Grid Interfacing of Three Phase Isolated-Winding Alternator Based WECS By Cascaded Multilevel Inverter

Akshay Satav[1], Alka Thakur[2]
[1]Research Scholar, [2]Research Guide and Asst. Professor
Sri Satya Sai Institute of Science & Technology, Sehore, M.P.

Abstract-* Recent power crisis has created an urge for setting up of alternative electricity generating systems preferably based on renewable sources such as solar and wind energy. Solar based generating units are functioning satisfactorily in low and medium power ranges. While reliable harnessing wind power is still an area of concern and needs cost optimal measures to make them more reliable. Thus this paper presents issues relating grid interfacing of wind energy conversion system based on a cascaded H-bridge multilevel inverter (CHBMLI) topology. The CHBMLI has been used as a VSI and operated in a current control mode in order to achieve the objectives of real power injection, load compensation, power factor correction, and harmonic compensation based on the proposed reference-generation scheme. The bonuses offered by CHB's are equal distribution of switching stress and power losses, reduction in their power ratings, and high quality of inverter output. The closed-loop performance of the VSI adequately achieves the control objectives, i.e., grid interface of wind energy resource in addition to load compensation. The simulation studies were performed by using matlab© simulink® package.

***Index Terms*—Cascaded H-bridge multilevel inverter (CHBMLI), Permanent Magnet Generators (PMG), wound induction generator (WIG), Off-shore plants, Deepwater wind energy systems, wind energy conversion system (WECS), Cascaded H-bridge multilevel inverter (CHBMLI), grid interface, split-winding alternator (SWA), Isolated winding Alternatr(IWA).**

I. INTRODUCTION

Wind energy conversion systems convert the kinetic energy of the wind into electricity or alternative forms of energy. Recent power crisis has created an urge for setting up of alternative electricity generating systems preferably based on renewable sources such as solar and wind energy and has been recognized as an environmentally friendly and economically competitive means of electric power generation. This quest for clean energy was paced by the Kyoto Protocol which sets targets for participating industrialized countries to reduce their emissions on average by at least 40% by 2020, as compared to 1990 emissions while developing countries should reduce their greenhouse gas emissions by 15 to 30% as compared to the projected growth of their emissions by 2020. According to the U.S. Energy Information Administration, world electricity consumption will increase from 12,833 TWh in 1999 to 22,230 TWh in 2020, mainly driven by developing countries, where two billion people are still without access to electricity [1].

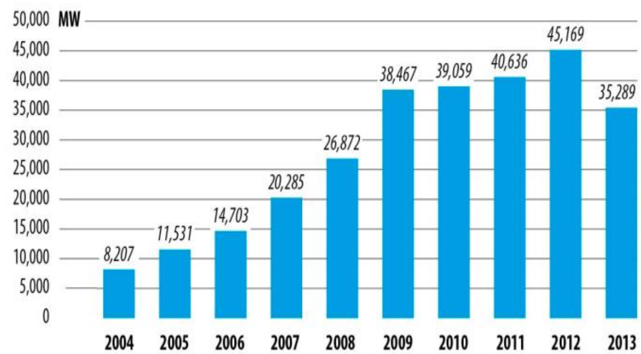


Fig1: Global annual wind installed capacity.

Power ratings of 3–5 MW per machine are becoming common in areas with large wind potentials, especially offshore wind installations [1], [2]. The major problem in interfacing such machines to the grid is the limitation imposed by the ratings of currently available switching devices in the converter. The ratings of the semiconductor devices used in the conventional two-level or three-level VSI topologies do not support the higher power ratings necessary for the grid interface of such large machines. This has motivated designers to go for medium-voltage converters as these are more compact than low-voltage converters for power larger than 1.5 MW [3].

