Effect of Synchronverter on a Wind Farm in a MMC-Based HVDC System

Bastin John Antony[1], Mr.Mahujith T[2]
[1,2]*Dept. of Electrical and Electronics Engg, SCET*

Abstract- **The paper talks the effects of synchronverter on a wind farm in a MMC-based HVDC system. A synchronverter is an inverter. The control of the wind farm connected to the power systems is done using synchronverter. It operates the same way as synchronous generators. The stability of an offshore wind power network connected through a high-voltage dc (HVDC) transmission line can be challenging since a strong ac collection (ACC) bus might not be available, when there is no rotating machine connected in that bus. Resonances or instability phenomena have been reported in between wind farms and MMC-HVDC systems. They are arguably originated due to interactions between the MMC and the wind power inverters. In addition, the synchronization unit (phase-locked loop, PLL) has shown to have a significant impact in achieving satisfactory performance. To tackle this problem, this paper has proposed a wind energy conversion system (WECS) controller for such an ACC bus based on the synchronverter concept. The dedicated synchronizing unit is been replaced by the self-synchronizing synchronverter. It synchronizes itself with the grid before and after the connection and adjust to the grid frequency. This considerably improves the performance, reduces the complexity, and computational burden of the controller.**

I. INTRODUCTION

HIGH-VOLTAGE dc (HVDC) transmission is attractive for large offshore wind farms that are located far from the onshore power grid. Conventional HVDC technology based on line-commutated converters (LCCs) requires reactive power and voltage support for the offshore ac bus by either a dedicated static synchronous compensator, which significantly increases the overall cost, or through control of individual turbine inverters, which is technically challenging. New HVDC technology based on voltage-source converters (VSCs), including modular multilevel converters, avoids the need for reactive power support and also has the ability to black start the system. These make VSC-based HVDC technology the natural choice for offshore wind applications. MODULAR multilevel converter-based high-voltage dc (MMC-HVDC) transmission technology has become a promising solution for grid integration of large-scale offshore wind farms, due to its advantages, such as modular design, high efficiency, low distortion of output voltage, easily scalable in terms of voltage levels, and so on.

As more energy devices are connected to power systems increases, often via dc/ac converters (also called inverters). The most important and basic requirement for such applications is keeping the inverters synchronized not only before connection is established with the grid but also after connected to the grid so that 1) an inverter can be connected to the grid and 2) the invertor operation is in a way that only the desired power is given to the grid even when the grid voltage changes its frequency, phase, and amplitude. In this paper, we propose a method by which an inverter can be operated to mimic the behavior of an SG. The dynamic equations are the same; only the mechanical power exchanged with the prime mover (or with the mechanical load, as the case may be) is replaced with the power exchanged with the dc bus. We call such an inverter (including the filter inductors and capacitors) and the associated controller a synchronverter. To be more precise, a synchronverter is equivalent to an SG with a small capacitor bank connected in parallel to the stator terminals. A synchronverter will have all the good and bad properties of an SG, which is a complex nonlinear system.

II.MMC-BASED HVDC SYSTEM STRUCTURE

Fig. 1 shows a single-line diagram of the study system. The system comprises two back-to-back connected MMCs which are hereinafter referred to as MMC-1 and MMC-2. The ac ends of each MMC are given to a utility grid through a series connected filter, a three-phase transformer. Two three-phase shunt filters installed at the low-voltag side of the transformer

