A Practical Model and an Optimal Controller for Variable Speed Wind Turbine Permanent Magnet Synchronous Generator

Najmeh Rezaei[1], Kamyar Mehran[2] and Calum Cossar[3]

Abstract— **The aim of this paper is the complete modeling and simulation of an optimal control system using practical setup parameters for a wind energy conversion system (WECS) through a direct driven permanent magnet synchronous generator (D-PMSG) feeding ac power to the utility grid. The generator is connected to the grid through a back-to-back PWM converter with a switching frequency of 10 KHz. A maximum power point tracking (MPPT) control is proposed to ensure the maximum power capture from wind turbine, and a PI controller designed for the wind turbine to generate optimum speed for the generator via an aerodynamic model. MATLAB/Simulink results demonstrate the accuracy of the developed control scheme.**

Index Terms— **MPPT, PI controller, PMSG, WECS.**

I. INTRODUCTION

Wind energy is a clean and renewable energy source. In recent years, many wind turbine generation systems (WTGS) have been installed in many countries from the viewpoints of global warming and depletion of fossil fuels. In addition, WTGS have lower overall costs in comparison with other renewable generation systems [1]. Since the late 1990s, variable speed constant frequency (VSCF) wind energy conversion systems (WECS) have been widely adopted in order to maximize wind energy utilization [2]. Compared to other wind turbine systems used for commercial power generation, the accelerated evolution of the direct-driven wind turbine (WT) with a permanent magnet synchronous generator (PMSG) is attributed to its simple structure, no gearbox requirement, low cost of maintenance, high conversion efficiency and high reliability [3].

Increasing the average energy production (AEP) in wind power is mainly due to developments in integrated power electronic modules. Over the last few years the conduction/switching losses in power device modules have reduced significantly with a corresponding reduction in high power converters/inverters losses. As a result, the full rating inverter/converter-based wind energy conversion system using the permanent magnet synchronous generator (PMSG) has become widely-used [1].

The WECS considered under this study is called a direct drive permanent magnet synchronized generator. The three-phase D-PMSG converts the mechanical power from the wind turbine into variable voltage/frequency ac electrical power, which is then converted to dc power through a PWM rectifier with a dc link allowing an optimal power extraction by the use of an MPPT algorithm. A pulse width modulation (PWM) inverter ensures the injection of produced power with constant voltage and frequency to the power grid.

The main advantages of this structure are the full decoupling between two inverters, and for grid disturbance, the grid side converter is controlled to support the voltage recovery by supplying reactive power while it secures the transient grid stability [4]. Several control techniques suggested in the literature for MPPT including optimum tip speed control, hill climbing and search, power signal feed-back method, fuzzy logic and neural networks [5]. In this study, a version of optimum tip speed control is implemented to fit in our practical setup measurement and produce the maximum power tracking. Several PI controllers are used to control the converter parameters. Proportional-Integral-Derivative (PID) control is the most common control algorithm used in industry and has been universally accepted in the industrial control. The popularity of PID controllers can be attributed partly to their robust performance in a wide range of operating conditions and partly to their functional simplicity, which allows engineers to operate them in a simple, straightforward manner [6]. A PID controller is the feedback loop controlling mechanism to reduce the error of a measured process value to reach a desired set point. [7].

There have been numerous papers outlining the optimisation of energy production in wind turbines at an overall system level [8-10]. To compliment these studies this paper focuses on the inner control loops of the generator using real machine parameters and laboratory optimised control algorithms to explore actual generator performance for a variable wind regime.

II. SYSTEM DESCRIPTION AND MODELING

A. Block diagram of the proposed system

The typical structure of a direct-driven PMSG WT system is shown in Fig.1. The control scheme of PMSG is a complete

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back-to-back convertor between the PMSG and power grid with an intermediate storage capacitor. This converter connects the stator winding of the synchronous generator to the grid. Typically, the Machine-side converter (MSC) controls the active and reactive power output of the PMSG. In contrast, the Grid-side converter (GSC) maintains the dc-link voltage and controls the reactive power exchange between the dc link and the grid, i.e., the GSC transfers the active power extracted from the wind turbine to the grid at an adjustable power factor. The dc chopper circuit, which consists of power electronic modules and dump resistors connected in series, is used to maintain a stable dc-link voltage during power grid faults [11].

