Control of Bidirectional DC/DC Converter for Back to Back NPC-based Wind Turbine System under Grid Faults

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***Abstract*—Viability and reliability of the wind power has made Wind Turbine Systems (WTSs) a popular renewable energy resource. A bidirectional DC/DC converter is proposed in this study for the WTS. The proposed DC/DC converter controls the DC-link voltage by injecting the difference between the extracted power from permanent magnet synchronous generator (PMSG) and the output power of the grid-tied inverter, to the energy storage system. The proposed DC/DC converter controller compensates the shortage of extracted active power from PMSG under wind reduced speed condition in order to inject the constant power to the grid during normal operation. The back to back (BTB) neutral point clamped (NPC) converter is proposed to extract the maximum power from PMSG and inject the extracted power to the grid. The proposed WTS structure achieves fault ride through capability and it can inject reactive power to the grid in order to enhance the PCC voltages under voltage sags. The proportional resonant (PR) current controller is implemented for both rectifier and grid-tied inverter due to its fast response and low steady state error. The adaptive space vector modulation (ASVM) is used to generate the switching signal while balances the DC-link capacitor voltages. The performance of the proposed controller is investigates under grid faults as well as reduced wind speed condition and results have proven the applicability of the proposed controller.**

***Keywords*—Wind Turbine System, DC/DC Converter, Back to Back NPC Converter, Bidirectional Energy Storage System, Proportional Resonant Controller.**

I. Introduction

With the motto of "Clean Power Plan" USA is moving fast towards renewable energy. In fact, the whole world is moving towards greener and cleaner energy with target of achieving an environmentally better world. The driving force is not just the inspiration to make the world a better place but the alarming issue of reducing vault of limited fossil fuel available. Wind Power is one of the chief sources of renewable energy. Along with all other renewable sources, wind energy conversion is on a radical rise. In last two decades the increase of mainstream wind power has been remarkable as the exponential rise is seen from 6 MW in 1996 to 282.6 GW in 2012 [1]. And now the rise is not to settle down as investments in this sectors estimates the capacity to rise about 800 GW by 2020, if not more. The advancement in Wind Energy sector is marked by groundbreaking break through not only in mechanical features but also in electrical traits as well.

With high penetration of wind power in the previously stable power networks, numerous concerns regarding stability, efficiency and power quality have emerged. As a result of this issue many countries have already implemented grid codes for large scale wind power generations that are connected to the grid [2]. As a solution, power electronics has been playing a major role in improving the wind generated power.

Some companies are building larger wind turbines having generation capability as high as 10 MW [3]. This range is expected to double by 2020. In higher power conversion ranges, more complicated power conversion topologies are required. For low power applications, two-level is more efficient whereas for high power applications the converter capacity is limited due to the semiconductor current and voltage limitations. Consequently, multi-level converters are gaining much popularity for higher power applications [4]. Generally, Back to Back (BTB) power conversion is used in Wind Turbine System (WTS) to get full control of the active and reactive power [5]. BTB Neutral Point Clamped (NPC) has come up as a popular industrial solution for medium voltage converter applications [2], [6], [7].

Three-level NPC converter is used along with DC choppers for WTS in [8]. The DC choppers are considered to control the DC-link voltage under grid fault. The difference of power between the extracted power from the wind generator (P_{0_PMSG}) and the injected power to the grid (P_{0_Inv}) is converted to heat in DC chopper resistor [8]. However, the energy (P_{0_PMSG}- P_{0_Inv}) can be stored in a storage system. A bidirectional DC/DC converter along with an energy storage system (ESS) is proposed in this paper in order to store P_{0_PMSG}- P_{0_Inv} under grid faults. On top of that the stored energy can be used to regulate the output power of the inverter under wind speed variations.

Various topologies like Electric Double Layer Capacitor (EDLC) or supercapacitor are researched for the ESS in WTS. High energy density with fast dynamic response along with long life cycle of supercapacitors made them suitable for WTSs [9]. However, the supercapacitor cannot be deployed independently due to the issues of controllability and limited voltage range [10], [11].