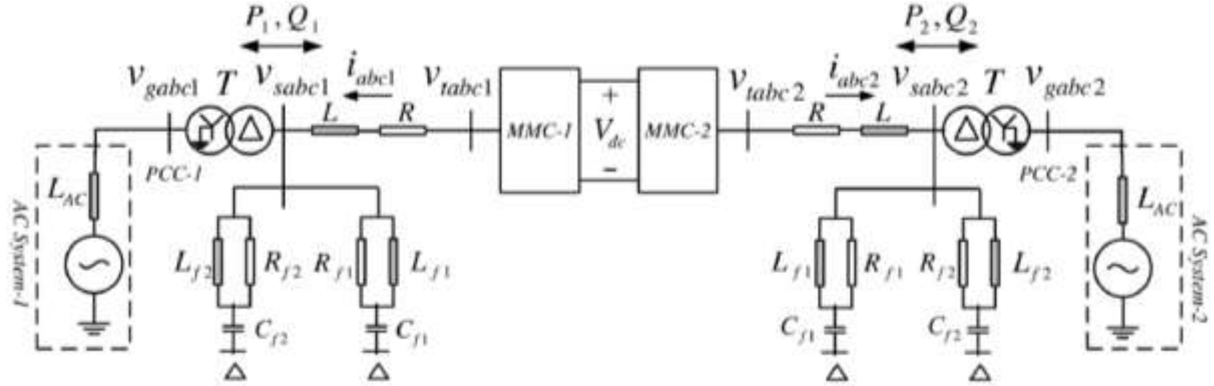

Fig. 1. single-line diagram representation of the MMC-HVDC system

III. SYNCHRONVERTER

A synchronverter is an inverter that imitates an ordinary SG. As a result, grid-connected energy device and distributed generation can easily take part in the control of frequency and voltage of the system. A synchronverter consists of a power part, as shown in Fig. 2, and an electronic part, i.e., the controller, as shown in Fig. 3.