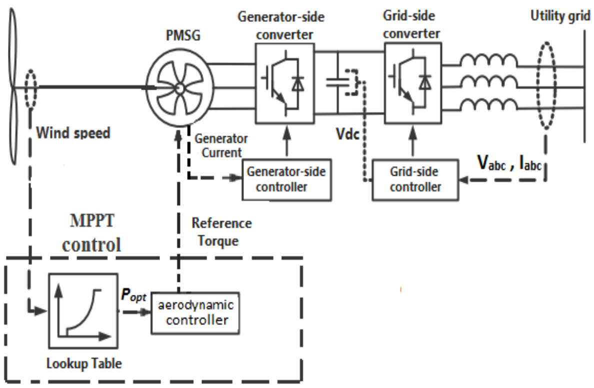

Fig. 1. Block diagram of the system.

B. Wind Turbine Aerodynamics Modeling

In the wind energy system, mechanical energy is captured in the airflow and converted to electrical energy. Wind turbine controllers are very important for both machine operation and power production. They include sensors, controllers, power amplifiers, switches, actuators and computers /microprocessors [12]. A wind turbine must generate electricity at different wind speeds; therefore multiple control systems need to be implemented. To control the output power of wind turbine, there are several ways which depend on the design of the wind turbine and its parameters. Torque control is chosen for this study as one of the standard control methods. The wind turbine structure for the model is shown in Fig. 2.

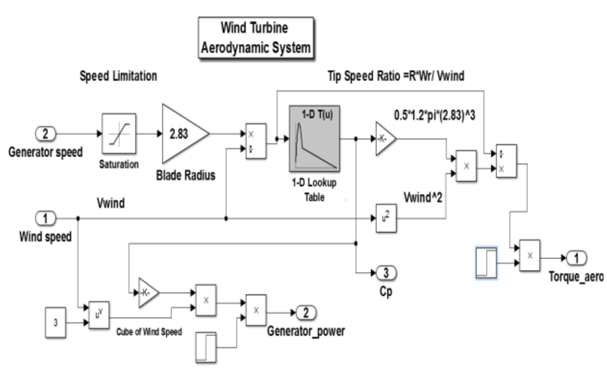

Fig. 2. Wind turbine structure.

The amount of kinetic energy in the air flow that can be captured depends on the size of the wind turbine and wind speed. This mechanical power, P_{MECH}, can be expressed by:

$$P_{MECH} = 0.5\, \rho_{AIR}\, \pi\, R^2\, C_P(\lambda, \beta)\, V_{WIND}{}^3. \tag{1}$$

where ρ_{AIR} is the air density (i.e., 1.225 kg/m^3), R is the blade radius (m), V_{WIND} is the wind speed (m/s), C_P is the power efficiency coefficient that is a highly nonlinear power function of tip speed ratio λ and the blade pitch angle β; and

$$\lambda = \frac{R\, \omega_t}{V_{WIND}}. \tag{2}$$

where ω_t is the rotor angular speed of the wind turbine and R is the rotor blade radius. The pitch angle (β) indicates how the wind velocity impacts the wind turbine blades. The pitch angle is the angle between the wind flow direction and the turbine blade. When $\beta = 0$ the blade is fully impacted by the wind velocity, and the wind turbine will capture the maximum power in the wind. It can be shown that the theoretical static upper limit of C_P is 16/27 (approximately 0.593). This means theoretically we can extract about 59.3% of the kinetic energy of the wind (Betz's limit) [13].

Assuming a constant wind speed, V_{WIND}, the tip-speed ratio, λ, will vary proportionally to the rotational speed of the wind turbine rotor. If the $C_P(\lambda, \beta)$ curve is known for a specific fixed pitch wind turbine with a turbine rotor radius R it is easy to construct the curve of C_P against rotational speed for any wind speed, V_{WIND}. Therefore, the optimal operational point of the wind turbine at a given wind speed V_{WIND} is determined by tracking the rotor speed to the point λ_{opt} [13].

$$\lambda_{opt} = \frac{R\, .\, \omega_t}{V_{WIND}} \rightarrow \omega_{t_{opt}} = \frac{\lambda_{opt}.V_{WIND}}{R}. \tag{3}$$

