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A Hybrid Grid-Wind Energy System Using Voltage Oriented Control and Class C Chopper For An Electric Charging Station

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Abstract. A shunt interconnection made from a wind driven DC machine system, a three phase grid voltage supply, and a DC load representing an electric charging station is investigated The wind driven DC machine system participates with maximum power to the overall active power flow. It uses a class C chopper circuitry controlled properly by a typical maximum power point tracker (MPPT) controller. The grid has the role of supplying active power in case of any power deficiency needed by the DC electric charging station load. Similarly, it has also the role of absorbing active power in case of any additional power generated by the wind driven DC machine system and not needed by the DC load. This is done by using an AC/DC power electronic converter. Hence, the AC/DC power electronic converter should operate either under rectifier or inverter modes. The AC/DC power electronic converter is also operated under the next two conditions: 1-the reactive power expected at the grid voltage bus should be nearly null, 2-harmonics currents often encountered in the grid line currents waveforms should be tolerable. The two latter conditions are fulfilled by using the principle of voltage oriented control (VOC) technique. The performance of the investigated interconnection is simulated in Matlab/Simulink platform. Quite satisfactory results are obtained. The satisfaction about the obtained simulation results persists on being able to integrate easily the wind driven system with the AC grid while extracting maximum power from the wind energy system and having a unity power factor at the AC grid bus and less encountered harmonics in the ac line currents..

Key words. Grid-Tied Wind Energy system; AC/DC Converter; Class C Chopper; Maximum Power Point Tracker; Voltage Oriented Control.

1. Introduction

Even though electric vehicles stations are providing electric energy to electric cars, the main source of energy to such stations is still supplied by the conventional energy sources. Such conventional sources are pollutant sources. To ease or control the undesirable pollution released from such conventional energy sources, alternate renewable energy resources should be thought as primary energy sources. Unfortunately, most (if not all) renewable energy resources suffer from the lack of providing constant power. This is due to the uncontrollable change of the surrounding weather and environmental conditions. The other constraint or obstacle that will be imposed on using only renewable energy resources, that the released energy will be definitely (for sure) insufficient to satisfy the tremendous electric transportation energy demand. A possible and practical solution to overcome the problem of relying on the power generated by the renewable energy resources is to constitute a hybrid DC grid made of a combination of parallel renewable energy resources and interconnect it to the AC grid [1-2]. The DC grid is usually linked to the AC grid through conventional power inverter modules[1-2]. Interconnecting such renewable energy sources with the grid should not harm the performance of the AC grid and that can be possible by respecting standards that have been developed in this regard like the one stated in reference [3]. Most of the developed standards in this regard insist on: 1- controlling the level of harmonics generated by interconnecting power electronics circuitry and injecting them into the AC grid 2- monitoring AC grid bus power factor level. Poor power factor level is manifested by drawing reactive power from AC the grid and consequently creating unnecessary ohmic losses in the AC grid network.

The present article proposes an electric interconnection constituting of a wind driven DC machine, a three phase grid voltage supply, and a DC load representing an electric charging station. It is intended from the wind driven DC machine to participate with maximum powers to the overall active power flow. This is possible by using a class C chopper circuitry [4] controlled properly by a typical maximum power point tracker (MPPT) controller. The three phase grid is connected to the DC bus through an AC/DC converter that can work as a rectifier as well as an inverter. The AC/DC converter operation is controlled by the voltage oriented control (VOC) technique and that is by targeting almost unity power factor level at the AC grid bus and non-generation of harmonic currents in the grid line currents. The DC bus should be kept near desired fixed DC voltage level regardless the needed DC power level by the anticipated electric vehicle.

2. Proposed Energy System

Fig. 1 illustrates the scheme of the proposed energy system. Fig. 1(a) indicates the main blocks and shows the desired active/real power flows. Fig. 1(b) shows the six main components of the system which are (1) A three phase AC voltage source representing the three phase 50-Hz power-grid, (2) a three phase feeder, (3) a three phase AC/DC bridge power electronic converter, (4) a shunt DC load representing an electric charging station connected to a point that is often known as the point of common coupling (PCC), (5) a class C chopper configuration, and (6) a wind driven DC machine in series with a smoothing reactor.