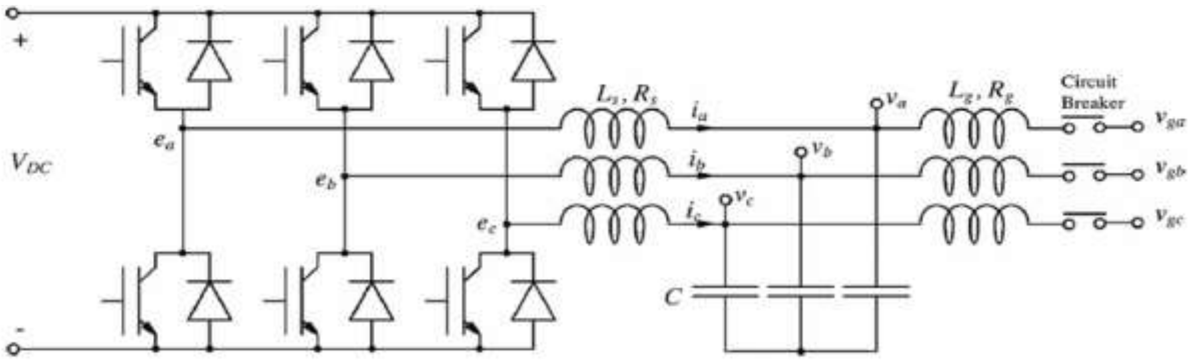

Fig. 2. Power part of a synchronverter

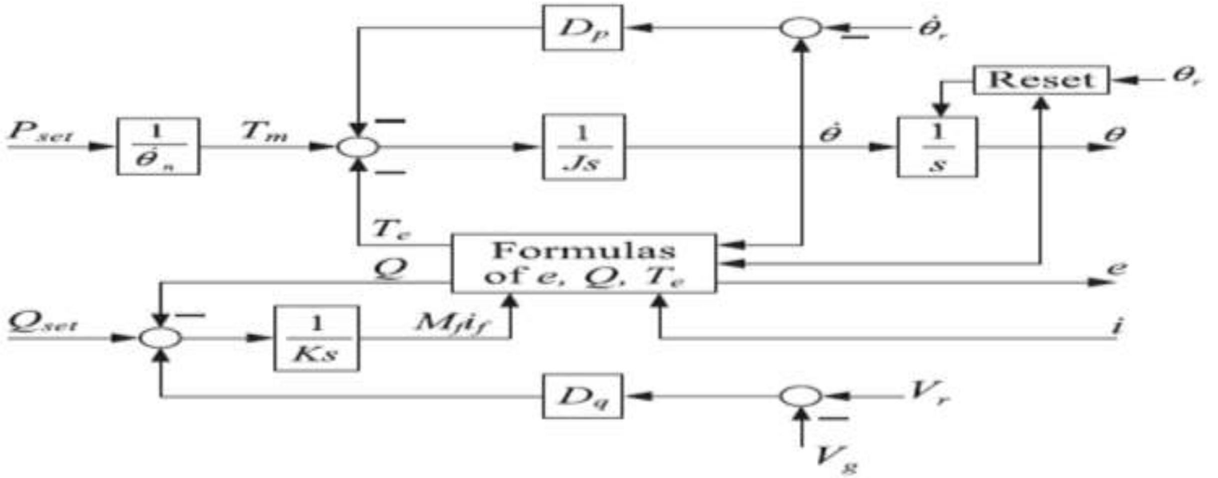

Fig. 3. Electronic part (controller) of a synchronverter, where the provision of the frequency reference θ˙r , the phase reference θr , and the voltage reference Vr , normally via a dedicated synchronization unit, is not shown

It is assumed that the dc bus of the synchronverter is constant. Otherwise, a dc-bus voltage controller, together with an energy storage system if needed, can be introduced to maintain the DC bus voltage constant, e.g., via regulating the reference of the real power for the synchronverter or regulating the power flow into and out of the energy storage system. The controller includes the mathematical model of a three-phase round-rotor synchronous machine described by

$$\ddot{\theta} = \frac{1}{J}(T_m - T_e - D_p\dot{\theta}) \qquad (1)$$

$$T_e = M_f i_f \left\langle i, \widetilde{\sin}\,\theta \right\rangle \qquad (2)$$

$$e = \dot{\theta} M_f i_f \widetilde{\sin}\,\theta \qquad (3)$$

$$Q = -\dot{\theta} M_f i_f \left\langle i, \widetilde{\cos}\,\theta \right\rangle \qquad (4)$$

where *Tm*, *Te* , *e*, *θ*, and *Q* are the mechanical torque applied to the rotor, the electromagnetic torque, the three-phase generated voltage, the rotor angle, and the reactive power, respectively. *J* is the imaginary moment of inertia of all the parts rotating with the rotor. *if* is the field excitation current and *Mf* is the maximum mutual inductance between the stator windings and the field winding. $\theta^{\cdot}$ is the virtual angular speed of the machine and also the frequency of the control signal *e* sent to the pulse width modulation (PWM) generator, and *i* is the stator current (vector) flowing out of the machine. _sin*θ* and _cos*θ* are defined as

$$\widetilde{\sin}\theta = \begin{bmatrix} \sin\theta \\ \sin\left(\theta - \frac{2\pi}{3}\right) \\ \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}, \quad \widetilde{\cos}\theta = \begin{bmatrix} \cos\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}$$

It is assumed that the number of pairs of poles for each phase is 1 and hence the mechanical speed of the machine is the same as the electrical speed of the electromagnetic field.

Similarly to the control of a synchronous generator, the controller of a synchronverter has two channels: one for the real power and the other for the reactive power. The real power is controlled by a frequency droop control loop, using the (imaginary) mechanical friction coefficient *Dp* as the feedback gain. This loop regulates the (imaginary) speed $\theta^{\cdot}$ of the synchronous machine and creates the phase angle *θ* for the control signal *e*. The reactive power is controlled by a voltage droop control loop, using the voltage droop coefficient Dq . This loop regulates the field excitation Mf if , which is proportional to the amplitude of the voltage generated. Hence, the frequency control, voltage control, real power control, and reactive power control are all integrated in one compact controller with only four parameters. For grid-connected applications, a synchronization unit is needed to provide the grid information for the synchronverter to synchronize with the grid before connection and for the synchronverter to deliver the desired real and reactive powers after connection.

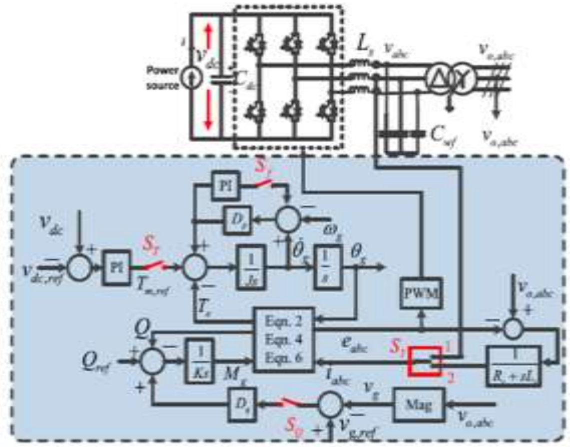

Fig. 4. Synchronverter (grid-side WECS VSC) including both the electrical and the electronic part.

