

Self-synchronisation of Wind Farm in MMC-based HVDC System

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Abstract—The stability of an offshore wind power network connected through a high voltage dc (HVDC) transmission line is a critical problem since there is no direct connection to a strong ac collection (ACC) bus. Field experience has shown that sub-synchronous oscillation (SSO) and harmonic resonance can occur between the wind farms and the HVDC systems. The oscillations can appear in the presence of background harmonics and is arguably resulting from the controller interaction of the Wind Energy Conversion System (WECS) converter controller and the HVDC converter controller. The design of the synchronization unit (Phase-Locked-Loop) has shown to have a significant impact in achieving satisfactory performance. However, both slow and very fast synchronization units could directly affect the control performance and degrade the system stability. This paper proposes a controller design without a Phase-Locked-Loop (PLL) for the WECS grid-side converter which does not have a dedicated synchronization unit (PLL) in the controller. This controller is implemented on the WECS converters of the ACC side to synchronize them to the Modular Multi-level Converter (MMC)-based HVDC system. A detailed analysis is presented and the results are compared with the widely used decouple dq -frame control structure. The impedance frequency responses for both the dq -frame control and the synchronverter-based control are presented to show a comparison of the system performance. Time domain simulation results are presented to show how the self-synchronisation impacts on the system performance compared to the classical dq -frame control solution.

Index Terms—Synchronverter, HVDC, MMC, WECS, Offshore Grids Wind farm.

I. INTRODUCTION

The stability of offshore wind power network connected through HVDC transmission line is a critical problem [1], [2]. Field experience has shown that wind farms connected through HVDC system are suffering from sub-synchronous oscillation, harmonic resonance, and poor system performance, since there is no strong grid or rotating machine connected to the ac collection (ACC) bus [3]. The resonance caused by the long transmission cables [4], the passive filters [5], the transformers [6], and the series compensated capacitors [7] are investigated in existing literature. The possible causes of the oscillatory phenomena resulting from the interaction of the WECS converter controller and the HVDC system converter controller are investigated in [1]. Moreover, the WECS and the HVDC converter require dedicated synchronization unit, for example, a PLL which has significant impact on the system stability [8]- [9]. A slow synchronization unit could directly

affect the control performance and degrade the system stability but a complex synchronization unit, on the other hand, adds significant computational burden to the controller [10], [11].

This paper proposes a control technique for ACC bus side WECS Voltage Source Converter (VSC) which can synchronize with the grid without a PLL [12]. The interconnected system under this study includes a WECS employing full scale converter connected to main ac grid through MMC-based HVDC system. A type-IV full-scale back-to-back connected WECS is considered for this investigation. A self-synchronization control technique is implemented to ACC bus side WECS converter which does not require a PLL. This converter mimics synchronous generator (SG) and it can automatically synchronize itself before connecting and can track the ACC bus frequency after connection [12].

The investigated system is shown in Fig. 1. The wind farms are connected to the ACC bus through a offshore sea cable. The control architectures of the converters are as follows.

- The ACC bus side WECS VSC operates as a synchronverter. A compact control structure of power, voltage and frequency control will be implemented in this converter.
- The ACC bus side offshore MMC-HVDC converter is used to control the ac voltage. The ac grid side onshore MMC-HVDC converter regulates the dc link voltage and the reactive power. A circulating current suppression control (CCSC) is also implemented in the MMC HVDC converter.

A detailed analysis will be presented and the results will be compared with widely used decouple dq -frame control structure. Finally, the time domain simulation results are presented to show the effectiveness of the proposed control method.

II. WIND ENERGY CONVERSION SYSTEM MODELING AND CONTROL

A. System Configuration

The system depicted in Fig. 1 is an offshore wind farm which is connected to an ac grid through a MMC-based HVDC transmission system. The wind farm consists of the Wind Turbine Generators (WTGs) which are based on a two-level full power back-to-back converters. The wind power conversion system for each WTG is depicted in Fig. 2. The grid side VSC

