ESTIMATION OF DOUBLY FED INDUCTION GENERATOR BASED WIND ENERGY CONVERSION SYSTEM WITH HAMMERSTEIN-WIENER MODEL

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Abstract *— The aim of this paper is to estimate the parameters such as real power, reactive power, DC link voltage and generator torque of the doubly fed induction generator based wind energy conversion system with Hammerstein-Wiener models. The Hammerstein-Wiener models are developed for the complete wind energy conversion system and the parameters of Hammerstein-Wiener models are estimated with different procedures such as piecewise linear, sigmoid network, saturation, dead zone, wavelet network and one dimensional polynomial. Wavelet network and sigmoid network are found to be the techniques which produce the best fit percentage for all the parameters except for the generator torque in the low wind speed region and real power of medium wind speed region. Dead zone technique produces the best fit percentage for generator torque in low wind speed region. Similarly, saturation technique produces the best fit percentage for real power of doubly fed induction generator in medium wind speed region. The stability is analyzed with transient response, frequency response and pole-zero maps of the appropriate models.*

Keywords: *Wind Energy Conversion System, Doubly Fed Induction Generator, Hammerstein-Wiener model, Wavelet network, Sigmoid network.*

1 INTRODUCTION

System identification technique plays a very important role in the Wind Energy Conversion System (WECS). It enables to design a very efficient controller which enables more efficient energy generation with better quality. Consequently, such a control system has a direct impact on the cost of energy produced by the system [1]. Variable Speed Variable Pitch Horizontal Axis Wind Turbine with Doubly Fed Induction Generator (DFIG) with 2MW capacity is considered in this paper. Variable speed WECS has two operating regions [2] as shown in Fig.1.

This paper concentrates in developing the suitable models for the parameters including generator torque, dc link voltage, reactive power and real power in both the partial load region and full load region. Hammerstein-Weiner (HW) models are developed and the parameters are estimated using the procedures such as piecewise linear, sigmoid network, saturation, dead zone, wavelet network and one dimensional polynomial for DFIG based WECS. Suitable models are selected by comparing the model properties such as fit percentage, Final Prediction Error [FPE] and loss function. The selected models can be used as reference input and efficient controller can be designed in such a way that DFIG based WECS can produce efficient power with better quality.

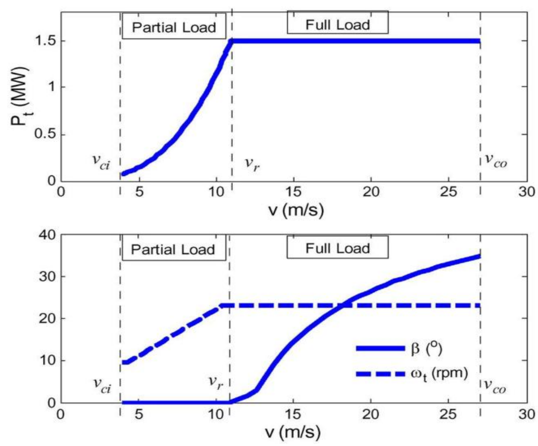

Fig.1: Ideal power curve for WECS

2. A DFIG BASED WECS

A DFIG based WECS is shown in Fig.2. It consists of a three bladed wind turbine rotor coupled to a wound rotor induction generator through a gear box. Entire WECS is built with several interconnected subsystems such as wind speed simulator system, aerodynamic system, drive train system, DFIG system, back to back voltage source converter system consists of Rotor Side Converter (RSC) and Grid Side Converter (GSC) connected to Direct Current (dc) link.

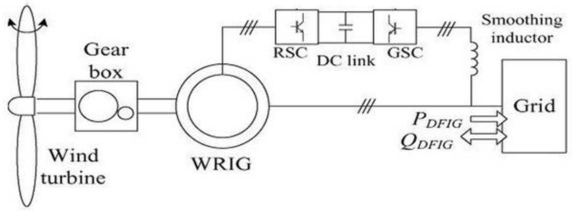

Fig.2: DFIG based WECS

2.1. Wind Speed Simulator

A realistic wind speed model is essential to identify and model the DFIG based WECS. Wind speed is generated with Von Karman spectrum [1] combined with white noise at the normal height of the wind turbine of 80 meters to get the turbulence in the wind speed. Partial load region and full load region are divided into low wind speed region, medium wind speed region and high wind speed region as shown in Table.1.

Table 1. Classification of partial load region and full load region

Load Region		Wind Speed range (m/sec)	
		Minimum	**Maximum**
Partial Load Region	Low Wind speed	4	8.7
	Medium Wind Speed	8.7	11
Full Load Region	High Wind speed	11	26

2.2. Aerodynamic and drive train system

The power contained in the wind is given by the kinetic energy of the flowing air mass per unit time [3]. In aerodynamic subsystem, wind passes over the blades generating a lift and exerting a turning force, which is otherwise called as aerodynamic torque. The drive train system consists of shaft and gear box. The rotating blades turn the low speed shaft, which goes into a gearbox. The gearbox increases the rotational speed of the shaft, which is appropriate for the generator. The aerodynamic torque and the shaft torque of the drive train system are determined by using the equations A.3–A.14 in Appendix A.