IV. NUMERICAL ANALYSIS AND STABILITY TEST

In order to determine the stability of the interconnected system, an impedance-based stability method is adopted.The impedances of both the wind power inverter and the MMC-HVDC converter are analytically derived, and the analytical model is verified by comparing the frequency responses obtained from numerical simulation. The ac impedance model of synchronverter can be obtained from by dividing the phase voltage by current.

$$Z_{SYNC} = -\frac{\tilde{v}_a}{\tilde{i}_a}$$

Including the filter capacitor C_{fw} and transformer impedance, $Z_{T\ ,W\ \ ECS}$, the total impedance of Syncronverter is given by

$$Z_{TOTAL} = \frac{Z_{SYNC}}{1 + sC_{fw}Z_{SYNC}} + Z_{T,WECS}.$$

The impedance model derived analytical is verified by numerical simulation in MATLAB Simulink.Fast Fourier Transform (FFT) tool from SimPower System is used to analyze the different harmonic voltages and currents. The impedance is calculated by dividing the voltage by current at each frequency. The impedance characteristics of synchronverter alone is similar to the behavior of simple *RL* circuit. It has less cascaded control structure which reduces the interaction between controllers. Positive and negative sequence impedances are presented for *dq*-domain control.

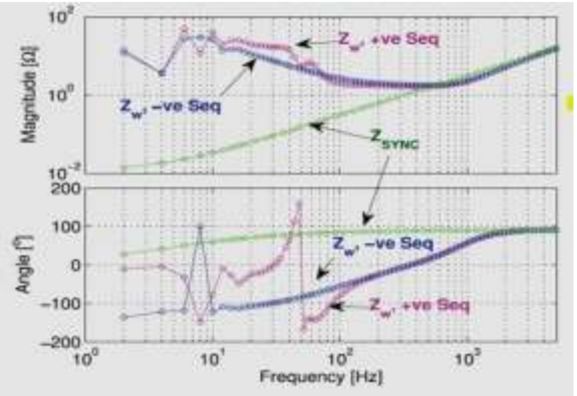

Fig. 5. Comparison of impedance frequency response. Synchronverter control mode and the dq-domain control mode with PLL obtained from numerical simulation.

