Modeling and Development of Wind Turbine Emulator for the Condition Monitoring of Wind Turbine

Himani Garg[‡], Ratna Dahiya

Department of Electrical Engineering, National Institute of Technology, Kurukshetra, India.

(singlahimani@gmail.com, ratna_dahiya@nitkkr.ac.in)

[‡] Corresponding Author; Himani Garg, Department of Electrical Engineering, National Institute of Technology, Kurukshera, India, Tel: +01744 233208, Fax: +01744 23835, singlahimani@gmail.com

Received: 19.02.2015 Accepted: 03.04.2015

Abstract-This paper presents the modeling and development of a Wind Turbine Emulator (WTE) using a 2.5 kW, 1750 RPM DC motor coupled to a 1.5 kW, 1500 rpm Self Excited Induction Generator (SEIG) to assist the condition monitoring of wind turbine. Mathematical modeling of wind turbine, separately excited DC-motor and SEIG coupled with capacitor bank is realized in Matlab/Simulink environment. The system is implemented using Advantech-4704 real-time interface card and LabVIEW real-time software. The validity of the setup has been proved by comparing the simulation and experimental results. Using FFT, the operating performance of the generated current and voltage has been analyzed. The developed WTE can be reconfigured for condition monitoring of wind turbine.

Keywords: Wind Turbine Emulator (WTE), DC Motor, Self Excited Induction Generator (SEIG), Advantech-4704, Wind Turbine (WT)

1. Introduction

Wind energy is one of the most promising renewable energies. There is a steady increase in the production of electrical power by wind turbines (WT) due to serious environmental concerns. For the researches in the field of hardware design and control strategies of wind power generation, a controlled test bench is necessary for building an emulator of wind turbine representing the output characteristics of real wind turbine. The emulator should drive the wind turbine generator in a similar way as a wind turbine reproducing the torque developed for a given wind velocity under laboratory conditions.

The fundamental aspects for modeling the aerodynamic effects of WT are widely available in literature [1] where the mechanical power output of the turbine is a function of parameters such as wind speed, air density, turbine rotor speed and area. This relationship is fundamental in building a WTE. There are a number of ways for emulating wind turbine in a laboratory and it is generally done by using an electric drive coupled directly to the shaft of the wind generator. The drive can be a DC motor drive [1-6] or AC motor drives [13-15]. DC motors are the main choice for a WTE as these are armature current controlled that has a direct relationship with the torque produced by the machine. DC motor is easy to control and there dynamic characteristics are excellent [2]. A DC motor controlled by hysteresis regulator is proposed in [5] with the approach implemented on DS1104 real- time interface. To simulate the dynamic and static characteristics of real wind energy conversion system with DC motor the authors of [6] have developed an experimental setup. Permanent Magnet Synchronous Motor (PMSM) and Brushless DC motor has also been use as prime mover [8-9]. Another alternative for an accurate torque control is induction motor drive using field oriented control [12].

In this paper a 2.5 kW separately excited DC motor loaded by Self Excited Induction Generator is used. DC motor is a usual choice to emulate the wind turbine rotor instead of PMSM or IM. The software part implemented in LabVIEW receives load torque signals and the pre-set wind speed as inputs and generates a reference current as an output signal. The reference current is connected to the set point of a Proportional Integral (PI) current controller that drives the thyristor bridge for armature control of the DC motor. A good deal of match between simulated and experimental results has been achieved.

2. Mathematical Modeling

2.1. Wind Turbine Modeling

The principle of working of wind turbine is based on aerodynamics. The turbine's aerodynamic output power is given as[10],[14],[16],[17]:

$$P = {}^{1}/_{2}\,\rho C_p A v^3 \tag{1}$$

Where v is the velocity of air, C_pC is the power co-efficient, ρ is the air density and A is the area swept by rotor blades. The conversion efficiency or C_pC is the ratio of available wind energy to the turbine's shaft mechanical energy. It is a function of tip speed ratio (λ) and pitch angle (β).

$$C_p = f(\beta, \lambda) \tag{2}$$

Tip speed ratio (λ) is given by:

$$\lambda = wR/v \tag{3}$$

Here, w in (rad/s) is the rotor angular velocity. The numerical approximation of power coefficient is given by [1]:

$$C_p\,(\lambda i) = 0.22(116 / \lambda i - 5)e^{-12.5/\lambda i} \tag{4}$$

$$\text{With } {}^{1}/_{\lambda i} = {}^{1}/_{\lambda} - \frac{.003}{\beta^3+1} \tag{5}$$

The graph between tip speed ratio and Power coefficient is shown in Fig 1.