In this paper a single unit Bidirectional Energy Storage System (BESS) is proposed in order to overcome the operational constrains of an independent supercapacitor. A BTB three-level NPC converter is proposed for the wind power

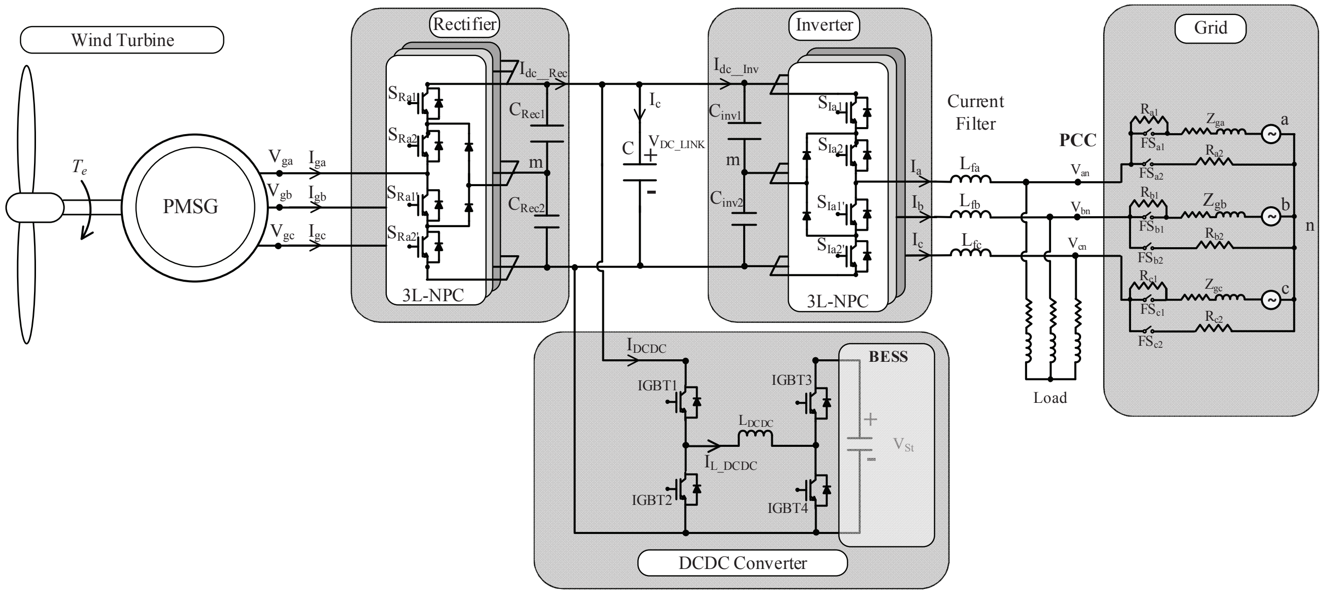

Fig. 1. Proposed PMSG WTS with BTB three-level NPC Converter and bidirectional DC/DC Converter with BESS

system due to its advantages compared to the two-level converters [4], [12]. Though, the implementation of the conventional PI current controller is simple, it suffers from multiple frame transformation and high computational complexity [13]. Consequently, a proportional resonant (PR) controller is applied for the control of the NPC converter. The performance of the proposed structure is investigated on a 50 kW wind power plant under various operational conditions and results have proven the validity.

II. Proposed System Structure

A comprehensive schematic of the proposed WTS is depicted in Fig. 1. The system is consisted of three parts: permanent magnet synchronous generator (PMSG), BTB NPC converter and bidirectional DC/DC converter. The PMSG converts the mechanical energy of the wind to electrical energy while BTB NPC converters extract the maximum power from PMSG and inject it to the grid. The bidirectional DC/DC converter is connected to the DC-link.

A. Permanent Magnet Synchronous Generator

WTS with PMSG requires BTB full scale energy conversion [4]. In direct drive, the wind turbine is directly connected to the generator. The mechanical power obtained from the wind is given by

$$P_m = \frac{1}{2}\rho\pi R^2 V^3 C_p(\lambda) \tag{1}$$

where ρ is the air density (kg/m^3), R is the radius of rotor (m), V is the wind speed (m/s), C_p is the coefficient of performance, λ is the tip speed ratio of the wind turbine blades ($\lambda = \frac{\omega_t R}{V}$).

