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Robust Controller Design for IG Driven by Variable-Speed in WECS using μ-Synthesis

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Abstract
This paper presents robust controller design for a wind-driven induction generator system using structured singular value (μ -synthesis) method. The controller was designed for a static synchronous compensator (STATCOM) and a variable blade pitch angle in a wind energy conversion system (WECS) in order to achieve the required voltage and mechanical power control. The results indicated that this controller offers satisfactory damping characteristics for closed loop systems. Effects of various system disturbances on dynamic performance of the WECS were evaluated in this study by a time domain nonlinear simulation and compared with the output feedback controller. The proposed designed controller showed to be more effective in regulating the load voltage and stabilizing the generator rotating speed for WECS.

Keywords: Induction generator, Static synchronous compensator, Wind energy conversion system, Robust controller, Structured singular value.

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1. Introduction

Wind energy is one of the fastest growing industries at present and it will continue to grow worldwide, as many countries have plans for future development. Induction generators (IGs) are being increasingly utilized in a wind energy conversion system (WECS) since they are relatively inexpensive, rigid, and require low maintenance. However, the impact of ever-changing wind speed on power quality, coupled with the need of excitation current for IG, make the mechanical power control and voltage regulation indispensable to the wind-driven IG system. By far, the most effective way of controlling the mechanical power captured by the wind turbine (WT) is to adjust the rotor blade pitch angle. Blade pitch is analogous to the throttle value in conventional steam turbines, except that the speed of control is much faster than the governor control in a steam turbine. It can be employed to regulate mechanical power input and real power output of the WECS [1-2].
However, the reactive power required by the IG can be provided by a shunt capacitor bank, but it may cause excessive over-voltage during disconnection. Moreover, for excitation varies with the generator speed, the amount of capacitance is required [3]. Thus, if a fixed shunt capacitor is connected across the terminals of the IG, the terminal voltage will vary with generator speed. In order to achieve continuous voltage regulation under varying system conditions, static synchronous compensators (STATCOMs), have been employed in the literatures [4-8]. The basic principle of a STATCOM installed in an electric power system is to generate a controllable AC voltage behind a coupling transformer and a filter by a voltage-sourced inverter (VSI) connected to a DC capacitor. The output voltage of the VSI can be controlled to be greater than the line voltage in order to provide reactive power to the wind-driven IG.
Actual systems always include indeterminacy and uncertainty. This indeterminacy can be the result of modeling errors, changes in operating conditions, and variations of the system load. Therefore, conditions of nominal operating point change with change of operating point or disturbance occurrence in power system and the controller should have necessary flexibility for proper performance. This problem has led to the study of applying robust control. To cope with the system uncertainties and improving its stability and performance, several authors have applied robust control methodologies [9-12].
In this paper, a new approach based on structured singular value (μ-synthesis) is proposed for controller design. The effectiveness of the proposed control strategy on damping of oscillations was evaluated under various operating conditions and disturbances to demonstrate its robust performance. The results revealed that system performance with the proposed controller in spite of disturbance and various uncertainties is very satisfactory.

2. System under study

Fig. 1 depicts the single-line diagram of an induction generator driven by a variable-speed WT connected to a grid through a transmission line. A robust controller is utilized to control the WT mechanical power through the variable blade pitch and the STATCOM. The reactive power required by the IG in steady-state operating condition is supplied by a fixed shunt capacitor bank, as shown in Fig. 1. To maintain constant load bus voltage (V_l) under disturbance conditions, a STATCOM, which is capable of adjusting its output voltage and reactive power output based on system requirements, is employed. The STATCOM is connected to the load bus through a coupling transformer and a filter. System parameters are given in Appendix A.

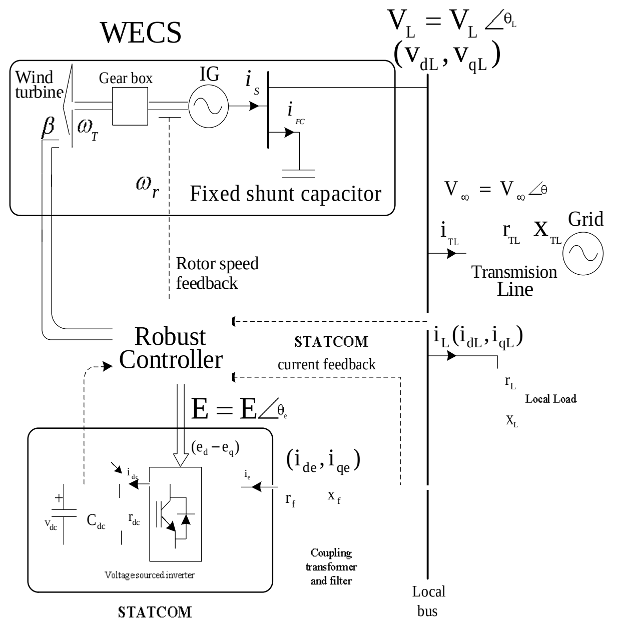


Fig.1. System under study

2.1. Generator model

The flux-linkages per unit of the stator and rotor circuits for the IG described in d- and q- axes are [13, 14]:

$$\dot{\phi}_{ds} = \omega_b (V_{dl} + r_s i_{ds}) + \omega_s \phi_{qs} \tag{1}$$

$$\dot{\phi}_{qs} = \omega_b (V_{ql} + r_s i_{qs}) - \omega_s \phi_{ds} \tag{2}$$

$$\dot{\phi}_{dr} = \omega_b (V_{dr} - r_r i_{dr}) + (\omega_s - \omega_r)\phi_{qr} \tag{3}$$

$$\dot{\phi}_{qr} = \omega_b (V_{qr} - r_r i_{qr}) - (\omega_s - \omega_r)\phi_{dr}, \tag{4}$$

where ω_b and ω_r are base and rotor angular speed; V_{dl} and V_{ql} stator voltage in d-axis and q-axis; V_{dr} and V_{qr} rotor voltage in d-axis and q-axis; r_s and r_r stator and rotor resistance; ϕ_{qs} and ϕ_{ds} stator flux-linkage in q-axis and d-axis; and ϕ_{qr} and ϕ_{dr} are rotor flux-linkage in q-axis and d-axis, respectively.

A synchronous reference frame rotating at the electrical angular speed corresponding to the fundamental frequency of the grid voltage, herein denoted as ω_s, is adopted.

The electromechanical torque in per unit can be written in terms of stator flux-linkages and currents as:

$$T_e = \varphi_{ds} i_{qs} - \varphi_{qs} i_{ds} \tag{5}$$

The per unit rotor acceleration is given by

$$\dot{\omega}_r^u = \frac{1}{2H_T}(T_m - T_e - D_T \omega_r^u), \tag{6}$$

where T_m is the per unit mechanical torque of the WT, and H_T and D_T are the equivalent inertia constant and the equivalent damping constant of the WT-IG system, respectively.

2.2. Wind turbine model

The mechanical power output of a WT can be written as [2]:

$$P_m = \frac{1}{2}\rho A C_p V_w^3, \tag{7}$$

where ρ is the air mass density, V_w is the wind speed, A is the rotor swept area, and C_p is a power coefficient representing the fraction of power extracted from the aerodynamic power in the wind by a practical WT.

The power coefficient C_p varies with the wind speed, the rotational speed of the turbine, and the turbine blade parameters. In this study the MOD-2 WT model [15, 16] with the following functional approximate relationship for C_p is used:

$$C_p = \frac{1}{2}\left(\frac{R}{\gamma} - 0.022\beta^2 - 5.6\right)e^{-\frac{0.17R}{\gamma}} \tag{8}$$

The tip speed ratio γ is defined as:

$$\gamma = \frac{w_T R}{V_w}, \tag{9}$$

where ω_T is the rotational speed of the WT as shown in Fig. 1. It is observed from Eqs. (7-9) that the mechanical power output of a WT is related to the turbine speed ω_T, wind speed V_w, and the pitch angle β. An increase in the pitch angle β, which results in a decrease in the power of WT when P_m continues to increase with increasing wind speed.

In this study, the initial pitch angle ($\beta_\circ$) is chosen to be 13.46° such that the WT delivers a mechanical power of 0.81 pu for a 30 miles/h (mph) wind at hub height.

2.3. STATCOM model

In a balanced three-phase system, the STATCOM model can be described in per unit using the variables in d- and q-axes synchronous reference frame as [4, 17]:

$$\dot{i}_{de} = -\frac{\omega_b r_f}{X_f} i_{de} + \omega_s i_{qe} + \frac{\omega_b}{X_f}\left(V_{dl} - e_d\right) \tag{10}$$

$$\dot{i}_{qe} = -\frac{\omega_b r_f}{X_f} i_{qe} - \omega_s i_{de} + \frac{\omega_b}{X_f}\left(V_{ql} - e_q\right), \tag{11}$$

where r_f and x_f are resistance and reactance of voltage-sourced inverter, respectively.

In Fig. 1, the instantaneous powers at the AC and DC sides of the voltage-sourced inverter are equal, giving the following power balance equation:

$$v_{dc} i_{dc} = e_d i_{de} + e_q i_{qe} \tag{12}$$

The per unit DC-side circuit equation is:

$$\dot{v}_{dc} = \frac{1}{c_{dc}}\left(i_{dc} - \frac{v_{dc}}{r_{dc}}\right), \tag{13}$$

with r_{dc} and c_{dc} being switching loss resistance and DC-link capacitance, respectively.