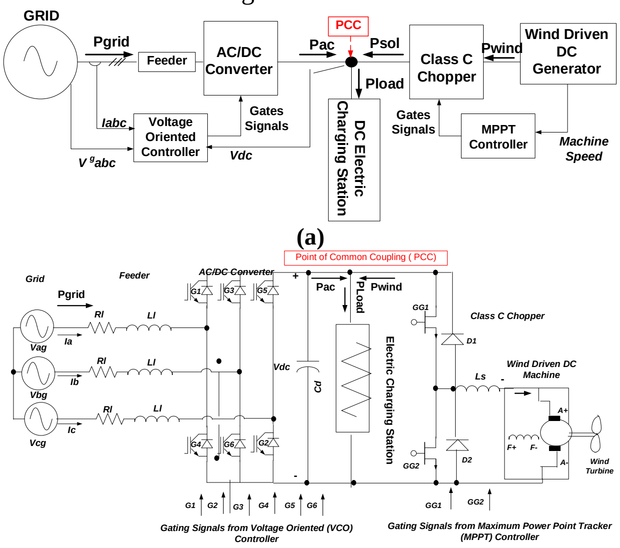

Fig. 1 Proposed Energy System a) One Line Diagram b) Detailed Circuit

Full description of the different blocks of Fig. 1 as well as their controllers is detailed in the next subsections:

2.1 Wind Driven DC Generator

The wind driven DC generator consists of a separately excited DC generator driven by a wind turbine. The DC generator feeds its output electric power to the DC point of common coupling (PCC) through a class C chopper as depicted in Fig. 2(a). This is to prove that by supplying gate signals GG1 and GG2 to the controlled semiconductors switches of the class C chopper configuration, the power is fed to the DC bus side. To satisfy such DC power supply condition, GG1 should be periodic, characterized by a high frequency value, and having a duty cycle less than 50%. The duty cycle value will be decided by the maximum power point tracker controller as will be elaborated later. One notes that GG2 pulse is no more than the complimentary of GG1 pulse.
Figure 2(b) sketched rough patterns of time varying waveforms of the output voltage across the DC machine terminals (vo), the DC armature current (ia) , the DC side current (is) for a certain pretended duty cycle (< 50%) for GG1 pulse. As can be deduced the DC current is always entering the positive pole of DC side bus voltage source, and consequently the power is fed to the DC bus side. . It is worth to note that Class C chopper is operated in quadrant II known usually as the regenerative mode quadrant.

2.1.1 Wind Turbine Power

In order to develop a model to the wind turbine, Betz theory [5] is usually used. Betz assumes that the wind turbine rotor is ideal and that is to say; it has no hub and an infinite number of blades offering no resistance drag to the passage of air.

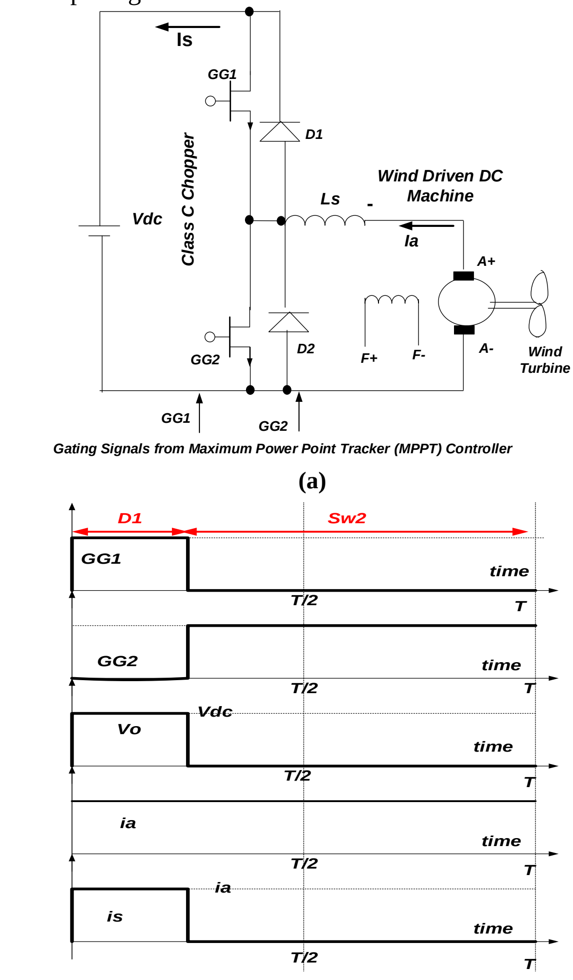

Fig. 2 Wind Driven Machine connected to DC source through Class C Chopper. a) Circuit Connection b) Draft Expected Voltage and Current time varying waveforms

