Design and Analysis of a Microgrid with a PMBLDC Generator Based WECS and Solar-PV with Decoupled Real and Reactive Power Control Strategy

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Abstract— **This paper presents the design of a micro-grid with permanent magnet brushless DC (PMBLDC) generator based wind energy conversion system (WECS) and Solar PV along with stand-alone loads. The output of the PMBLDC is converted to a controlled DC bus voltage using a PWM rectifier through which independent real and reactive power control are achieved. This DC bus is common to both solar PV and WECS. A Simulink model for the Solar PV Array is created and the output voltage is regulated to match up to the DC bus voltage using a DC-DC converter. A Hysteresis band pulse width modulation technique sends gating signals to the devices of the common inverter, which controls real and reactive powers and thereby achieving power factor control at the grid/load end. The entire system is modelled and simulated in MATLAB/Simulink environment. The presented results demonstrate the excellent performance of the micro-grid under different operating conditions.**

Keywords—Micro-grid, Wind energy conversion system, permanent magnet brushless DC generator, Solar PV, PWM Rectifier, HBPWM, Power Factor Correction

I. INTRODUCTION

The need for energy is increasing drastically with the increased population every year. Conventional power generation techniques using fossil fuels have led to climate change and global warming, necessitating the exploration of alternative sources of electricity such as wind and solar due to their eco-friendly nature and abundance. These distributed generation resources combined with some loads within a certain topographical structure make up a micro-grid. These are capable of running in an islanded fashion or in grid-connected mode and hence more reliable. Due to being smaller in size, they are easier to manage, generation can be matched exactly to the demand and storage; they are characterized by higher efficiency as the generation is close to the loads thus eliminating the transmission losses almost completely. In this paper, a micro-grid consisting of a wind energy conversion system (WECS) based on a Permanent Magnet Brushless DC generator (PMBLDCG) and a solar PV along with some loads is being explored. PMBLDC generators are more reliable and have lesser ripples in the output DC voltage due to the trapezoidal back EMF and have 15% higher power density than a permanent magnet synchronous machine (PMSM) of comparable rating [1] and thus a better alternative

for WECS. Solar PV is also being used as another source of electricity in this work.

The DC output voltages from both these sources are boosted to the same voltage level and this is fed to a single phase voltage source inverter whose switches are controlled by hysteresis band current controller which controls the power factor. The stand-alone WECS and Solar PV are modelled along with the accompanying power electronic converters and control circuits in MATLAB/ Simulink environment and the performance of the micro-grid is simulated under various operating conditions to assess the viability of the proposed system.

II. SYSTEM CONFIGURATION

Fig. 1 shows the system configuration of the microgrid composed of PMBLDCG based WECS and Solar PV. The various components of the system are the Wind turbine, PMBLDC generator, PWM rectifier, Solar PV accompanied by a boost converter, a sinusoidal PWM inverter connected to the common DC bus and the load. The generator is connected to a PWM rectifier whose output is connected to a common DC bus where the boosted output of the Solar PV is also tied up.

A. Wind Turbine

Wind turbine extracts the wind energy from the fast blowing winds and converts the kinetic energy into mechanical energy by the turbine shaft; a PMBLDC generator is coupled to this shaft which converts the machnical energy into electricity.
The tip speed ratio of a wind turbine is defined as:

$$\lambda = \omega \frac{R}{\vartheta} \tag{1}$$

where, λ is the tip-speed ratio, ω is the rotor rotational speed in rad/sec, R is the radius of the rotor in m, ϑ is the wind speed in m/sec. The power generated from the wind can be represented by equ (2).