The use of multilevel VSI topology for distributing voltage stress and power losses between number of devices has been reported [5], [6] and the multilevel inverters are suitable for modern high-power wind-turbine applications [7]. Due to the great demand of medium-voltage high-power converters in industry, the cascade H-bridge multilevel inverter (CHBMLI) has drawn remarkable interest ever since its inception. This converter topology is based on the series connection of single-phase H-bridge cells with separate dc sources. It requires the least number of components and is known to eliminate the excessively large number of bulky transformers required by the multipulse inverters, clamping diodes required by the diode-clamped multilevel inverters (DCMLIs), and additional capacitors required by the flying-capacitor multilevel inverters (FCMLIs). The CHBMLI topology with equal dc-link voltages for each H-bridge cells and fixed switching frequency will be able to provide equal switching stress and power handling for all the CHB cells.

Traditionally, wind turbines have been operated only as energy sources and have not been expected to provide grid support functions like voltage support, frequency control, fault ride through, and spinning reserve, but as the penetration of wind in the overall generation mix increases, new grid codes have been constituted, which stipulate that wind farms must provide some of these functionalities [10]. Recently, it has been suggested that wind farms may be used to provide reactive power support to the grid as a part of the ancillary service provisions [11], [12].

Recently, multiple-pole permanent magnet alternators (PMAs) have been suggested for the grid interface of the wind power through five-level cascaded multilevel inverters using power electronics building blocks[6]. Each PEBB in this application consists of a rectifier, a dc link, and an H-bridge cell. The split windings in the three phases produce ac voltages with equal peak values that can be rectified and used as independent and isolated dc sources for the CHB cells of the multilevel inverter. With PMA, the independent control of terminal voltage is not possible as the main field is setup by permanent magnets. A conventional synchronous generator with external excitation has the capability of terminal voltage control and hence gives an additional control over dc-link voltages.

A CHB multilevel inverter has been proposed in this paper with an IWA in order to interface the high power available from a large wind turbine to the grid. The cascaded multilevel inverter is modulated using phase-shifted multicarrier pulse width modulation (PWM) under closed loop to maintain symmetry of switching among all the H-bridges [5]. The closed-loop performance of this current control loop has been shown to be adequate and fully achieves the control objectives, i.e., grid interface of distributed energy resource (wind) in addition to the load compensation with changing load and wind conditions.

II. STRUCTURE OF WECS

The major components of a typical wind energy conversion system include a wind turbine, generator, converter units, control circuits and apparatus, transformer (optional), as shown in Figure 2.

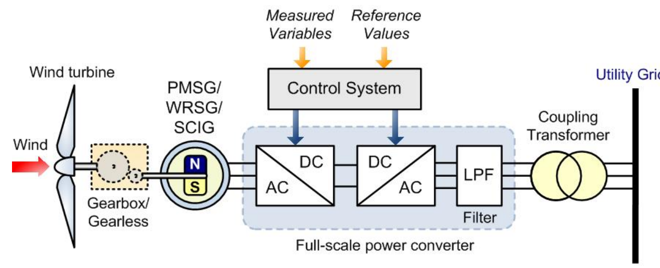


Fig2: Wind energy conversion system Structure

Wind turbines can be classified as vertical axis type and horizontal axis type. Today's wind turbines use a horizontal axis configuration with three or lesser blades, operating either down-wind or up-wind.

Variable speed wind turbines can produce upto 15% more energy output as compared to its constant speed counterparts, however, they utilize power electronic converters to provide a fixed frequency, voltage and power to loads. Majority manufacturers provide gear arrangements between the low speed turbine rotor and high speed three-phase generators. Direct drive configuration with generator coupled to the rotor of a wind turbine directly offers high reliability, low maintenance, and low cost for certain turbines.

III. WECS USING –ISOLATED WINDING ALTERNATOR

In this paper, a variable-speed wind turbine has been proposed as it can achieve a larger yearly energy yield as compared to a fixed-speed wind turbine [6]. Since these turbines make a better utilization of the investment, all modern large wind energy systems above 2 MW now use variable-speed turbines.