For every value of wind speed V_{WIND}, there is an optimum rotor speed $\omega_{t_{opt}}$ which produces maximum power recovered from the wind turbine. By considering the torque in (4) where P_{MECH} is mechanical power in Watts and ω_t is angular velocity in rad/sec; the aerodynamic mechanical torque on the rotating shaft in (Nm) unit can then be calculated as:

$$\Gamma_m = \frac{P_{MECH}}{\omega_t}. \tag{4}$$

$$\Gamma_m = \frac{0.5\, \rho_{AIR}\, \pi\, R^2\, C_P(\lambda, \beta)\, V_{WIND}{}^3}{\omega_t}. \tag{5}$$

It is essential to maintain $\omega_t = \omega_{t_{opt}}$ to maximize P_{MECH}, which is an objective of the maximum power point tracking (MPPT) control. This means C_p has to reach its maximum value $C_{p\,max}$, so the maximum power is extracted from the wind. This is implemented by controlling the electrical rotational speed of the generator rotor ω_e, which has the following relationship with ω_t:

$$\omega_e = N_{pp}\omega_m \qquad (6)$$

where N_{pp} is the number of pole pairs in the PMSG, and ω_m is the mechanical rotational speed of the generator rotor [13]. This mechanical speed (ω_m) accelerates or decelerates with respect to wind turbine driving the following torque equation [14]:

$$\Gamma_e - \Gamma_m = J_{eq}\frac{d\omega_m}{dt}. \qquad (7)$$

where Γ_e and Γ_m are the electromagnetic and the mechanical torque of the generator, respectively, and J_{eq} is the total equivalent inertia of the generator (the turbine inertia plus the generator inertia).

C. Machine-Side Converter Controller Model

Machine-side converter (MSC) controller regulates the speed of the generator to work at the maximum power point and defines the required current. It has two sub-systems, one is to regulate the generator speed and the other is to control the current. It consists of three PI controllers. In the speed controller block (Fig. 3), the actual rotor speed of the generator is compared with a reference speed and then by using a PI controller the reference current for the current controller block is defined. In the current controller block (Fig. 4), the rotor position works as an input for the sine wave function blocks to generate the proper current references and is subsequently decoded to create the commutation signals for upper and lower phase gate drivers in the generator side converter. This is implemented by a sine-triangle pulse width modulation (STPWM) controller. The output signal of the PI controller is compared with a high frequency (10 kHz) triangular signal to generate the control signals for the converter switches. In the PWM system, the sinusoidal control waveform establishes the desired fundamental frequency of the inverter output, while the triangular waveform establishes the switching frequency of the inverter. To investigate the required phase relationship between the generator back electromotive force (EMF) and the switch commutation control signals, a star connected resistor network with the inverter disconnected from the generator is carried out. In addition, a hysteresis current control is added to control the upper phase leg switches.

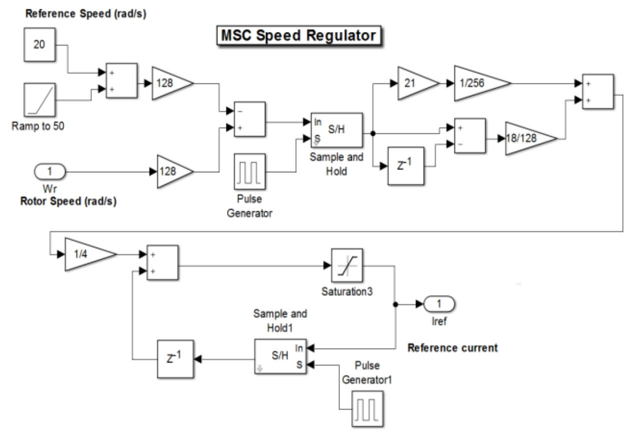

Fig. 3. Machine-side converter (MSC) speed regulator.

