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Three Phase Grid Connected Neutral Point Clamped (NPC) Multilevel Inverter Fed by Two Wind Turbines

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ABSTRACT

This paper presents two gear driven wind turbine generators (WTG) feeding a single three level grid connected NPC inverter. Each component of WTG is made up of wind turbine, 2-mass gear drive, permanent magnet synchronous generator (PMSG), AC-DC-AC power converter. A simple advanced hill climbs search (AHCS) maximum power point tracking algorithm that uses the mechanical power from the Wind turbine was developed to generate proper duty cycle for the control of single stage DC/DC boost converter. The DC link voltages are series interconnected and fed to a sinusoidal pulse width modulation (SPWM) controlled high power inverter. The complete model is simulated using MATLAB/SIMULINK software under fixed and fluctuating wind speed conditions. Simulation results have shown that WECs exhibit variability in their output power as a result of changes in their prime movers (wind speed).

Keywords: Advanced hill climb search (AHCS), DC-DC boost converter, neutral point clamped inverter, total harmonic distortion (THD), wind energy conversion system, wind turbine generator

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INTRODUCTION

Every system in the universe requires energy in order to maintain its existence and the need of this energy has been increasing continuously with the growth in population (Sener AGALAR, 2016). For example, Nigeria is one of the highly ranked producer of crude oil in the world, but its exploration has caused so much devastating effects in the environment leading to serious unrest

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by the militants. The result of the unrest is the vandalism of so many oil pipe lines leading to serious decline in the electricity generation in the country which amongst other factors cripples the national economy.

The need for alternatives to the fossil fuels owing to global crisis arising from its rapid depletion, green-house gas emission and restrictions to their extensive utilization due to cost, adverse and hazardous environmental effects has led to rapid development in renewable energy (RE) sources which also enhances new technological trends in the field of power electronics converters.

Wind is a typical source of RE and its use has increased drastically over the last decades. The proposed eyesight of “20% Wind Energy by the year 2030” prepared by the U.S Unit of Energy is one of several reasons that embolden wind power development (Veilleux & Lehn, 2010). The advantages of the wind energy are that; it is cost effective, pollution free, and safe (Bull, 2001). It has proven to be the best choice among the RE sources. This paper is focusing on the wind energy conversion systems (WECS) to meet the world energy demand. The wind energy is obtained by the system consisting of a wind turbine, a generator, power electronic converters and control systems. Power electronic converters play a vital role in obtaining high efficiency and good performance of the WECS (Porselvi & Muthu, 2014) and their developments have tremendously enhanced the active and reactive power control at the grid.

However, with this conspicuously growth and the requirement for extra energy demand, single wind turbine generators (WTG) in isolated places are being substituted with arrays of WTGs, forming wind farms. Among the importance of wind farms are; spatial averaging, enhanced capacity and centralized control. Numbers of ways that have been suggested to connect WTGs in a wind farm to the grid can be found in (Chompoo-Inwai et al., 2005; Reidy & Watson, 2005). The interconnection of individual wind turbine generator via a separate DC/AC inverter and with a provision for an optional transformer is one of the simplest method of achieving a wind farm (Reidy & Watson, 2005). Due to the increased number of system units, the failure rate is increased and hence the unreliability. However, interconnection of the DC link voltages has been suggested (Jayasinghe et al., 2010; Nishikata & Tatsuta, 2010; Veilleux & Lehn, 2010). Under this topology, rectified outputs of individual WTGs are connected to a common DC bus either in parallel connection or series connection and fed to a single inverter. Thus, making the system very simple, and the inverter can be placed everywhere without restraint. By that, an optimum site can be selected for wind turbine/generators with a long-distance DC transmission line (Nishikata & Tatsuta, 2010). Another advantage of this topology from economic point of view is that, the cost of system installation and maintenance is reduced and this directly translates to reduction in cost per KWhr of electricity sold to the consumers.