The equations for the PMSG in the d-q coordinate are given by:

$$u_q = -R_s i_q - L_s(\frac{di_q}{dt}) - \omega_e L_s i_d + \omega_e \lambda_f \tag{2}$$

$$u_d = -R_s i_d - L_s\left(\frac{di_d}{dt}\right) + \omega_e L_s i_q \tag{3}$$

$$T_e = \frac{3}{2} P_n \lambda_f i_q \tag{4}$$

where, L_s is the Synchronous Inductance, R_s is the synchronous resistance, i_d and i_q are the d-q currents, u_d and u_q are the d-q voltages, ω_e is the rotor speed, λ_f is the flux of the permanent magnet and P_n refers to the PMSG pole pairs.

B. Back to Back Power Conversion Topology

In the proposed BTB NPC energy conversion topology, a three-level NPC rectifier is deployed to convert the output AC-power of the PMSG to the DC-power of the DC-link. Additionally, another three-level grid-tied NPC inverter is considered to convert the DC-power to AC- power and inject to the grid, as shown in Fig. 1. It can be seen that both rectifier and inverter circuits are consisted of two pairs of IGBT switches (S_{Ra1} and S_{Ra2} for the rectifier and S_{Ia1} and S_{Ia2} for the inverter) with their complementary switches. The rectifier controls the PMSG by controlling its output currents (I_{ga}, I_{gb}, I_{gc}) according to the MPPT controller. The NPC Rectifiers are connected to two series of capacitors (C_{Rec1} and C_{Rec2}) so are the NPC Inverters (C_{Inv1} and C_{Inv2}). The NPC operates with three different switching states to synthesize the three output pole voltage stepped levels at $V_{DC\_LINK}/2$, 0 and $-V_{DC\_LINK}/2$ with respect to the midpoint m of DC-link.

Despite the increasing demands of renewable energy resources, several regulations such as IEEE Std. 1547-2003 and IEEE Std. 929-2000 must be complied strictly to ensure the power quality of the renewable grid-connected system. Therefore, lower current harmonic distortion can be achieved with the aid of output filter inductors which are connected between the inverter and the grid. Due to the intelligent synthesis of three-level output voltage waveforms, the filter

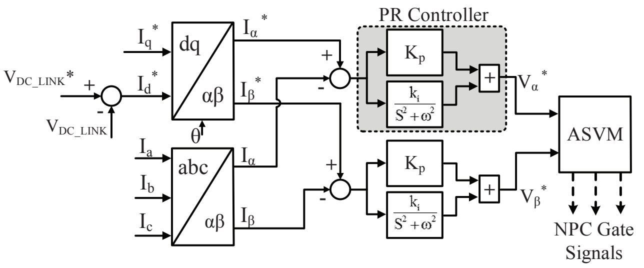

Fig. 2. VOC-PR controller for BTB NPC converter

size can be much smaller compared to the conventional two-level inverters [13].

C. Bidirectional DC/DC Converter with BESS

The proposed bidirectional DC/DC Converter consists of four IGBTs and an Inductor (L_{DCDC}), as shown in Fig. 1. Buck-boost capability can be achieved by controlling the IGBT switches in different modes. The DC/DC converter is connected to the BESS which is consisted of supercapacitor and battery storage system. Based on the voltage of the DC-link and BESS the controller performs the buck or boost operation either charging or discharging of the BESS.

III. Control Structure

The proposed WTS is consisted of three independent controllers: NPC rectifier controller, NPC inverter controller and the DC/DC converter controller. The NPC rectifier controller regulates the extracted power of the PMSG based on the MPPT [14]. The NPC inverter adjusts the injected power to the grid to the extracted power from the PMSG and synthesizes its currents to the grid voltages.

Due to the high penetration of distributed generation units in the power system, fault ride through (FRT) capability is one of the requirements of new standards and grid codes [15] which should be implemented in the control of the WTS. During normal grid operation, the grid-tied inverter adjusts the DC-link voltage to its nominal value by regulating the injected active power to the grid. However, under grid faults, the grid-tied NPC inverter should inject reactive power to the grid according to grid codes and hence it cannot control the DC-link voltage. Consequently, the proposed DC/DC converter controller is responsible to regulate the DC-link voltage by charging or discharging the BESS. The details of the proposed controllers are as follows.