Moreover, the conditions over the whole area swept by the wind turbine rotor are supposed to be uniform and the speed of the air through and beyond the turnine rotor is assumed to be axial. The power of the moving air through the wind turbine rotor can be expressed as [5]:

$$P_o = \frac{1}{2} A_r \rho V_W^3 \qquad (1)$$

A_r represents the swept area by the motor rotor and it will be set in this investigation to $A_r = \pi r^2$.

r represents the radius of the turbine rotor.

ρ: density of the air which may be taken at normal temperature and pressure as equals to 1.25 kg/m^3.

V_w: is the wind speed in meter/second (m/s).

The moving air power (P_o) can be converted partially to a mechanical power. The mechanical power that can be extracted from such moving air power can be expressed as [5]:

$$P_w = P_o C_p$$

$$P_w = \frac{1}{2} A_r \rho \, V^3 C_p \qquad (2)$$

C_p is a dimensionless performance power coefficient and its value is naturally always < 1. There is no radical theoretical basis that can lead to the development of a well defined analytical expression for the power coefficient C_p. Investigators [6] dealing extensively with the subject of wind energy have proposed a handy formula or expression of the form:

$$C_p = C_1(C_2 - C_3 p - C_4 p^x - C_5)\ e^{-C6} \quad (3)$$

where

$C_1= 0.5$, $C_2= 116/\lambda_i$, $C_3=0.4$, $C_4=0.$, $C_5=5$, $C_6=21/\lambda_i$, $x= 1.5$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\,p} - \frac{0.035}{p^3+1} \quad \text{and} \quad \lambda = \frac{r\,\omega_W}{V_W}$$
(4)

ω_W: angular velocity of the wind turbine (rad/sec)

V_W: wind speed (m/s)

r: radius of the rotor of the wind turbine (m) 0 < D < 50 %

p: pitch angle between the blade element with respect to the plane of rotation. Such an angle is fixed in this investigation and is set to be equal to $\pi/180$ radian.

λ: is known as the tip speed ratio.

2.2 Maximum Power Point Tracker (MPPT) Controller

Examining equation 2, one can deduce that for each possible wind speed (V_w) , the extracted wind power (P_w) can be maximized when the power coefficient C_p is maximized. The power coefficient C_p attains its maximum when the condition $dC_p/d\lambda = 0$ is satisfied. Such condition is reached and can be checked when the tip speed ratio λ is equal to 7.97534. Such condition can be deduced from the analysis done in reference [7]. The corresponding value of the coefficient C_p at such tip speed ratio is $C_{p,max} = 0.413815$ [7].

Thus, for the sake of extracting maximum wind power ($P_{w,max}$) at a certain wind speed (V_w), the DC machine speed has to be controlled and made rotating at the following angular velocity:

$$\omega_W = \frac{7.97534 * V_w}{r} \quad (5)$$

The corresponding maximum mechnical power that can be extracted from the wind power is of the form:

$$P_{w,max} = \frac{1}{2} A_r \rho\, V^3 C_{p,max} = \frac{0.4138158}{2} A_r \rho\, V^3 \quad (6)$$

Satisfying equation (5) is done by using the block diagram and flowchart shown in Fig 3. In other words, any proposed control circuitry should guarantee the DC machine speed operation near the vicinity of equation 5 and should be self-adapting at any possible wind speed. In doing so, the possible wind power from the surrounding wind is extracted at the pretended wind speed.

2.3 Voltage Oriented Controller (VOC)

The main objective of the voltage oriented controller (VOC) is to generate desired voltages $V^c_{a,b,c}$ ($V^c_{a,b,c}$=[V^*_a V^*_b V^*_c]) through proper switching states with a certain required phase shift from the grid phase voltages $V^g_{a,b,c}$($V^g_{a,b,c}$=[V_{an} V_{bn} V_{cn} $]^g$ and by keeping the PCC bus DC- voltage shown in Fig. 1 at a certain desired or reference value [8-10].