$$P_T = \frac{\rho}{2}.A.C_P(\lambda, \beta).\vartheta^3 \tag{2}$$

where P_T is the power output from the rotational motion of the wind turbine, ρ is the density of air, A is the area swept by the turbine in m^2, C_P is the coefficient of power.
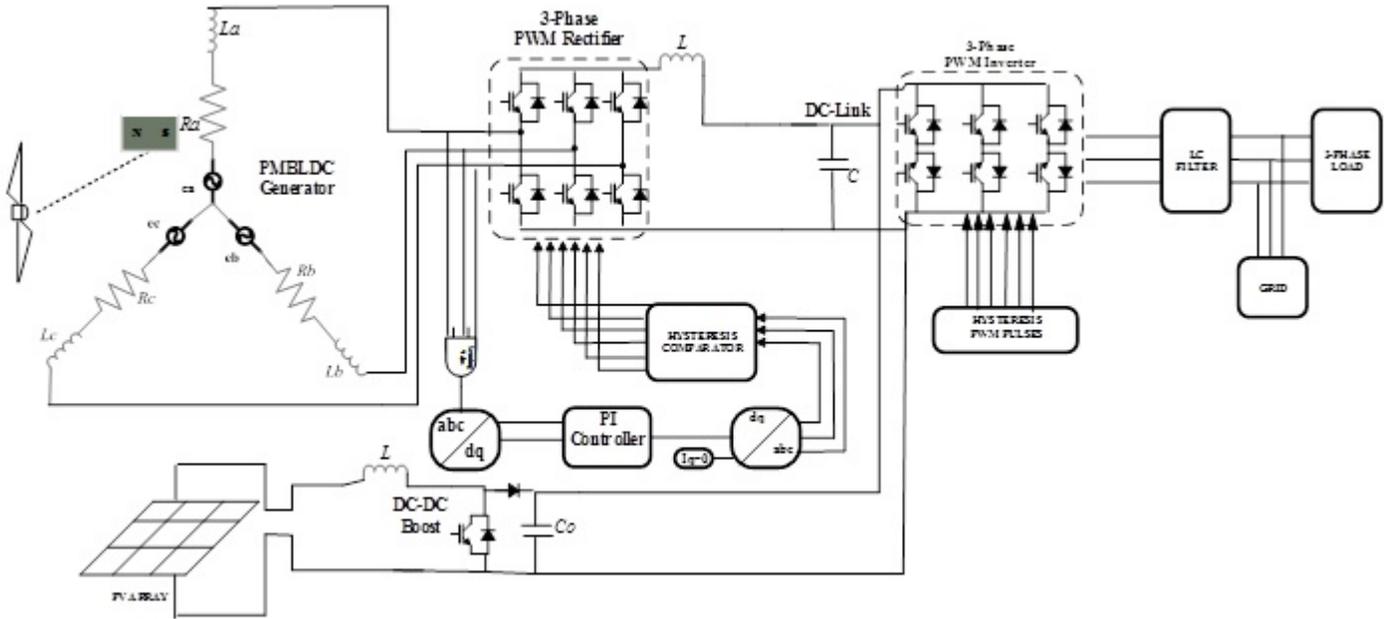
Fig.1 Configuration of the Micro-grid system with PMBLDC generator based WECS and Solar PV.

The mechanical equation that demonstrates the wind turbine torque-speed characteristics is as follows:

$$T_m - T_{load} = J\frac{dw}{dt} \qquad (3)$$

where T_m-turbine's mechanical torque, T_{load} is the torque demanded by the generator, w is rotor speed in rad/s and J the inertia of the total wind system. Wind turbines are usually constructed offshore, for better wind speed and greater power requirements, the maximum wind speed in such cases being 12m/s. It is also observed that generated power varies with the variations in wind speed; at a given wind speed, the power is maximized at a specific rotor speed. The wind turbine is modelled here to yield a maximum power of 1.5 kW at a wind speed of 12 m/sec.