2.3 DFIG system

The mathematical equations of DFIG system are given in the equations A.15–A.20 in Appendix A. The ratings and specifications of the DFIG are given in Appendix B. The DFIG uses two back to back converters in the rotor circuit. The main purpose of the RSC is to control the active and reactive power by controlling the d-q components of rotor current (i.e. idr and iqr), while the GSC is to control the dc-link voltage and ensures the operation at unity power factor by making the reactive power drawn by the system from the utility grid to zero. Generator controller based on vector control techniques are described in [4, 5]. Description of the GSC connection to the grid and DC link are given in [1].

3. SYSTEM IDENTIFICATION

It refers to the determination of dynamic models from experimental data. It includes the set up of the identification experiment, the determination of the suitable form of the model as well as its parameters and a validation of the model [6]. Validation is done to validate the estimated model output compared to the real output from the experiments. The model validation can be accepted if it satisfies the percentage of fit and other criterions [6, 7].The designed DFIG based WECS is modeled using HW method.

3.1 Hammerstein Wiener Models

In non linear DFIG based WECS identification, the input-output relationship is decomposed into two or more interconnected elements. The HW model achieves this configuration as a series connection of static nonlinear blocks with a dynamic linear block [8]. The block diagram shown in Fig. 3 represents the structure of a Hammerstein-Wiener model.

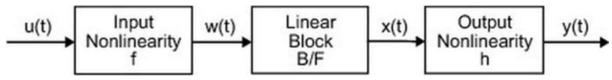

Fig.3: Structure of HW model

Here $w(t)= f(u(t))$ is a nonlinear function transforming input data $u(t)$. $w(t)$ has the same dimension as $u(t)$. $x(t) = (B/F)w(t)$ is a linear transfer function. $x(t)$ has the same dimension as $y(t)$, where B and F are similar to polynomials in the linear Output-Error (OE) model. HW model have a special structure that facilitate their application to non linear model predictive control [9].

3.2. Parameter Estimation

In this section, DFIG based WECS with 2MW capacity is modeled and parameter estimation procedures are done by using System Identification Toolbox in Matlab [10]. The non linearity in the HW model is estimated and approximated using the techniques such as piecewise linear, sigmoid network, saturation, dead zone, wavelet network and one dimensional polynomial. The approximation of the nonlinear function with the discontinuous first derivative as well as the discontinuous nonlinear functions is done with the above mentioned techniques. The redundancy of “linear parameters” is a special property of the piecewise-linear Hammerstein model, which becomes important during parameter identification [11]. Sigmoid network function is used in the parameter estimation, because it saturates at large values of time‘t’. In the wavelet network expanding each function using truncated wavelet decompositions, the multivariate nonlinear networks can be converted into linear in the parameter regressions, which can be solved using least-squares type methods [12]. This makes the wavelet functions well suited for non linear system identification. Fit percentage is an important property to be considered in model selection. FPE criterion provides a measure of model quality by simulating the situation where the model is tested on a different data set. The most accurate model has the smallest FPE. It is defined by the equation(8)

$$FPE = V\left[\frac{1+\frac{d}{n}}{1-\frac{d}{n}}\right] \quad (8)$$

where V is the loss function, d is the number of estimated parameters, and n is the number of values in the estimation data set. Since the objective is to find the minimum of the function, it is called the loss function. One of the properties of the loss function is the quadratic scaling of errors, which favors many small errors over a few large ones [13]. The loss function V is defined by the equation (9).

$$V = \det\left(\frac{1}{N}\sum_{1}^{N}\varepsilon(t,\theta_N)(\varepsilon(t,\theta_N))^T\right) \quad (9)$$

where θ_N represents the estimated parameters and N is the number of iterations. To achieve the minimum of loss function, its gradient must be equal to zero.

4. RESULTS AND DISCUSSION

Each sub system of WECS is designed individually, and parameter estimation of HW models is done with different procedures. The obtained models are analyzed using the model properties and the models are accepted only when the validation of the models are successful by comparing measured output and simulated model output. To narrow down on the model, the pole and zero plot for each model is observed. The best model will have all its poles and zeros within the unit circle to show the stability. This is called a minimum phase model and this model address to the rule of causality and stability and it would be used for further analysis and to derive a relation between the input and output [10]. The transient response provides the system's response characteristics including quite slow rise time, no overshoot, fast settling time and small steady state error. Time delay and the time constant of the best model are calculated from the transient response. In the low wind speed HW model time delay and time constant of the system are 0.1 and 0.9 sec respectively. In the medium wind speed HW model time delay and time constant of the system are 0.1 and 1.8 sec respectively. In the high wind speed HW model time delay and time constant of the system are 0.15 and 0.25 sec respectively. In the exact wind speed model time delay and time constant of the system are 1 and 6 sec respectively.