The diagram for a conventional synchronous generator with fully rated converter-based WECS is shown in Fig. 3. Here, a three-phase alternator coupled to a large wind turbine is connected first to a three-phase uncontrolled diode bridge rectifier (DBR) followed by a dc–dc converter for dc voltage regulation.

The fixed dc output is then interfaced to the grid through a conventional three level dc–ac converter; Transfer of high power through this arrangement has to be at high voltage and/or current, and hence leads to higher thermal stress on the power semiconductor switching devices used. This requires the use of devices and components with higher power handling capability.

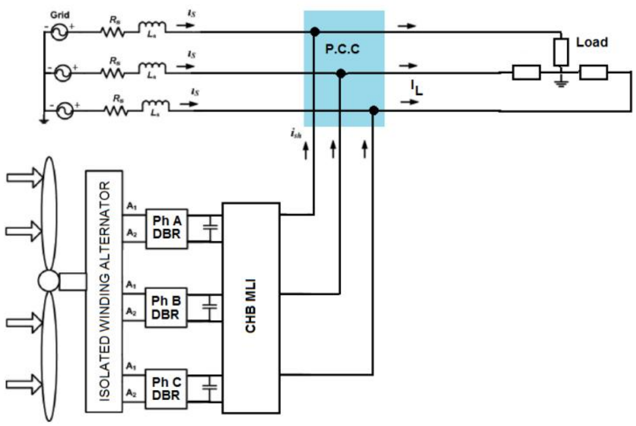


Fig. 3. The IWA and cascaded multilevel inverter .

Additional problems are that of current sharing and difficulty in loss distribution among the many switches, which might have to be used in series or parallel in order to handle large voltages or currents. In addition, it also produces an output, which has higher low-order harmonic contents. Use of additional switches in the form of CHB cells resulting in CHBMLI has been considered as a better option as it eliminates the lower order harmonics, and produces a better quality output and performance in addition to reduced ratings for the switches. In particular, a five or seven-level converter topology alongside an IWA has been suggested in this paper.

The studied WECS consists of the wind turbine, IWA, and the ac/dc/ac conversion system, as shown in Fig. 3. The switches used are insulated gate bipolar transistors (IGBTs) with anti parallel diodes. A brief description of each element of the system is given in the following.

A. Variable-Speed Wind Turbine

Variable-speed wind turbine can be operated over a wide range of rotational speeds in order to optimize the power capture from the wind turbine within the safe operating range of wind speeds. In such a turbine, the rotational speed of the turbine is controlled such that it corresponds to the optimal tip-speed ratio (TSR) for a particular wind speed. In order to accomplish this, the generator to be used must be designed for the appropriate operating speed range.

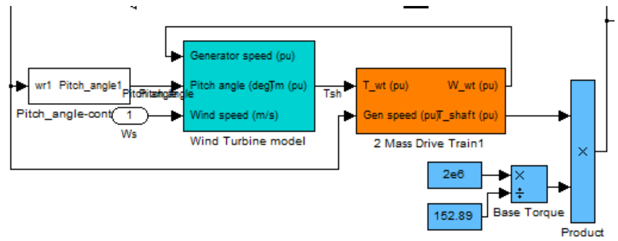
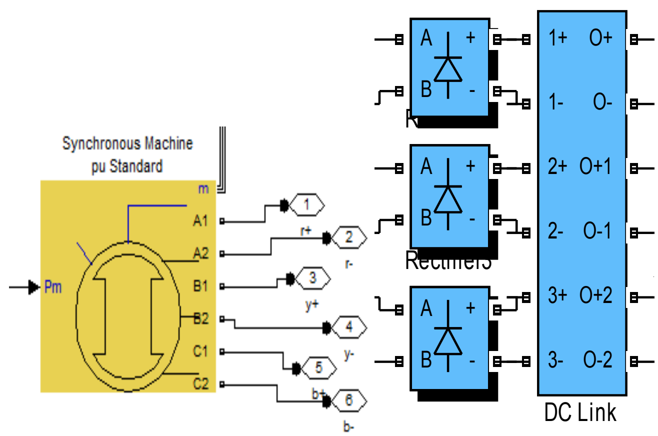