B. PMBLDC Generator

PMBLDC generator is chosen over PMSM due to its low maintenance and high reliability [2-4]. It has three stator windings that behave as magnetic poles and the rotor is made up of permanent magnet. It does not have commutator and brushes; it is electrically commutated. The modelling of PMBLDC generator is based on the following equations:

$$\begin{aligned} e_{an} &= v_{an} - Ri_a - p\lambda_a \\ e_{bn} &= v_{bn} - Ri_b - p\lambda_b \\ e_{cn} &= v_{cn} - Ri_c - p\lambda_c \end{aligned} \qquad (4)$$

where p is the derivative operator; v_{an}, v_{bn}, v_{cn} are the three phase terminal voltages with respect to ground and e_{an}, e_{bn}, e_{cn} are the three-phase back-emfs which are trapezoidal in nature. The flux linkages are can be defined as:

$$\begin{aligned} \lambda_a &= L_s i_a - M(i_b + i_c) \\ \lambda_b &= L_s i_b - M(i_c + i_a) \end{aligned} \qquad (5)$$

$$\lambda_c - L_s i_c - M(i_b + i_a)$$

where L_s is the self-inductance of the phase windings and M is the mutual inductance between them. The mechanical equation for the generator is:

$$T_s - T_l = J\frac{dw_r}{dt} \qquad (6)$$

where J is the rotor inertia (kgm^2), w_r is the rotor speed (rad/s) and T_s is the electromagnetic torque (Nm). The PMBLDC generator is modelled in MATLAB/Simulink with these three equations.

C. PWM Rectifier

Voltage fed three phase PWM Rectifier made up of six IGBTs arranged in a three-leg-bridge. It has many advantages over the diode rectifier as it has the capability to control the DC bus voltage and PF. Further, it has the capability to handle bi-directional power flow and also it can have independent control of active and reactive power. Suitable control strategy adopted for this PWM rectifier can result in reduced input current harmonics. It is widely used in high-power and high frequency applications. However, here the PWM rectifier handles only one direction of power flow, i.e., from the generator to the load.

D. Solar PV

The basic building block of any PV cell is a simple p-n junction, which converts light energy into electricity directly. The modelling of any PV module is based on the perfect fit of its I-V characteristic curve. The output voltage and current are temperature and irradiance dependent [5-7]. Fig. 2 depicts the equivalent circuit of a single PV cell.

I_{PV} and V_{PV} are the PV array's output current and voltage respectively. I_{ph} is the cell's photocurrent which depends on the temperature and irradiance. R_{sh} is the non-linear resistance of the p-n junction.
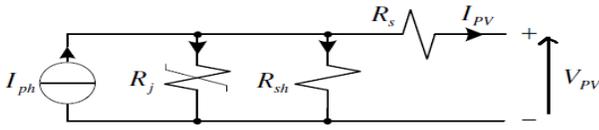

Fig. 2: Equivalent Circuit of a PV cell.

There are adverse effects of temperature and insolation (G) on the PV array characteristics as the following equations define:

$$
\begin{aligned}
I_{ph} &= I_{pun}(1 + k_i(T - T_n))G/1000 \\
V_{oc} &= V_{ocn}(1 + k_v(T - T_n)) \\
T &= T_o + (\frac{NOCT-20}{800})G
\end{aligned}
\tag{7}
$$

where I_{pun} and V_{ocn} are the short circuit current and open circuit voltage of the PV module, at a cell operating temperature of 25°C and Irradiation of 1000W/m². k_i (0.0033/°C) and k_v (-0.0786/°C) are the temperature coefficients for the short circuit current and open circuit voltage respectively and G is the solar insolation. T_o is the ambient atmospheric temperature, NOCT is the normal operating cell temperature [5-7]. It is the cell temperature in a module, when the ambient temperature is 20°C, and the solar insolation is 800W/m² [5]. T is the cell operating temperature and T_n= 298.15K which is the reference temperature. The PV Model [8-9] is then built based on the following equation:

$$
I_{PV} = n_p.I_{ph} - n_p.I_{rs}.[exp(\frac{q}{k.T.A}.\frac{V_{pv}}{n_s}) - 1]
\tag{8}
$$