Multilevel inverter represents the driving force in achieving a high voltage, high power in today's RE integration, most especially in wind energy conversion systems. Multi-level inverter (MLI) has the following advantages over two-level inverter; Reduction in Total harmonic distortions (THD), reduced stress on the power switches, modular structure, improved efficiency, smaller output AC filter requirement and lower electromagnetic interference (Do & Nguyen, 2018; Samadaei et al., 2018). In literature, various topologies that have been investigated are; Neutral point clamped (NPC) inverter, diode clamped that was derived from NPC, Flying capacitor, and cascaded H-bridge inverter (Guo et al., 2018; Peng et al., 2010). Cascaded H-bridge inverter has advantages of eliminating capacitor voltage balancing problem and have modularized bridge structure but has serious limited applications in WECS because of the number of DC sources required. Higher number of levels results in reduced harmonics and external filter may not be necessary while adopting flying capacitor topology but is faced with the challenges of complicated switching control and very expensive capacitors. Among the various multi-level inverter topologies, NPC has always been the preferred choice in wind energy applications and has been selected in this paper because of its relatively simple method of control, requiring only one DC source, and high efficiency for fundamental switching frequency.

In order to make optimal use of the available wind energy, variable wind turbine is explored and this can be achieved using doubly fed induction generator (DFIG) or permanent magnet synchronous generator (PMSG). Compared to DFIG, PMSG has the following qualities; its generator has an improved efficiency because of the low rotor losses, generator can be brushless and the grid-fault ride-through capability is less complex (Li & Chen, 2008; Yaramasu et al., 2017), no requirement for excitation and gear drive. Actually, PMSG has the demerit of requiring large converter sizes (100% of rated power compared to 30% of DFIG) but it is still better in terms of overall system efficiency and reliability and is mostly used in modern wind energy conversion systems. Several PMSG based WECS have been proposed (Aliprantis et al., 2000; Nishikata & Tatsuta, 2010; Samanvorakij & Kumkratug, 2013) and different ways of optimizing the aerodynamic power have also been discussed in (Eltamaly et al., 2013).

This paper presents a comprehensive investigation of the proposed topology, which employs series interconnection of the DC link as shown in Figure 1. Uncontrolled rectifier has been used for the AC/DC conversion because of its simplicity. The two-stage voltage source inverter (VSI) with a boost converter is the conventional solution for renewable energy systems (Nguyen et al., 2019). A simple advanced hill climbs search (AHCS) algorithm has been incorporated within each wind turbine to generate the duty cycle necessary for the control of DC/DC Boost power converter and the optimization of aerodynamic power. The AHCS concept is essentially an ''observe and perturb" concept that is used to traverse the natural power curve of the turbine. A single high-power inverter is therefore used to connect the DC link interconnection to the grid via an LC line filter to assist in the reduction of total harmonic distortion (THD).

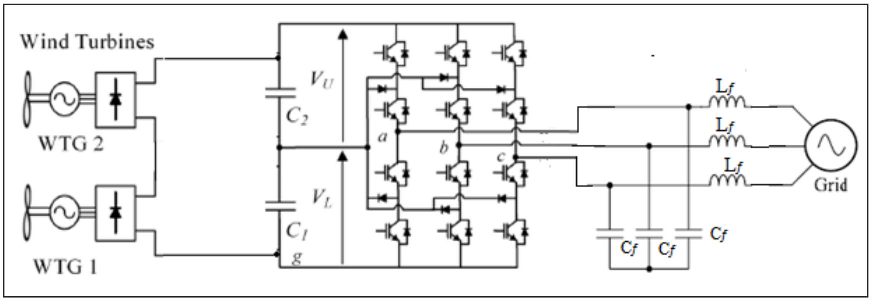


Figure 1. Schematic of the proposed model

MATERIALS AND METHODS

The block diagram of the proposed model is shown in Figure 2. It is made up of two WTGs, each consisting of aerodynamic unit, drive train, AC-DC-AC power converters. The DC link of the two WTGs were series interconnected and fed to an inverter module.