The torque reference T_{ref} can be calculated by using torque coefficient C_T as,

$$C_T = C_p/\lambda \tag{6}$$

$$T_{ref} - \frac{P}{w} = \frac{1}{2}\rho\pi R^3 C_T v^2 \tag{7}$$

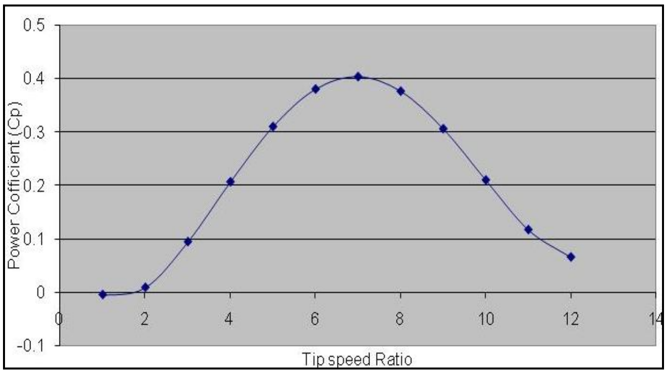

Fig. 1. Power coefficient versus tip speed ratio

2.2. Wind Turbine Emulation

The emulation schematic of the wind turbine is shown in Fig. 2. The model inputs are the turbine radius the wind velocity and the angular velocity of motor. As the actual speed of WT rotor is lesser than DC motor speed so to match their characteristics a gear ratio conversion is necessary. The values of λ, C_p, torque coefficient C_T and torque reference T_{ref} are calculated. PI controller generates control signal for full wave half controlled rectifier which is a combination of two diodes and two thyristors. It provides rectified armature voltage controlled by applying triggering pulses to thyristors. The armature voltage variation in turn controls armature current according to the current reference till the system reaches a steady state. The algorithms to control WTE are implemented using software LabVIEW and data acquisition card (DAQ).

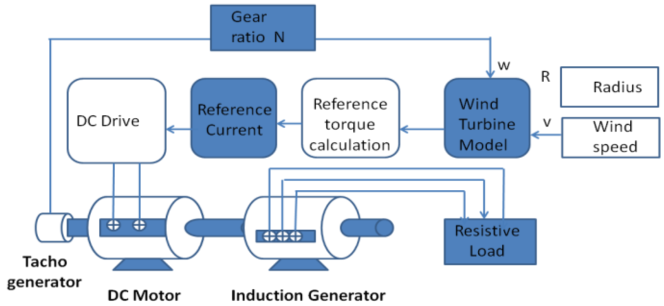

Fig. 2. Schematic of wind turbine emulator

2.3. DC motor Mathematical Modeling

In order to achieve WT emulation with a DC motor, it is required to study its torque speed characteristics. The schematic representation of a separately excited DC motor is in Fig 3. In case of this motor, the armature and field are given separate DC supply. V_aVa is the voltage applied to the motor armature, R_a, R_e and L_a, L_e are the resistance and inductance of the armature and field respectively[11].

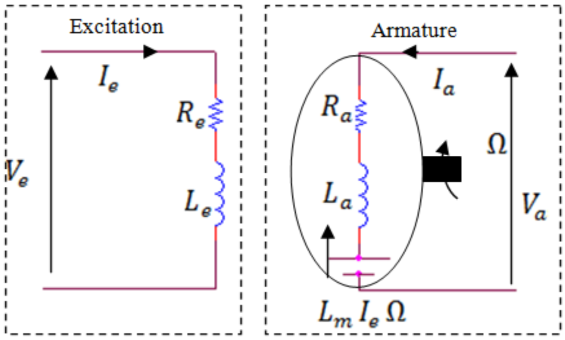

Fig. 3. The electric model of the DC machine

$$V_e = I_e R_e + L_e \frac{dI_e}{dt} : \text{For the excitation} \tag{8}$$

$$V_a = I_a R_a + L_a \frac{dI_a}{dt} + L_m I_e \Omega : \text{For the armature} \tag{9}$$

$$T_{em} = T_r + f_{mcc}\Omega + J_{mcc}\frac{d\Omega}{dt} \tag{10}$$

$$T_{em} = K_c I_a \qquad K_e = L_m I_e \qquad K_c = K_e \tag{11}$$

T_r : Resistive Torque

L_m : Mutual inductance excitation-armature

f : Coefficient of friction

J : Inertia moment

K_e : Torque constant

The functional diagram of the DC motor is shown below in Fig. 4.