A. Inverter and Rectifier Control

The control of the rectifier is done basing on the maximum power point obtained from the MPPT of the PMSG. As shown in Fig. 3, the controller of the inverter or rectifier has a phase locked loop (PLL), voltage oriented controller (VOC) and adaptive space vector modulation (ASVM) [16].

The measured DC-link voltage (V_{DC_LINK}) is compared to its reference value and the difference is fed into the PI controller which produces the reference d-axis current (I_d^*). The q-axis reference current (I_q^*) is set to zero for unity power

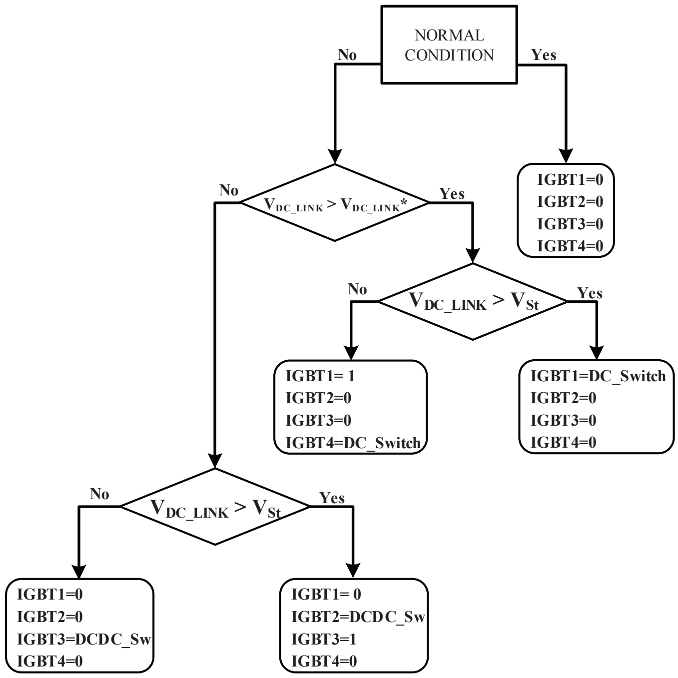

Fig. 3. Proposed DC/DC Converter Control Algorithm

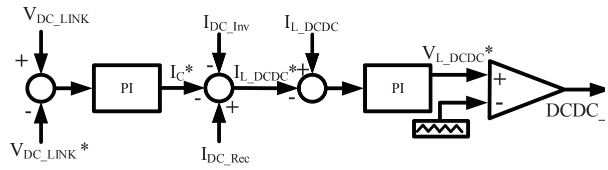

Fig. 4. Proposed DC/DC Controller

factor operation. Though the conventional PI controller has simple implementation, this paper proposes a PR controller for controlling the converter currents in stationary coordinate (αβ-coordinate). The measure three phase currents of the converter (I_{ga}, I_{gb} and I_{gc} for rectifier and I_a, I_b and I_c for grid-tied inverter) are transferred to stationary frame through the Clark transformation. The transfer function of the PR controller is given below:

$$G_{PR} = K_P + \frac{K_i}{(S^2 + \omega^2)} \tag{5}$$

where,

K_P : Proportional gain term

K_i : Integral gain term

ω : Resonant frequency

The reference voltages (V_α* and V_β^*) are obtained from the PR controller and can be directly fed into the ASVM without the need of inverse Park or Clark transformation. The voltage balancing of the capacitors are found better in the ASVM than the classical SVM. This technique can balance the DC-link capacitor voltages by selecting the appropriate switching state. The detailed implementation of the ASVM is presented in [16].

B. Proposed DC/DC Converter Control:

During the normal condition of the grid, the DC/DC converter is dormant or inoperative and all the DC/DC converter IGBTs are switched off. Under the grid fault there are four operating conditions that can be visualised through the control algorithm as shown in Fig. 3.