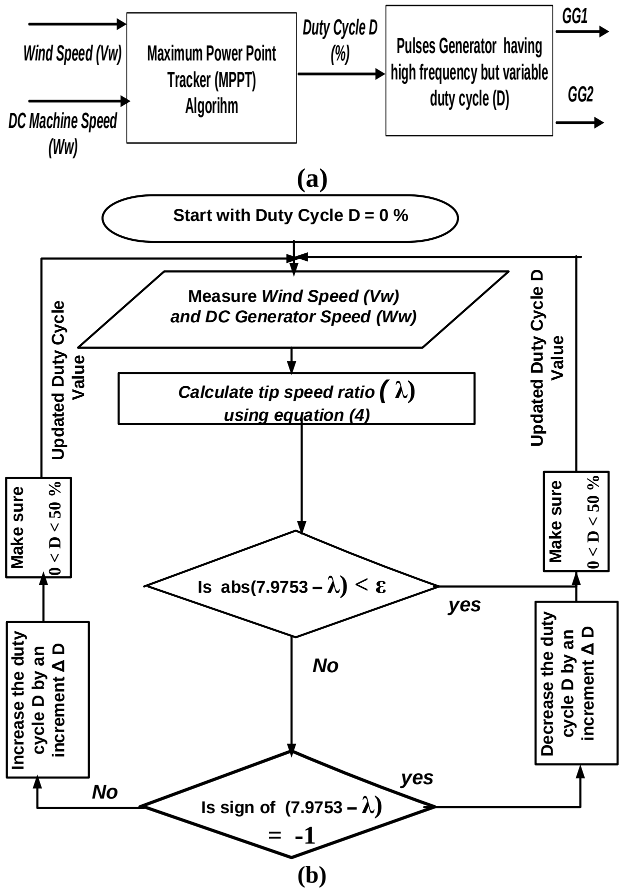

Fig 3. : Class C Chopper Controller a) Maximum Power Point Tracker and Gates Pulses Generation b) Maximum Power Point Tracker (MPPT) Flowchart

Actually, the essence of the voltage oriented control (VOC) technique is to decompose the AC line current into two separate current components responsible of controlling the active and reactive powers flows. Indeed, the line current is split into a q-current component termed i_q and a d-current component termed i_d. Current i_d governs the active power flow while current i_q governs the reactive power flow. A unity power factor condition is obtained if the grid line currents $i^g_{a,b,c}$ are aligned with the grid phases voltages $V^g_{a,b,c}$. This condition occurs when a desired q-current component is set or fixed to zero ($i^*_q = 0$) [11].

Fig. 4 represents the blocks diagram of the voltage oriented controller (VCO) that has been used in this investigation. It consists mainly of five blocks: Phase locked loop, abc-dq transformation, decoupled controller, dq-abc transformation, and PWM blocks. The Phase locked loop serves at finding an angle θ corresponding to the angle between a synchronous rotating d-axis frame and a fixed α-axis frame. The angle θ is used for all abc-dq and dq-abc transformation blocks.

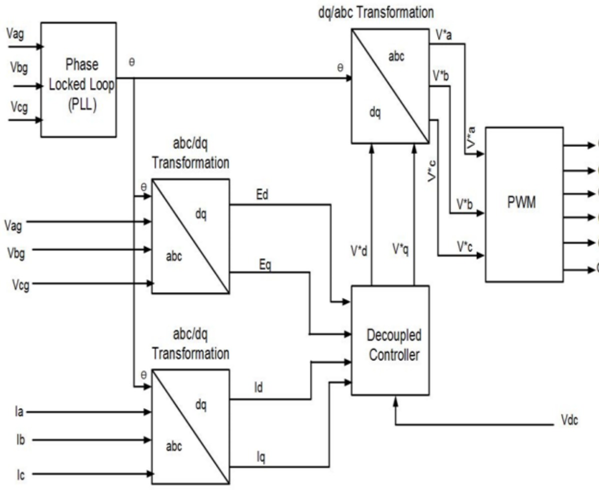

Fig 4. Voltage Oriented Controller (VCO) Block

The angle θ is continuously calculated as follows:

$$\begin{pmatrix}U\alpha\\U\beta\end{pmatrix} = \sqrt{\frac{2}{3}}\begin{pmatrix}1 & 1/2 & 1/2\\0 & \sqrt{3}/2 & -\sqrt{3}/2\end{pmatrix}\begin{pmatrix}Vag\\Vbg\\Vcg\end{pmatrix} \qquad (7)$$

$$\theta = \arctan\left(\frac{U\beta}{U\alpha}\right) \qquad (8)$$

The abc-dq transformation blocks perform their task by executing the following algebraic equations:

$$\begin{pmatrix}Ed\\Eq\end{pmatrix} = A(\theta)\begin{pmatrix}Vag\\Vbg\\Vcg\end{pmatrix} \;\; and \;\; \begin{pmatrix}id\\iq\end{pmatrix} = A(\theta)\begin{pmatrix}ia\\ib\\ic\end{pmatrix} \qquad (9)$$

Where

$$A(\theta) = \sqrt{\frac{2}{3}}\begin{pmatrix}\cos(\theta) & \cos(\theta + \frac{2\pi}{3}) & \cos(\theta - \frac{2\pi}{3})\\ \sin(\theta) & \sin(\theta + \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3})\end{pmatrix}$$

Note Vag, Vbg, Vcg are the grid phase voltages whereas ia, ib, ic are the grid line currents. The content of the decoupled block is shown in Fig. 5. The decoupled controller block contains three Proportional-Integrator (PI) controllers: Two PI current controllers and one PI voltage controller. The intention behind the operation of a proper decoupled controller is to have the measured PCC point DC voltage bus near a pre-set or a reference DC voltage (Vdc,ref). Moreover, the decoupled controller has the duty of forcing the q-component current (iq) of the line currents to be zero (iq,ref=0) when reaching steady state conditions. In doing so the reactive power delivered or absorbed by the grid becomes null. This will correspond to a unity power factor at the power grid bus.

The transformation of the voltage components V_d^* and V_q^*, obtained as outputs of the decoupled controller, to the controlled phase voltages V_a^*, V_b^*, and V_c^* is done through the dq-abc transformation block.

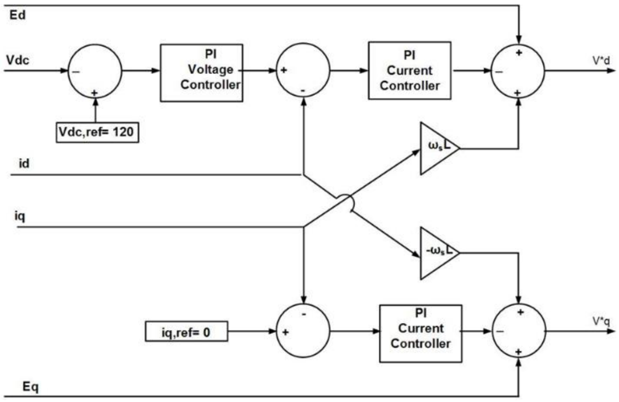

Fig 5. Contents of the Decoupled Controller of Fig. 4

his is done mathematically as :

$$\begin{pmatrix}V_a^*\\V_b^*\\V_c^*\end{pmatrix} = \begin{pmatrix}\cos(\theta) & \sin(\theta)\\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3})\\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3})\end{pmatrix}\begin{pmatrix}V_d^*\\V_q^*\end{pmatrix} \qquad (10)$$

The last three controlled voltages V_a^*, V_b^*, V_c^* are fed as inputs to a pulse width modulation block (PWM block of Fig. 6). The PWM is responsible of generating convenient pulses to the gates of the IGBTs switches of Fig. 1(b). The gate pulses are generated by going through the tabulation of the logic operations or steps shown in Fig. 6.