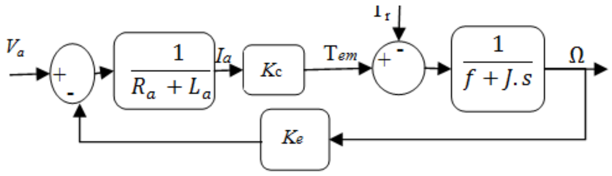

Fig. 4. The electric model of the DC motor

As it is a separately excited motor the flux created by inductive winding is constant, given by:

$$\varphi_e = L_m I_e = K_e \tag{12}$$

The resulting torque is proportional to the vector product of flux by the armature current. The speed variation of the DC motor is obtained simply by action on the voltage of the armature and/or the excitation current.

$$T_e = K_e . I_a \tag{13}$$

2.4. Mathematical Modeling of Self-Excited Induction Generator (SEIG)

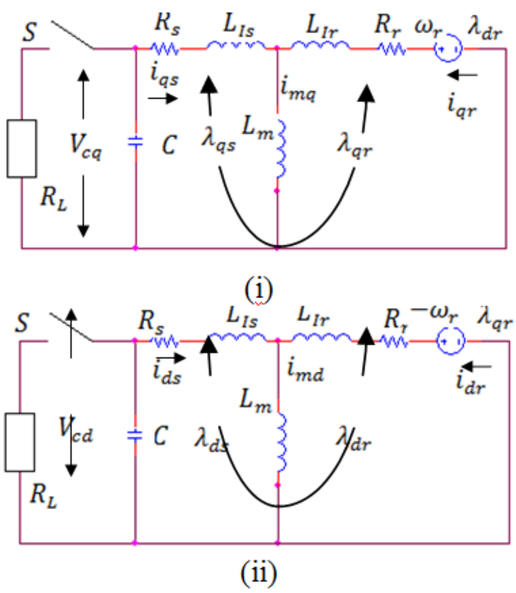

Fig. 5. d-q axes equivalent circuit of SEIG

Fig. 5 (i) & (ii) shows the equivalent d-q axis circuit of SEIG. Across the stator windings of the generator a capacitor is connected. Using Kirchhoff's voltage the loop equations (14)-(17) of the SEIG equivalent circuit are written as[7][17][19]:

$$R_s i_{qs} + L_{ls}\frac{di_{qs}}{dt} + L_m\frac{di_{qr}}{dt} + \frac{1}{C}\frac{di_{qs}}{dt} = V_{cq} \tag{14}$$

$$R_r i_{qr} + L_{lr}\frac{di_{qr}}{dt} + L_m\frac{di_{qs}}{dt} + \frac{1}{C}\frac{di_{qr}}{dt} = \omega_r\lambda_{dr} \tag{15}$$

$$R_s i_{ds} + L_{ls}\frac{di_{ds}}{dt} + L_m\frac{di_{dr}}{dt} + \frac{1}{C}\frac{di_{ds}}{dt} = -V_{cd} \tag{16}$$

$$R_r i_{dr} + L_{lr}\frac{di_{dr}}{dt} + L_m\frac{di_{ds}}{dt} + \frac{1}{C}\frac{di_{dr}}{dt} = -\omega_r\lambda_{qr} \tag{17}$$

At each step of integration the magnetizing current has to be updated. Therefore, by using the equation (18), the new magnitude of the magnetizing current is obtained

$$|i_m| = \sqrt{(i_{qs} + i_{qr})^2 + (i_{qs} + i_{qr})^2} \tag{18}$$

Hence, in the steady state the magnitude of the generated air gap voltage of SEIG is

$$E_g = \omega L_m |i_m| \tag{19}$$

L_m is not a constant but depends on magnetizing current $|i_m|$. This dependency is determined by a synchronous impedance test and can be expressed as

$$L_m = f_m |i_m| \tag{20}$$

The developed electromagnetic torque Te and torque balance equations are.

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right) L_m (i_{dr}\, i_{qs} - i_{qr}\, i_{ds}) \tag{21}$$

$$T_{shaft} = T_e + J\left(\frac{2}{P}\right) p\omega_r \tag{22}$$

The torque balance equation can be expressed in speed derivative form as

$$p\omega_r \left(\frac{P}{2J}\right) = T_e - T_{shaft} \tag{23}$$

The generated stator voltage and currents are derived from d-q axes values using the equations below

$$\begin{aligned}
V_a &= V_1 \cos\theta_1 + V_2 \sin\theta_1 \\
V_b &= V_1 \cos(\theta_1 - \omega_1) + V_2 \sin(\theta_1 - \omega_1) \\
V_c &= V_1 \cos(\theta_1 + \omega_1) + V_2 \sin(\theta_1 + \omega_1) \\
i_a &= I_1 \cos\theta_1 + I_2 \sin\theta_1 \\
I_b &= I_1 \cos(\theta_1 - \omega_1) + I_2 \sin(\theta_1 - \omega_1) \\
I_c &= I_1 \cos(\theta_1 + \omega_1) + I_2 \sin(\theta_1 + \omega_1)
\end{aligned} \tag{24}$$