If the DC-link voltage is greater than the reference DC-link voltage ($V_{DC\_LINK} > V_{DC\_LINK}$*), indicates that the extracted power from the PMSG (P_{O_PMSG}) is larger than the injected power to the grid (P_{O_Inv}). Therefore the difference between these two values (P_{O_PMSG}-P_{O_Inv}) should be injected to the ESS. Accordingly, the direction of the power in the DC/DC converter is from DC-link to the ESS and IGBT4 will remain off. Based on the V_{DC_LINK} and voltage of ESS (V_{St}), the converter should perform boost or buck conversion and accordingly the switches will be controlled. Hence four different operation modes can be implemented as follows:

- If the $V_{DC\_LINK} > V_{DC\_LINK}$* and $V_{DC\_LINK} > V_{st}$, then the IGBT1 is controlled and all other IGBTs are set to 0.
- If $V_{DC\_LINK} > V_{DC\_LINK}$* and $V_{DC\_LINK} < V_{st}$, IGBT1 is set to 1, IGBT 2 and 3 are set to 0, IGBT 4 is controlled (DC_Switch).
- If $V_{DC\_LINK} < V_{DC\_LINK}$* and $V_{DC\_LINK} > V_{St}$, IGBT 4 and 1 are set to 0, IGBT 3=1 and IGBT 2 is controlled.
- If $V_{DC\_LINK} < V_{DC\_LINK}$* and $V_{DC\_LINK} < V_{St}$, only IGBT 3 is controlled and all other are set to 0.

The proposed controller of IGBTs is portrayed in Fig. 4. The instantaneous DC-link voltage is compared to its nominal value and the error is controlled through a PI controller while calculates the reference capacitor current (I_C^*). It can be seen from Fig. 1 that the DC/DC inductor reference current (I_{L_DCDC}) can be calculated as follows:

$$I_{L\_DCDC}{}^* = I_{DC\_Rec} - I_{DC\_Inv} - I_C{}^* \qquad (6)$$

where, I_{DC_Inv} : the instantaneous inverter input current
I_{DC_Rec} : the instantaneous rectifier output current

The current of the DC/DC inductor is controlled through the PI controller which results in the reference inductor voltage (V_{L_DCDC}*). Subsequently, the IGBT switching signal (DCDC_Sw) is generated through a PWM technique.

IV. Result Evaluation

The performance of the proposed WTS structure is investigated in simulations models that are developed in Matlab/Simulink© and PSIM Software. The PMSG is modelled according to a medium voltage PMSG for Wind Turbine specifications. The PMSG is connected to a back to back (AC/DC/AC) full scale converter. The considerations of grid voltage, grid frequency, line inductance, DC-link capacitance, DC-link voltage and the switching frequency of NPC converters are tabulated in Table I. The performance of the system in three different conditions are considered. *Case A* being normal performance, *Case B* is the performance of the proposed system under grid fault and *Case C* is the system response analysis for sudden drop in wind speed.