4.1 LOW WIND SPEED HW MODEL

Low wind speed HW model is simulated with the wind speed range between 4 to 8.7m/sec. Model properties of the parameters are shown in Table. 2.

Table.2: Model properties of different parameters for low wind speed

Model properties of Estimation Approaches		**Real Power (pu)**	**Reactive Power (pu)**	**DC link Voltage (V)**	**Generator Torque (rad/sec)**
Piecewise Linear	Fit %	47.89	30.09	8.528	61.5
	FPE	0.012	0.0011	3.667	0.001803
	Loss Fcn	0.006	0.0006	1.88	0.0009
Sigmoid	Fit %	***60.05***	17.01	43.95	31.95
	FPE	***0.0054***	0.0019	0.005	2.396
	Loss Fcn	***0.0023***	0.0008	0.002	1.021
Saturation	Fit %	4.477	17.04	1.598	65.43
	FPE	0.016	0.001249	2.507	0.000792
	Loss Fcn	0.013	0.00106	2.128	0.000672
Dead zone	Fit %	43.28	31.78	5.523	***92.86***
	FPE	0.0141	0.000851	2.456	***3.463e-005***
	Loss Fcn	0.012	0.000722	2.084	***2.939e-005***
Wavelet Network	Fit %	52.17	***66.4***	***71.69***	55.84
	FPE	0.0048	***0.000210***	***0.5077***	0.001626
	Loss Fcn	0.0033	***0.000129***	***0.1762***	0.001117
One dimensional Polynomial	Fit %	48.28	14.85	15.3	50.67
	FPE	0.0051	0.00101	1.964	0.004031
	Loss Fcn	0.0042	0.000843	1.639	0.003365

Fig.4 shows the low wind speed input. Sigmoid network produce the best fit percentage for the real power and the wavelet network gives the best fit percentage for both the reactive power and dc link voltage. Parameter estimation using dead zone results in best fit percentage for the generator torque. The simulation results of the measured output and model output of the generator torque, dc link voltage, real power and reactive power are shown in Fig. 5, 6, 7 and 8 respectively. These results are obtained with best fit percentage and lowest FPE and Loss function. The pole–zero map is shown in Fig.9. The transient response is shown in Fig. 10 and the frequency response of the model, the Bode plot is shown in Fig. 11.