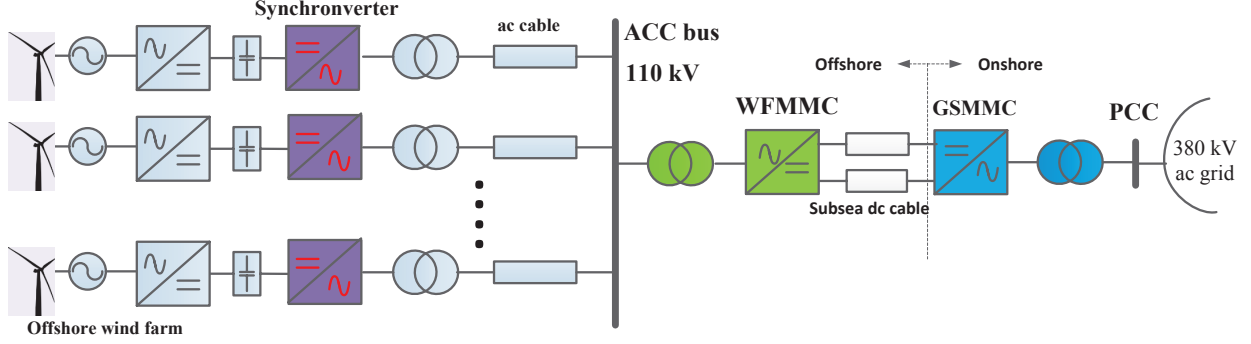


Fig. 1: Configuration of offshore wind farm integration via MMC-HVDC transmission system

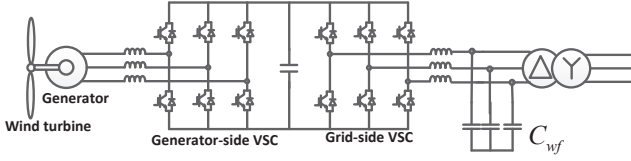


Fig. 2: Wind power conversion system for WTGs

of the WECS is decoupled with generator side VSC by the dc-link capacitor [1], therefore, the turbine mechanical system including the generator and the generator side VSC can be replaced by a power source. For simplification of analysis, an aggregated model of wind farm is assumed in which the wind farm is lumped into one unit of same generation capacity as the wind farm. The wind farm is connected to the ACC bus via a step-up transformer.

B. Synchronverter-based WECS Control

A control strategy based on synchronverter is adopted for the grid-side WECS VSCs. The synchronverter proposed in [13] is an inverter which regulations are chosen such that the inverter behaviour mimics the behaviour of conventional Synchronous Generator (SG). For the purpose of implementing the synchronverter control strategy, we recall the structure of an idealized three-phase round rotor SG [14]. The stator winding is assumed to be a concentrated coils having a self-inductance, L and a mutual-inductance, $-M$ with a typical value of $1/2L$. The field winding is assumed to be a concentrated coil having a self-inductance, L_f . The phase terminal voltage, $v_{abc} = [v_a \ v_b \ v_c]^T$ can be written as

$$v_{abc} = -R_s i_{abc} - L_s \frac{di_{abc}}{dt} + e_{abc} \quad (1)$$

where $i_{abc} = [i_a \ i_b \ i_c]^T$ is the stator phase currents vector; R_s and $L_s = L + M$ are the stator winding resistance and inductance, respectively and $e_{abc} = [e_a \ e_b \ e_c]^T$ is the back electromotive force (EMF) due to the rotor movement given by

$$e_{abc} = M_g \dot{\theta}_g \widetilde{\sin\theta}_g \quad (2)$$

where M_g is the flux field; θ_g is the rotor angle and

$$\widetilde{\sin\theta}_g = [\sin\theta_g \ \sin(\theta_g - \frac{2\pi}{3}) \ \sin(\theta_g + \frac{2\pi}{3})].$$

The mechanical part of the machine can be written by

$$J\ddot{\theta}_g = T_m - T_e - D_p\dot{\theta}_g \quad (3)$$

where J is the moments of inertia of all the parts rotating with rotor; T_m is mechanical torque; T_e is the electromagnetic torque and D_p is a damping factor. The electromagnetic torque, T_e can be found from the energy stored in the magnetic field of the machine and can be given by

$$T_e = M_g \langle i_{abc}, \widetilde{\sin\theta}_g \rangle \quad (4)$$

where $\langle \cdot, \cdot \rangle$ denotes the conventional inner product in \mathbb{R}^3 . The real and reactive power generated by the SG can be given by, respectively

$$P = M_g \dot{\theta}_g \langle i_{abc}, \widetilde{\sin\theta}_g \rangle \quad (5)$$

$$Q = M_g \dot{\theta}_g \langle i_{abc}, \widetilde{\cos\theta}_g \rangle. \quad (6)$$