Fig4: Variable Speed wind turbine model

B. Isolated-Winding Alternator

A synchronous generator has been proposed for this application with each phase drawn out of the alternator separately having equal number of turns and equal current ratings. These three windings each for different phase can feed a separate line rectifier and as the peak values of the ac voltages of each of the windings are equal, for balanced load condition, the dc-link voltages for all cells will be equal. The alternator will operate within its rated duty if the individual winding voltages and currents are restricted to their rated limits and the three-phase loads on the ac side are kept balanced. The field winding is on the rotor and is supplied through two slip rings as usual.



(a) (b)

Fig5 :(a)Isolated winding synchronous generator model (b) Rectifier Unit & DC link

C. Rectifier Unit

Simple uncontrolled DBRs have been used for rectifying each of the isolated ac voltages derived from the windings. The rectified dc voltage sources act as the isolated dc voltage sources for the CHBMLI. Two schemes of dc-link voltage control are possible.

The first is to use a separate dc–dc converter after each DBRs in order to control the dc-link voltages, which feed the CHBMLI, and the second scheme is to use field excitation control to control induced ac voltages and consequently control the dc-link voltages simultaneously. Thus, a single excitation voltage variable can be used in order to simultaneously control all the input dc-link voltages of the three-phase CHBMLI.

D. Closed-Loop Multicarrier Modulation of CHBMLI

In this proposed scheme, the IWA gives one dc sources per phase, which have been used to build a five-level CHBMLI. Each phase of the inverter has five levels and nine level line voltage transitions.

A dc-link capacitor has been used after each DBR to hold the dc input voltages to the CHBMLI. The three H-bridge cells per phase are connected in series on the ac side, and the output is connected straight to the medium-voltage distribution grid without the need of any interfacing transformer.

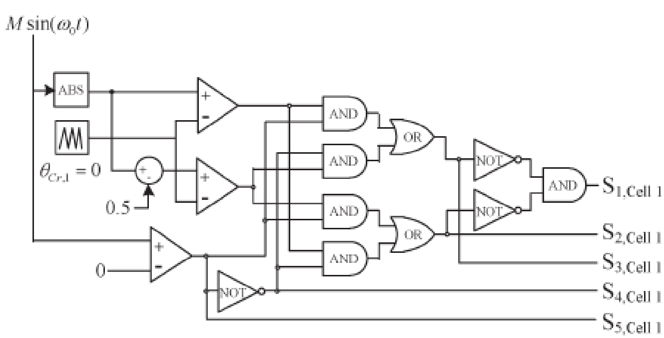


Fig. 6: Closed-loop modulation of CHBMLI.

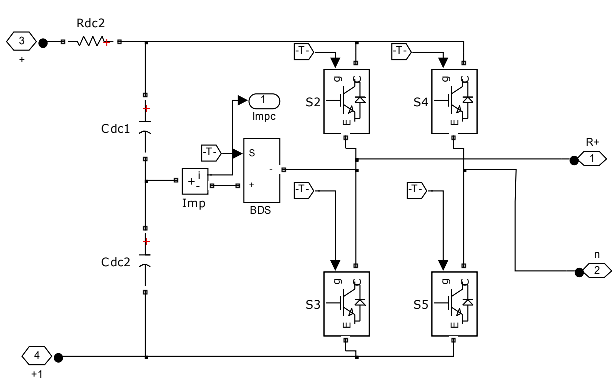


Fig7: CHB topology used.