where n_s and n_p are the number of cells in series and parallel, 'q' is charge of electron which is 1.602 X 10⁻¹⁹ Couloumb, k= Boltzmann constant = 1.3807 X 10⁻²³ JK⁻¹, A =1.3 is the junction diode's ideality factor, T = 298.15K is the temperature of the cell and I_{rs} is single cell reverse saturation current. A Solar PV array of 750W peak power capacity is modelled according to the above equation which is simulated in MATLAB/Simulink. The parameters of the solar PV are estimated at a standard solar irradiance of 1000W/m². The detailed data for the solar are presented in the Appendix.
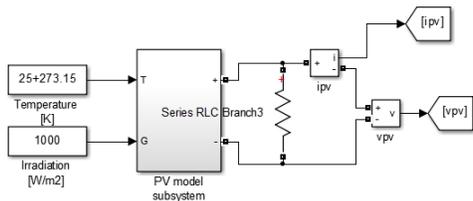

Fig. 3 Model for Solar PV

E. DC DC Boost Converter

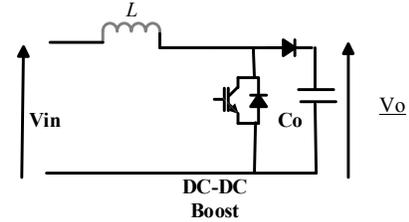The basic circuit of a DC-DC Boost converter is shown below:

Fig. 4 DC-DC Boost Converter

This is designed with the calculated values for the inductance and capacitances with the known parameters of input voltage Vin = 236V required output voltage of 530V and the switching frequency f_{sw} of 10kHz. The inductance and capacitance are designed based on the following equations:

$$
\begin{aligned}
L_{min} &= \frac{D(1-D)^2 R}{2f_{sw}} \\
Co\left(\frac{\Delta V_o}{V_o}\right) &= D/Rf_{sw}
\end{aligned}
\tag{9}
$$

Where D=duty ratio, R=load resistance and V_o is the output voltage. The minimum values are 0.03mH and 10 µF for the circuit to be in continuous conduction mode . The chosen values are presented in the Appendix

F. PWM Inverter

The voltage source inverter (VSI) topology is shown in Fig.1 itself. This VSI converts the DC bus voltage to 3-phase, 415V, 50Hz AC to be supplied to the loads. It consists of six power switches in the three arms and is controlled by a common control method bipolar sine-triangle pulse width modulation (SPWM) technique. The switching must ensure that both the switches in the same leg should not be fired at the same time to avoid shoot-through. Sinusoidal bipolar PWM is beased on comparing the instantaneous value of the reference signal (V_{sine}) with the triangular carrier (V_{tri}). The sinusoidal control waveform decides the frequency of the inverter output and the triangle frequency establishes the switching frequency. The switches in each of the three legs are switched ON and OFF based on the following comparison:

$$
\begin{aligned}
V_{sine}(\text{phase-A}) &> V_{tri}, \text{ Ta+ is on} \\
V_{sine}(\text{phase-A}) &< V_{tri}, \text{ Ta- is on} \\
V_{sine}(\text{phase-B}) &> V_{tri}, \text{ Tb+ is on} \\
V_{sine}(\text{phase-B}) &> V_{tri}, \text{ Tb- is on} \\
V_{sine}\text{phase-C}) &> V_{tri}, \text{ Tc+ is on} \\
V_{sine}(\text{phase-C}) &< V_{tri}, \text{ Tc-is on}
\end{aligned}
\tag{10}
$$

The rating of the switches are designed according to the consumer load whose rating is taken here as 1 kW. Thus to power the load at 220V, 50 Hz, the capability of switch current is calibrated to be 6A. Due to nonlinear nature of the load conditions, switches ratings are chosen with a factor of safety as in [3].

