A MODULAR MFT CONVERTER BASED WIND ENERGY CONVERSION SYSTEM USING FUZZY LOGIC CONTROLLER USED FOR OFFSHORE WIND FARM

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Abstract—**Offshore wind farms have very low global warming potential per unit of electricity generated, comparable to that of onshore wind farms. Offshore installations also have the advantage of limited impact of noise and on the landscape compared to land-based projects. Offshore wind power development using modular converters has great advantage. The complexity and bulkiness of the entire system, in using medium voltage applications can be reduced by interconnecting these structures. The configuration presented mainly consists of a permanent magnet synchronous generator connected to a passive rectifier, a medium frequency transformer based modular converter, then to grid via a svpwm controlled current source converter. The paper mainly concentrates on medium frequency transformer based dc-dc converter - the evenly distribution of power and voltage among the cascaded structure and also decoupling between power/voltage balancing of the modular converter. Finally, the results were evaluated by simulation in Matlab**.

Keywords— ***Current source converter, permanent magnet synchronous generator, wind energy conversion system, medium-frequency transformer, cascaded DC-DC converter***

I. INTRODUCTION

Wind power is making the great progress in many countries as a good renewable energy resource. Since wind is free and clean, it can be considered as a better replacement of conventional fuel sources. In onshore applications large land area will be required for mega scale generation. Also wind turbulence and large size of the turbines required are other concerning issues. Besides, offshore wind resources has advantages that land area is not concerned and also steady and less turbulent wind source is available with mere environmental effects/issues. Moreover, emerge of wind farms can bring great economic development which attracts both investments and jobs [1].

In wind energy conversion system, the generator and power converter are the main two electrical components. Different designs and combination of these two components lead to a wide variety of Wind energy conversion system (WECS) configurations. The wind generators can be classified into fixed speed and variable speed generators. In fixed speed wind generators like SCIG, a power converter interface is not necessary since its rotational speed depends on frequency of grid and poles in stator. But in variable speed generators like PMSG the output speed of the generator can be controlled according to the wind speed by adjusting the duty cycle of the power converter. With a fully rated power converter in between the generator and grid, the generator can be fully decoupled from the grid side. Since the power generated in offshore is to be transmitted to onshore, a long distance transmission is required. Hence HVAC transmission is avoided due to the need of reactive power compensation at both ends, so HVDC transmission is employed. Also due to medium voltage power generation, wind farms will be connected in series, thereby costly and bulky offshore substation can be avoided. The grid side converters can be voltage source converters or current source converters. In earlier literature VSC based WECS dominates the offshore wind farm applications. A back to back neutral point clamped VSC with induction generator is discussed in [2]. The multilevel converters and their current trends in industrial applications is studied in [3]. Later a four level diode clamped inverter for decoupled active and reactive power control is proposed in [4]. A nine level active NPC [5], and a matrix based converter [6] is studied later. Since the power flow from generator to grid is unidirectional a low cost passive rectifier topology for PMSG wind turbines is discussed in [7]. Later on literatures featured the advantages of current source converters. They have simple converter topologies, grid/load friendly waveforms, reliable short circuit protection and limited dynamic performance. CSC are more suitable for medium voltage applications [8].

The present work mainly focuses on CSC based wind farms. The reactive power and harmonic compensation schemes with passive, active and hybrid methods for PMSG based wind farms was discussed in [9]. A current source inverter topology for multi megawatt wind turbines is studied in [10]. It proposes a new methodology for harmonic reduction. Ref. [11] also focuses on reactive power compensation. Different trends in wind power technology for grid interface is described in [12]. Multiple wind turbine interfacing is established in [13], where the wind turbine modules are connected in parallel and an onshore CSI is used to deliver full power from wind farm to grid. A main challenge is the power rating of CSI to withstand the full power of wind farm. A PWM current source converter based WECS [14] was proposed where a CSC is employed as a