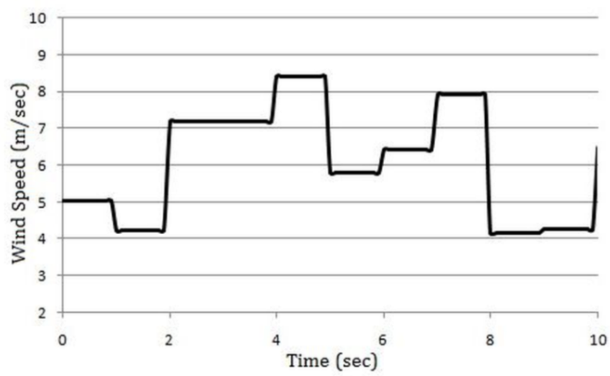

Fig. 4: Low wind speed input

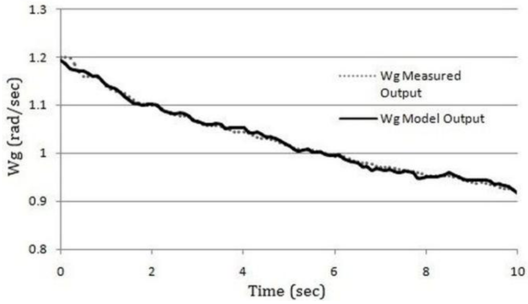

Fig. 5: Generator Torque of DFIG for low wind speed

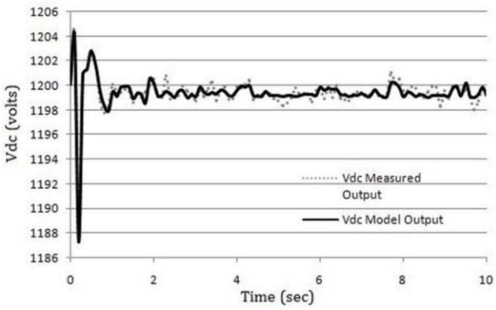

Fig. 6: DC Link Voltage of DFIG Based WECS for Low Wind Speed

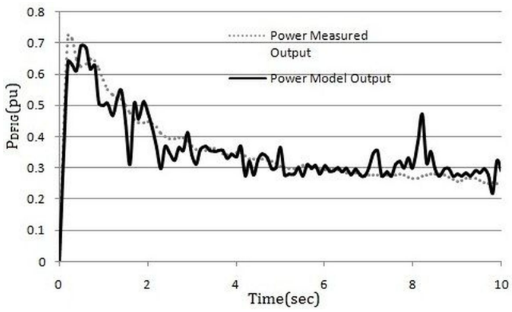

Fig. 7: Real Power of DFIG Based WECS for Low Wind Speed

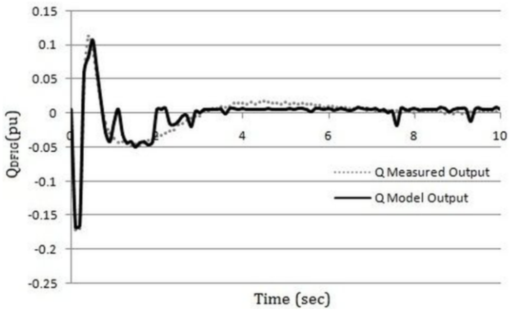

Fig. 8: Reactive Power of DFIG based WECS for Low Wind Speed

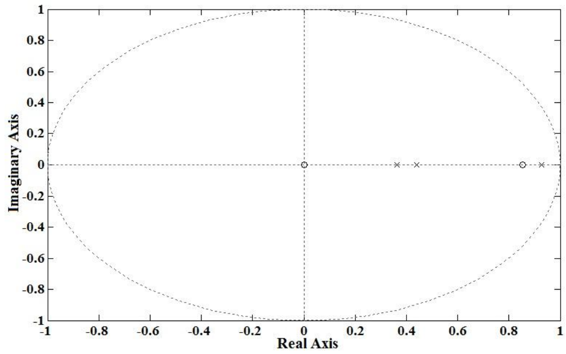

Fig 9: Pole-Zero Map for Low Wind Speed

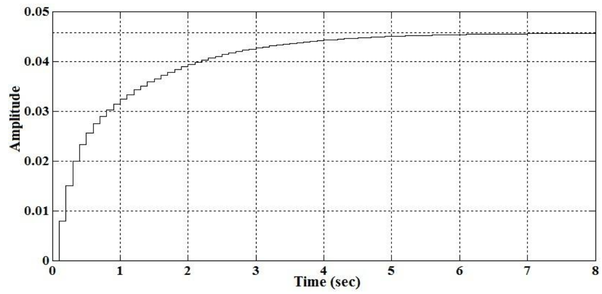

Fig 10: Transient response for low wind speed

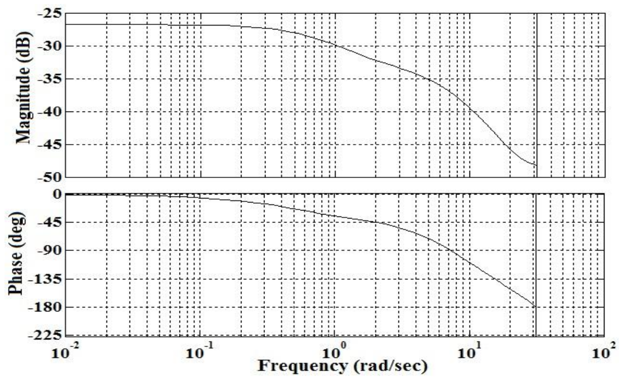

Fig 11: Frequency response for low wind speed

4.2 MEDIUM WIND SPEED HW MODEL

Medium wind speed HW model is simulated with the wind speed range between 8.7 to 11m/sec. Model properties of the parameters are shown in Table. 3.

Table.3: Model properties of different parameters for medium wind speed

Model properties of Estimation Approaches		Real Power (pu)	Reactive Power (pu)	DC link Voltage (V)	Generator Torque (rad/sec)
Piece wise Linear	Fit %	85.73	35.94	32.64	34.28
	FPE	0.00041	0.00106	2.97	0.000522
	Loss Fcn	0.00021	0.00054	1.523	0.000268
Sigmoid	Fit %	60.32	46.68	12.09	20.94
	FPE	0.01388	0.00094	4.814	0.001247

	Loss Fcn	0.00591	0.0004	2.051	0.000531
Saturation	Fit %	***89.59***	38.67	15.49	8.299
	FPE	***9.614 e-005***	0.00064	2.23	0.000561
	Loss Fcn	***8.16e-005***	0.00054	1.893	0.000476
Dead zone	Fit %	33.23	11.32	7.582	68.3
	FPE	0.00886	0.00131	2.915	7.195 e-005
	Loss Fcn	0.00752	0.00111	2.474	6.107e-005
Wave let Net work	Fit %	85.66	***52.57***	***57.06***	***81.64***
	FPE	0.00027	***0.0005***	***1.118***	***4.059e-005***
	Loss Fcn	0.00016	***0.00031***	***0.4887***	***2.679e-005***
One dimensional Polynomial	Fit %	88.35	36.91	10.88	51.04
	FPE	0.00012	0.00063	2.705	0.00021
	Loss Fcn	0.00010	0.00052	2.258	0.000175

Fig.12 shows the medium wind speed input. Saturation method produce the best fit percentage for the real power and the wavelet network gives the best fit percentage for both the reactive power, dc link voltage and generator torque. The simulation results of the measured output and model output of the generator torque, dc link voltage, real power and reactive power are shown in Fig. 13, 14, 15, and 16 respectively. These results are obtained with best fit percentage and lowest FPE and Loss function. The pole-zero map is shown in Fig.17. The transient response is shown in Fig. 18 and the frequency response of the model, the Bode plot is shown in Fig. 19.