Where

$$\begin{aligned}
V_1 &= V_{qs} \cos\theta + V_{ds} \sin\theta ; \\
V_2 &= -V_{qs} \sin\theta + V_{ds} \cos\theta ; \\
I_1 &= I_{qs} \cos\theta + I_{ds} \sin\theta; \\
I_2 &= -I_{qs} \sin\theta + I_{ds} \cos\theta;
\end{aligned} \tag{25}$$

$$\omega_1 = \frac{2\pi}{3} \quad \theta = \omega_e t \quad \theta_1 = 0$$

2.5. Realization of Wind Turbine Simulator

The wind turbine emulation has been done using a DC motor drive under current control [10],[12],[16][18]. In the setup a 2.5 kW, 1750 rpm DC motor is used. The reference current is calculated using equations (1-8). A real time Laptop interface provides for monitoring and control parameter adjustments whilst in operation. The control panel designed in LabVIEW (Fig. 6) and the DAQ allows real time communication between the setup and the user. Various turbine parameters like the wind velocity and turbine radius can be set by the user. To calculate current reference; the program reads wind velocity from the input data file and speed from tacho-generator. The data of wind can be generated in different ways depending on actual test conditions or anemometer's real time data. The calculated reference current is passed to drive through analog output channel of DAQ. The time plot of the main magnitudes wind velocity, power coefficient, speed, torque, power and energy can be displayed.

Fig. 7 and Fig. 8 show the circuit and experimental set up for the torque control of DC Motor. The electromagnetic torque reference is calculated as a function of the generated wind turbine torque by acting on the armature current winding. Measured values of current and speed from the DC motor are conditioned at the interface and passed to A/D-converters and then to the control routine. The co-ordinate transformations, controllers and further calculations are carried out and current reference values are given to the PI controller. The switching signals are passed to the hardware interface by the DAQ and finally to the DC drive where the firing pulses are generated. Here the power module is a Full wave half controlled thyristor bridge comprising of two thyristors and two diodes.