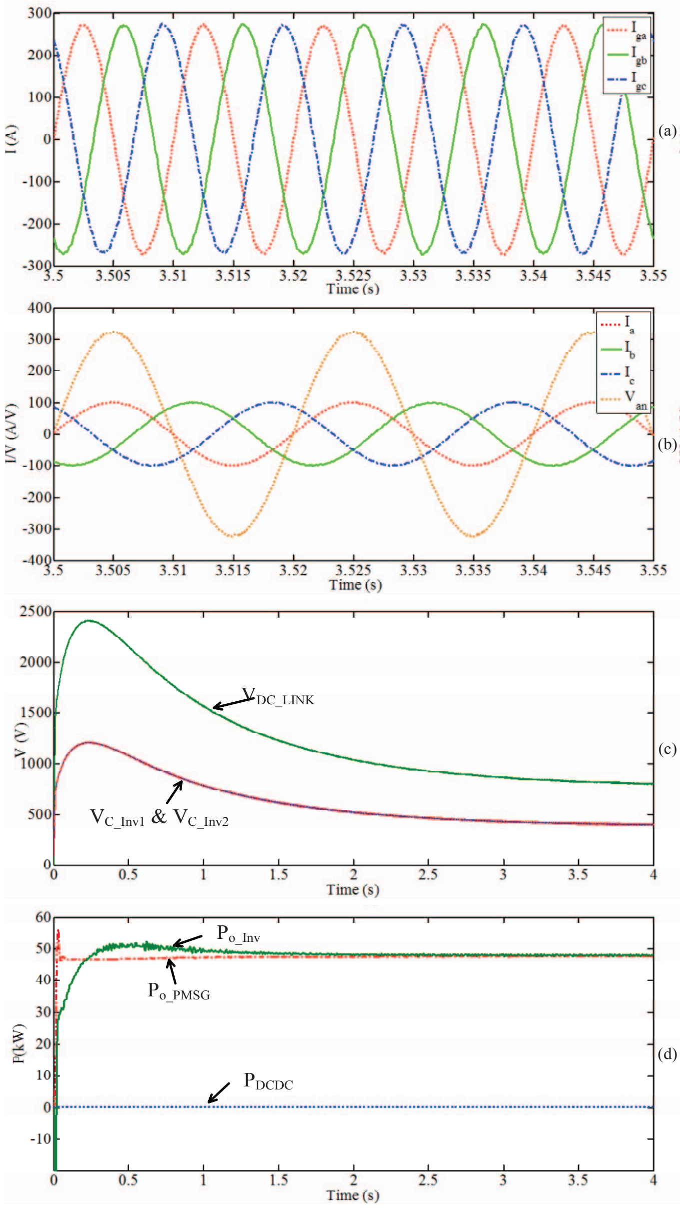

Fig. 5. *Case A*: Performance of the proposed Wind Energy Conversion System under steady state: (a) PMSG Three-Phase Currents, (b) NPC Inverter Three Phase Currents and Phase-A Voltage (c) DC-link Voltage (d) Extracted Power from PMSG injected to the Grid and Storage System

TABLE I. Simulation Parameters

Parameter	Symbol	Value
Grid Voltage	$V_{PCC\text{-}ab}$	400 $V_{l\text{-}l,rms}$
Grid Frequency	f	50 Hz
Line Inductor	L_f	5 mH
DC/DC Converter Inductor	L_{DCDC}	1 mH
DC-link Capacitor	C	2.2 mF
DC-link Voltage	V_{dc}	770 V_{dc}
NPC Switching Frequency	$f_{s,inv.}$	10 kHz

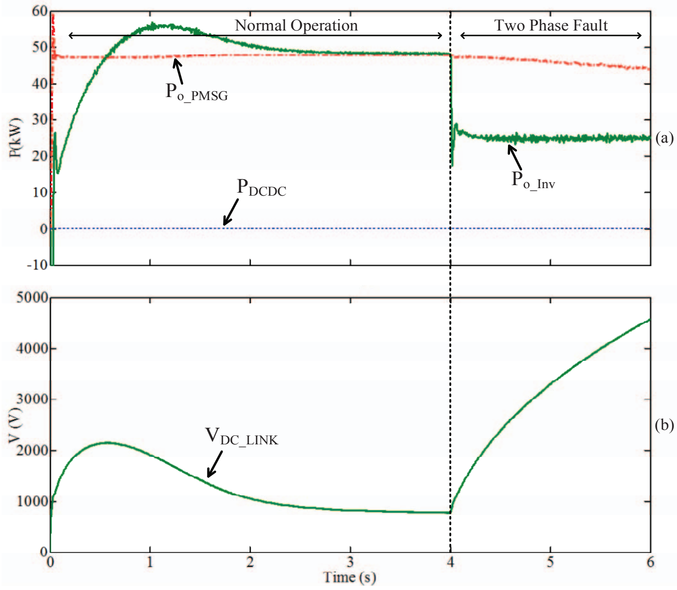

Fig. 6. *Case B*: Performance of the proposed WTS under two phase fault without DC/DC converter: a) Extracted power from PMSG, injected power to the Grid and storage system and (b) DC-link Capacitor Voltage