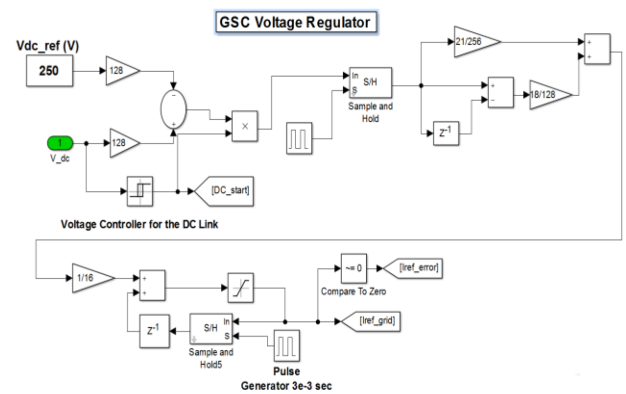

Fig. 5. Grid-side converter (GSC) voltage regulator.

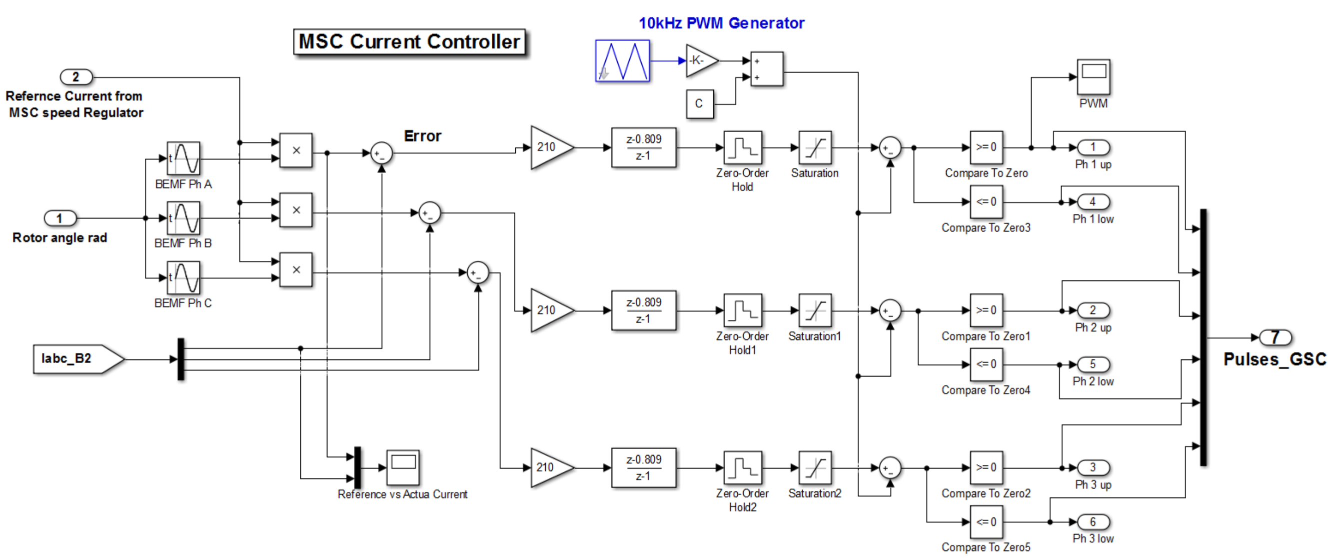

Fig. 4. Machine-side converter (MSC) current regulator.

D. Grid-Side Converter Controller Model

The main objective of grid-side converter (GSC) controller is to maintain constant dc voltage in the dc bus and providing the power requirement. it has two sub-systems, current controller and voltage regulator. In the grid side current regulator, the grid phase voltages determine the phase of the reference currents (the PM machine is generating). To maintain system stability, there must be a dc link voltage controller, controlling the amplitude of the current that is injected into the grid. The dc link controller regulates the relevant voltage at a given reference level as shown in Fig. 5.

III. Simulation Analysis and Result Discussion

A PMSG-based WECS is implemented to investigate the effectiveness of the proposed control scheme. PI controller parameters, obtained by an experimental setup of the system in the University of Glasgow, UK, are used to test the control performance of the PMSG variable speed wind turbine. A classical method of tuning the parameters is adopted. The PMSG-based wind power unit is connected to the utility grid via a two-level PWM back-to-back converter. Since dc output voltage from the converter will contain harmonics due to switching, a RL series filter is used to refines harmonics from voltages. The MPPT algorithm at variable wind speed from the cut-in wind speed of 6 m/s which is changing gradually to the rated wind speed 12 m/s is implemented to acquire the generator optimum speed. All block system parameters are listed in the table 1. The MSC and GSC modules are built with two level six power electronic semiconductor switches (IGBT's) in parallel with diodes allowing bidirectional current flow and unidirectional voltage blocking capability. The topology of MSC is that of GSC (Fig. 7). The wind speed profile is presented in Fig. 8. The main component is a variable block which represents the wind speed is changing