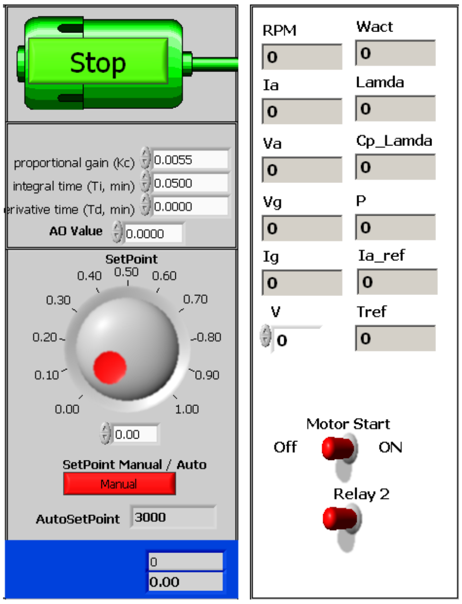

Fig. 6. Control Panel for Wind Turbine Emulation

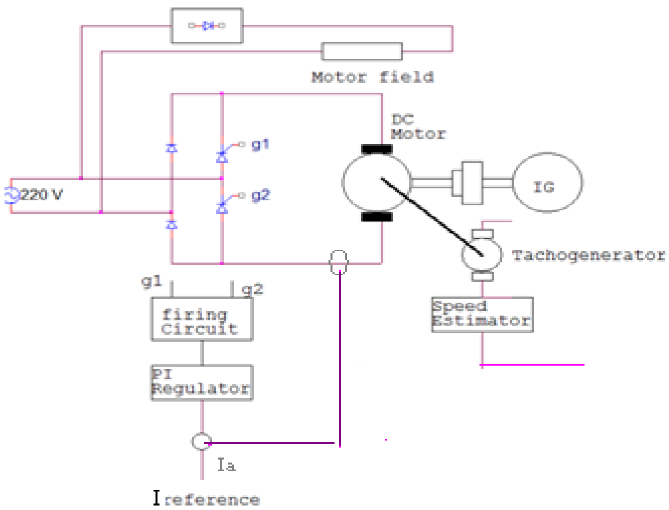

Fig. 7. Control Schema for full wave half controlled rectifier

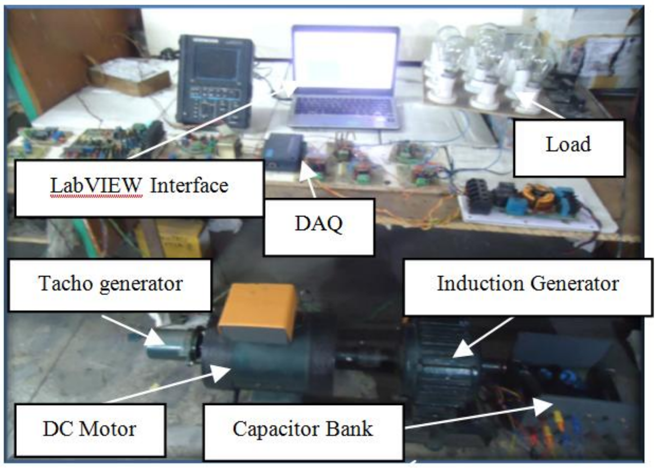

Fig. 8. Experimental setup of complete laboratory based WECS

The tacho generator signal is separately conditioned and passed to a special tacho reference unit. Special routines and lookup tables provides the reference values for the optimum power angles and torque in order to achieve maximum wind power conversion and minimal electrical losses. Error signals are also passed to the hardware interface.

3. Experimental Results

Experiments were carried out on the test bench to validate the developed control strategy. The system control has been designed and implemented under LabVIEW environment. The real time control of the system is ensured by an Advantech-4704 DAQ board. The WTE setup is run for three experiments

1) Static behavior of wind turbine

2) Dynamic behavior of wind turbine

3) Response of SEIG under various loading conditions

3.1. Experiment 1: Static behavior of wind turbine

To determine the WTE characteristics in real-time, a constant wind speed of 7 m/s is applied to the WT model. The load on the SEIG coupled to the DC motor used for emulation is gradually varied. To obtain steady state operating point, a balanced three - phase load is applied on the generator. Fig. 9 shows the results of power characteristics of WTE for different wind velocities. Solid line represents the theoretical calculations of wind turbine and dots represent the experimental measurements. As it can be depicted from the figure, there is a right degree of agreement between the calculated and measured values. From results it can be verified that the WTE can efficiently reproduce the steady state characteristics of a given wind turbine for different wind conditions. A comparison of both WT output power and DC motor power is carried out in the real time code. This procedure is repeated for different wind speeds to obtain power versus angular speed characteristics of the WTE.

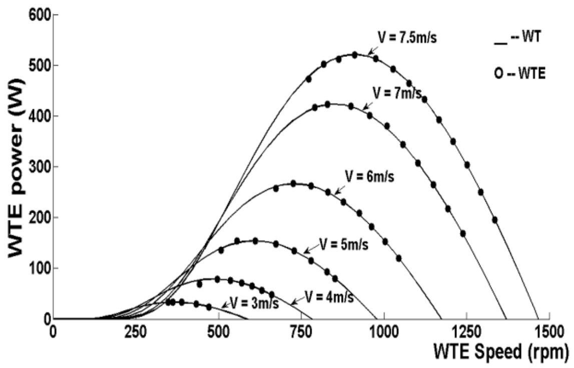

Fig. 9. Power output of wind turbine

The WT power is calculated from the WT mathematical model and is taken as the reference power. The DC motor electromagnetic torque is calculated from the armature current and multiplied with the actual shaft speed to obtain the DC motor power.

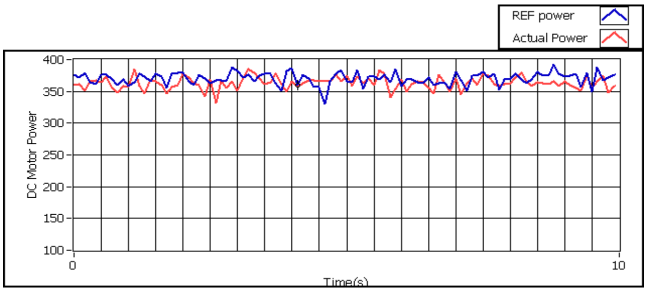

Fig. 10. Response of performance comparison of reference power and actual power on WTE for a constant wind speed 7 m/s