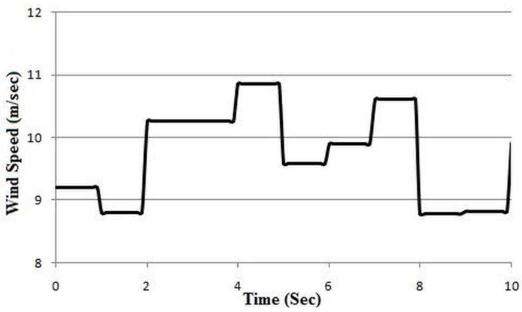

Fig.12: Medium wind speed

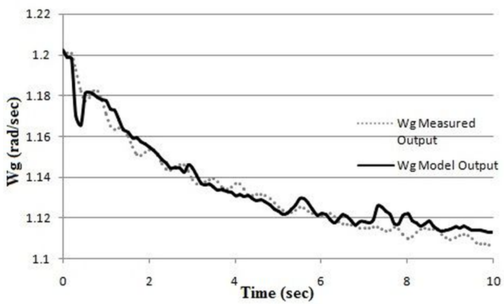

Fig. 13: Generator Torque of DFIG for medium wind speed

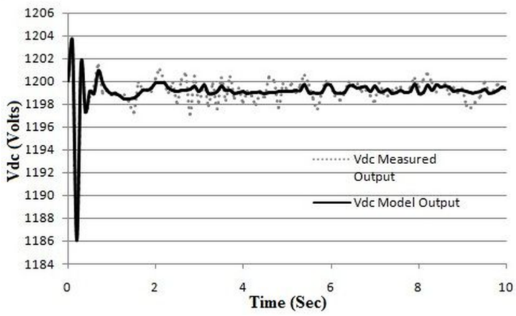

Fig. 14: DC link voltage of DFIG based WECS for medium wind speed

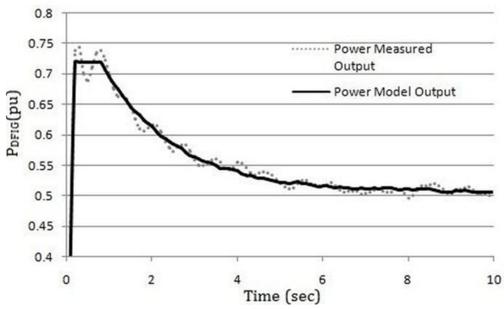

Fig. 15: Real power of DFIG for medium wind speed

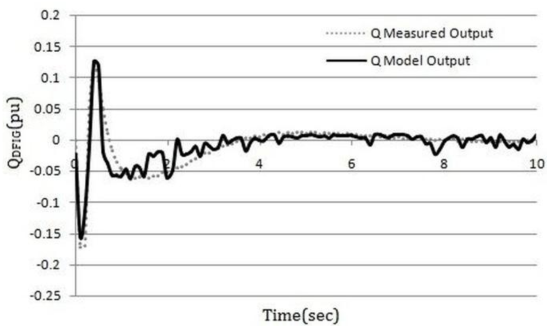

Fig. 16: Reactive power of DFIG for Medium Wind speed

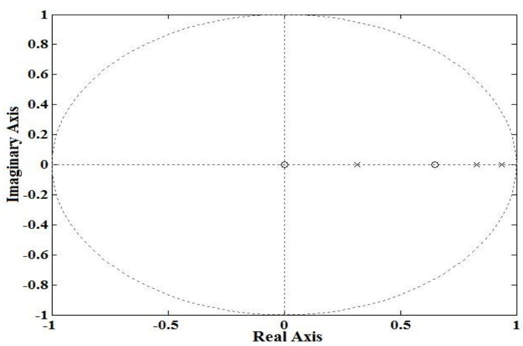

Fig 17: Pole-Zero map for medium wind speed

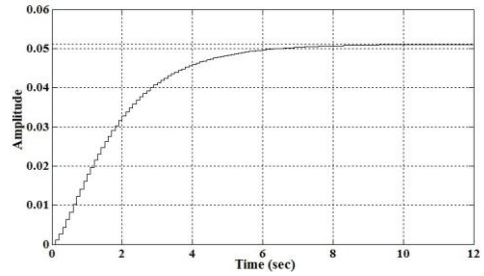

Fig 18: Transient Response for medium wind speed

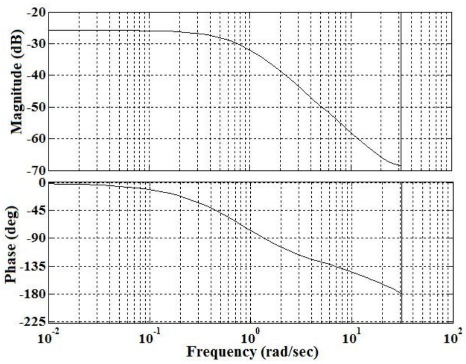

Fig 19: Frequency Response for medium wind speed

4.3 HIGH WIND SPEED HW MODEL

High wind speed HW model is simulated with the wind speed range between 11 to 26 m/sec. Model properties of the parameters are shown in Table. 4.