The inverter is fed by the boosted DC voltage output from the rectifier and is connected to the load through an LC filter. LC Filter is used to eliminate switching frequency (and higher order) harmonics from the 50Hz output of the VSI to the load. The capacitance is designed considering a ripple of 1% of V_c which is 3.25V, as below:

$$C_o = \left[\frac{V_o}{2Rf_{sw}\Delta V_o} \right]$$
(11)

where V_o is the output voltage of 325V and f_{sw} is the switching frequency of 20kHz, C_o is the output capacitance is calculated as 15μF. The inductance is also designed according to the resonant frequency of the filter after choosing the capacitance. Considering the higher order harmonics to be eliminated and using that switching frequency value, the filter inductance is expressed as:

$$L = \left[\frac{1}{4\pi^2 f_{sw}^2 C_o} \right]$$
(12)

The inductance is calculated as 2mH.

G. Power Factor Control

The inverter current is controlled such that the real and reactive components of current are controlled independent of each other. As per the requirement of the load current, the three phase currents are converted into dq components (abc to dq) using Clarkes's and Parks's transformations. If the quadrature axis reference current I_q is set to zero, then, power factor achieved will be unity. $Iq < 0$ refers to lagging power factor and $Iq > 0$ refers to leading power factor. The reference currents from the power factor control module are compared with the actual grid currents using a hysteresis controller and its output is used to trigger the devices in the inverter. Thus the currents of the VSI are placed at appropriate power factor.

III. SIMULATION RESULTS

The rating of the wind turbine is 1.5kW at a wind speed of 12m/s. This produces a torque of 0.7pu which is applied to the PMBLDC generator shaft. The generator with trapezoidal back-EMF of 100V supplies the 3-phase voltage to the PWM rectifier which is then rectified to a DC voltage of 160V. The PWM rectifier works in boost mode to yield 530V of DC-Link voltage in order to feed the inverter which is connected to a grid of 415V RMS. The output of the PV array constructed as a single module is 236V, 3.2 A. This voltage is also boosted up to 530 V using a boost converter whose inductance is 3mH and the capacitance is 100 μF.

Fig. 5 shows the voltage and current at the terminal of the solar PV under standard temperature and irradiance conditions which are 25°C and 1000W/m² respectively. It is clearly seen that the solar PV delivers a power of 750W; but the voltage has to be boosted to 530V DC to be able to supply to the PWM inverter. Fig. 6 shows the power generated by the generator at two different wind speeds at 12m/s and 10m/s respectively, as can be clearly seen from the figure maximum power is at 12m/s. Fig. 7 shows the output voltages of the 3-

phases of PMBLDC generator at a wind speed of 12 m/sec. It is clearly seen that the three phase voltages are trapezoidal in nature. This is rectified with the help of a PWM rectifier after which both the DC outputs of Solar PV (along with boost converter) and the PMBLDC generator become 530V as shown in Fig.8. Both the voltages i.e., at the WECS and solar PV terminals are connected to a single VSI.

Fig. 9 shows the value of the boosted PV output when the temperature is varied from 25°C to 40°C at 0.1s and from 40°C to 50°C at 0.5sec. It can be seen from the figure that the boost converter is able to step up the voltage to 530V irrespective of the variations in Solar PV output.

Fig. 10 shows the voltages and currents at the grid interface point along with the DC link voltage.
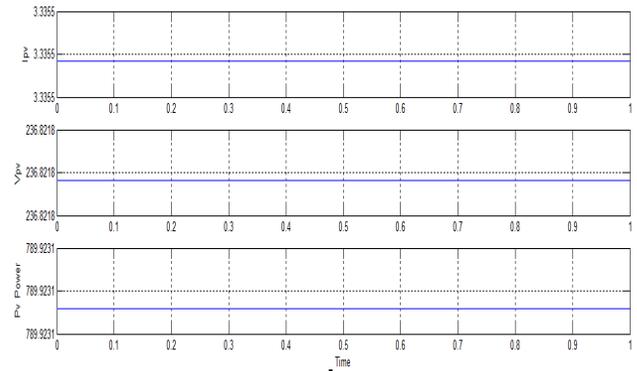