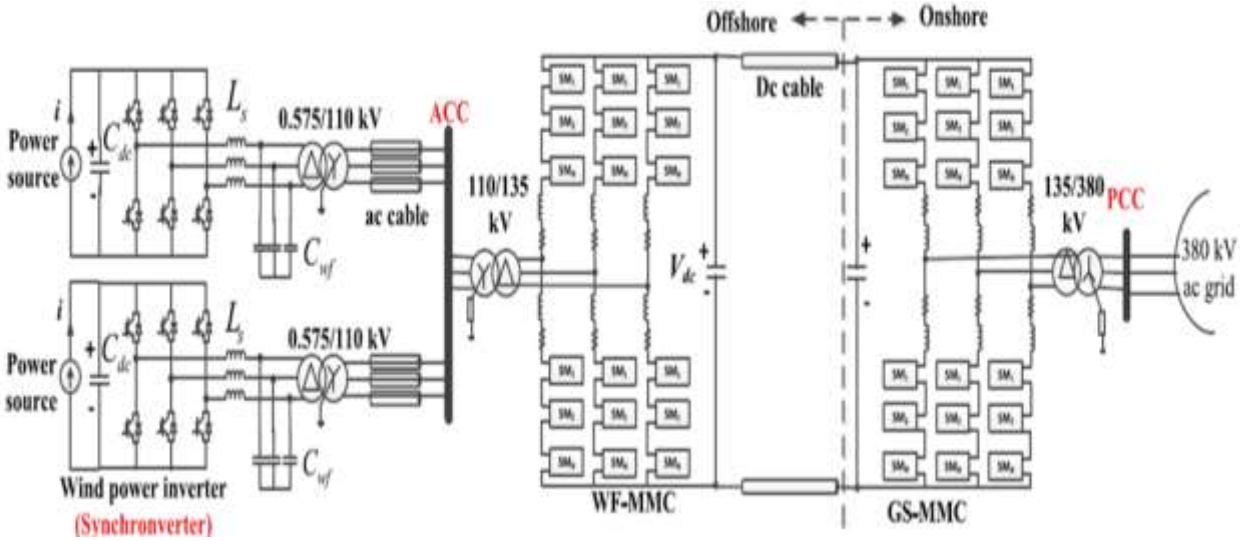

Fig. 6.Simplified model of the interconnected system of wind farm and the HVDC system

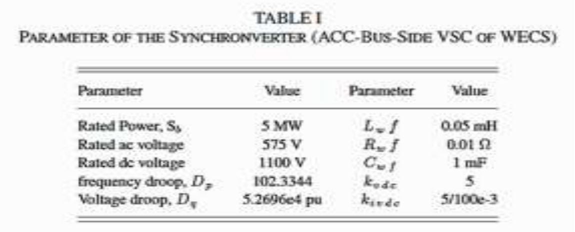

TABLE I
PARAMETER OF THE SYNCHRONVERTER (ACC-BUS-SIDE VSC OF WECS)

Parameter	Value	Parameter	Value
Rated Power, S_b	5 MW	$L_w f$	0.05 mH
Rated ac voltage	575 V	$R_w f$	0.01 Ω
Rated dc voltage	1100 V	$C_{w f}$	1 mF
frequency droop, D_p	102.3344	k_{vdc}	5
Voltage droop, D_q	5.2696e4 pu	k_{ivdc}	5/100e-3

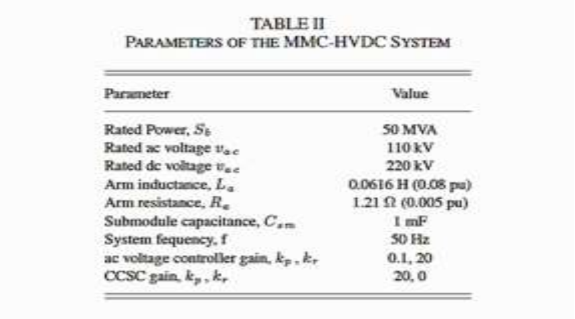

TABLE II
PARAMETERS OF THE MMC-HVDC SYSTEM

Parameter	Value
Rated Power, S_b	50 MVA
Rated ac voltage v_{ac}	110 kV
Rated dc voltage v_{ac}	220 kV
Arm inductance, L_a	0.0616 H (0.08 pu)
Arm resistance, R_a	1.21 Ω (0.005 pu)
Submodule capacitance, C_{sm}	1 mF
System fequency, f	50 Hz
ac voltage controller gain, k_p , k_r	0.1, 20
CCSC gain, k_p , k_r	20, 0

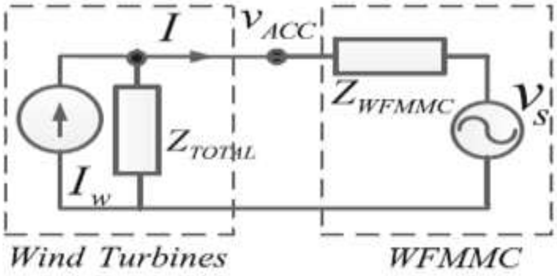

Fig. 7. Small-signal equivalent impedance model of the system

The stability of the interconnected system is found out by an impedance-based method in frequency domain is adopted. The system stability can be determined by checking whether the minor loop gain, [L(s)] satisfies the Nyquist stability criterion.