Table. 4: Model Properties of different parameters for High Wind Speed

Model properties of Estimation Approaches		**Real Power (pu)**	**Reactive Power (pu)**	**DC link Voltage (V)**	**Generator Torque (rad/sec)**
Piecewise Linear	Fit %	62.76	40.93	15.25	55.74
	FPE	0.01077	0.0018	9.131	0.000774
	Loss Fcn	0.00552	0.0009	4.682	0.000397
Sigmoid	Fit %	***80.05***	42.4	20.36	***69.42***
	FPE	***0.002***	0.002	9.444	***0.000347***
	Loss Fcn	***0.0008***	0.0008	4.025	***0.000148***
Saturation	Fit %	76.8	0.0506	5.665	47.41
	FPE	0.0019	0.003	6.531	0.000515
	Loss Fcn	0.0012	0.0025	5.543	0.000437
Dead zone	Fit %	64.3	34.75	16.07	60.57
	FPE	0.0064	0.0014	6.099	0.000374
	Loss Fcn	0.0054	0.0012	5.176	0.000317
Wavelet Network	Fit %	73.81	***46.33***	***22.61***	55.58
	FPE	0.0021	***0.0011***	***6.263***	0.000633
	Loss Fcn	0.0015	***0.0007***	***3.834***	0.000328
One dimensional Polynomial	Fit %	70.49	7.274	18.86	58.13
	FPE	0.0024	0.0028	4.951	0.000395
	Loss Fcn	0.0020	0.0023	4.133	0.000329

Fig.20 shows the high wind speed input. Sigmoid network method produces the best fit percentage for the real power and the generator torque. Similarly wavelet network gives the best fit percentage for both the reactive power and dc link voltage. The simulation results of the measured output and model output of the generator torque, dc link voltage, real power and reactive power are shown in Fig. 21, 22, 23 and 24 respectively. These results are obtained with best fit percentage and lowest FPE and Loss function. The pole-zero map is shown in Fig.25. The transient response is shown in Fig. 26 and the frequency response of the model, the Bode plot is shown in Fig. 27.