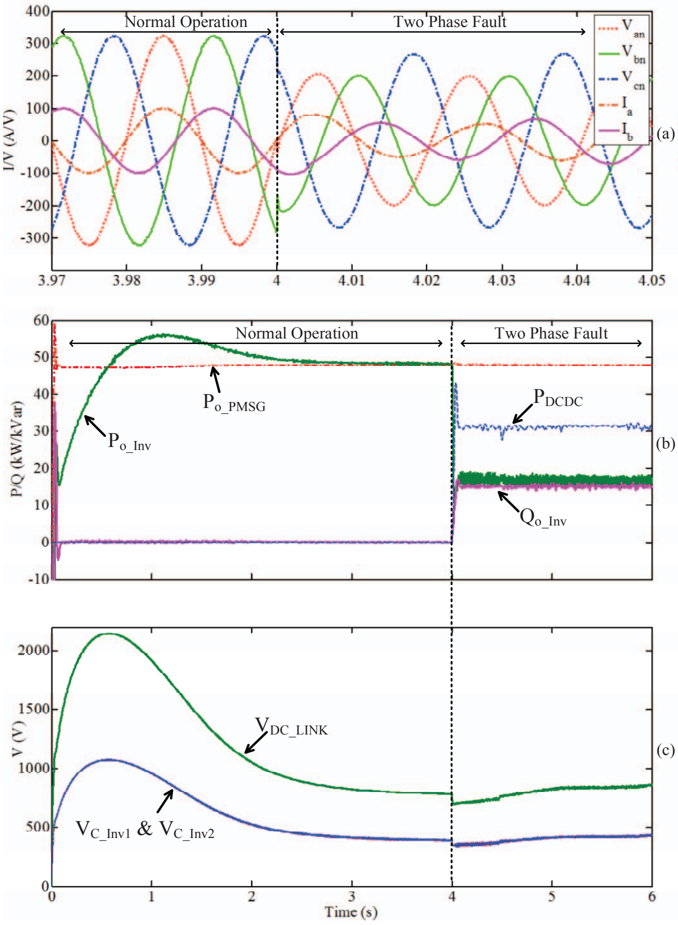

Fig. 7. *Case B*: Performance of the proposed WTS under grid two phase fault with DC/DC Converter: (a) Grid Phase Voltage and Inverter output current, (b) Extracted Power from PMSG, injected power to the grid and storage system, Injected Power to the Grid and (c) DC-link capacitor voltage

A. Case A:

The steady state performance of the proposed controller is shown in Fig. 5. The output phase currents of the PMSG are depicted in Fig. 5(a) which are sinusoidal with less harmonic contents due to the three level voltage operation of the NPC rectifier. The inverter output currents are depicted in the Fig. 5(b). It can be seen that there is no phase shift between Phase A current (I_a) and its voltage (V_{an}) which proves the unity power factor operation of the proposed controller. The capacitor voltage balancing performance of the ASVM is shown in Fig. 5(c). Additionally, It can be observed that the DC-link voltage which is at steady state value due to the controlled operation of the NPC inverter in adjusting the P_{o_inv} with the P_{o_PMSG} as depicted in Fig. 5(d). During this steady state operation all power from the PMSG is transferred to the grid and the DC-link voltage is constant.

B. Case B:

A two-phase fault is occurs in the grid which results a voltage sag at the PCC at t=4.0 s. The performance of the WTS without considering the proposed DC/DC converter controller is depicted in Fig. 6. Because of the voltage sag, the inverter injects reactive power to the grid and consequently its injected active power is reduced even though the PMSG is taking maximum active power from wind (Fig. 6(a)). Due to the difference of P_{0_PMSG} and the P_{0_Inv} the voltage at the DC-link capacitor exceeds its nominal value as shown in Fig. 6(b). This situation would trigger the DC-link capacitor protection devices and would disconnect the WTS from the grid.

Again the same scenario is analyzed but this time activating the DC/DC converter with the proposed controller. After the fault occurred, the resulting voltage sag is shown in Fig 7(a). During the steady state, there is no phase shift between the voltages and current because the inverter only injects active power and the injected reactive power is zero as shown in Fig. 7(b). However after t=4.0 s, the inverter starts to inject reactive power to the grid and consequently it's active power is reduced. The power difference is injected to the BESS through the DCDC converter which is around 30 kW. The DC-link capacitor voltage is fairly constant and the inverter capacitor voltages are also balanced due to the performance of the ASVM. As a result the WTS does not pose any threat to the grid and thus this operation provides the system fault ride through (FRT) capability.