$$L(s) = Z_{WFMMC}(s)Z_{WP}^{-1}(s)$$

$$Z_{WP,i} = Z_{TOTAL} + Z_{ac,cable}$$

where i=1,2,3,... is the number of wind farms and Zac,cable is the ac cable impedance. The investigated system under this study has two wind farms, hence the total impedance can be given by

$$Z_{WP} = 1/\left(\frac{1}{Z_{WP1}} + \frac{1}{Z_{WP2}}\right)$$

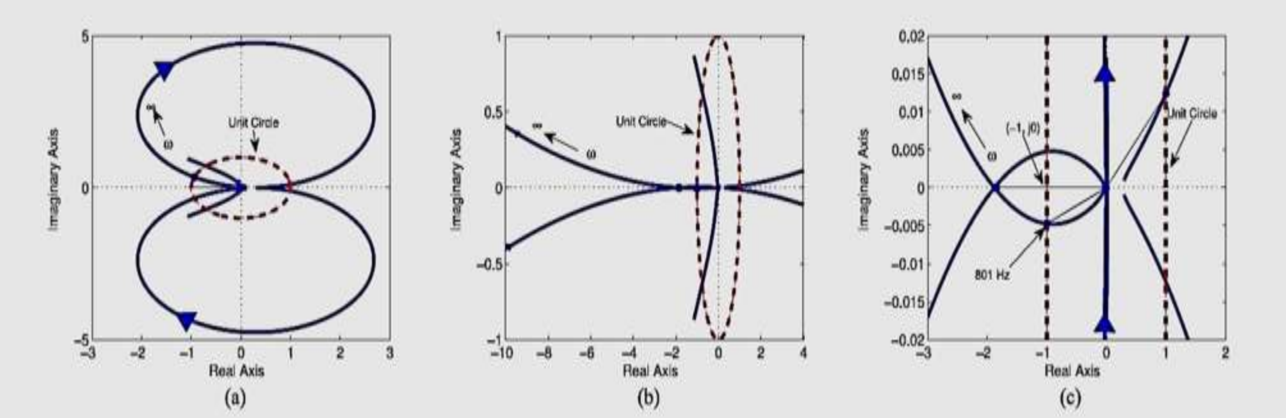

Fig. 8 (a) Nyquist plot of minor loop gain (impedance ratio). (b) Nyquist plot of minor loop gain for high value of wind power inverter inductor and (c) zoom view of (b) (blue line is minor loop gain and red line is unit circle).

Based on the parameter listed in Tables I and II, the impedance of the WFMMC and wind power inverter are calculated for full wind power output condition.The Nyquist plot of the minor-loop gain does not encircle the point (−1, j0), therefore the system will operate stably for this condition. By increasing this inductor we are reducing the power rating of the wind power inverter. However, the impedance is calculated for base power condition with 5 MW wind power output. The minor loop gain encircles the point (−1, j0), the interconnected system is predicted to be unstable. The crossing point at frequency around 801 Hz is the closest point to (−1, j0), the system can have an oscillation at this frequency. The variation of wind power does not have any impact on the stability of the system.