The cascaded multilevel inverter is controlled using closed loop multicarrier PWM method, as proposed in [22]. The phase-shifted PWM (PS-PWM) uses multiple carriers to control each power switch of the converter. In this method, multiple triangular carrier signals of frequency fcarrier and amplitude Ac are used to generate four unipolar PWM signals needed for the four semiconductor switches in each H-bridge cell, as shown in Fig. 7. The advantage of this method is that the switches in the multilevel converter operate at a fixed switching frequency fcarrier. It is assumed that the converter has to inject the current ish . This current i_{sh} is compared with the reference current ish ref and generates an error signal. This error is amplified by a suitable gain K to generate the switching function signal KError . This signal is then compared with the carrier, as shown in Fig. 4, to generate the gating signals for the switches Sw 11, Sw 12, Sw 13, and Sw 14 of the first H-bridge [22], [23]. The resultant voltage levels for this H-bridge are obtained as +Vdc, 0, and −Vdc. The same process is repeated with the remaining H-bridges with the carriers phase-shifted by predefined angles.

IV. SIMULATION PARAMETERS

The methodology and scheme discussed so far was modeled using matlab simulink package and the configuration parameters used were taken in accordance with Paulson et-al [2] and Izumi et-al [3].

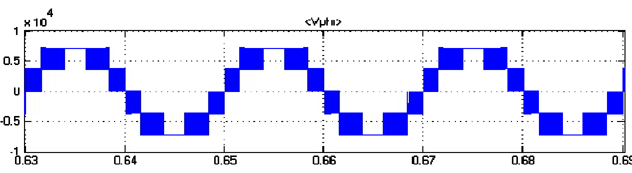
Table 1: Simulation model parameters

Grid & PCC	
Base Voltage	6.6 kV rms (L-L), 1500kVA
Frequency fs	50Hz
Feeder impedence Lsh, Rsh	28 mH, 1.0 Ω
Net shunt impedence Ltk, Rtk	10.2 mH, 1.57 Ω
DC link Voltage Vdc	4 kV
DC link Capacitance Cdc	10000 µF
Load	
Load Linear unbalanced(Case-I)	a: (64+j21.5)Ω, b:(80+j26.4) Ω , c: (96+j31.4)Ω
Load Linear Balanced (Case-II)	(10+j25)Ω / phase
Wind Turbine Characteristic	
Rated Power (Pnom)	2MW
Blade radius	40m
Air density	1.229 kg/m^3
Turbine Coefficient Cp	0.44
Generator	
Rated Output (Pg)	2MW
Rated Voltage (Eg)	8 KV (L-L)

Resistance (Rs)	20µΩ
d,q axis inductance (Ld, Lq)	5.5 mH & 3.75mH
Number of pole pairs (p)	11
Equivalent Inertia (Jeq)	300000kg.m^2

V. SIMULATION RESULTS

The simulation model as discussed in previous sections was developed using matlab 2012b version, the model was simulated using ODE45 in discrete mode with a sample time of 5µs and for duration of 0.7 seconds. The simulation results so obtained are given in this section. The results have shown in figure 8 the effect of the wind-turbine-supported VSI on the PCC voltages and source currents, and the effect of the VSI on sharing of the load power between the grid and wind turbine.



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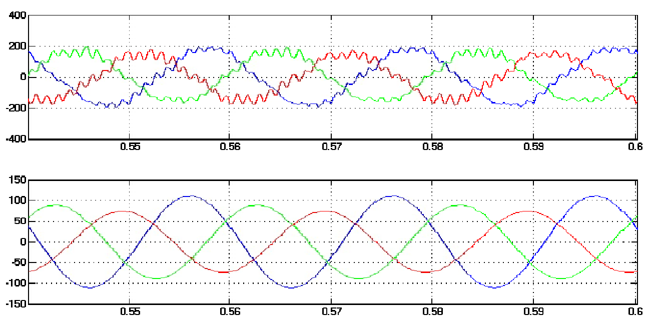