The synchronverter concept is developed based on the SG model (1)-(6). The electrical circuit of the synchronverter (grid-side WECS VSC inverter) including the controller part is given in Fig. 3. The electrical circuit part can be called as power part which consists of the power switches, the LC filter and a step-up transformer. The lower part of the Fig. 3 can be called electronic part of the synchronverter which control the switches of the power part. Such a control structure is assumed to be equivalent to an SG with a capacitor bank connected in parallel with the stator terminal [13].

The voltage in (2) corresponds to the back EMF of the virtual rotor. The inverter switches are operated such that over a switching period, the converter outputs are to be equal to e_{abc} as given in (2) and it is achieved by PWM technique.

The swing equation for the synchronverter can be given by

$$\ddot{\theta}_g = \frac{1}{J}(T_m - T_e - D_p\dot{\theta}_g) \quad (7)$$

where the mechanical torque, T_m is a control input and the electrical torque, T_e depends on i_{abc} and θ_g according to (3).

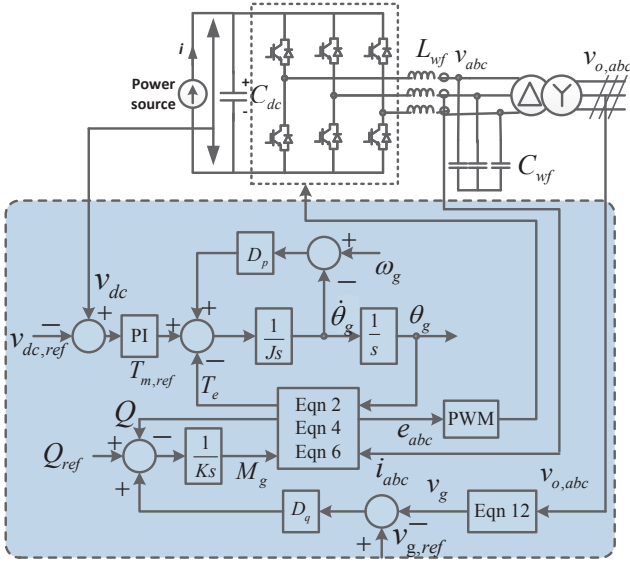


Fig. 3: Model of Synchronverter (Grid-side WECS VSC): Power part comprises a three phase inverter, LC filter and step-up transformer. Electronic part includes dc and ac voltage and reactive power control

To have similar behaviour as an SG, the following frequency droop control loop is proposed

$$T_m = T_{m,ref} + D_p(\omega_g - \dot{\theta}_g) \quad (8)$$

where $T_{m,ref}$ is the mechanical torque applied to the rotor. The grid-side WECS VSC converter controls the WECS dc-link voltage and the reactive power. The WECS dc-link voltage can be controlled by means of controlling the mechanical torque. The mechanical torque reference can be given by

$$T_{m,ref} = (k_{pvdc} + \frac{k_{ivdc}}{s})(v_{dc} - v_{dc,ref}) \quad (9)$$

where k_{pvdc} and k_{ivdc} are the proportional and integral gain of the dc voltage controller, respectively.

In order to regulate the field excitation, M_g , the reactive power is controlled by a voltage droop control-loop using voltage droop coefficient, D_q . The control of the reactive power is shown in the lower part of Fig. 3 where the inner loop is the ac voltage (amplitude) loop and the outer loop is the reactive power loop. The time constant, τ_v of the ac voltage loop can be estimated by $\tau_v \approx \frac{K}{\dot{\theta}_g D_q}$ as variation $\dot{\theta}_g$ is very small where K follows if τ_v and D_q have been chosen. The magnetic field excitation, M_g and the reactive power reference, $Q_{m,ref}$ can be given by

$$M_g = \frac{1}{K_s}(Q_{g,ref} - Q) \quad (10)$$

$$Q_{m,ref} = Q_{ref} + D_q(v_{g,ref} - v_g) \quad (11)$$

where v_g is the output voltage magnitude.