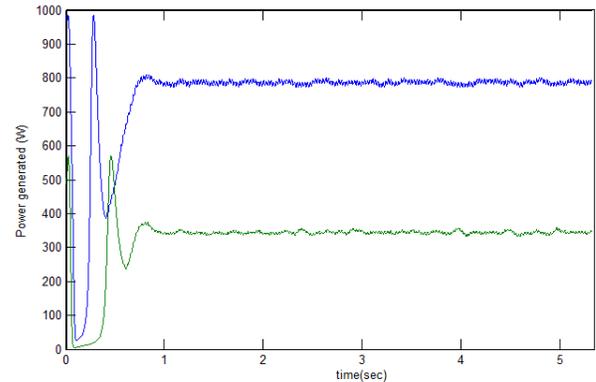Fig.5 Voltage, Current and Power Outputs of the PV Array

Fig 6: The power generated by PMBLDC at 2 different wind speed 12m/s and 10m/s respectively
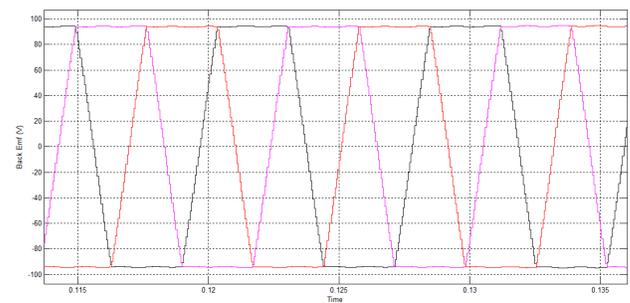

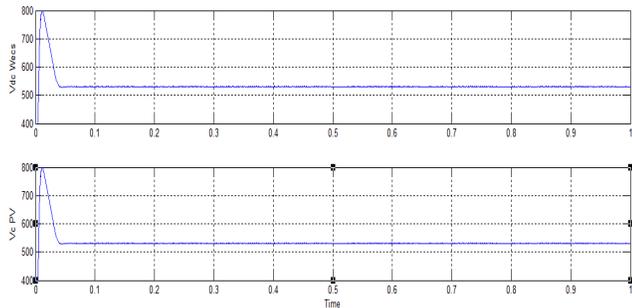Fig 7 The three-phase induced EMFs of the PMBLDC generator.

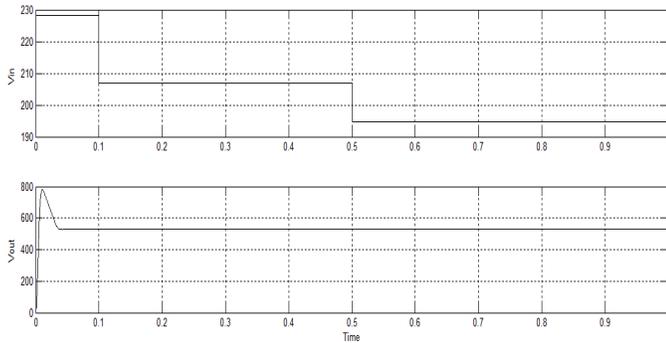Fig.8 DC bus voltages at the terminals of WECS and Solar PV

