Nonlinear Disturbance Control in a Wind Energy Conversion System Using Theta-D Control

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ABSTRACT-In this paper a Nonlinear Control technique is proposed to capture maximum power output from the wind in a Variable Speed Wind Turbine system. It is obtained by rotor speed control of Variable Speed Wind Turbine system. The design of the controller is to track the desired rotor speed and to adjust the control variable. By synthesis of generator torque control variable rotor speed is adjusted.The controller is designed for the nonlinear model of the wind turbine by employing advanced nonlinear Theta-D control. Simulation is carried out using MATLAB and the results shows the better performance of the proposed controller to track the optimal value of rotor speed and to produce maximum power coefficient values for all wind speeds in a wind turbine system.

Keywords*-Wind Turbine System, Nonlinear Controller, Theta-D Method, Maximum Power Output.*

I. INTRODUCTION

It is necessary to optimize Wind Energy Conversion System (WECS) for increasing the wind energy electric power production. Wind Turbines (WT) are optimized to produce maximum power output at variable speeds. Wind turbines can either operate at fixed speed or variable speed. For a fixed-speed wind turbine the generator is directly connected to the electrical grid. For a variable-speed wind turbine (VSWT) system the generator is controlled by a power electronic converter called matrix converter to control active and reactive power. Variable speed wind turbine gives maximum power output compared to the fixed speed [3].

For a VSWT, mechanical power output is $P_t = \frac{1}{2} C_P \rho \Pi R^2 V_w^3$, where $P_t$the turbine power,$C_P$is the power coefficient, R is the turbine radius and $V_w$is the wind velocity. A WT can only generate a certain percentage of power associated with the wind. This percentage is represented by $C_P$which is a function of wind speed, turbine rotational speed and the pitch angle of specific wind turbine blades.

The tip speed ratio λ of the WT is $\lambda = \frac{RW_t}{V_w}$ where turbine shaft speed $W_t = \frac{P_t}{T_t}$ and T_t is the turbine torque. Fig 1 non-linear relationship between $C_P$and λ that can be obtained experimentally for any given WT. As shown in Fig.2, for a particular wind speed within the range from cut in to rated wind velocity, the turbine rotational speed can be adjusted so that the maximum $C_P$can be obtained. This, in turn, causes the WT to generate a maximum power at that wind speed [3].

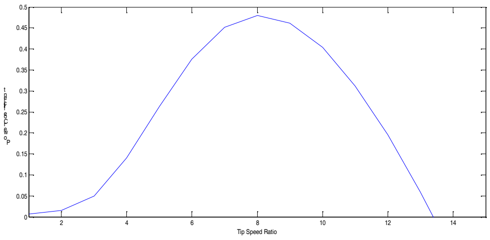

Fig1 Power Coefficient of the Wind Turbine model

Many of the WT control systems are based on linear models. For low wind speeds, it is more important to optimize wind power capture while it is recommended to limit power production and rotor speed above the rated wind speed. The controller, for power capture optimization, that takes into consideration the nonlinear nature of the WT behaviour is designed considering the control state inputs. To overcome the limitations of linear controller's, nonlinear controller are used [3].

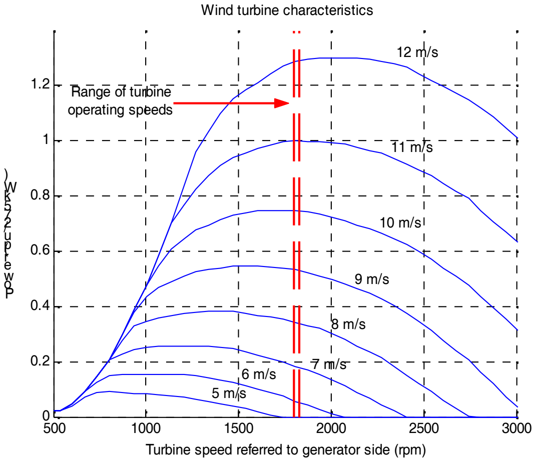

Fig2 Power Characteristics of the Wind Turbine

The organization of rest of the paper is as follows: The section 2 focuses on the wind energy conversion system. The section 3 demonstrates the numerical method of

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Theta-D control. While section 4shows the proposed technique in wind turbines and section 5 talks about conclusion and future work.