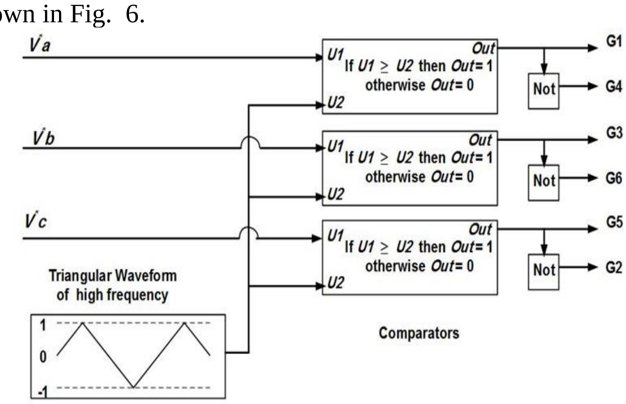

Fig 6. Pulse Width Modulation (PWM) Block Content

3. System Performance

The performance of the proposed energy system of Fig. 1 has been investigated and evaluated via extensive simulation studies done in MATLAB Simulink platform. The used system data are shown in Table 1. The input mechanical power extracted from the wind turbine is fed as an input mechanical torque to DC generator as shown by the next equation (i.e equation 11):

$$\boldsymbol{T_L} = -\frac{0.4138158}{2} A_r \rho \frac{V^3}{\omega_w} \qquad (11)$$

The negative sign in the previous torque equation is to force the DC machine to work as generator. This means that the machine armature current is getting out from the positive terminal of the armature while the machine speed rotation is clockwise .

Table 1. Proposed Energy System Data

Three Phase Power Grid Voltage			
RMS line to line Voltage: 36√3 V		Frequency: 50 Hz	
Feeder			
Series Resistance: Rf =7.7 mΩ		Series Inductance Lf= 10 mH	
Wind Turbine			
Radius R= 2 m	Pitch angle π/180 radian	Air Density 1.25 kg.m²	
Separately Excited DC generator			
Armature winding	Resistance **Ra=** 0.1 **Ω**	Inductance **La=** 150 mH	
Field Voltage **Vf=** 220 V	Field Winding Resistance **Rf=** 110 Ω	Field Winding Inductance **Lf** = 220 mH	
Armature Constant **Kaϕ=** 2 V.s	Inertia Constant **J =** 1 kg.m2	Applied Variable Load Torque $T_L = -\frac{0.4138158}{2} A_r \rho \frac{v^3}{\omega_w}$	
Series smoothing Inductance with DC Generator **Ls=** 750 mH			
PCC Smoothing DC Capacitor **Cd** = 470 μF			
Voltage Oriented Controller (VCO) Reference Values			
Vdc,ref = 120 V		**Iq, Ref** = 0 A	
VCO Decoupled Controller PI Blocks Parameters			
PI voltage controller constants		PI Current controller constants	
Kp = 0.01	**Ki** = 10	**Kp** = 5000	**Ki** = 20000
Class C Chopper			
Gates Pulses Frequency 4000 Hz		Gates Pulses Duty cycle Limited between 0 to 50 %	
DC Bus Representing Electric Vehicles Charging Station Variable Resistance			
R= 36 **Ω** corresponding to a 400 W DC Power Demand.			

Assuming a desired charging station load and pretending a certain surrounding wind speed level, the performance of the proposed hybrid energy system is assessed based on recording the following measurements:

- Active power contributions by Class C chopper, power delivered/generated by the grid systems to the DC bus representing the electric vehicles charging station Bus.
- The voltage level at the PCC DC bus and its comparison with a desired reference bus voltage (Vdc,ref).
- Power Factor value at the power grid bus Grid line currents quality and their Total Harmonic distortion factor (THD)
- The level of the duty cycle of the pulses supplied to the gate of class C chopper controlled switches.

Fig. 7 depicts the pattern of the active or real powers when pretending two surrounding wind speed values. Figs 7(a) to 7(d) represent the assumption of a 400 W, corresponding to choosing R = 36 Ω, at the PCC charging DC bus As can be seen clearly from Fig. 9(b) the Charging bus gets its constant power regardless of the change that may occur in wind speed . Examining Fig. 9(c) and 9(d), one can deduce the wind energy system has injected its real/active power to the PCC point and its amount depends on the surrounding wind speed level. The injected wind power shown in Figs. 9(c) is always near its possible maximum power point (MPP). This demonstrates that the proposed maximum power point tracker (MPPT) controller has adequately performed its intended task. Fig. 9(d) indicates the active or real power drawn from or supplied to the power grid source. Actually, the results depicted in Fig 9(d) indicates that the AC/DC converter played two roles/modes: the role of rectifier when the active power is drawn from the grid and that was at 4 m/s wind speed and the role of inverter when the active power is supplied to the grid and that was a 6 m/s wind speed.