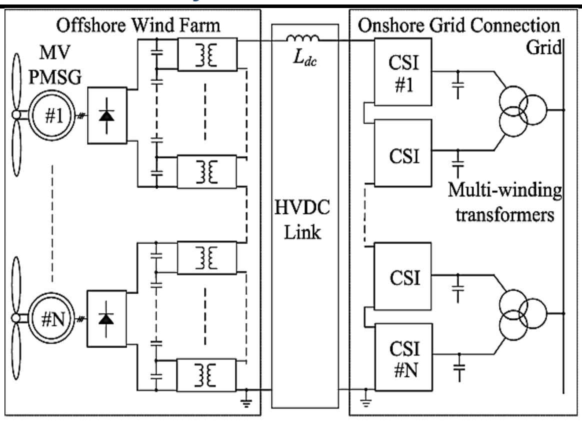

Figure 1. Offshore wind farm structure [16]

bridge between the generator and the grid for high power WECS. Based on this a series connected offshore structure, where PWM CSCs are cascaded at both generator and grid side was proposed [15]. Using this configuration bulky and costly offshore substation can be avoided. But need of a low frequency and high power rating transformer for generator insulation increases the burden on offshore construction.

In this paper, a medium frequency transformer base WECS is proposed which is connected to the grid through series packed CSIs (Fig. 1). The configuration consists of a wind turbine connected to a MV PMSG , a diode bridge rectifier, a MFT based modular dc dc converter and onshore CSI which is connected to grid through a multi winding transformer. The two major issues of an offshore wind farm is the bulky and costly offshore substation and bulky and heavy low frequency transformer. Both the problems are eliminated in this work by choosing series connected wind farm configuration and using medium frequency transformer instead of the low frequency one. Also the current work concentrates to ensure evenly distributed power and voltage among the constituent modules.

II. Proposed WECS Configuration

The proposed configuration is shown in Fig. 1. But the present work concentrates on a single MV PMSG based WECS from the whole series connected wind farm configuration as shown in Fig. 2. It consists of a permanent magnet synchronous generator, a diode bridge rectifier, a capacitor filter and cascaded converters connected to onshore CSI through an HVDC link. Filter capacitors are connected at output to assist current commutation and to filter out the switching harmonics. At the grid side a step up transformer is employed to provide isolation and grid integration. N number of cascaded converters are there in the structure. Fig. 3 illustrates it in detail. They are voltage fed current output converters. For each module there should be an input capacitor and at the output side they are directly connected to dc link without a capacitor filter.

In offshore configuration, wind generator is placed far away from the grounding point. So it should withstand full transmission voltage. In earlier cases, where a transformer based solution is chosen to alleviate the problem, a high power (same as that of PMSG) and low frequency three phase transformer is employed.

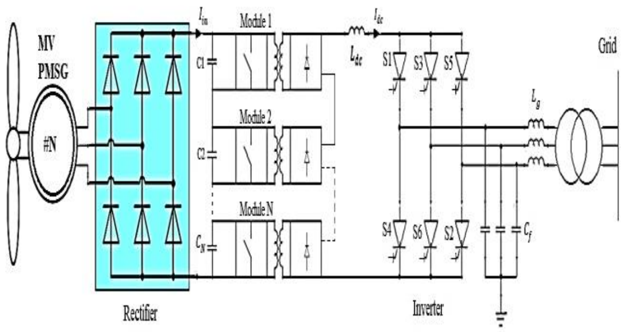

Figure 2. Proposed MV PMSG based WECS. [16]

But its bulkiness increases the size of offshore substation [17]. In this paper a medium voltage frequency based solution is proposed. It has high power density and smaller in size which is an advantage in offshore applications. Since only unidirectional power flow is required, diode bridge rectifiers are preferred at the secondary side of MFT. They can provide high voltage insulation for the system. All these components are similarly rated, but the insulation level varies.

III. Analysis of MFT Based Modular dc-dc Converter

A MFT based modular dc-dc converter is a power electronics device which is used to control the transfer of energy. It performs two important roles in the system, first it is used to achieve the MPPT control by adjusting the duty ratio of the module and second for generator side insulation. Further, since it is a modular design a number of cells are connected series at input and output. Instead of using a single MFT of large power rating, the design helps to reduce the burden of implementation as one transformer accounts for only a part of the megawatt power.

A. Medium Frequency Transformer

In applications like offshore wind farms, where size of the structure has a great concern, the need of a compact system is always appreciable. Frequent checking is also not feasible in such cases. So reliability of a low frequency technology is always questionable. Here comes the need of more advantageous medium frequency transformer, whose application mainly lies in the reduction of volume, material and weight. The modular dc-dc converter used here employs a medium frequency based conversion; a voltage fed current output full bridge converter. The main roles of the MFT are to realize zero voltage switching of the primary switches through its leakage inductance and then to perform the isolation.