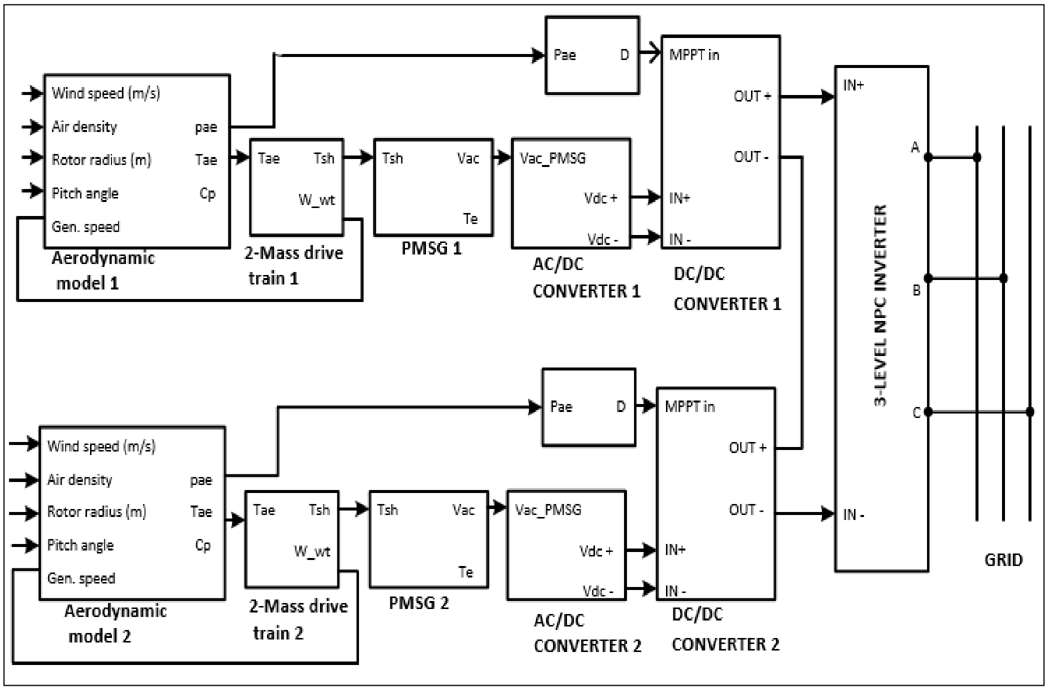


Figure 2. Complete block diagram of the proposed model

Mechanical output power (P_m) of the wind turbine is given by (Samanvorakij & Kumkratug, 2013) as follows;

$$P_m = \frac{1}{2}\rho A v_w^3 C_p(\lambda,\beta) \qquad (1)$$

The mechanical torque developed by the wind turbine T_m, and the tip speed ratio (λ) of the wind turbine are given by the following equations;

$$T_m = \frac{P_m}{\Omega} \qquad (2)$$

$$\lambda = \frac{\Omega R}{v_w} \qquad (3)$$

Where R is the turbine radius and Ω is the angular velocity (rad/sec) of the turbine. There are numbers of fitted equations for power coefficient, C_p, but a more generic one is given as (Eltamaly et al., 2013);

$$C_p(\lambda,\beta) = 0.5176\left\{\left(\frac{116}{\lambda_i}\right) - 0.4\beta - 5\right\}e^{-\frac{21}{\lambda_i}} + 0.0068\lambda \qquad (4)$$

Where; $\lambda_i = \dfrac{1}{\lambda + 0.08\beta} - \dfrac{0.035}{1+\beta^3}$

In this study, pitch angle, β was set to zero.

Gear train is important in WECs due to the large speed difference between the wind turbine and the generator. In this paper, two mass models were considered. Figure 3 illustrates the schematic of two mass drive train models. The self-damping (D_t) is used to cancel any oscillations that exists in the turbine blade. The generator self-damping (D_g) is the mechanical friction and windage. The mutual damping (D_m) represents balancing dynamics that exists due to varying speeds between the generator rotor and the turbine shaft. Turbine and generator self-damping can be neglected and the resulting mathematical models are given by Aliprantis et al., (2000); and David, (2010).

$$\frac{dw_t}{dt} = \frac{1}{2H_t}(T_m - T_e) \qquad (5)$$

$$\frac{1}{w_{ebs}}\frac{d(\theta_t - \theta_r)}{dt} = w_t - w_r \qquad (6)$$

$$T_e = K_s(\theta_t - \theta_r) + D_t\frac{d(\theta_t - \theta_r)}{dt} \qquad (7)$$

Where;

K_s = Stiffness constant; w_t and w_r are turbine and generator rotor speeds in per units; θ_t and θ_r are turbine and generator angular displacements in rads; T_e = shaft torque.