II. WIND ENERGY CONVERSION SYSTEM

The wind turbine system shown in the Fig4 consists of a wind turbine, a gearbox, doubly fed induction generator and a matrix converter [4]. The matrix converter interfaces the induction generator with the grid and implements a shaft speed control to achieve maximum power-point tracking at varying wind velocities. It also performs power factor control at the grid interface and satisfies Var demand at the induction generator terminals.

MC as an electronic power converter/static frequency changer interfaces the DFIG with the grid and implements shaft speed control. The MC input is connected to the grid and the generator terminals are connected to the MC output. It consist of nine bidirectional switches with LC filter to filter out the high frequency harmonics of the input current.Also it provides direct AC/AC conversion and bidirectional power flow.

Rotor of the DFIG is connected to the grid by matrix converter (direct AC-AC power conversion) between rotor circuit and grid. Stator of the generator is directly connected to the utility grid. DFIG works in Sub Synchronous and Super Synchronous mode.Stator power is delivered to the grid in both the modes.Rotor active power is supplied to the machine in sub synchronous mode and delivered to the grid in super synchronous.

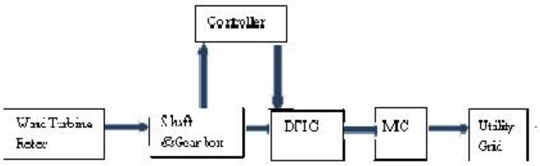

Fig3 Wind Energy Conversion System

III. THETA-D CONTROL TECHNIQUE

This method is a nonlinear optimal control synthesis technique, achieves suboptimal solutions to a class of nonlinear optimal control problems characterized by a quadratic cost function and a plant model that is affine control. An approximate solution to the Hamilton-Jacobi-Bellman (HJB) equation is sought by adding perturbations to the cost function. This method overcomes the large-control-for-large-initial-states problem that occurs in some other Taylor series expansion based methods. Also it does not require excessive online computations like the recently popular state dependent ricatti equation technique. It provides a closed-form non-linear feedback control [8].

Let us consider nonlinear time-invariant system described by

$$\dot{x} = f(x) + gu$$

The objective is to find a controller that minimizes the quadratic cost function, J given by

$$J = \frac{1}{2}\int_0^\infty (x^T Qx + u^T Ru)dt$$

The necessary condition for optimality leads to

$$u = -R^{-1}g^T \frac{\partial V(x)}{\partial x}$$

Where, V(x) is the optimal cost. The solution can be obtained through a continuously differentiable optimal cost satisfying the HJB partial differential equation shown below.

$$V_x^T f(x) - \frac{1}{2}V_x^T gR^{-1}g^T V_x + \frac{1}{2}x^T Qx = 0$$

Applying Theta-D control includes approximation by the addition of a vanishing power series to the cost function and assuming a power series solution to the gradient of the optimal cost V [8].

$$J = \frac{1}{2}\int_0^\infty \left[x^T\left(Q + \sum_{i=1}^{\infty} D_i\theta^i\right)x + u^T Ru\right]dt$$

Where θ is a scalar and D_i is a perturbation matrix. It is chosen such that $Q + \sum_{i=1}^{\infty} D_i\theta^i$ is semi positive definite.

Original state equation is written as

$$\dot{x} = f(x) + gu = \left\{A_0 + \theta\left[\frac{A(x)}{\theta}\right]\right\}x + gu$$

Where A_0a constant matrix such that (A_0, g) is a stabilizable pair and $[A_0 + A(x), g]$ is point wise controllable.

Defining $\lambda = V_x$, making perturbed HJB in terms of λ.Assuming a power series expansion of λ in terms of θ as$\lambda = \sum_{i=0}^{\infty} T_i\theta^i x$.Where $T_i$are to be determined and assumed to be symmetric.

Substituting λ in perturbed HJB equation and equating co-efficient of powers of $\theta$to zero we get the following equations where $T_0 \ldots\ldots T_i$can be determined.

$$T_0A_0 + A_0^T T_0 - T_0 gR^{-1}g^T T_0 + Q = 0,$$

$$T_1(A_0 - gR^{-1}g^T T_0) + (A_0^T - T_0 gR^{-1}g^T)T_1 =$$

$$-\frac{T_0A(x)}{\theta} - \frac{A^T(x)T_0}{\theta} - D_1,$$

$$T_2(A_0 - gR^{-1}g^T T_0) + (A_0^T - T_0 gR^{-1}g^T)T_2 =$$

$$-\frac{T_1A(x)}{\theta} - \frac{A^T(x)T_1}{\theta} + T_1 gR^{-1}g^T T_1 - D_2,$$

This extends up to T_n^{th}equation.