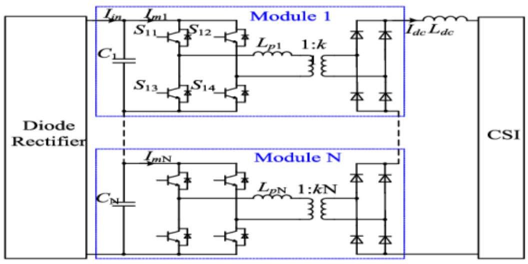

Figure 3. Modular dc dc converter configuration. [16]

B. Operation Principle of the Converter

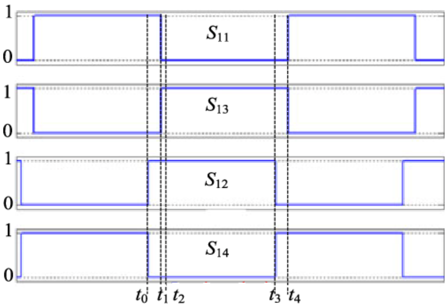

Fig. 4. Steady State waveform of Module 1.

The advantage of using modular design is that the drive signals for switches S_{11}, S_{12}, S_{13} and S_{14} are same for all modules. So here one module is considered for explaining the operation principle. A duty cycle of 0.5 is fixed and the phase of switches in second leg is shifted to transfer power. The switching pulses are shown in Fig. 4 and the circuit to describe operation principle in Fig. 5. Before t_0, S_{11} and S_{14} are on, so D_{11} and D_{14} and power is transferred to load. At t_0, S_{14} is turn off and transformer primary current commutates from S_{14} to parallel diode of S_{12}, thus aiding the zero voltage switching (ZVS) of the device. During this period primary and secondary current of the transformer decreases. But dc link current is still maintained by CSI, therefore D_{12} and D_{13} and turns on along with D_{11} and D_{14}. So no power is transferred to load during $t_0 < t < t_1$. At t_1, S_{11} is turn off and S_{13} is turn on with ZVS. During the period $t_1 < t < t_2$ all diodes are on and no power get transferred to load. At time t_2 D_{11} and D_{14} turn off and power get transferred to load during $t_2 < t < t_3$. At t_3 S_{12} turn off and S_{14} turn on with ZVS and the same operation as in $t_0 < t < t_1$ occurs and the process repeats.

C. Input Capacitor Voltages Sharing in the Modular Converter

The constituent modules of the modular converter (see Fig.3) are designed to be identical. Given existing manufacturing techniques, however, the components used may not display exactly same characteristics. For example, the turn ratios of MFTs may be slightly mismatched with 1: k1 ≠ 1: k2 ≠ ... 1:k5 (see Fig. 3). As a result, the operation of the cascaded converter is destabilized if a common duty ratio alone is employed [17].The module with the lowest turn ratio has the highest input capacitor voltage and constitutes the largest proportion of total power. Therefore, input capacitor voltages must be shared among the constituent modules. This aspect is thoroughly discussed in the next section.

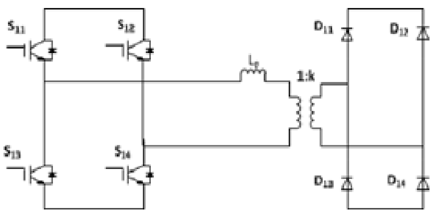

Figure 5. Circuit diagram of single module

IV. Control Scheme of Proposed WECS

The main control requirements in wind energy conversion system are MPPT, input voltage sharing among modular converters, minimum dc link current control and grid side re-active power control. Two converters are used in the proposed system. The MPPT control and input side voltage sharing is achieved by the generator side converter i.e. the modular dc-dc converter. The dc link current and reactive power control are regulated by the grid side converter i.e. the current source inverter. The whole control scheme is shown in Fig. 6.

A. Generator Side Control Scheme

The main two control objectives of the generator side are: to extract maximum power from the wind turbine that is to obtain MPPT and to optimize generator operation by ensuring equal voltage sharing among the modules. Optimal tip speed ratio control is applied to achieve MPPT. Considering all the h bridge converters are identical, they are simplified into a simple buck converter with duty ratio d_{common}. From the measured wind speed generator speed reference is determined according to

$$\boldsymbol{\lambda} = \frac{\omega_{ref}}{Vw} * \boldsymbol{R} \tag{1}$$

Where λ is the optimal tip speed ratio, R is the radius of the blade, and V_w is the wind speed. The PI controller output gives the Torque reference of the generator. P and φ are the pole pairs and flux of the generator. Then $Idc_{generator}$ is calculated and then d_{common} is determined by comparing $Idc_{generator}$ with dc link current. By applying d_{common} MPPT can be achieved.