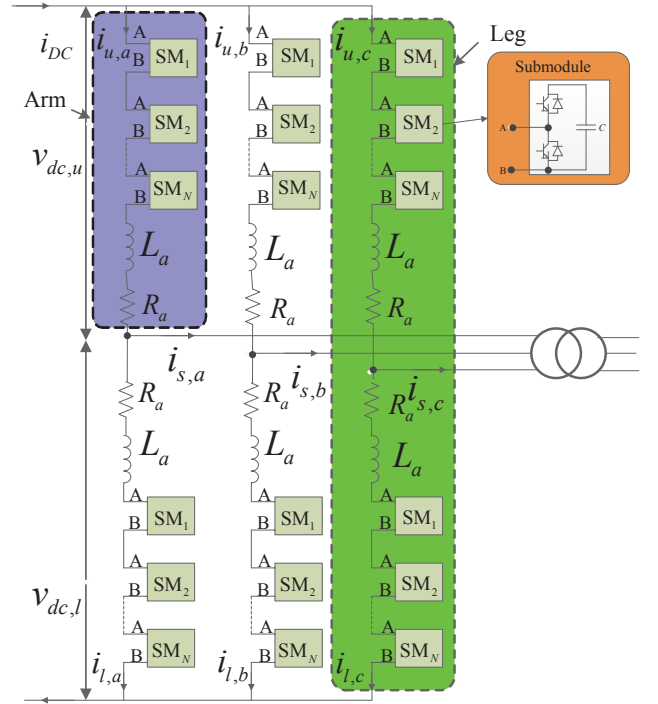


Fig. 4: Basic structure of MMC topology for MMC-HVDC system.

III. MMC-HVDC SYSTEM MODELING AND CONTROL

The MMC-based HVDC system comprises the converter transformers, the wind farm side offshore MMC (WFMMC), the subsea dc cable and the grid side onshore MMC (GSMMC). The point-to-point connection HVDC system installed in the purpose of integrating a wind farms must have the dc and ac voltage control objectives. The GSMMC converter regulates dc link voltage. Assuming the dc voltage controller performance is satisfactory and providing a constant dc voltage at the WFMMC converter dc side, therefore for simplification of analysis, it is reasonable to use a constant dc voltage source instead of the GSMMC-HVDC converter.

A basic structure of a MMC topology for MMC-based HVDC system is depicted in Fig. 4. Each phase leg of the MMC consists of one upper and one lower arm i.e., an upper arm represented by subscript u and a lower arm represented by l , connected in series with the dc-terminal. Each arm has N number of identical submodules (SMs) and a series connected arm inductor, L_a and also its equivalent resistor, R_a to represent the losses within the arm. The arm inductors suppress the high frequency components from $i_{u,abc}$ and $i_{l,abc}$. The SMs provide two different voltage level at its terminal depending on the stage of the complementary switches. A sorting algorithm is adopted to balance and maintain the SM capacitor voltages at v_{dc}/N .

An ac voltage controller is adopted in the WFMMC to provide an ac voltage source for the wind farm. The controller is implemented in dq -reference frame as shown in Fig. 5

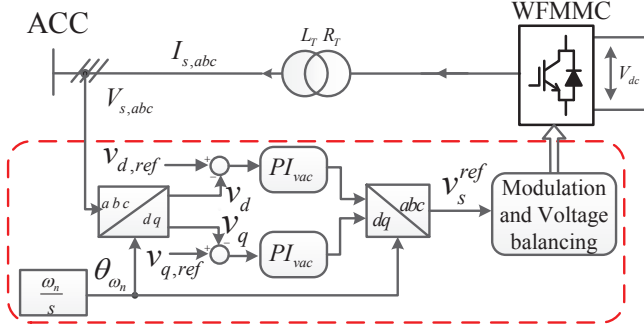


Fig. 5: Control of WFMMC: ac voltage control.