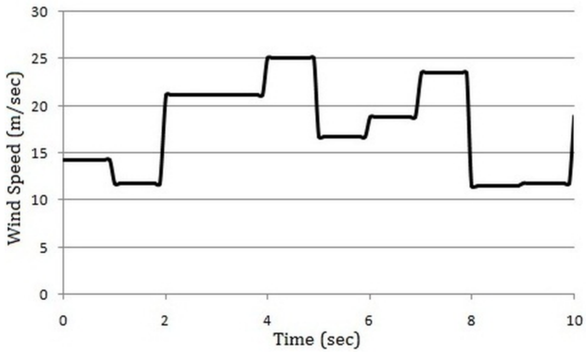

Fig.20: High Wind Speed input

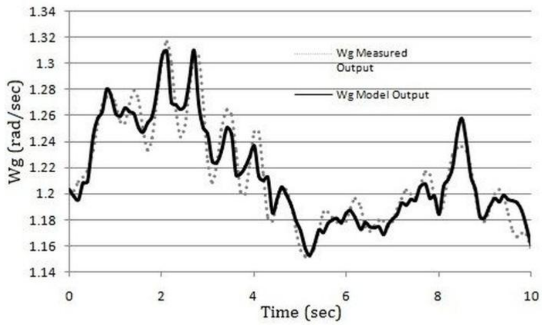

Fig.21: Generator Torque of DFIG for High Wind Speed

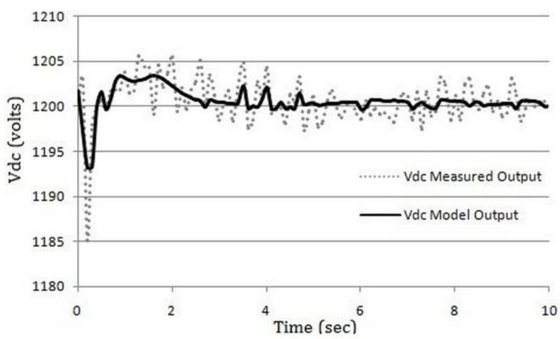

Fig.22: DC link voltage of DFIG based WECS for high wind speed

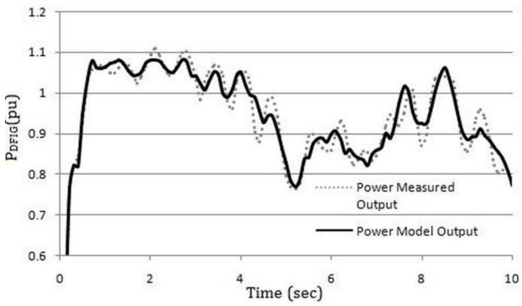

Fig.23: Real power of DFIG for high wind speed

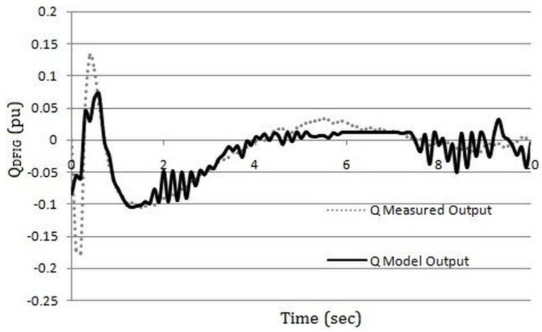

Fig.24: Reactive Power of DFIG for High Wind Speed

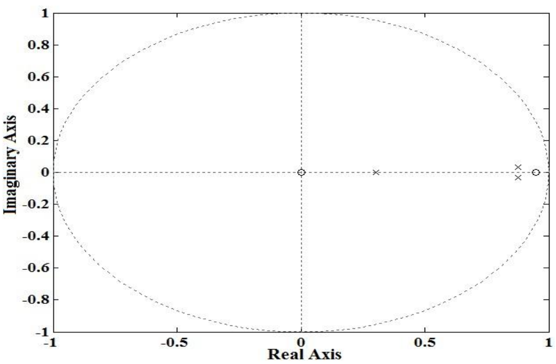

Fig 25: Pole-Zero map for high wind speed

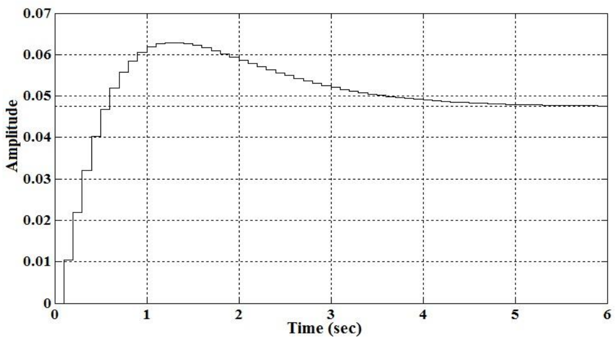

Fig 26: Transient Response for High Wind Speed

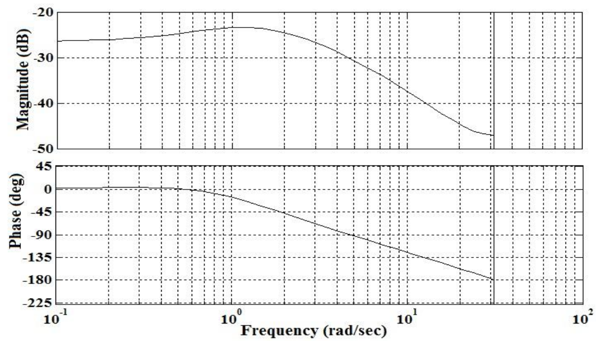

Fig 27: Frequency response for high wind speed

5. CONCLUSION

The HW model obtained for the parameters including generator torque, dc link voltage, real power and reactive power of DFIG based WECS is estimated using different procedures which comprises of piecewise linear, sigmoid network, saturation, dead zone, wavelet network and one dimensional polynomial. Comparing all these methods sigmoid network and wavelet network produce the best fit percentage for most of the parameters of DFIG based WECS. It is observed that designed DFIG based WECS is a nonlinear and unstable system. But the HW model developed for the designed DFIG based WECS is stable and bounded. The classical controllers developed with the selected models as reference input is able to produce the efficient power generation with better power quality. The performance of the classical controllers can further be improved by tuning the controller parameters with soft computing techniques.

APPENDIX

A.1 DFIG based WECS

1. Pitch Actuator System

$$\dot{\beta} = -\frac{1}{\tau}\beta + \frac{1}{\tau}\beta^* \qquad (A.1)$$

$$\beta_{\min} \le \beta \le \beta_{\max}, \dot{\beta}_{\min} \le \dot{\beta} \le \dot{\beta}_{\max} \qquad (A.2)$$

Here τ is the time constant of the pitch system and •max(•min) is the maximum limit of •