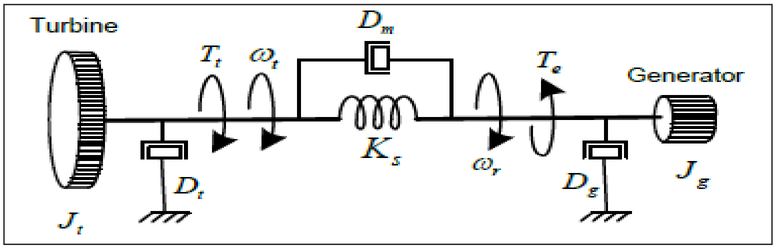


Figure 3. Two-mass drive train model of a wind turbine

Implementation of AHCS Algorithm

Advanced hill climb search MPPT algorithm was used to optimize the aerodynamic power without necessarily requiring wind speed data, it is a sensor-less MPPT controller. The AHCS control algorithm continuously searches for the maximum power of the wind turbine. The optimum power can be derived from WTG without necessarily requiring information about the wind and generator speeds (Eltamaly et al., 2013).

This paper uses a speed control loop concept where the present power is directly compared to the previous power. The MPPT block uses the mechanical power from the Wind turbine model to generate proper duty cycle, which is fed to the DC/DC converter circuit. The time period for which this signal should be ON is generated by the embedded block and is given to the comparator. The comparator output signal is the duty ratio (d) for the boost converter. This block contains an MPPT algorithm which is programed based on the flow chart shown in Figure 4.

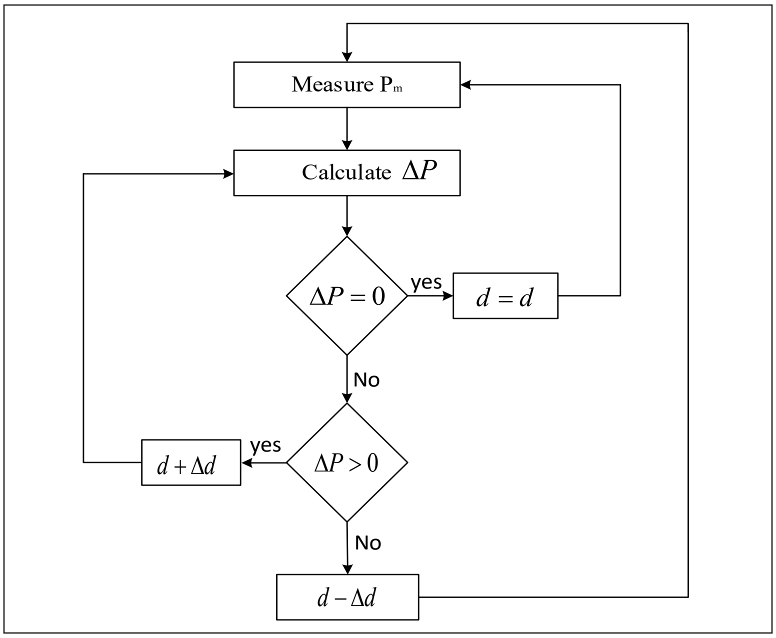


Figure 4. Flow chart of the MPPT algorithm

The three conditions programmed are;

Condition 1: if $\Delta P_m > 200$ then $d = d + \Delta d$

Condition 2: if $\Delta P_m < 200$ then $d = d - \Delta d$

Condition 3: if $\Delta P_m = 200$ then $d = d$

Where;

200 = Reference speed; ΔP_m is the difference between the current power and the previous power; d is the ON time of the duty cycle; Δd is the change in the ON time of the duty cycle. The new power is passed after a delay of sometime and the duty cycle changes till it reaches the optimum condition ($\frac{dP}{dw} = 0$) i.e it extracts the optimum power for the corresponding wind speed.

Design of DC/DC Boost Converter for Continuous Current Mode (CCM)

DC/DC Boost converter is a necessary component for achieving an AC-grid wind turbine. They are used to raise and achieve a stable output DC voltage from a varying input rectifier voltage resulting from wind variations. They also play a vital role in maximizing power generation even at low wind speeds. The objectives here are to design a boost converter with reduced cost, and small settling time. The parameters in Table 1 below are defined by the design specification operating in the Continuous Conduction Mode (CCM).

Table 1
Boost converter design specifications

Design specifications for CCM		
Parameters	**Symbols**	**Values**
Input voltage (Volts)	V_i	100 - 600
Output Voltage in (Volt)	V_o	700
Switching Frequency in (kHz)	f_s	100
Output Power in (KW)	P_o	12.5
The voltage ripple in Volt, $V_r / V_o = 2$ %	V_r	14

The lowest or critical value of inductance for CCM operation is given as;

$$L_{crit} = \frac{R_{max} D_{max}}{2 f_s}(1 - D_{max})^2 \quad for\ D_{min} < \frac{1}{3} \qquad (8)$$

Minimum capacitance value for CCM operation can be obtained using equation (9).

$$C_{min} \geq \frac{D_{max} V_o}{f_s R_{min} V_r} \qquad (9)$$

Detailed information on the design of DC/DC boost converter can be obtained in (Mohamed et al., 2013). Figure 5 shows the complete design schematic of AC-DC, DC/DC converters with gate signal control.