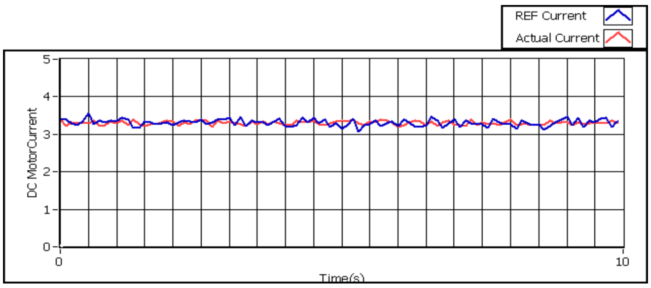

Fig. 11. Response of performance comparison of reference current and actual current on WTE for a constant wind speed 7 m/s

As shown in Fig. 10 and Fig. 11 it is observed that the actual power and current of the WTE is around 400 W and 3 A which is same as that of the reference parameters calculated from the WT model. The WTE actual characteristics for power and current matches with that of the WT reference characteristics.

3.2. Experiment 2: Dynamic behavior of WTE

A wind profile varying from 6 to 7 m/s is applied to the WT model as shown in Fig.12. The reference power and current generated by the WT model also follow the wind speed. The reference power obtained from the WT model varies from 250 W to 360 W (Fig. 13), while the current calculated from the model varies from 2.0 A to 2.4 A (Fig. 14).

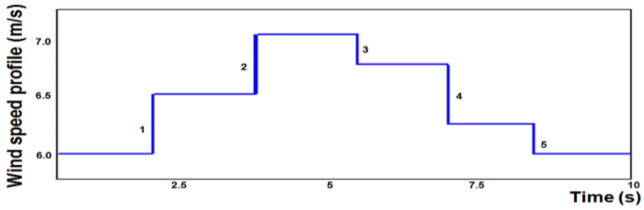

Fig. 12. Application of varying wind speed from6 to 7m/s

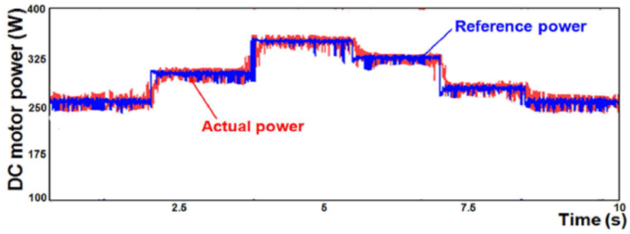

Fig. 13. Response of performance comparison of reference power and actual power on WTE for a variable wind speed

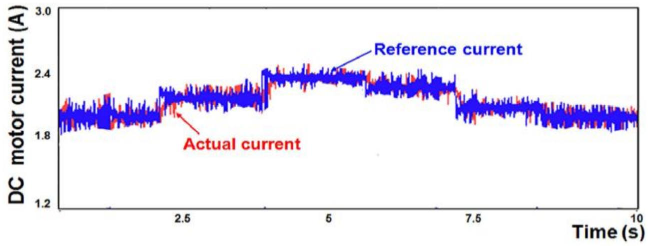

Fig. 14. Response of performance comparison of reference current and actual current on WTE for a variable wind speed

3.3. Experiment 3: Response of SEIG

At the induction generator end which is driven according to wind turbine characteristics the output voltage profile of the SEIG is observed experimentally for no load in figures 15 and 16 and on load conditions as shown in figures 17 and 18.

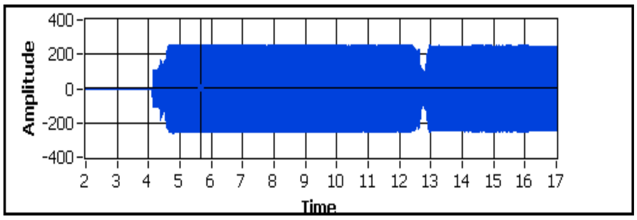

Fig. 15. O/P Voltage profile of SEIG for no load

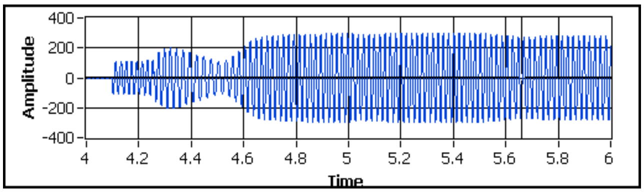

Fig. 16. Zoom in view of O/P Voltage profile of SEIG for no load

As visible in Fig 17 on loading the machine the current drawn from the SEIG raises..The torque required to drive the SEIG also increases which indirectly loads the DC motor. As a result the shaft speed of the DC motor reduces. The shaft speed of SEIG also reduces, since it is coupled to the WTE.

But the output voltage of the generator directly depends on the shaft speed. Therefore, as shown in Fig. 18 the generated voltage reduces around 9.5s on application of load.