TABLE 1
PMSG WT DRIVE PARAMETERS

Symbol	Parameter	value
r	WT Blade radius	2.83 m
β	WT Pitch angle	0 °
C_p	Maximum WT power coefficient	0.3643
V_{WIND}	Wind speed range	6 to 12 m/s
λ	Optimum tip speed ratio	12.3
Rs	Stator resistance	0.007 Ω
Ld,Lq	Stator inductances	0.02 H
Ψ_r	Magnetic flux linkage	0.3 Wb
Npp	Number of poles	2
J	Moment of inertia	0.1 kg.m^2
w_m	PMSG's Initial speed	20 rad/s
Pm	PM rated power	1.5 KW
-	Rotor type	Salient pole
S	Converter's Switches	IGBT-Diod
C	Dc bus capacitor	0.01 F
Vdc	DC link voltage	250 V
f_{sw}	Switching frequency	10 KHz
V_{abc}	Voltage of grid (V_{rms} ph-ph)	138 V
f	Frequency of grid	50 Hz
R	Resistance in RL filter	0.1 Ω
L	Inductance in RL filter	10e3 H

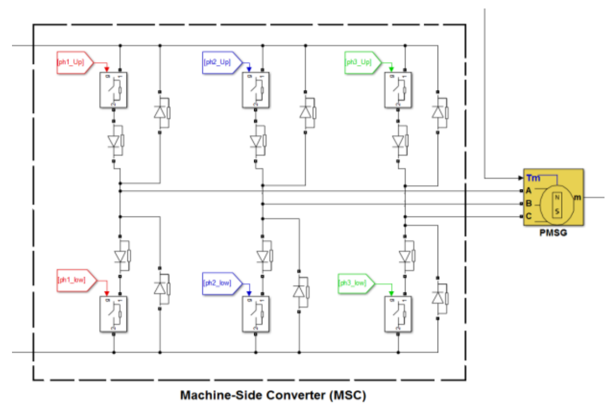

Fig. 7. MSC structure: two level six switches-diodes PWM converter.

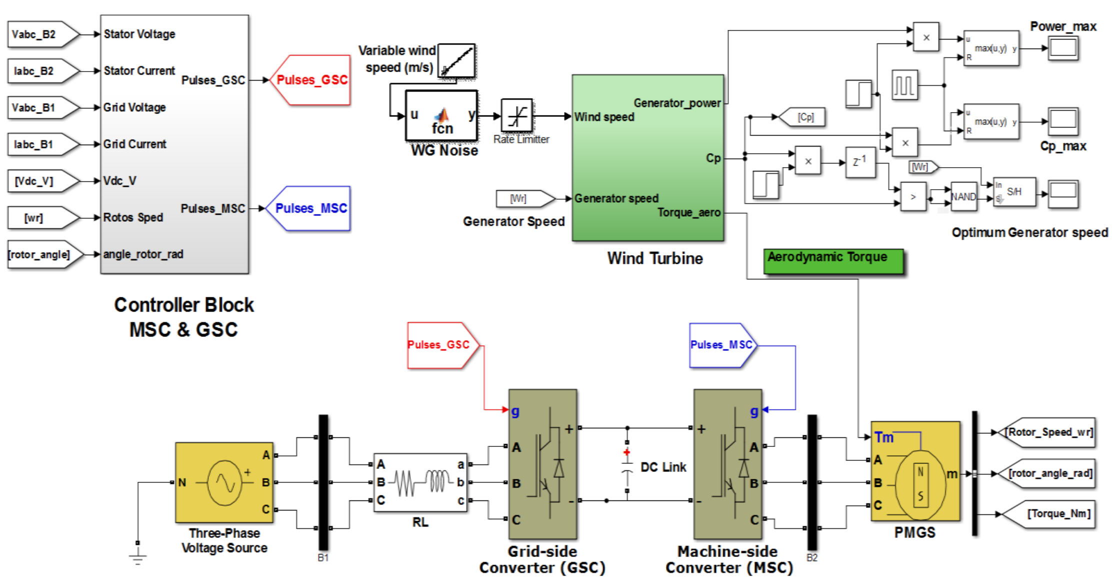

Fig. 6. Permanent magnet synchronous generator based variable speed wind turbine system in MATLAB/Simulink.