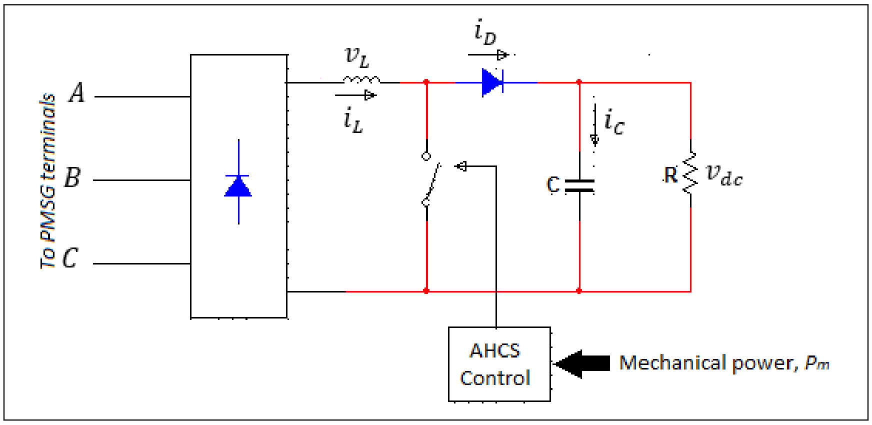


Figure 5. Diode rectifier and DC boost circuit

Inverter performance is influenced by switching strategy, and relate to output voltage harmonic content. There are numbers of inverter switching control techniques, but phase deposition sinusoidal pulse width modulation (PDSPWM) technique has been used in this paper. A high frequency triangular career signal was compared with a low frequency sinusoidal modulating signal to generate gate signals for the control of power switches.

Design of LC filter

In order to reduce grid harmonics injected by the grid connected power converters, LC line filter has been adopted. In most cases, only the output voltage harmonic is explicitly stated. However, the unique value of LC filter cannot be solely specified based on output voltage harmonics. Equations (7)-(9) are derived based on additional criterion that is also based on minimization of reactive power which indirectly minimizes sizes, losses and cost of the filter (Bhende et al., 2011; Dahono & Purwadi, 1995).

$$K = \sqrt{\frac{\left(k^2 - \frac{15}{4}k^4 + \frac{64}{5\pi}k^5 - \frac{5}{4}k^6\right)}{1440}} \tag{10}$$

$$L_f = \frac{V_o}{I_o f_s}\left\{K\frac{V_{dc}}{V_{o,av}}\left[1 + 4\pi^2\left(\frac{f_r}{f_s}\right)^2 K\frac{V_{dc}}{V_{o,av}}\right]\right\}^{1/2} \tag{11}$$

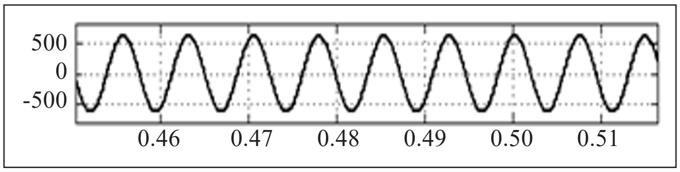
$$C_f = K\frac{V_{dc}}{L_f f_s^2 V_{o,av}} \tag{12}$$

Where; k =Modulation index
V_o = Load voltage (rms) in volts
I_o = Nominal current (A)
$V_{o,av}$ = Total harmonic load voltage= 5% of V_o
f_r = Fundamental frequency =50Hz
f_s = Switching frequency = 100 KHz
L_f= Filter Inductance
C_f= Filter Capacitance

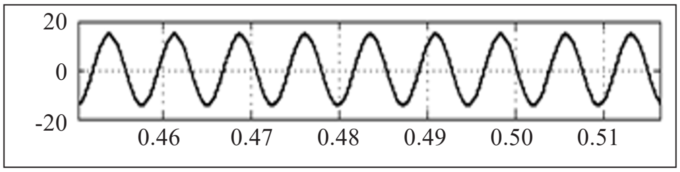
RESULTS AND DISCUSSIONS

The simulations had been carried out using MATLAB/ SIMULINK software at a wind speed of 9m/s and the parameters for the modelling of the drive train, PMSG and wind turbine are as given in Appendix A. Figure 6 illustrates the result for PMSG line voltage and line current without AC-DC-AC converters connected to its terminals. Figure 7 illustrates three phase voltage of PMSG with phase shift of 120 degrees between any two phases.