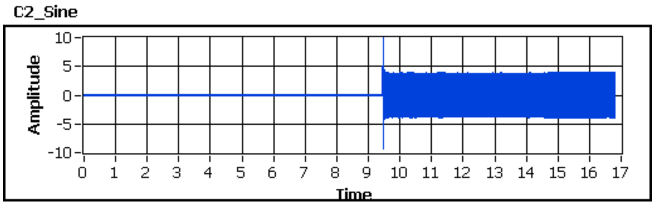

Fig. 17. O/P Current profile of SEIG on load

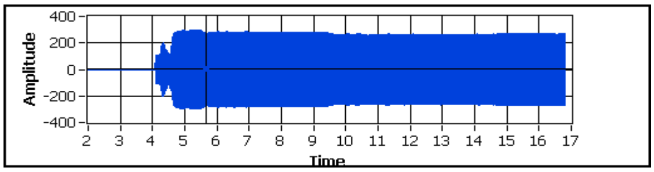

Fig. 18. O/P Voltage profile of SEIG on load

3.4. FFT of generated voltage and current

A frequency domain approach of signal processing has been used to analyze the frequency components of generated voltage. Fast Fourier transform (FFT) algorithm was used to obtain the single phase stator voltage and current spectrums shown in Fig.19 and fig. 20. The fundamental frequency for both voltage and current is 50 Hz and there are no predominant side bands. On application of faults there should be presence of side bands for condition monitoring purpose.

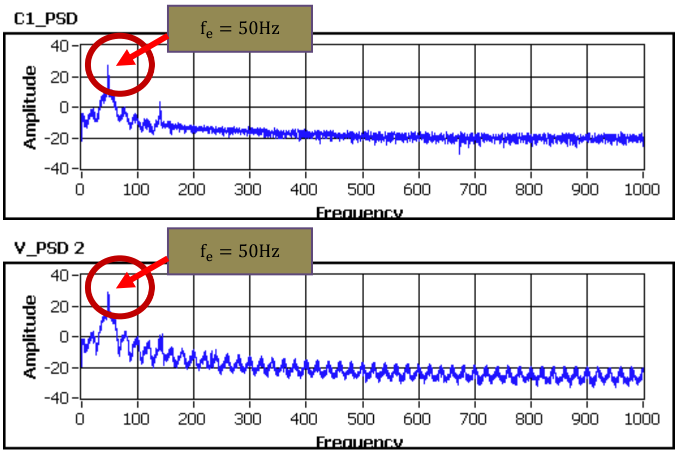

Fig. 19. FFT of generated voltage and current

4. Conclusion

Wind turbine emulator using 2.5 kW 1750 rpm DC motor coupled to a 1.5 kW 1500 rpm SEIG has been modeled and developed. It consists of a real time control program and a commercial DC drive controlled DC motor coupled to SEIG to simulate the real wind turbine characteristics. The control program provides an interface to control the torque of the motor for different wind profiles. The power spectrum analysis of the generated voltages and current has been done for condition monitoring. The results are given to show that the characteristics of the WTE fits well to those of wind turbine and the proposed setup can meet the condition monitoring requirements.

References

[1] J.M. Nye, J.G. Bat, M.A. Khan and P. Barendse, "Design and Implementation of a Variable Speed Wind Turbine Emulator", IEEE 20th International Conference on Electrical Machines (ICEM'12), 2-5 September 2012, pp. 2060-2065, Marseille.

[2] L. Guangchen, W. Shengtie and Z. Jike, "Design and Realization of DC Motor and Drives Based Simulator for Small Wind Turbine", IEEE Asia-Pacific Power and Energy Engineering Conference (APPEEC'10), 28-31 March 2010, pp. 1-4, Chengdu.

[3] W. Li, D. Xu, W. Zhang and H. Ma, "Research on Wind Turbine Emulation based on DC Motor", IEEE 2nd International Conference on Industrial Electronics and Applications, 23-25 May 2007, pp. 2589-2593, Harbin.

[4] M. Monfared, H.M. Kojabadi and H. Rastegar, "Static and Dynamic Wind Turbine Simulator Using a Converter Controlled Dc Motor", Renewable Energy, Vol. 33, No. 5, pp. 906-913, May 2008.

[5] S. Kouadria, S. Belfedhal and Y. Meslem, "Development of Real Time Wind Turbine Emulator Based on DC Motor Controlled by Hysteresis Regulator", IEEE International Renewable and Sustainable Energy Conference (IRSEC'13), 7-9 March 2013, pp. 246-250, Ouarzazate.