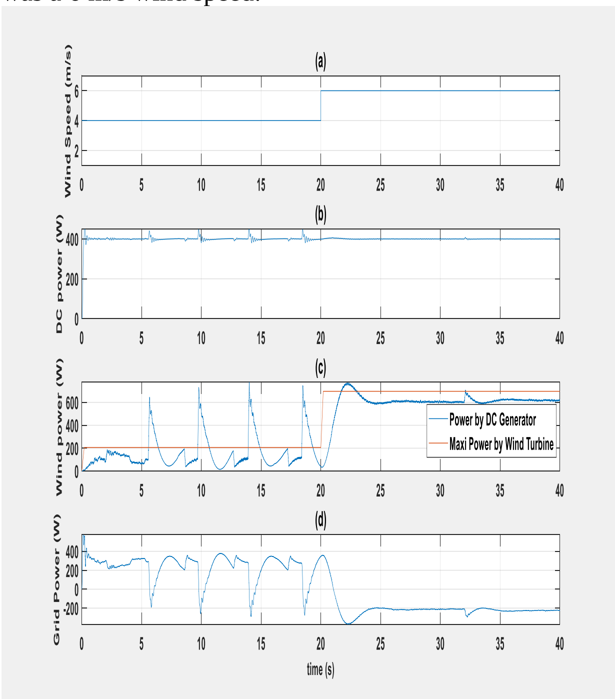

Fig 7. : Active Powers Flow
(a) Pretended Wind Speed Level
(b) Charging Station (PCC) DC Bus Power
(c) Wind Energy System Power Contribution
(d) Grid Power Contribution

Fig. 8 indicates the performance of the voltage oriented controller (VOC). Fig. 8(b) represents the maintainability of the charging station DC bus near its desired reference voltage. Fig. 8(c) depicts the online computation of the power factor at the grid voltage bus. It is clearly shown that when the AC/DC converter plays the role of rectifier the power factor is unity. This is equivalent of saying the grid does not supply any amount of reactive power. Similarly, when the AC/DC converter plays the role of inverter, the power factor is also unity (-1 is shown in Fig. 8(c)) to indicate inverter mode of operation) . Hence the grid does not generate nor absorb any amount of reactive power.

Fig. 9 depicts the performance of the maximum power point tracker. Fig. 9(b) represents the tip speed ratio compared with its desired reference value in guarantying maximum power extraction from the wind energy system. Fig. 9(c) represents the duty cycle level of the pulses needed by GG1 gate. For a 4 m/s wind speed, the duty cycle kept oscillating near 20% value but when for a 6 m/s the duty cycle increased to 30% value. Hence, it is quite clear that such duty cycle level is self-adapted by the proper operation of MPPT controller of Fig. 3.

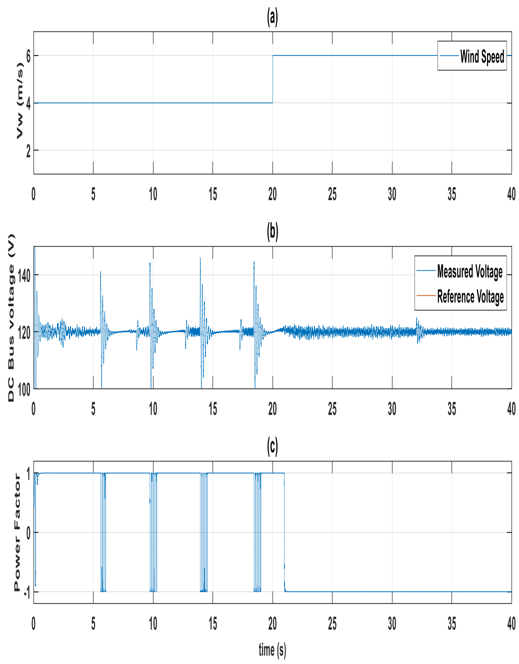

Fig 8. Voltage Oriented Controller (VCO) Performance (a) Pretended Wind Speed Level (b) DC voltage (c)Power Factor at Grid Voltage bus