2. Aerodynamic System

$$E_k = \frac{1}{2} m v^2 \qquad (A.3)$$

$$m = \rho A d \qquad (A.4)$$

$$Theoritical\_Power = \frac{E_k}{t}$$

$$\frac{E_k}{t} = \frac{\rho A d v^2}{2t} = \frac{\rho A v^3}{2} \qquad (A.5)$$

$$Actual\_P_m = \frac{\rho A C_p(\lambda,\beta) v^3}{2} \qquad (A.6)$$

$$T_t = \frac{P_m}{\omega_t} = \frac{C_p(\lambda,\beta)\rho\pi R^3 v^2}{2\lambda} \qquad (A.7)$$

$$C_p(\lambda,\beta) = 0.22\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-22.5}{\lambda_i}} \qquad (A.8)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad \text{(A.9)}$$

$$\lambda = \frac{Blade\_tip\_speed}{wind\_speed} \quad \text{(A.10)}$$

Where E_k is the Kinetic energy, m is the Air mass per unit time, ν is the Wind velocity in m/sec, ρ is the Air density (1.255 kg/m^3), A is the rotor swept area in m^2, d is the distance swept by the rotor in m, t is the time in seconds, C_p is the power coefficient of the turbine, P_m is the mechanical Power,T_t is the Turbine Torque in NM, R is the radius of the rotor blades in m, ω_t is the speed of the low speed shaft in rad/sec and λ is the tip speed ratio.

3. Drive Train System

$$T_{tw} = 31.84e + 04\theta_{tw} + 212.2[i\omega_t - 41.87] \quad \text{(A.11)}$$

$$\frac{d\omega_t}{dt} = \frac{-i}{J_t}T_{tw} + \frac{1}{J_t}Tt \quad \text{(A.12)}$$

$$\frac{d\omega_g}{dt} = \frac{1}{J_g}T_{tw} - \frac{1}{J_g}Tg \quad \text{(A.13)}$$

$$\frac{dT_{tw}}{dt} = K_s i\omega_t - K_s\omega_g - [\frac{i^2 B_s}{J_t} - \frac{B_s}{J_g}]T_{tw} + \frac{iB_s}{J_t}T_t + \frac{B_s}{J_g}T_g \quad \text{(A.14)}$$

Here θ_{tw} is the angle of the drive train and ω_t is theturbine speed; J_t and J_g are the inertia of the turbine and the generator respectively; T_{tw} is the drive train torsional torque; i is the gear ratio; and K_s, B_s are the shaft stiffness and damping coefficients, respectively [2]. The ratings and specifications of wind turbine, drive train and pitch system are in Appendix B.

4. DFIG System

Stator Voltage Equations:

$$V_{qs} = P\lambda_{qs} + \omega\lambda_{ds} + r_s i_{qs}$$
$$V_{ds} = p\lambda_{ds} - \omega\lambda_{qs} + r_s i_{ds} \quad \text{(A.15)}$$

Rotor Voltage Equations:

$$V_{qr} = p\lambda_{qr} + (\omega - \omega_r)\lambda_{dr} + r_r i_{qr}$$
$$V_{dr} = p\lambda_{dr} - (\omega - \omega_r)\lambda_{qr} + r_r i_{dr} \quad \text{(A.16)}$$

Power Equations:

$$P_s = \frac{3}{2}[V_{ds}i_{ds} + V_{qs}i_{qs}]$$
$$Q_s = \frac{3}{2}[V_{qs}i_{ds} - V_{ds}i_{qs}] \quad \text{(A.17)}$$

Torque Equation:

$$T_e = \frac{-3p}{4}[\lambda_{ds}i_{qs} - \lambda_{qs}i_{ds}] \quad \text{(A.18)}$$

Stator Flux linkage equation:

$$\lambda_{qs} = [L_{ls} + L_m]i_{qs} + L_m i_{qr}$$
$$\lambda_{ds} = [L_{ls} + L_m]i_{ds} + L_m i_{dr} \quad \text{(A.19)}$$

Rotor Flux linkage equations:

$$\lambda_{qr} = [L_{lr} + L_m]i_{qr} + L_m i_{qs}$$
$$\lambda_{dr} = [L_{lr} + L_m]i_{dr} + L_m i_{ds} \quad \text{(A.20)}$$

In (A.15)–(A.20), i, λ, r and L denote voltages, currents, flux linkages, resistances, and inductances, respectively. The subscripts $_d$ and $_q$ denote the direct and quadrature axis components, respectively. The subscripts $_s$ and $_r$ denote generator stator and rotor quantities, respectively. ω and p are the generator synchronous speed and the number of pole pairs of the generator, respectively.

A.2 Ratings and specifications

Wind Turbine/Drive Train/Pitch System

System rated power= 2MW, Rated turbine speed=23rpm, Min/Max turbine speed=9.5/25 rpm, Radius of the rotor blades=35m, $v_{ci}/v_{cr}/v_{co}$ = 4/11/26m/sec, Gear ratio (i) = 74.38, Turbine inertia constant=3s, Generator inertia constant =0.5s , Shaft stiffness= 0.5 pu, Shaft damping=0.01pu

DFIG system

Rated generator apparent power =2/0.9MVA, f_o =60Hz, P=3, r_s =0.00706p.u, L_{ls} =0.171pu, r_r =0.005pu, L_{lr} =0.156pu, L_m =2.9pu, r_f =0.15/100pu, L_f = 0.15pu C=1000µF, Rated dc link voltage = 1200V

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