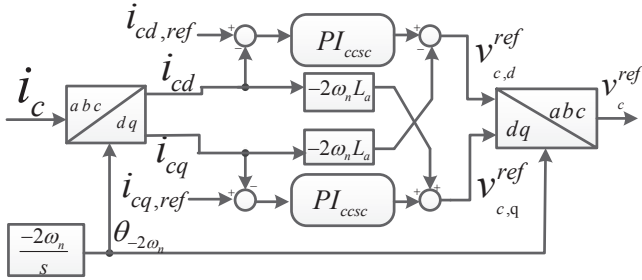


Fig. 6: Implemented circulating current suppression controller

and a PI controller is used to achieve the zero steady state error for sinusoidal quantities. The transformation angle, θ_{ω_n} for abc to dq transformation is obtained from the system fundamental frequency as $\theta_{\omega_n} = \int^t \omega_n dt$. The modulation voltage reference in the stationary abc -frame can be given by

$$v_s^{ref} = \begin{pmatrix} \sin \theta_{\omega_n} & \cos \theta_{\omega_n} \\ \sin(\theta_{\omega_n} - \frac{2\pi}{3}) & \cos(\theta_{\omega_n} - \frac{2\pi}{3}) \\ \sin(\theta_{\omega_n} + \frac{2\pi}{3}) & \cos(\theta_{\omega_n} + \frac{2\pi}{3}) \end{pmatrix} \begin{pmatrix} (v_{d,ref} - v_d)H_v \\ (v_{q,ref} - v_q)H_v \end{pmatrix} \quad (12)$$

where $v_{d,ref} = 1$ in pu and $v_{q,ref} = 0$ are the reference ac voltage in dq -frame, respectively and H_v is the PI controller transfer function as

$$H_v = k_{p,vac} + \frac{k_{i,vac}}{s} \quad (13)$$

where $k_{p,vac}$ and $k_{i,vac}$ are the proportional and integral gain of the ac voltage controller, respectively. A circulating current suppression controller as shown in Fig. 6 is implemented to limit the circulating current through switch [15]- [16].

IV. RESULT AND ANALYSIS OF THE INTERCONNECTED SYSTEM

The simplified configuration of the interconnected system is presented in Fig. 7. It has two wind farms which are connected to the ac collection bus through a 0.575/110 kV transformer. Each wind farm is assumed to have 5 turbines with 1 MW rating each. To simplify the system model, 5 turbines are lumped into one unit of 5 MW generation capacity. The generator side VSC is supplying the full power to the ACC

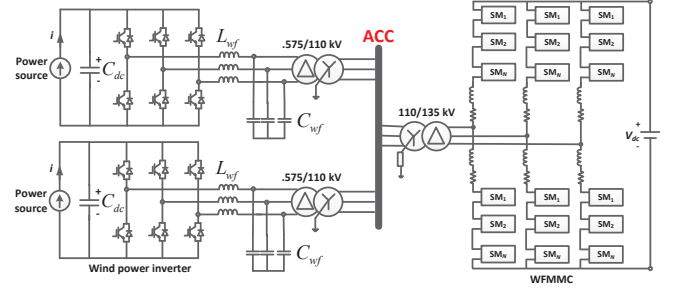


Fig. 7: Simplified configuration of interconnected system.

TABLE I: Parameter of synchronverter

Parameter	Value	Parameter	Value
Rated Power, S_b	5 MW	L_{wf}	0.05 H
Rated ac voltage	575 V	R_{wf}	0.01 Ω
Rated dc voltage	1100 V	C_{wf}	1 mF
Trans. inductance	0.04 pu	f	50 Hz
Trans. resistance	0.005 pu	C_{dc}	30 mF
frequency drop, D_p	102.3344	k_{vdc}	5
Voltage drop, D_q	5.2696e4 pu	k_{ivdc}	5/100e-3

bus through the grid side WECS VSC and it is necessary to regulate the dc link voltage of the WECS. The control topology of the synchronverter is implemented in the grid side WECS VSC. It, mimics the SG, regulates the dc-link voltage of the WECS and the reactive power. In addition, it has a frequency droop as like as the conventional SG. The parameters of the WECS is given in Table I. The simulation Model is implemented with detail switching model of the MMC with 24 SMs per leg and the VSC in the MATLAB/Simulink environment associated with the SimPowerSystem Blockset. The simulation results are presented to show the performance of the control in the interconnected system.