from the range of 6m/s to 12m/s. The White Gaussian noise is added to the wind speed profile. The rate limiter ensures that the wind speed is not under the cut-in speed of the turbine and is not above the cut-out speed of the turbine. Therefore, the wind speed is modeled to provide a more realistic representation of the mechanical output of the wind turbine in order to simulate the effect of the wind speed properly.

As shown in Fig. 9, from the start of simulation until 0.1s when reference current in generator side (step of 0.1s) starts to regulate the current, there is no current flowing in the generator. In Fig. 10, the actual generator current tracks the reference current after a few milliseconds of simulation running time. From 0.1s to the time that the dc link capacitor is charged and reaches 250 volts, which is 0.89 s, there is no current in the grid side as visible in Fig. 11. The capacitor is then discharged and the grid-side inverter is able to transfer power. It is evident from the grid current figure that stability is achieved early to ensure the stable and efficient operation of the WECS. The dc-link capacitor is charged by the generator-side inverter. The grid voltage is three-phase sinusoidal with the amplitude of 138 V_{rms} ac source as illustrated in Fig. 12.

Figure 9 shows that the ac current in the generator is maintained below a certain range due to the saturated input of the current controller, i.e. 50(A) in this study. The generator currents (phase a, phase b and phase c) are all sinusoidal currents and the harmonic content is observed to be minimized. Moreover, it can be seen that the amplitude of the current is changing since the inverter controller varies the amplitude of the current output in order to control the dc bus voltage constant. In Fig. 13, the dc link voltage is clamped to its desirable value of 250V due to the activation of the threshold level in the voltage controller circuit in the grid-side controller. As a result, the dc-link voltage is remained constant and stabilized at its reference value. The electromagnetic torque of generator is also shown in Fig. 14. The generator speed remains constant at 20 m/s until its reference value is accelerated to 50m/s after 0.6s in the speed regulator. The real power obtained from the WECS with the proposed controller achieves its maximum available power which is theoretically calculated based on MPPT algorithm at variable speed wind between 6m/s to 12m/s (see Fig. 15).

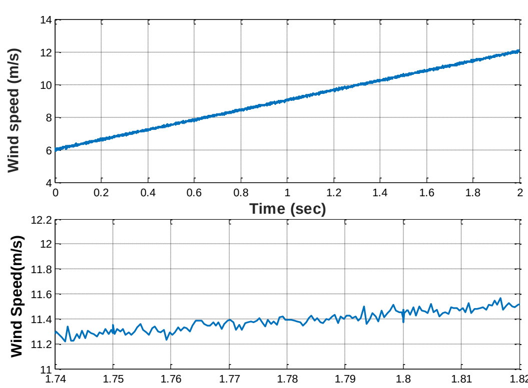

Fig. 8. The wind speed profile (m/s).

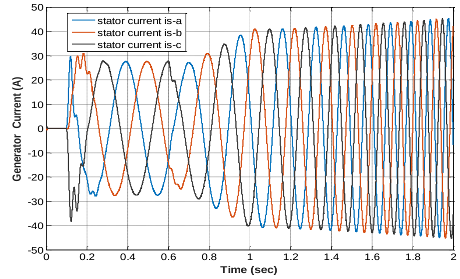

Fig. 9. The generator current (A).

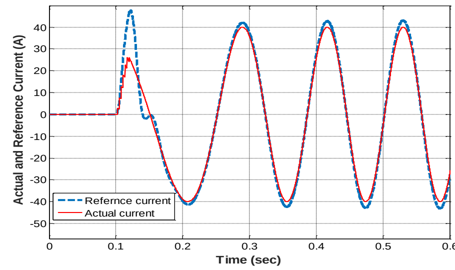

Fig. 10. The actual current versus the reference current (A).