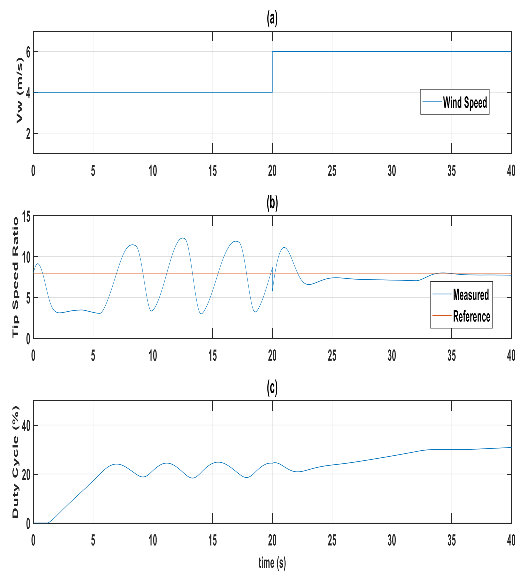

Fig 9. Performance of the Maximum Power Point Tracker (a) Pretended Wind Speed Level (b) Tip Speed Ratio (c) Pulse Duty Cycle Level.

As to the quality of the grid line currents, Figure 10 depicts their steady state time varying waveforms. Fig. 10(b) waveforms were obtained when the wind speed was pretended to be 4 m/s while Fig. 10(d) waveforms were obtained when the wind speed was pretended to be 6 m/s. The obtained THD levels in the obtained grid line currents were calculated and turned to be 6.74 % and 8.20 % for 4 m/s and 6 m/s wind speeds respectively. Such THD levels need to be checked whether they fall-in or not falling-in within the allowable standard limits [3] or [12]. One thing to note also in the obtained grid line currents waveforms is that they are in phase with the phase voltages in the case of 4 m/s wind speed (indicating the rectifier mode) and out of phase in case of 6 m/s wind speed (indicating the inverter mode).

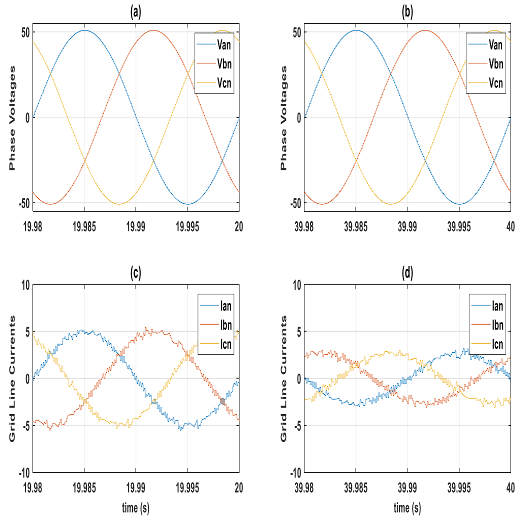

Fig 10. Grid Line Currents Performance: (a) and (b) Grid phase voltages (c) Grid line currents for a 4 m/s wind speed (d) Grid line currents for a 6 m/s wind speed

4. Conclusion

An interconnection of a hybrid energy system consisting of a wind driven DC generator and a three phase AC power grid feeding a DC bus representing a charging power station has been investigated. The proposed configuration contains a class C chopper, controlled by a maximum power point tracker, which connects the wind driven DC generator with the charging station DC bus. The proposed configuration has also an AC/DC converter which connects the power grid with the charging station DC bus. The AC/DC converter was controlled by a voltage oriented (VOC) controller. The AC/DC converter was able to operate in rectifier mode as well as in inverter mode. The voltage oriented controller (VOC) prevented the AC grid from drawing or generating reactive power. Moreover, the voltage oriented controller (VOC) conditioned the quality of the grid line currents waveforms to a certain acceptable extent. Extensive Simulink simulations results had demonstrated and validated the satisfactory performance of the proposed hybrid energy interconnection and that was done by pretending certain scenarios for the surrounding wind speed level and for a certain power demand at the charging station DC bus.

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