Fig. 9 Output of the solar PV and the Boost converter at different vlaues of temperatures which is varied from 25˚C to 40˚C at 0.1sec and from 40˚C to 50˚C at 0.5sec.
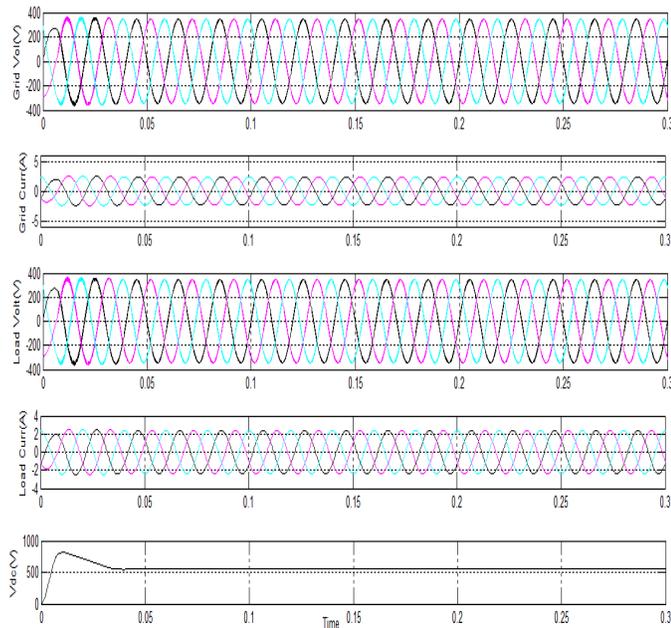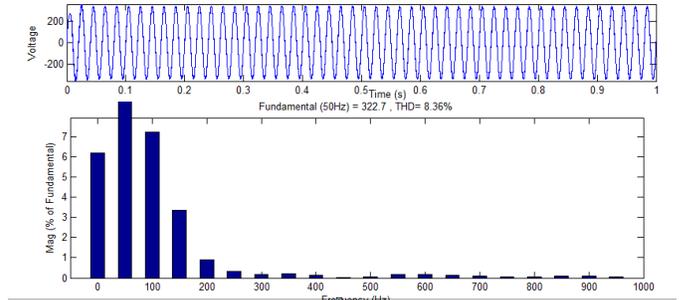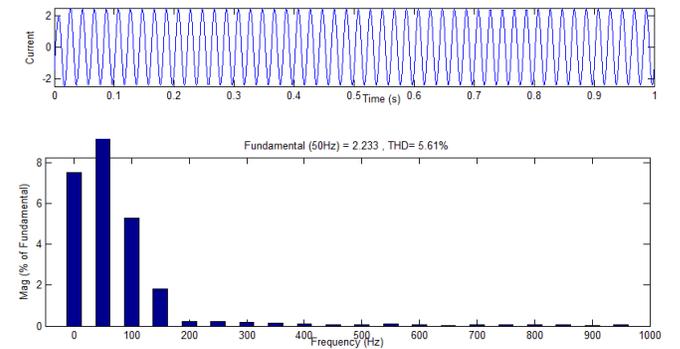

Fig. 10. Voltages and currents at the grid interface point along with Vdc

The voltages and currents obtained at the grid-interface point are analyzed and their harmonic spectra depicted in Fig. 11 show that the THD are well within the International power quality standards.

(a)   Voltage at the grid interface point and its THD

(b)   Current at the grid interface point and its THD
Fig. 9 Harmonic Spectra of Voltage and Current

IV. CONCLUSIONS

A Microgrid with Solar PV and PMBLDC generator based Wind Energy Conversion System is modelled and analyzed along with a few loads. The PWM rectifier at the terminals of the PMBLDC generator is able to accomplish independent real power and reactive power control and the voltage is set at 530V for the DC link. The VSI converts this DC voltage into 3-phase 415V 50Hz AC voltage with very minimal distortions. The complete system has been modeled and simulated in Simulink/MATLAB environment and it is found that the system works satisfactorily. The AC voltage and current obtained at the grid terminals have a THD which is well within the limits set by the International power quality standards.

APPENDIX

Wind Turbine: At a wind speed of 12m/s maximum power = 1.5kW.

Solar PV array of 750 W capacity.

A cell operating temperature of 25˚C and irradiance of 1000 W/m^2 is assumed.

Variations in current and voltage with respect to temperature in a solar PV.

$$k_i = 0.0033/°C$$

$$k_v = -0.0786/°C$$

No. of cells in series: $n_s = 36$

No. of cells in parallel: n_p =1

The reference temperature: T_n= 298.15K.

DC-DC Boost for PV Array: Lf = 3e-3 C_o = 100e-6

Output Filter: Lo =2mH C_o = 15μF.

Three-Phase Load: phase-to-phase voltage (Vrms) =400V

Load of Active Power = 1500W.

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