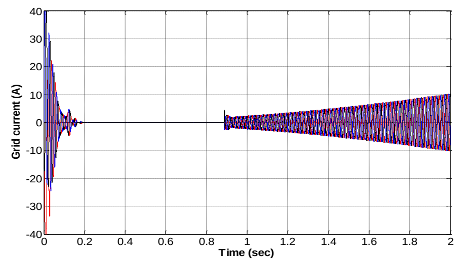

Fig. 11. The grid current (A).

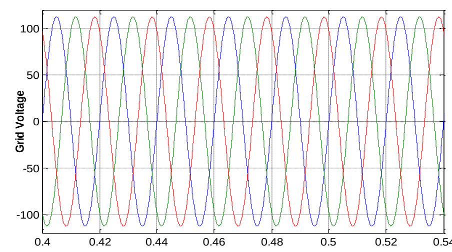

Fig. 12. The grid voltage (V).

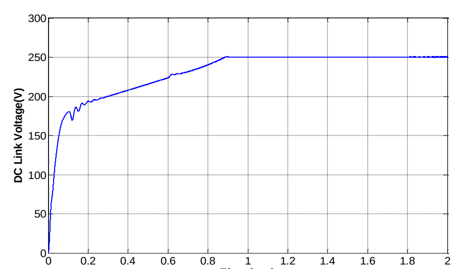

Fig. 13. The DC link voltage (V).

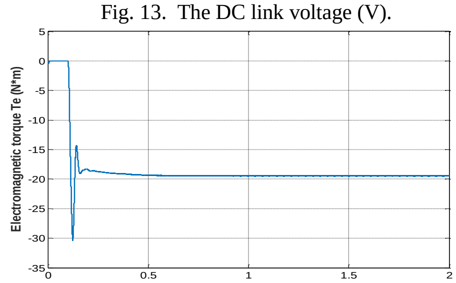

Fig. 14. The Electromagnetic torque (Nm) of the generator.

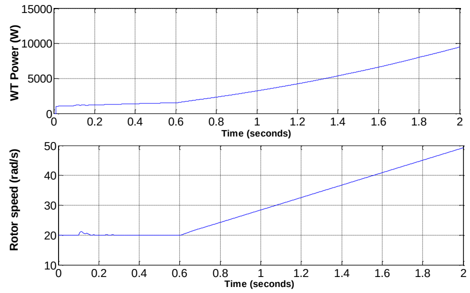

Fig. 15. The generator speed (rad/s) and WT power (W) for the variable wind speed.

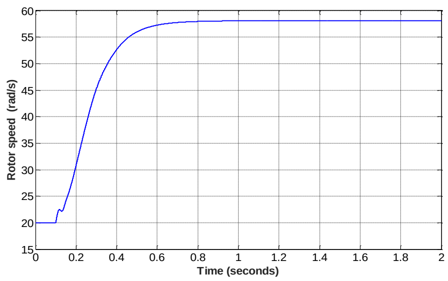

Fig. 16. The generator speed (rad/s) for fixed wind speed of 10 m/s.

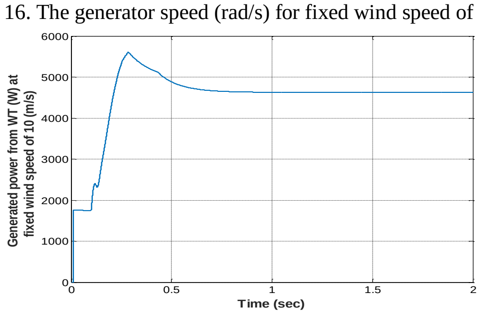

Fig. 17. The power (W) captured from WT at fixed wind speed =10m/s.

The validation of the proposed controller is observed. The integrated controller can be improved by adding a pitch angle controller. When the available wind power is beyond the equipment rating, the blade pitch angle controller increases the pitch angle to limit the mechanical power delivered to the shaft to the equipment rating, and when the available wind power is less than equipment rating, the blades are set at the minimum pitch to maximise the mechanical power. Various parameters in the system are chosen to provide desirable results during the entire operating range of the turbine.