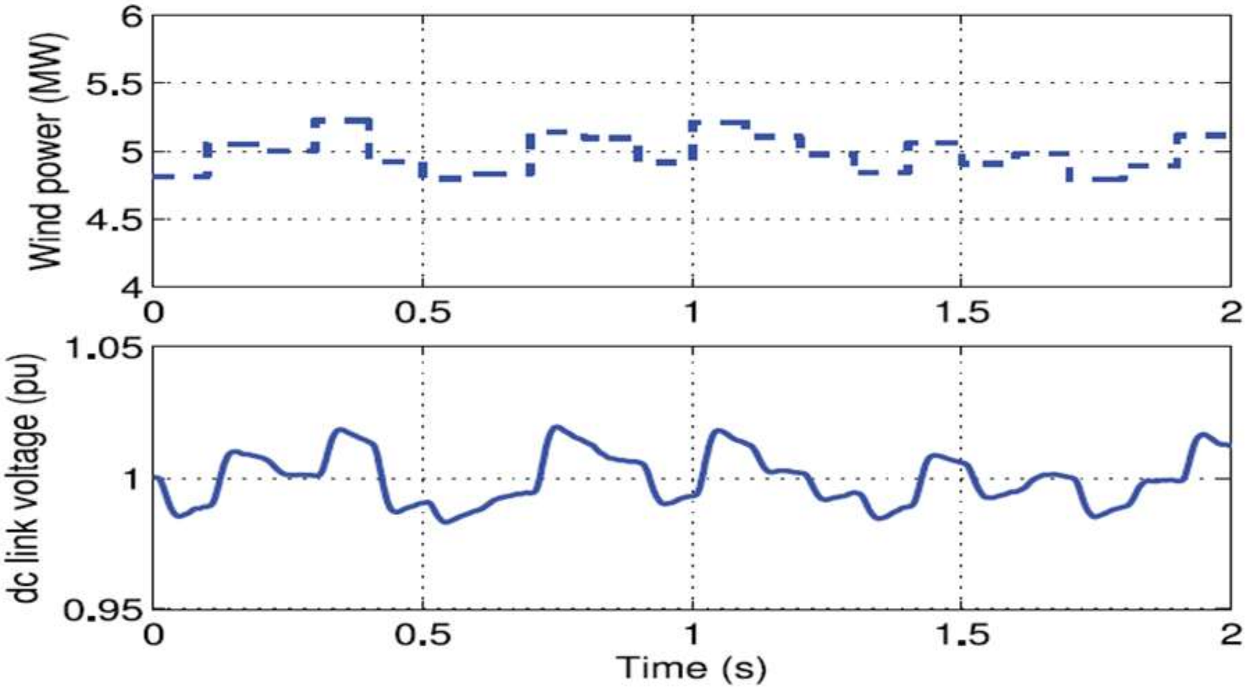

Fig. 8. Response of WECS DC link voltage with variable wind speed

V. CONCLUSION

The stability of the offshore wind power network connected through a HVDC transmission line is a critical problem since there is no direct connection to a strong ACC bus. To tackle this problem, this paper has proposed a WECS controller for such ACC bus based on the synchronverter concept. This controller minimizes the control interactions compared to decoupled dq frame, since the synchronverter control does not require a dedicated synchronization unit and it results in less cascaded control

Block. The impedances of both the wind power inverter and MMC-HVDC converter are analytically derived and analytical model is verified by comparing the frequency responses obtained from numerical simulation.

REFERENCES

[1] H. Liu and J. Sun, “Voltage stability and control of offshore wind farms with ac collection and HVDC transmission,” IEEE J. Emerg. Sel. Topics Power Electron., vol. 2, no. 4, pp. 1181–1189, Dec. 2014

[2] Mohammad Amin, Atle Rygg, and Marta Molinas, “Self-Synchronization of Wind Farm in an MMC-Based HVDC System: A Stability Investigation” IEEE Trans. Energy conv., vol. 32,no. 2, pp. 458-470, jan. 2017.

[3] Q.-C. Zhong, P.-L.Nguyen, Z. Ma, andW. Sheng, “Self-synchronized synchronverters: Inverters without a dedicated synchronization unit,” IEEE Trans. Power Electron., vol. 29, no. 2, pp. 617–630, Feb. 2014

[4] M. Amin and M. Molinas, “Understanding the origin of oscillatory phenomena observed between wind farms and HVDC systems,” IEEE J.Emerg. Sel. Topics Power Electron., vol. 5, no. 1, pp. 378–392, Apr. 2017

[5] J. Lyu, X. Cai, and M. Molinas, “Frequency domain stability analysis of MMC-based HVdc for wind farm integration,” IEEE J. Emerg. Sel. Topics Power Electron., vol. 4, no. 1, pp. 141–151, Mar. 2016

[6] M. Saeedifard and R. Iravani, “Dynamic performance of a modular multilevel back-to-back HVDC system,” IEEE Trans. Power Del., vol. 25, no. 4, pp. 2903–2912, Oct. 2010.

[7] Q.-C. Zhong and G. Weiss “Synchronverters: Inverters that mimic synchronous generators,” IEEE Trans. Ind. Electron., vol. 58, no. 4, pp. 1259–1267, Apr. 2011