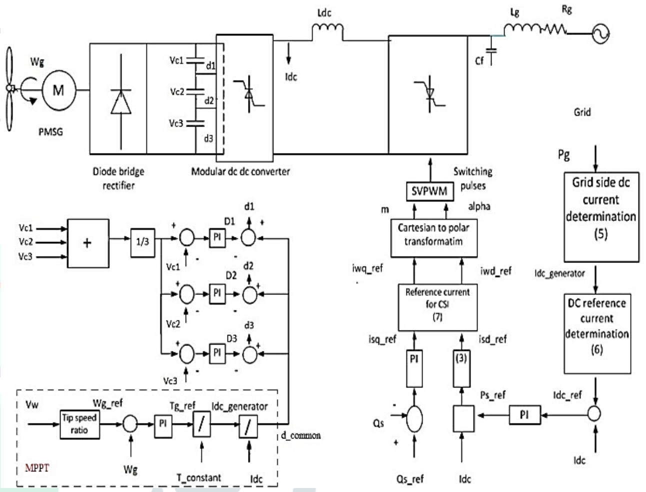

Figure 6. Overall control scheme of the system.

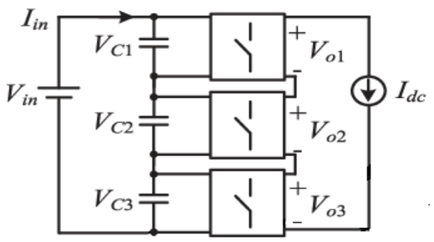

Fig. 7. Equivalent circuit of the MFT-based cascaded dc–dc converter.

The dc-link current is controlled by the CSI. Therefore, the equivalent circuit of the MFT-based cascaded dc–dc converter is derived shown in Fig. 7, where input voltage V_{in} is the output voltage of the rectifier. I_{in} is the input current of the MFT-based cascaded dc–dc converter the dc-link current; I_{dc} is represented by a constant current source. In this study, V_{in} and I_{dc} are variable according to different wind speeds and constant at a given speed.

The MFT-based converter is connected in series at the input and the output. Such converters share input and output currents I_{in} and I_{dc}, respectively. Through power conservation, the following is obtained

$$P_{in1} = V_{c1} I_{in} = V_{01} I_{dc} = P_{01}$$
$$\vdots$$

$$P_{in3} = V_{c3} I_{in} = V_{03} I_{dc} = P_{03} \tag{2}$$

where V_{C1}, V_{C2} and V_{C3} , and V_{o1}, V_{o2} and V_{o3} are the equilibrium values of the input and output voltages of the constituent modules, respectively. P_{in1}, P_{in2} and P_{in3}, and P_{o1}, P_{o2} and P_{o3} are the input and output power of each module, respectively. Assuming that the input capacitor voltage is balanced

$$V_{c1} = V_{c2} = V_{c3} = \frac{V_{in}}{3} \tag{3}$$

Then, output voltage is automatically achieved. Furthermore, total power can be distributed evenly among all the modules. Therefore, we need only focus on input capacitor voltage sharing to achieve both input/output voltages and power sharing in the MFT-based cascaded dc–dc converter.

The input and output of the constituent modules can be written as:

$$V_{01} = f(d_1) * V_{c1}$$

$$\vdots$$

$$V_{03} = f(d_3) * V_{c3} \tag{4}$$

Where d_1, d_2 and d_3 are the duty cycles of the modules. To achieve capacitor voltage sharing among the modules, the duty cycles should be adjusted according to (4). Thus Δ_{d1}, Δ_{d2} and Δ_{d3} arises from the input voltage balancing.

Thus the applied duty cycles is composed of two parts, d_{common} to achieve MPPT and Δ_d to achieve voltage sharing.