The simulation results for the control of DC/DC converter using AHCS algorithm is shown in Figure 8. Figure 8(c) illustrates the duty cycle characteristics, by changing d, the



(a)



(b)

Figure 6. PMSG output without AC-DC-AC converters:(a) line voltage; and (b) line current

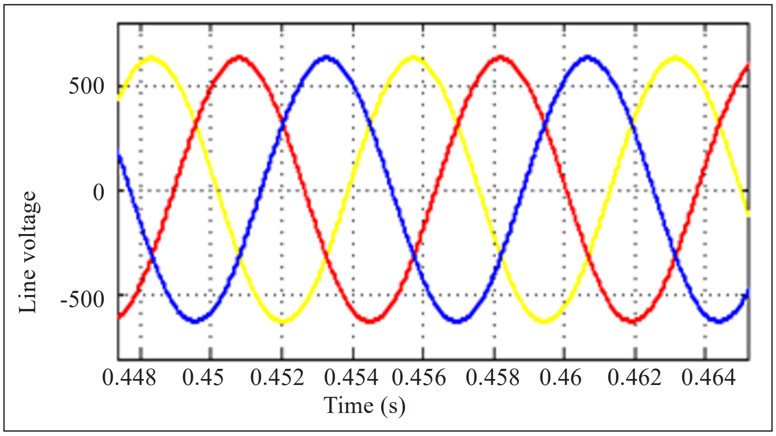
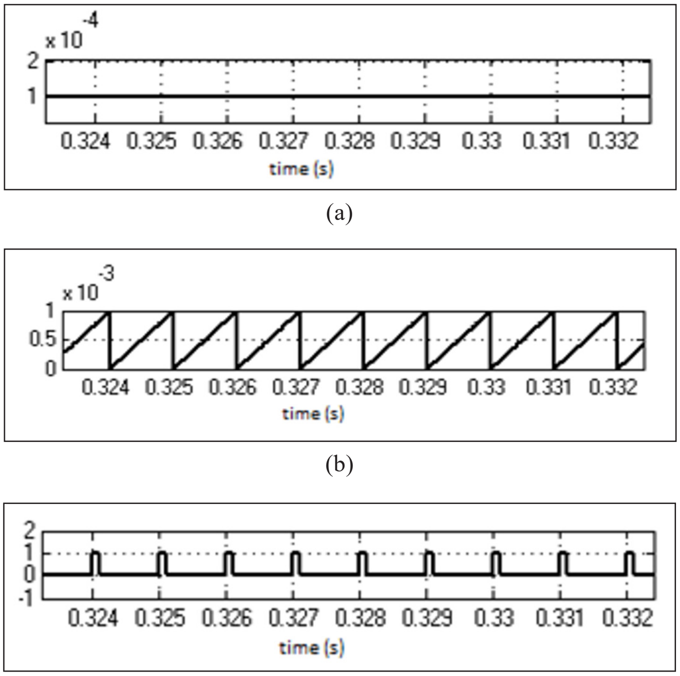


Figure 7. Three phase line-line output voltage of PMSG without power converters

aerodynamic power is changed accordingly and can be optimized. The input and output voltages of the proposed boost converter for continuous current mode at steady state is shown in Figure 9. At a wind speed of 9 m/s, the boost converter input voltage was stepped up from 556.7 Volt to an output voltage of 636.5 Volts. Before the steady state, the DC voltages follow through a transient process which is basically as a result of voltage build up (excitation) process in PMSG.