C. Case C*:*

The whole scenario is reassessed for the case of sudden drop of wind speed. The wind speed drops after t=4.0 s. The drop of wind speed causes the wind turbine to rotate less and thus the PMSG's input of mechanical power reduces. This eventually results in the decrease in the generated power. Fig. 8(a) shows the reduced frequency of the voltage and current due to the reduced wind speed at t=4.0 s. The target of any source is to operate undisrupted. The difference of the PMSG power and optimal active power is drawn from the storage system. As the P_{o_PMSG} reduces, the DC/DC converter is activated and provides the inverter with the required power for

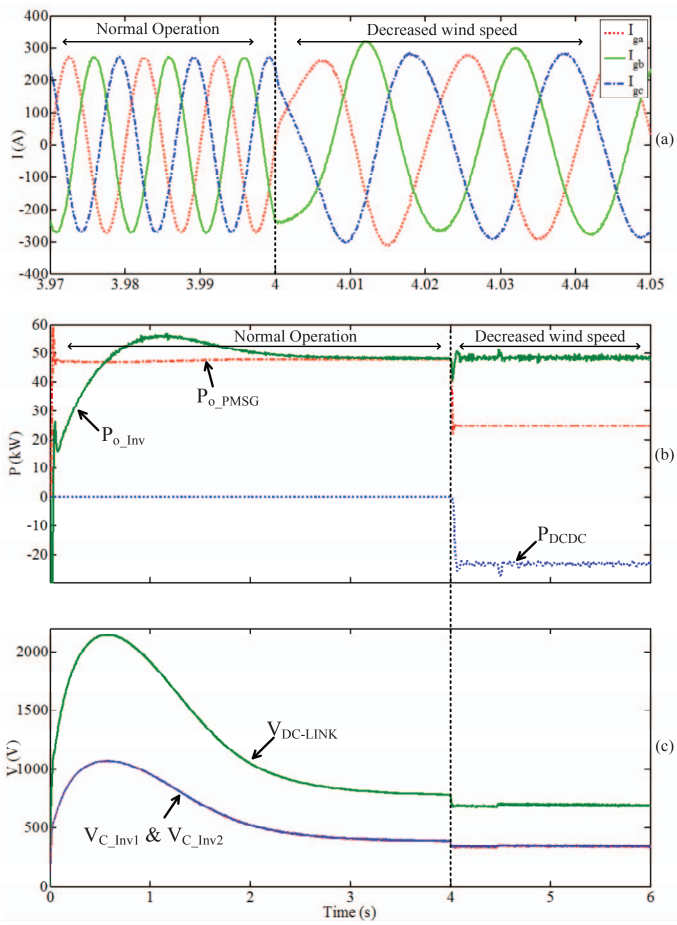

Fig. 8. *Case C*: Performance of the proposed WTS during decreased wind speed: (a) PMSG output currents, (b) Extracted power from PMSG, injected Power to the grid and the storage system and (c) DC-link Capacitor Voltage

continuous constant active power supply to the grid. As shown in the Fig 8(b), the difference in the PMSG power is compensated by the storage system. The inverter output power P_{0_Inv} goes though some glitches due to the reduction of input power from the generator but the compensation power P_{DCDC} ensures the output of the inverter to be fairly constant. During this operation the DC-link voltage remains near its nominal value though it decreases minimally. The NPC Inverter and the converter operates successfully. The V_{C_Inv1} and V_{C_Inv2} are balanced throughout the operation and varies with variations in the DC-link voltage.

V. Conclusion

This paper proposes the control of bidirectional DC/DC converter connected to the BESS. The DC-link voltage is remained at its nominal value due to performance of the proposed DC/DC converter controller while the reactive power is injected to the grid in order to enhance the PCC voltage. Besides the output power of the inverter remained constant due to the compensation of the power by the proposed DC/DC converter under reduced wind speed. The result evaluation proves the applicability of the proposed controller for the medium-power WTS.

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