B. *Grid Side Control Scheme*

The main control objectives of the grid side current source inverter are to regulate the dc link current and to control the reactive power output to the grid. The control scheme uses a phase locked loop to obtain the grid synchronous angle θ_g and grid angular frequency ω_g. The whole control scheme is shown in Fig.6. The controller contains two independent control loops to control real and reactive power independently. The real power P_s and reactive power Q_s is given as

$$P_S = 1.5 V_{sd} i_{sd} \tag{5}$$

$$Q_S = -1.5 V_{sd} i_{sq} \tag{6}$$

where V_{sd}, V_{sq}, i_{sd} and i_{sq} are the d- and q-axis components of the grid side voltage and current.

The reference current of the CSI i_{wd_ref} and i_{wq_ref} can be derived with the following [8], [14]:

$$\begin{aligned} i_{wd\_ref} &= i_{sd\_ref} + i_{cd} = i_{sd\_ref} - w_g C_f V_{cq} \\ i_{wq\_ref} &= i_{sq\_ref} + i_{cq} = i_{sq\_ref} + w_g C_f V_{cd} \end{aligned} \tag{7}$$

i_{cd}, i_{cq} and V_{cd}, V_{cq} are d-axis and q-axis components of the capacitor current and the voltage; these variables can be expressed as follows:

$$\begin{aligned} V_{cd} &= R_g i_{sd} + V_{sd} - w_g L_g i_{sq} \\ V_{cq} &= R_g i_{sq} + w_g L_g i_{sd} \end{aligned} \tag{8}$$

where L_g and R_g represent the grid-side line inductance and resistance, respectively.

Without loss consideration of the converter, the captured wind power is equal to the grid-injected power

$$P_s = P_g \tag{9}$$

With considering the maximum modulation index as $m_i = 1$ [8], [18], the minimum dc-link current $I_{dc\ grid}$ determined by the grid-side CSI can be derived based on (5)–(9):

$$\boldsymbol{i_{dc_{grid}}} = \left\{ \begin{array}{l} \left[\left(\mathbf{1} - \boldsymbol{w_g\, 2L_g C_f}\right)\left(\frac{\mathbf{2}\ \boldsymbol{P_g}}{\mathbf{3}\ \boldsymbol{V_{sd}}}\right) - \boldsymbol{w_g R_g C_f}\left(\frac{\mathbf{2}}{\mathbf{3}}\frac{\boldsymbol{Q_{s_{ref}}}}{\boldsymbol{V_{sd}}}\right)\right]^2 \\ + \left[\left(\mathbf{1} - \boldsymbol{w_g\, 2L_g C_f}\right)\left(\frac{\mathbf{2}}{\mathbf{3}}\frac{\boldsymbol{Q_{s_{ref}}}}{\boldsymbol{V_{sd}}}\right) + \boldsymbol{w_g C_f V_{sd}} + \boldsymbol{w_g R_g C_f}\left(\frac{\mathbf{2}\ \boldsymbol{P_g}}{\mathbf{3}\ \boldsymbol{V_{sd}}}\right)\right]^2 \end{array} \right\}^{\frac{1}{2}} \tag{10}$$

Therefore, the final minimum dc-link current reference $I_{dc\ ref}$ is expressed as:

$$I_{dc\_ref} = \max(I_{dc_{grid}}, I_{dc\_generator}) \tag{11}$$

where $I_{dc\ generator}$ is the minimum dc-link current determined by the generator side as indicated in Fig. 6.

By applying the minimum dc-link current reference, the WECS can, therefore, achieve the required control objectives and minimized loss.

C. *Decoupled Characteristics Between Voltage Balance Control and Other Control Objectives of the WECS*

On the basis of the control scheme presented in Fig. 6, we can obtained:

$$\begin{aligned} d_1 &= d_{common} - \Delta d_1 \\ d_2 &= d_{common} - \Delta d_2 \\ d_3 &= d_{common} - \Delta d_3 \end{aligned} \tag{12}$$

Under steady state, the following equation is valid when same PI controllers are employed:

$$\begin{aligned} \Delta d_1 &= k\left(\frac{V_{c1}+V_{c2}+V_{c3}}{3} - V_{c1}\right) \\ \Delta d_2 &= k\left(\frac{V_{c1}+V_{c2}+V_{c3}}{3} - V_{c2}\right) \\ \Delta d_3 &= k\left(\frac{V_{c1}+V_{c2}+V_{c3}}{3} - V_{c3}\right) \end{aligned} \tag{13}$$

where k is the gain of the PI controller under steady state. Combining (11) and (12) leads to

$$\frac{d_1+d_2+d_3}{3} = d_{common} \tag{14}$$

Equation (14) reveals that voltage balance control and the generator control are decoupled. On the other hand, the relationship between generator-side and grid-side control is not completely decoupled during the full operation range as the final dc-link current reference is the minimum reference between the generator-side and grid-side currents. However, the voltage/power balance control of the MFT-based modular dc–dc converter is decoupled with the grid-side control objectives (dc-link current control and reactive power control) because of (14).