(a)

(b)

(c)

Figure 8. (a) ON time; (b) sawtooth waveform; and (c) switching pulses

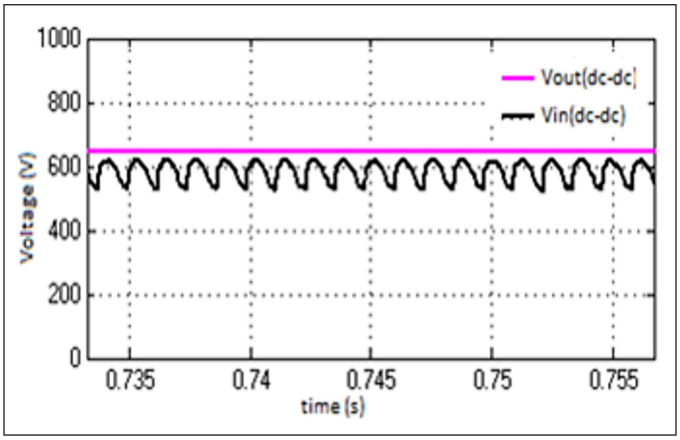


Figure 9. Input and output voltages of DC/DC boost converter

Figure 10 shows the output line voltage of three level NPC inverter. The positive voltage levels corresponds to $0, +\frac{1}{2}V_{dc}, +V_{dc}$, while the negative output voltage level corresponds to $0, -\frac{1}{2}V_{dc}, -V_{dc}$, all totaling to a five levels.

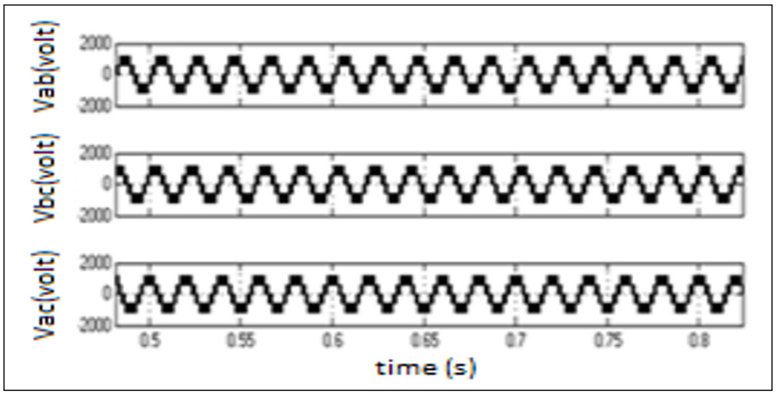


Figure 10. Three phase grid voltage (V_{ab}, V_{ac} and V_{bc}) before filtering

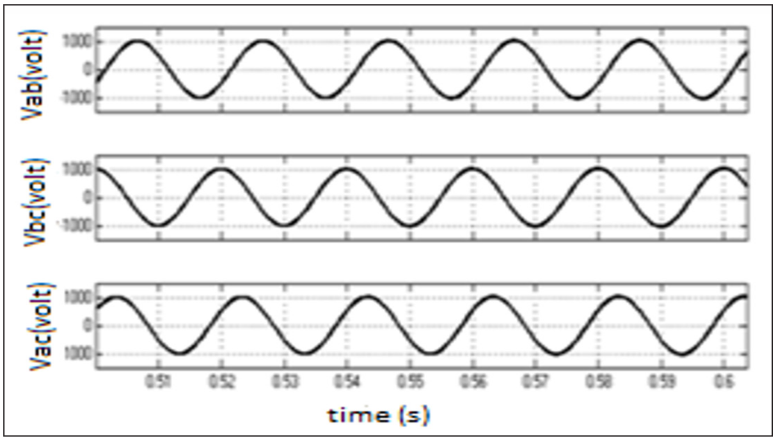
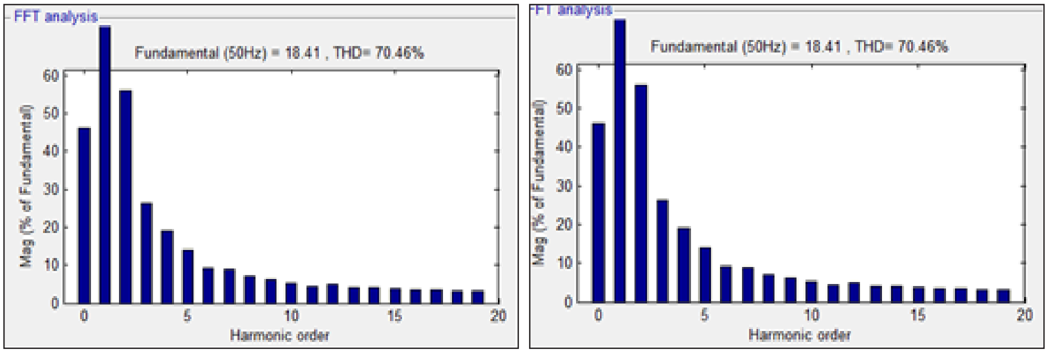