At the start of the simulation, a damped oscillation can be observed in the results due to the electrical and mechanical losses. After a period of acceleration, the electrical torque of the PM machine and the wind torque enter a balanced state and the rotor speed accelerates as the wind speed is increasing. In the case of fixed wind speed, the rotor speed stabilized to a constant value after acceleration as evident in Fig. 16 for fixed wind speed of 10m/s. It should be also considered, there can be a few systematic and mechanical limitations of the system. For instance, in the aerodynamic section, for tip speed ratio (TSR) calculation, both the wind speed and turbine speed need to be measured, and the optimal TSR must be given to the controller. The first challenge to implementing TSR control is the wind speed measurement, normally adding to system cost and making the practical implementation difficult. The second limitation also can be the need to obtain the optimal value of TSR which is different from one system to another. This mainly depends on the turbine/generator characteristics resulting in custom-designed control software tailored for individual wind turbines [15].

IV. CONCLUSION

It is shown that our proposed practical control strategy is capable of actively controlling the power injected to the electric grid. The MPPT algorithm is capable of extracting maximum power from the air stream at different given wind speeds. The results are shown based on our model of the PMSG-based WECS developed using the practical setup parameters. The analysis of the variable speed wind turbine with direct drive permanent magnet synchronous machine shows that the developed model is suitable for small wind energy conversion systems and the validation of the practical results.

REFERENCES

[1] S. M. Muyee, *Wind Energy Conversion Systems: Technology and Trends*, Berlin: Springer-Verlag, Jan 2012.

[2] Z. Ying, et al. "A novel maximum power point tracking control for permanent magnet direct drive wind energy conversion systems." *Energies* vol. 5, no. 5, pp. 1398-1412, 2012.

[3] P. Henk, et al. "Comparison of direct-drive and geared generator concepts for wind turbines." *IEEE Trans. on energy conversion* vol. 21, no. 3, pp. 725-733, 2006.

[4] O. B. K. Hasnaoui, J. Belhadj, and M. Elleuch. "Direct Drive Permanent Magnet Synchronous Generator Wind Turbine investigation (Low Voltage Ride Through capability, Dynamic behaviour in presence of grid disturbance)."http\\: journal. esrgroups. org/jes/papers/ vol. 43, no. 5, 2008.

[5] J. S. Thongam, and M. Ouhrouche, *MPPT control methods in wind energy conversion systems*. INTECH Open Access Publisher, 2011.

[6] "PID theory" [Online].
Available: http://www.ni.com/white-paper/3782/en/

[7] D. Priyadarshini, and S. Rai, "Design, Modelling and Simulation of a PID Controller for Buck Boostand Cuk Converter." *International Journal of Science and Research (IJSR)*, vol. 3, no. 5, May 2014.

[8] Q. Wang and L. Chang, "An intelligent maximum power extraction algorithm for inverter-based variable speed wind turbine systems", *IEEE Trans.on Energy Conversion*, vol. 19, no. 5, pp. 1242-1249, 2004.

[9] B. Boukhezzar and H. Siguerdidjane, "Nonlinear control with wind estimation of a DFIG variable speed wind turbine for power capture optimization," *Energy Conversion and Management*, vol. 50, no. 4, pp. 885-892, 2009.

[10] A. Tamaarat and A. Benakcha. "Performance of PI controller for control of active and reactive power in DFIG operating in a grid-connected variable speed wind energy conversion system." *Frontiers in Energy*, vol. 8, no. 3, 8.3, pp. 371-378, 2014.

[11] Wu. Zaijun, et al. "Operation and control of a direct-driven PMSG-based wind turbine system with an auxiliary parallel grid-side converter." *Energies* vol. 6, no. 7, pp. 3405-3421, 2013.

[12] J. F. Manwell, J. G. McGowan, and A. L. Rogers, *Wind energy explained: theory, design and application*. John Wiley & Sons, 2010.

[13] T. Ackermann, ed. *Wind power in power systems*. John Wiley & Sons, 2005.

[14] Yazdani and R. Iravani. *Voltage-sourced converters in power systems: modeling, control, and applications*. John Wiley & Sons, 2010.

[15] A. B. Raju, B. G. Fernandes, and K. Chatterjee. "A UPF power conditioner with maximum power point tracker for grid connected variable speed wind energy conversion system." *Power Electronics Systems and Applications, 2004. Proc. First International Conf. on*. IEEE, 2004.