duration, chopper ignition takes place when the threshold voltage is changed to a value of 110%.

Fig. 11 shows the results for a fault of a similar severity and duration but on the REC side. As can be seen, the effect on the DC voltage is more severe. With the power delivered at the REC decreasing abruptly to zero as a result of the fault and the power in-feed at the SEC remaining approximately constant, the significant DC voltage increase would lead to repeated chopper activation. In addition to the sample results shown above, multiple simulations were performed to ascertain that the model can easily be augmented with the basic functionalities of VSC-HVDC to reproduce its typical responses in a simulation environment. As a result, it can be concluded that for large-scale system studies regardless of the converter topology or complexity, the terminals of the VSC can in the simplest form be considered as voltage sources connected to the rest of the network via reactors. Together with the basic control functions incorporated into these basic elements, the VSC-HVDC can be modelled satisfactorily to study its dynamic interaction with the rest of the system.

6. CONCLUSION

In this paper a simplified method for modelling VSC-HVDC in large system studies introduced. The method is based on the assumption that VSC-HVDC can adequately be represented using controlled voltage sources. The simplified model unavoidably involves simplifying assumptions, and the results obtained using this model will be less accurate compared to those of the detailed model. But since the simplifications do not stunt the system behaviour fundamentally and the underlying physical phenomena remain visible, the approach represents an acceptable compromise. The most significant advantage of the simplified model is that it keeps the modelling of VSC-HVDC simple, yet the accompanying loss in accuracy for preliminary system studies or estimating grid code compliance remains within acceptable limits.

The simulation results show that the method can offer an easy way of simulating VSC-HVDC without the need to delve into the topology of a rather complex system as long as its system wide response is the focus. The simplified simulation which uses basic elements available in any commercial power system simulation software enables the user to adapt the model to any specific needs or emphasis.

REFERENCES

ABB, “It’s time to connect”, available at: http://www.tdproducts.com/files/36371732.pdf (accessed on 31.08.2013)

Bjorklund, P., Chengyan, J. Yue , P. and Srivastava, K., A new approach for modelling complex power system components in different simulation tools, available at: http://de.scribd.com/doc/50009375/A-NEW-APPROACH-FOR-MODELING-COMPLEX-POWER-SYSTEM

Cole, S. and Belmans, R., “A proposal for standard VSC HVDC dynamic models in power system stability studies”, *Electric Power System Research 81(2011),* pp. 967-973.

Erlich,,I.; Fischer, W.; Braun, R. and Brakelmann, H, „Dreiphasiges 16,7-HZ-System für die Übertragung von Offshore-Windenergie“, *ew Magazin für die Energiewirtschaft*,11/2013, Teil 1 und 12/2013, Teil 2.

Entsoe, “”Offshore Transmission Technology”, 2012 available at: https://www.entsoe.eu/publications/system-development-reports/north-seas-grid-development/

Li , S., Timothy, H. and Xu, L., “Control of HVDC light system using conventional and direct current vector control approaches”, *IEEE Transactions on Power Electronics*, Vol. 25, No. 12, December 2010.