Figure 11. Three phase grid voltage (V_{ab}, V_{ac} and V_{bc}) after LC filtering

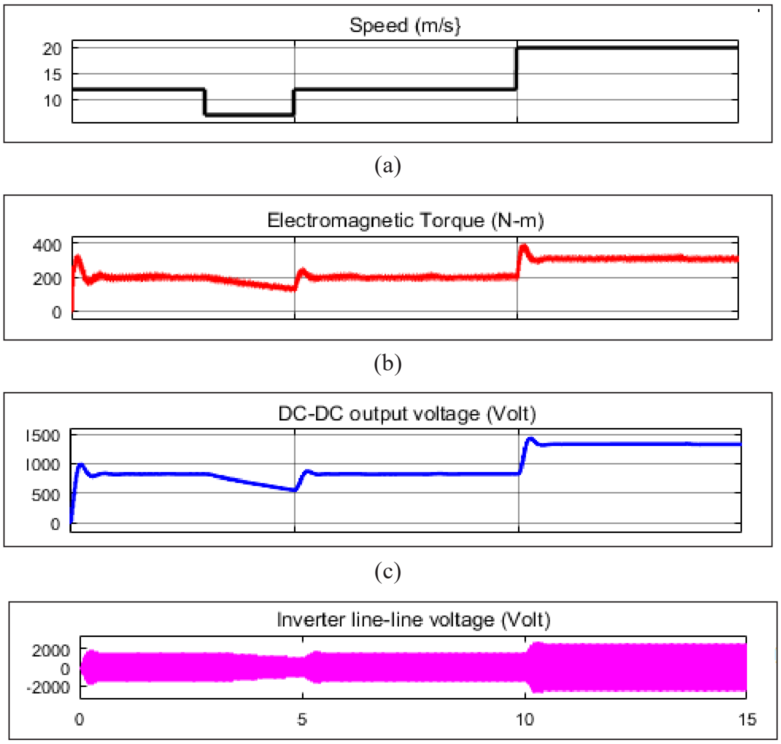
The response is sinusoidal-like and will therefore have a less total harmonic distortion (THD) compared to 2-level inverter. The more the number of levels, the more the response is sinusoidal-like and the less will be the THD. The ouput line to line voltages of the inverter after LC filtering is shown in Figure 11, which is typical of grid voltage. Figure 12 illustrate the voltage THD at the grid before and after the connection of LC line filter which are respectively obtained to be 70.46% and 37.40%.

The results show that the WECs parameters varies in accordance with the wind speed (Figure 13). The effect of this is the variation in operating temperatures which will consequently lead to variation in power losses of the power converters (PC) thereby heightening the unreliability.



(a) (b)

Figure 12. Voltage THD at the grid: (a) before filtering; and (b) after filtering



(a)

(b)

(c)

(d)

Figure 13. Impacts of wind speed fluctuations on WECS parameters: (a) wind speed variations; (b) electromagnetic torque; (c) DC-DC output voltage; and (d) inverter line-line voltage

In general, interfacing power converters with PMSG introduces low frequency harmonics which tends to distort output wave form of the PMSG and also heighten the level of grid THD. Multilevel inverter and line filtering are used to complement each other in combating level of grid THD. LC line filter is effective but it does have an effect of imposing limitations to the grid voltage.

CONCLUSIONS

In this paper, a topology to connect two wind turbine generators (WTGs) to the grid using only one 3-level NPC inverter has been suggested. Advanced hill climbs search (AHCS) MPPT algorithm was developed to generate proper duty cycle for the control of single stage DC/DC boost converter. In the proposed system, the outputs of the DC/DC converter of each WTG were connected in series to provide a single DC source for the high-power inverter**.** It was assumed that the two WTGs are similar in all respect so that the voltage across the DC link capacitors is twice the output voltage from any one of the WTG. The proposed system was simulated using MATLAB/SIMULINK and the results for all the parameters verified were satisfactory. The NPC inverter was controlled using SPMW technique and the output voltage was obtained to be three levels. Simulation results had also shown that WECs demonstrated variability in its parameters owing to variations in wind speeds. This introduces a new factor of ambiguity on the grid and constitutes a lot of problems to the power system grid integrity i.e. power system security, power system stability and power quality.

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