Thus the expression for control becomes,

$$u = -R^{-1}g^T V_x = -R^{-1}g^T \sum_{i=0}^{\infty} T_i(x,\theta)\theta^i x$$

This method is called as Theta-D method thus.

Constructing the expression for $D_i, i = 1,2..n$:

$$D_1 = K_1 e^{-l_1 t}\left[-\frac{T_0A(x)}{\theta} - \frac{A^T(x)T_0}{\theta}\right],$$

$$D_2 = K_2 e^{-l_2 t}\left[-\frac{T_1A(x)}{\theta} - \frac{A^T(x)T_1}{\theta} + T_1 gR^{-1}g^T T_1\right],\ldots$$

Up to D_n.Where $k_i and\ l_i > 0$,i=1…n are scalar adjustable design parameters that are problem dependent and selected in a least square sense.

IV. NONLINEAR THETA-D CONTROL METHOD IN WIND TURBINES

The control problem that can be stated to track optimal power extraction in the below-rated power zone takes the form of single-input single-output system. It consists in synthesising the generator torque T_g in order to adjust, for any given effective wind speed v, the rotor speed w to the optimal value [12].

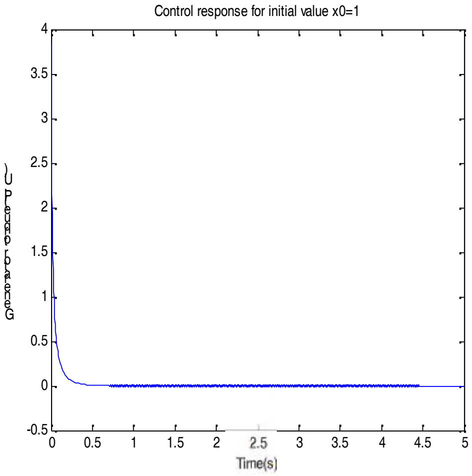

Fig4a control input T_g for initial control of 1

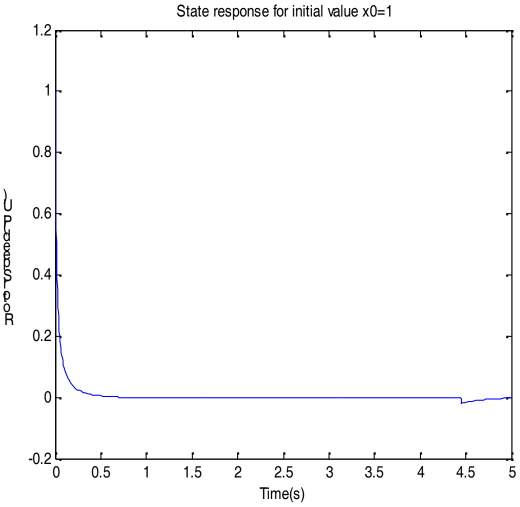

Fig4b State response for initial value of 1

A general nonlinear state dependent equation is of the form $\dot{x} = A(x)x + B(x)u$ and output is of the form $y = Cx + Du$, where A, B, C and D are the co-efficient matrices with respect to the state variables and control inputs of the system considered.

Considering the below system constraints with the objective function described as

$$J = \frac{1}{2}\int_0^\infty [\bar{x}(t)^T Q\bar{x}(t) + \bar{u}^T(t)R\bar{u}(t)]\,dt$$

With weighting matrices tuned and chosen as $Q = 1$ and $R = 1$. Considering the T_g as control inputs, the objective function J has to be minimized to track the desired output (power maximization).

The system constraints include $\dot{w} = -\frac{K_d}{J}w - \frac{1}{J}T_T w^2 - \frac{1}{J}T_g$