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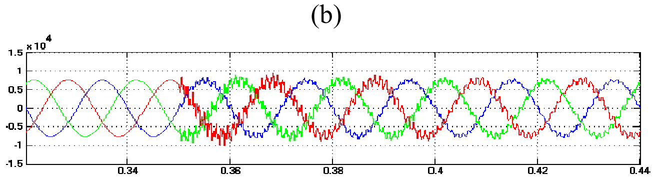

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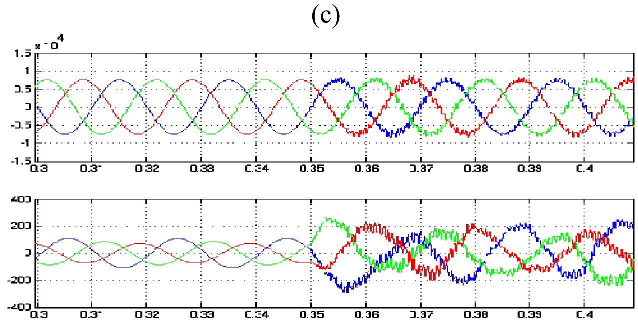

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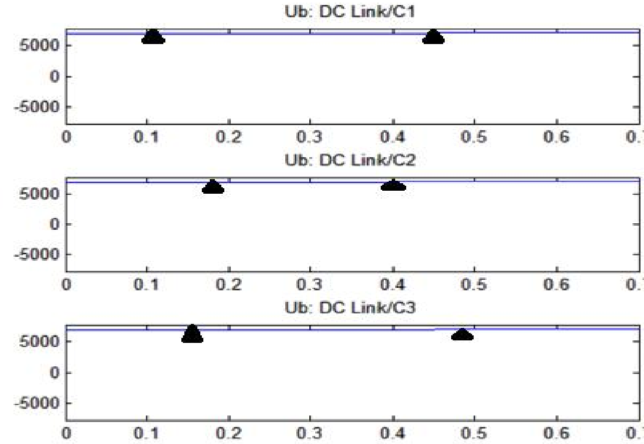
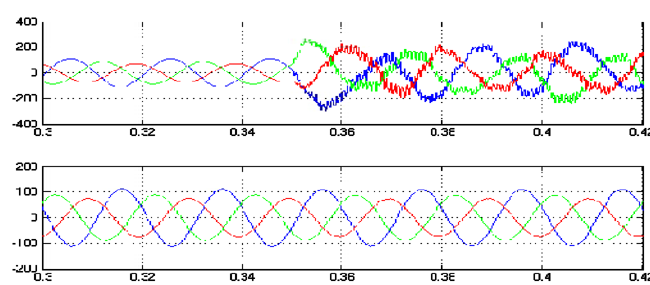


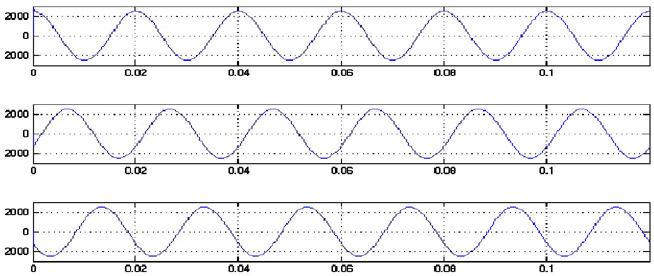
(e)

Fig 8: CASE1 outputs for Linear unbalanced Load: (a) Inverter terminal voltage (b) Grid & Load Currents (c) PCC terminal Voltage (d) PCC Phase Voltage & Currents(e) DC Link Voltages

While for case 2 the grid supplying a linear unbalanced load while the proposed WECS is operating in parallel with the PCC. The wind power is assumed constant. The dc-link voltage *V*dc is controlled to 6.6 kV between *t* = 0 and 0.10 s. At the instant *t* = 0.05 s, a predominantly reactive balanced linear load is connected to the PCC, as shown in Fig. 9 (a). The VSI shows inferior tracking due to increased reference current, i.e., beyond Mi = 1. The effect of this can be seen in Fig. 9 (a), where the source currents are no longer balanced and sinusoidal. The THD of source current increases to 4.7% from 0.26% initially and improves again to 0.20% after Vdc is increased. Fig. 9 (e) shows the phase A PCC voltage and source current, and it can be seen very clearly that the source current is in-phase with the PCC voltage.