[6] A. Mahdy, S.M. El-Hakim and H.H. Hanafy, "Small Wind Turbine Emulator with Separately Excited Dc Motor Using Analog Electronic Circuit", IEEE IET Conference on Renewable Power Generation (RPG'11), 6-8 September 2011, pp. 1-6, Edinburgh.

[7] B. Singh, M. Singh and A.K. Tandon, "Transient Performance of Series Compensated Three-Phase Self-Excited Induction Generator Feeding Dynamic Loads", IEEE Transactions on Industry Applications, Vol. 46, No. 4, pp. 1271-1280, Jul./Aug. 2010.

[8] Luminita Barote, Corneliu Marinescu, and Marcian N. Cirstea,"Control Structure for Single-Phase Stand-Alone Wind-Based Energy Sources", IEEE Transactions on Industrial Electronics,vol.60,NO.2, Feb. 2013,pp.-764-772.

[9] S. Tammaruckwattana and K. Ohyama, "Experimental Verification of Variable speed wind power generation system using permanent magnet synchronous generator by Wind Turbine Emulator", 38th Annual Conference on IEEE Industrial Electronics Society (IECON'12), 25-28 October 2012, pp. 5827-5832, Montreal, QC.

[10] A.S. Satpathy and N.C. Sahoo, "Development of Control Scheme for a Stand-Alone Wind System", IEEE Students' Conference on Electrical, Electronics and Computer Science (SCEECS'12), 1-2 March 2012, pp. 1-4, Bhopal.

[11] H. Chen, C. Liu and Z. Chen, "Simulation and Implementation of Wind Turbine Based on Switched Reluctance Motor Drive", 3rd IEEE International Symposium

on Power Electronics for Distributed Generation Systems (PEDG'12), pp. 114-118, Aalborg.

[12] H. Voltolini, M.H. Granza, J. Ivanqui and R. Carlson, "Modeling and Simulation of the Wind Turbine Emulator Using Induction Motor Driven by Torque Control Inverter", 10th IEEE/IAS Conference on International Industry Applications (INDUSCON'12), 5-7 November 2012, pp. 1-6, Fortaleza.

[13] B. Neammanee, S. Sirisumrannukul and S. Chatratana, "Development of a wind turbine simulator for Wind Generator Testing", International Energy Journal, pp. 21-28, August 2007.

[14] L. Chang, R. Doraiswami, T. Boutot and H. Kojabadi, "Development of a Wind Turbine Simulator for Wind Energy Conversion Systems", IEEE Canadian Conference on Electrical and Computer Engineering (CCECE'00), May 2000, pp. 550-554, Halifax, NS, Canada,

[15] R. Teodorescu, F. Iov and F. Blaabjerg, "Flexible Development And test System for 11 kW Wind Turbine", IEEE 34th Annual Power Electronics Specialist Conference (PESC'03), 15-19 June 2003, pp. 67-72, Acapulco, Mexico.

[16] M. Arifujjaman, M.T. Iqbal and J.E. Quaicoe, "Maximum Power Extraction from a Small Wind Turbine Emulator Using a DC-DC Converter Controlled by a Microcontroller", IEEEE 4th International Conference on Electrical and Computer Engineering (ICECE'06), 19-21 December 2006, pp. 213-216, Dhaka.

[17] D. Seyoum, C. Grantham and M. F. Rahman, "The Dynamic Characteristics of an Isolated Self-Excited Induction Generator Driven by a Wind Turbine", IEEE Transaction on Industrial Electronics nergy Conversion, Vol. 39, No. 24, pp. 936-944, July/August 2003.

[18] Himani and R. Dahiya, "Design and Development of Wind Turbine Emulator to Operate with 1.6kW Induction Generator", Advanced Energy: An International Journal (AEIJ), Vol. 1, No. 4, October 2014.

[19] K. Subramanian and S.P. Sabberwal, "Cost Effective Wind Energy Conversion Scheme Using Self-Excited Induction Generator", Advanced Materials Research, Vol. 768, pp. 143-150, September 2013.

APPENDIX-A

Table 1. Wind turbine parameters

Rated power	500 Watts
Rated wind Speed	7.5 m/sec
Radius of WT	1.4 m
Power coefficient	0.48

Table 2. DC motor parameters

Rated power	2.5 kW
Nominal Speed	1750 rpm
Armature resistance (Ra)	1.8711 ohms
Filed resistance (Rf)	470 ohms
Armature inductance (La)	98 mH
Filed inductance (Lf)	14.160 H

Table 3. Induction generator parameters

Rated power	1.5 kW
Nominal Speed	1500 rpm