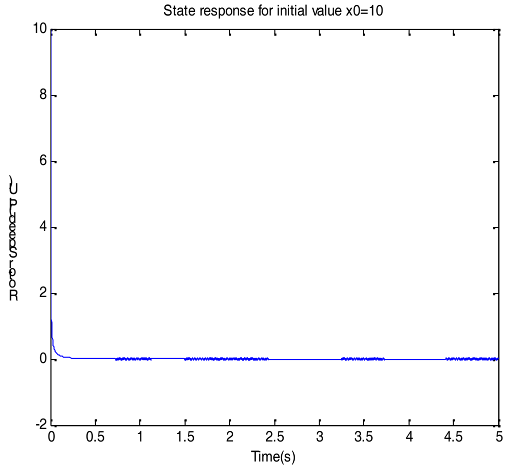

Fig5a State response for the initial value of 10

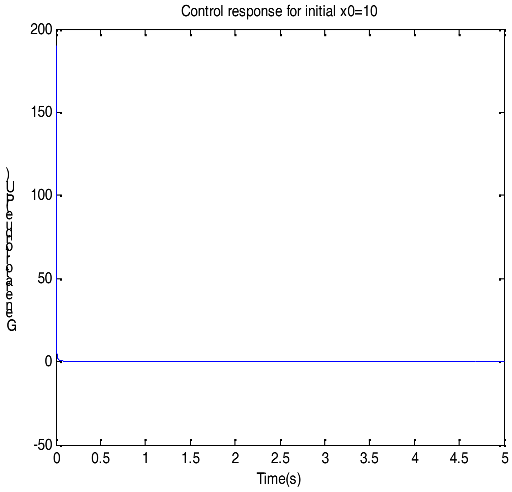

Fig5b Control response for initial value of 10

K_dIs the damping coefficient and the J is the inertia of the turbine considered. For the effective wind speed v, the rotor speed (w) is to be tracked to optimal value by adjusting the control variable T_g.

Applying these effects in Theta-D numerical control method, the states and the control obtained are shown in Fig4 and Fig5 to minimize the objective function J defined. Here the parameter values are g=-3.184,$A_0 = -0.987$, A(x)=-63.694x and K_1=0.993,K_2=0.993,l_1=2,l_2=0.18 for initial state value of $x_0 = 1$ and $x_0 = 10$.

The Fig4 and Fig5 show the generator torque synthesized and optimal value of the rotor speed tracking.

Thus attaining the turbine shaft control indirectly and obtaining the maximum power from the wind turbines.

The parameter values of the wind turbine system is J=0.314 kgm^2,$k_d = 0.3$kgm^2/s, R=1.81m, v=10 m/s.

V. CONCLUSION AND FUTURE SCOPE

The control of the generator torque gives maximum power output of the wind turbines by adjusting the rotor speed to optimal value. Further the higher order state space model can be implemented with the proposed control technique for control of the overall system for the large wind turbine systems.

REFERENCES

[1] L Zhang, C Watthanasarn and W. Shepherd (2009) Application of a Matrix Converter for the Power Control of a Variable-Speed Wind-Turbine Driving a Doubly-Fed Induction Generator.

[2] S.Masoud Barakati(2008) Modeling and Controller Design of a Wind Energy Conversion System Including a Matrix Converter Ph.D., thesis.

[3] Ming xin and S.N. balakrishnan(2002) A new method for suboptimal control of a class of nonlinear systems.

[4]. J. C. Mayo-Maldonado, R. Salas-Cabrera, H. Cisneros-Villegas, R. Castillo-Ibarra, J. Roman Flores, M. A. Hernandez-Colin(2011),Maximum Power Point Tracking Control for a DC Generator/Multiplier-Converter Combination for Wind Energy Applications.

[5] S. M. Barakati, J.D. Aplevich, (2007), Controller Design for a Wind Turbine System Including a Matrix Converter.

[6] S. M. Barakati,J.D. Aplevich,(2009), Maximum Power Tracking Control for a Wind Turbine System Including a Matrix Converter.

[7] M. Maureen Hand and Mark J. Balas National (2002) Systematic Controller Design Methodology for Variable-Speed Wind Turbines February, NREL/TP-500-29415M.

[8] Xingjia Yao,Shu Liu and Guangkun Shan Zuoxia Xing, Changchun Guo(2009) LQG Controller for a Variable Speed Pitch Regulated Wind Turbine.

[9] S.C. Thomsen, N.K. Poulse(2007) A disturbance decoupling nonlinear control law for variable speed wind turbines Informatics and Mathematical Modelling, Build 321,University of Denmark, Kgs. Lyngby, Denmark.

[10] Kasper Zinck, stergaard Vestas (2007) Gain-scheduled Linear Quadratic Control of Wind Turbines Operating at High Wind Speed Wind Systems Load, Aerodynamics and Control.

[11] Boubekeur Boukhezzar (2009) Comparison between Linear and Nonlinear Control Strategies for Variable Speed Wind Turbine Power Capture Optimization Automatic Control Department.

[12] Boubekeur Boukhezzar and Houria Siguerdidjane, (2005) Nonlinear Control of Variable Speed Wind Turbines without wind speed measurement.