(a)



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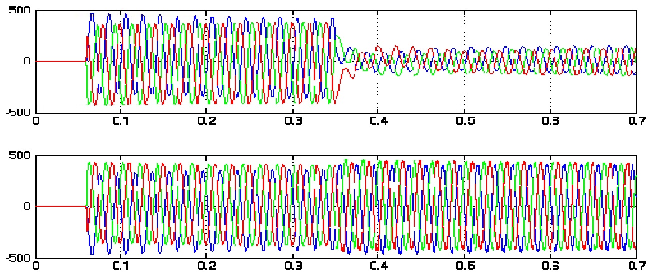

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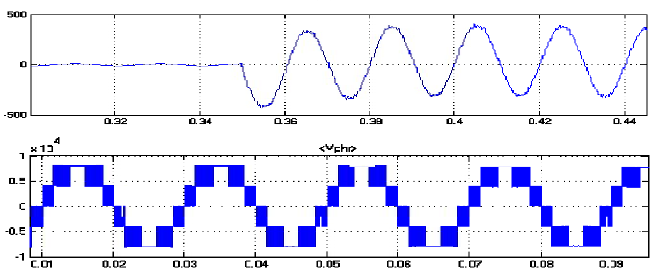

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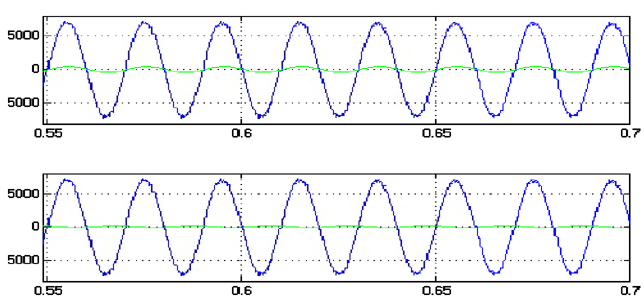

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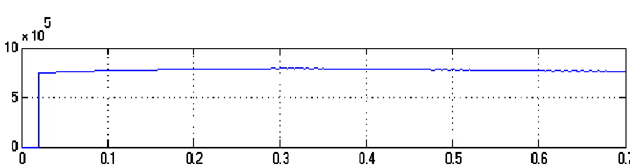

(f)

Fig.9: CASE II Linear balanced Load (a) Three phase source & Load Currents (b) Isolated winding voltages (c) Three phase grid & Source Currents(d) Inverter injected current & voltages (e) PCC voltage Load/Source currents (f) Injected wind power

VI. CONCLUSION

The analysis of a large sized WECS with an IWA and a CHBMLI is performed to interface a large sized wind turbine to the grid with better power quality at the PCC. The performance of the proposed scheme is shown analyzed based on simulation scheme in terms of real power injection depending upon the available wind power. The effect of wind and load variations on the distribution of power between the VSI and source has been demonstrated. It is shown that in case the wind power supply is more than the demanded load, the excess power is exported to the grid. It has been observed that although the VSI is designed for the maximum dc-link voltage, it need not always be operated at the maximum value as the VSI losses depending upon the dc-link voltages. The equal distribution of losses among three CHBs per phase makes it possible to use commonly available switching devices, which will help in reducing the cost of the power electronics component.

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AUTHOR"S PROFILE

AKSHAY SATAV[1] is M. Tech. Scholar (Power Electronics), Department of Electrical & Electronics Engineering, SSSIST Sehore, India.

ALKA THAKUR[2] is Assistant Professor in the Department of Electrical Engineering, SSSSIST Sehore, M.P., India.