A. Control Tuning of the Synchronverter

One of the main advantages of the synchronverter is the controller tuning. The structure of the classical generators for which controls are well-known can be adopted with the synchronverter. Initially, the frequency droop coefficient, D_p is chosen such that a frequency drop of 0.5% causes the torque to increase by 100% from its nominal value and the voltage droop coefficient, D_q is chosen such that a drop of 5% voltage causes the reactive power to increase by 100%. However, these values could not be the optimized parameter and could not directly apply in the synchronverter based WECS. A specific tuning method based on the eigenvalue and participation factor analysis of the individual states is presented in [17]. The optimized parameters used in this work are $D_p = 102$ and $D_q = 52696$. The time response for the frequency droop and the voltage droop are kept 1 ms and 80 ms, respectively. The voltage controller proportional gain is set to 5 and the response time is 100 ms.

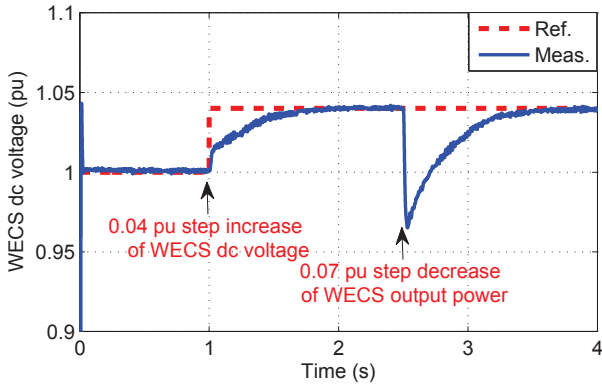


Fig. 8: The dc link voltage of Synchronverter based WECS.

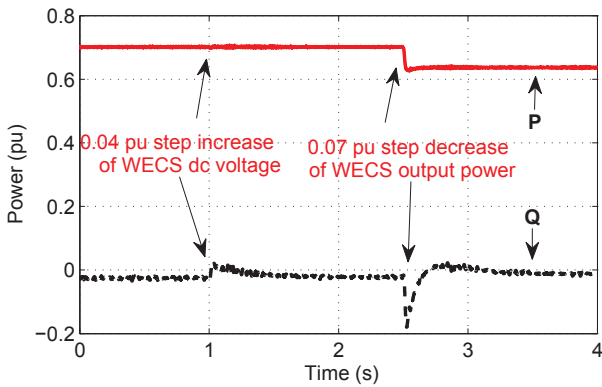


Fig. 9: The active and reactive power output at ACC bus.

B. Time Domain Simulation

A time domain simulation is carried out and the resulting time domain responses are presented in Fig. 8 and 9. Two transient events are introduced to show the performance of the control designed for the Synchronverter based WECS. At 1 s, a step increase of 0.04 pu dc voltage reference of Synchronverter based WECS is applied and at 2.5 s, a step reduction of 0.07 pu active power has been applied. The dc link voltage of the WECS is shown in Fig. 8. The performance of the dc voltage controller is satisfactory, it can follow the reference. When the dc voltage reference is step-up 0.04 pu at 1 s, the voltage controller can track the reference, the delay to follow the reference depends on the dc voltage PI controller time response. The output power step reduction is applied at 2.5 s which reduces the WECS dc link current and follows the dc voltage reduction; however the synchronverter dc voltage control function recovers the dc voltage and follows the reference value in steady-state. The active and reactive power of the wind farm are shown in Fig. 9. The wind farm active power output is constant and doesn't have any oscillatory component. The reactive power has good response during transient events, since the ac voltage of ACC bus is supported by the Synchronverter by means of controlling the reactive power.

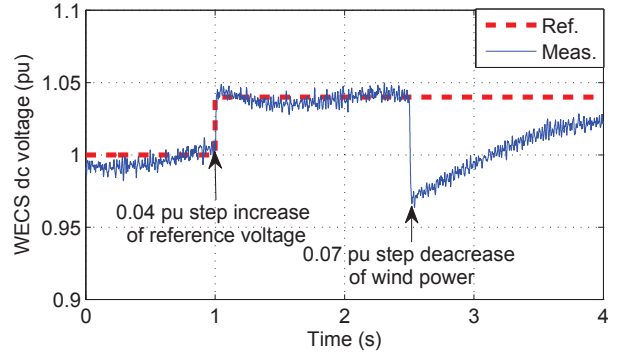


Fig. 10: The dc link voltage of dq control WECS.