V. Fuzzy Logic Controller

Fuzzy logic control is a non-mathematical decision algorithm that is based on an operator's experience. This type of control strategy is suited well for nonlinear Systems. Fig.9 shows the structure of the fuzzy logic control algorithm.

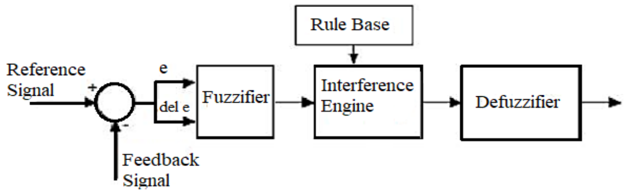

Fig. 8. Block diagram of fuzzy logic controller

Fuzzifier Fuzzy logic uses linguistic variables instead of numerical variables. In a closed loop control system, the error (e) between the reference voltage and the output voltage and the rate of change of error (dele) can be labeled as zero (ZE), positive small (PS), negative small (NS), etc. In the real world, measured quantities are real numbers (crisp). The process of converting a numerical variable (real number) into a linguistic label (fuzzy number) is called fuzzification.

The Fuzzy Logic Controller the inputs are mapped into these membership functions and a degree of membership is found for how much the input belongs to that particular linguistic label. The membership can take on a value from zero to unity for each of the linguistic labels. The waveforms are evenly distributed about the range of operation of the variables. For each of the input and output variables, the following seven linguistic labels are assigned to the membership functions: NL = Negative Large NM = Negative Medium NS = Negative Small ZE = Zero PS = Positive Small PM = Positive Medium PL = Positive Large Once the membership is found for each of the linguistic labels, an intelligent decision can be made to what the output should be. This decision process is called inference.

The rules of a fuzzy logic controller give the controller its intelligence, assuming the rules are developed by a person who has a experience with the system to be controlled. A programmer with more experience with the system will create a better controller. From this desired goal, rules are made for every combination of voltage and rate of change of voltage on what the output should be in order to stabilize. It is convenient when dealing with a large number of combinations of inputs, to put the rules in the form of a rule table.

TABLE: I

FUZZY LOGIC RULE TABLE

e ec	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	ZE
NM	PB	PB	PM	PM	PS	ZE	ZE
NS	PB	PM	PS	PS	ZE	NM	NB
ZE	PB	PM	PS	ZE	NS	NM	NB
PS	PM	PS	ZE	NS	NM	NB	NB
PM	PS	ZE	NS	NM	NM	NB	NB
PB	ZE	NS	NM	NM	NB	NB	NB

TABLE : II

SIMULATION PARAMETERS

System	Value
Wind power	1MW
Wind speed	12m/s
Frequency	60Hz
Grid voltage	4160v
PMSG	
No. of phases	3
Pole pairs	4
Stator resistance	0.0485Ω
Armature inductance	0.395mH
MFT based converter	
No. of modules	3
Turns Ratio	1:1/1:1.005/ 1:02
Input capacitance	$1\mu F$
Switching frequency	1620Hz
Current Source Inverter	
DC link inductor	30mH
Grid side inductor	2.55mH
Grid side capacitor	$153\mu F$
Switching frequency	1200Hz
Modulation scheme	SVPWM

VI. Simulation Results

The performance of the proposed configuration has been verified by both MATLAB/Simulink simulation and experimental tests. The system parameters used are listed in Table I. The Wind Turbine and Permanent Magnet Synchronous Generator used in this simulation by MATLAB/Simulink. The turbine model receives the wind speed and provides an optimized reference speed to the control system.

In this simulation, the constant is reduced to achieve a faster speed response compared with that in a real system. Three modules are employed in the MFT-based converter; to introduce imbalance into this converter, the turn ratios of the three transformers are purposely set to 1:1 (module 1), 1:1.005 (module 2), and 1:1.02 (module 3). In the following simulation, operation of proposed WECS under conditions of with/without voltage balance control is conducted:

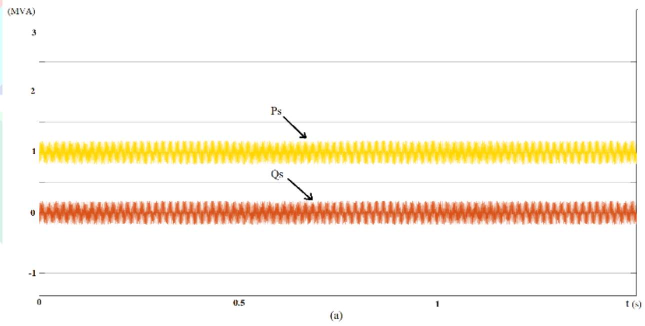

Fig. 8. Grid-side injected real and reactive power (P_s, Q_s)

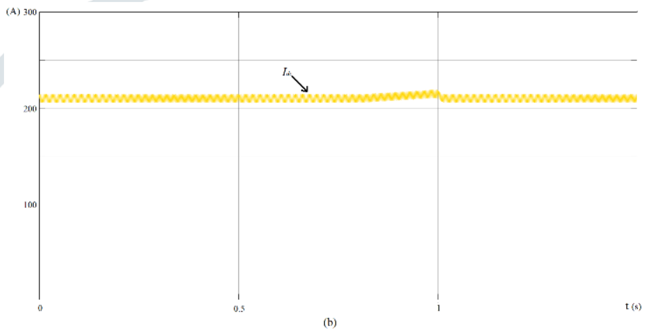

Fig. 9. Dc-link current I_{dc}

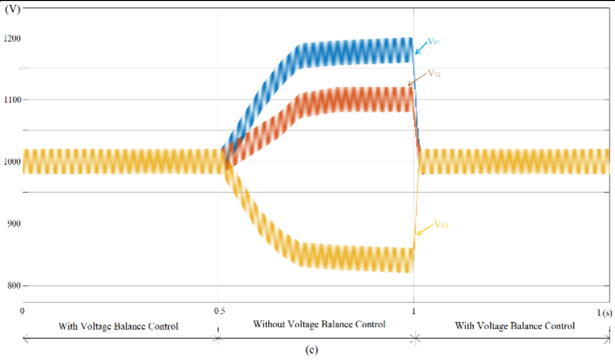

Fig. 10. Input capacitor voltages of the MFT-based cascaded dc–dc converter (V_{C1}, V_{C2} & V_{C3}).

Above results illustrates the simulated performance under conditions of with/without voltage balance control scheme (see Fig. 6). Before t = 0.5 s, the system operates in steady state with voltage balance control. The grid-side injected real and reactive power (P_s, Q_s) are 1 MW and 0 MVA. Input voltage is balanced for the MFT-based converter with $V_{C1} = V_{C2} = V_{C3}$ = 1000 V. At t = 0.5 s, the voltage balance control scheme is deactivated (all three modules operate under the common duty cycle d_{common} [see Fig. 6]). However the dc-link current (I_{dc}) and the real/reactive power are still being controlled effectively, the input capacitor voltages (V_{C1}, V_{C2}, V_{C3}) begin to diverge. This disclose that voltage balance control of the modular converter is decoupled from other control objectives of the WECS (MPPT, dc-link current, and reactive power control). V_{C1} is the highest (1200 V) because the duty ratio of its transformer (module 1) is the lowest (see Table II). At t = 1 s, the voltage balance control scheme is reactivated and input capacitor voltages quickly converge to nominal values.

VII. Conclusion

In this paper, an MFT-based WECS is proposed for CSC-based offshore wind farms. The proposed configuration is composed of an MV PMSG, a passive rectifier, a modular MFT-based converter, and a CSI. The proposed method is analyzed using MATLAB/SIMULINK software. It is characterized by (a) no offshore substation; (b) high power density due to the adaption of a modular MFTs instead of a low-frequency transformer; (c) high reliability and flexibility due to the use of a modular converter; and (e) all the advantages of a CSC. Aside from conventional control scheme (MPPT, dc-link current, and reactive power control) of a WECS, extra attempt is made to assure that uniformly distributed power and voltage sharing between the fundamental modules. The characteristic of decoupling between voltage/power balances is analyzed. Finally, simulation verification is provided to demonstrate the converter's performance of the proposed WECS.

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