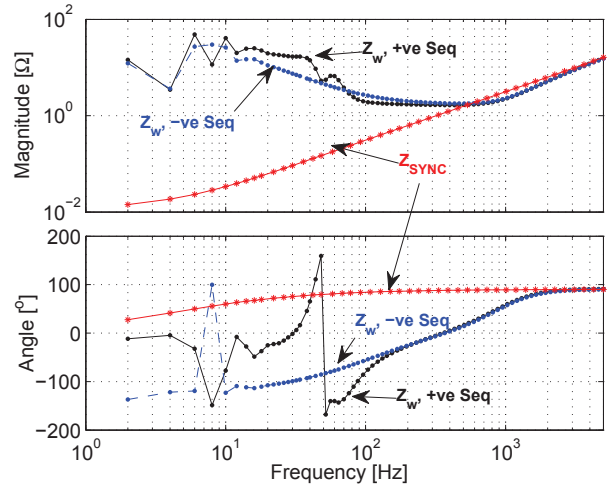


Fig. 11: Comparison of Impedance frequency response between Synchronverter control mode and dq -domain control mode with PLL obtained from numerical simulation.

The dq -frame control is also implemented on the ACC bus side WECS VSC to have a view of comparison in performance with the synchronverter control technique. The inner loop current control is assumed and in the outer loop a dc voltage control is implemented. The current controller is tuned based on the modulus optimum tuning criteria and the dc voltage controller proportional and integral gain are set to 5 and $5/100e-3$. The detailed control structure in dq -frame is not further discussed since it is available in literature [2]. The resulting time domain responses are shown in Fig. 10. The results clearly show that the synchronverter based control has better performance in integrating offshore wind farm through MMC-based HVDC system.

As can be seen in Fig. 8 and 9, both the dc voltage of the WECS and the power do not have any oscillatory behavior during the step transient. In order to understand the behavior, the impedance frequency responses of the WECS VSC in synchronverter control mode and the dq -frame control mode are presented. A control structure of the wind power inverter in the dq -frame including a PLL is discussed in [1], [2] and

the impedance frequency response of this type converter in wind power inverter application is presented in [1]. Fig. 11 shows the comparison of the impedance frequency responses between the synchronverter control mode and the PLL based synchronization in dq -domain control mode. Both positive and negative sequence impedance are presented for the dq -domain control. In the case of synchronverter, the positive and negative sequence impedance are equal. As can be seen from the impedance in Fig. 11, the impedance characteristics of the synchronverter is similar to the behavior of a simple RL circuit. It is due to having similar control structure as an SG. In comparison with the decouple dq -frame control structure, it has less cascaded control structure which simplifies the control interaction and the impedance behavior becomes first order equation which is similar to a RL circuit instead of being higher order equation caused by the cascaded inner-loop current controller, the outer-loop controller and the PLL in dq -frame control. As can be seen at frequency higher than 2 kHz, the impedance of the dq -frame control mode is inductive; however, below 2 kHz the impedance is a kind of composite which consists of different resonance points. In addition, the impedance magnitude is significantly higher than the synchronverter control mode. The disadvantage of having different resonance point in the dq -frame impedance characteristics prone to oscillatory behavior and the high impedance could result a voltage instability problem.

V. CONCLUSION

The stability of the offshore wind power network connected through a HVDC transmission line can be challenging since a strong ac collection bus might not be available, when there is no rotating machine connected in that bus. To tackle this problem, this paper has proposed a WECS controller for such an ACC bus based on the synchronverter concept. A synchronverter -an inverter that mimics the synchronization mechanism inherent to SG- is adopted in the grid side of WECS VSC where the wind farms are connected to the ac network through MMC-based HVDC system. The design of the synchronverter, based on the well known structure of the classical SGs, is embedded in the VSC controller to mimic the way SG synchronize. The control strategy supports the ACC bus voltage that helps to achieve the stable system. The observed results show that this controller minimizes the control interactions compared to the decoupled dq - frame, since the synchronverter control does not require a dedicated synchronization unit (PLL) and it results in less cascaded control blocks. The detailed analysis and the results presented and compared with the decoupled dq control structure show the benefits of this controller and its potential for the stability. The results highlights the synchronverter's ability in keeping better performance in point of stability and control in integrating the offshore wind farm through MMC-based HVDC system. Further work will be dedicated to a rigorous comparison of the stability properties of this controller through the eigenvalue and the impedance-based stability tool.

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