2.4. Fixed shunt capacitor model

The fixed shunt capacitor equations are as follows [4]:

$$\dot{v}_{dl} = \omega_s v_{ql} + \omega_b X_c i_{dfc} \tag{14}$$

$$\dot{v}_{ql} = -\omega_s v_{dl} + \omega_b X_c i_{qfc}, \tag{15}$$

where i_{dfc} and i_{qfc} refer to fixed capacitor current in d- and q- axes.

2.5. Transmission line model

The transmission line equations are as follows [4]:

$$\dot{i}_{dtl} = -\frac{\omega_b r_{tl}}{X_{tl}} i_{dtl} + \omega_s i_{qtl} + \frac{\omega_b}{X_{tl}}\left(v_{dl} - v_{d\infty}\right) \tag{16}$$

$$\dot{i}_{qtl} = -\frac{\omega_b r_{tl}}{X_{tl}} i_{qtl} - \omega_s i_{dtl} + \frac{\omega_b}{X_{tl}}\left(v_{ql} - v_{q\infty}\right), \tag{17}$$

where r_{tl} and x_{tl} are line resistance and reactance; and, $v_{d\infty}$ and $v_{q\infty}$ are infinite bus voltage in d- and q- axes.

2.6. Load model

Equations of load model in series R-L elements form are written as follows [4]:

$$\dot{i}_{dl} = -\frac{\omega_b r_l}{X_l} i_{dl} + \omega_s i_{ql} + \frac{\omega_b}{X_l} v_{dl} \tag{18}$$

$$\dot{i}_{ql} = -\frac{\omega_b r_l}{X_l} i_{ql} - \omega_s i_{dl} + \frac{\omega_b}{X_l} v_{ql}, \tag{19}$$

where r_l and x_l are load, resistance and reactance, respetively.

3. State equations of study system

The system dynamic equations derived in section 2 are nonlinear. In order to realize output feedback controller [13] and the proposed robust controller, these dynamic equations should be linearized around a nominal operating point. The linearized state equations are of the forms [5]:

$$\begin{aligned} \Delta\dot{x} &= A.\Delta x + B.\Delta u, \\ \Delta y &= C.\Delta x, \end{aligned} \tag{20a}$$

where

$$\begin{aligned} \Delta x \ = [&\Delta v_{dl}, \Delta v_{ql}, \Delta i_{dl}, \Delta i_{ql}, \\ &\Delta \omega_r^u, \Delta v_{dc}, \Delta\phi_{qr} \Delta\phi_{dr}, \Delta\phi_{ds}, \\ &\Delta\phi_{qs}, \Delta i_{dtl}, \Delta i_{qtl}, \Delta i_{de}, \Delta i_{qe}]^T \end{aligned} \tag{20b}$$

is the state vector.

Inputs for the state equations in (20a) are:

$$\Delta u = [\Delta e_d, \Delta e_q, \Delta\beta]^T \tag{21}$$

and the output vector is as follows:

$$\Delta y = [\Delta v_l, \Delta v_{dc}, \Delta\omega_r^u, \Delta i_{de}, \Delta i_{qe}]^T = C\,\Delta x, \tag{22}$$

where the output matrix C is given by

$$C = [C_1^T, C_2^T, C_3^T, C_4^T, C_5^T]^T \tag{23}$$

and the sub matrices C_1, C_2, C_3, C_4 and C_5 are defined as: $\Delta v_l = C_1\Delta x$, $\Delta v_{dc} = C_2\Delta x$, $\Delta w_r^u = C_3\Delta x$, $\Delta i_{de} = C_4\Delta x$, and $\Delta i_{qe} = C_5\Delta x$, respectively.

Note that the mechanical power can be conditioned by a variable blade pitch angle β in Eq. (21) through a controller with IG speed error $\Delta\omega_r^u$ as the primary stabilizing signal in the output vector in Eq. (22).

3.1. Steady-state errors elimination

To ensure zero steady-state errors for load bus voltage V_L and DC-capacitor voltage V_{dc}, two integral terms $\int \Delta V_L dt$ and $\int \Delta V_{dc} dt$ are required in addition to the state variables in Eq. (20b). Furthermore, the operating point of the IG changes with wind speed and load and different reference values for Δi_{qe} and Δi_{de} may be required by the STATCOM to achieve good regulation of load bus voltage V_L and DC-capacitor voltage V_{dc}. In order for the STATCOM currents Δi_{qe} and Δi_{de} to follow the reference values Δi_{qe}^* and Δi_{de}^* and ensure tight regulations for $\delta i_{qe} = \Delta i_{qe}^* - \Delta i_{qe}$ and $\delta i_{de} = \Delta i_{de}^* - \Delta i_{de}$, we need two additional state variables $\int \delta i_{qe} dt$ and $\int \delta i_{de} dt$. In the present work, the integral terms $\iint \Delta V_L dt$ (which is related to $\int \delta i_{qe} dt$) and $\iint \Delta V_{dc} dt$ (which is related to $\int \delta i_{de} dt$) are employed as the additional state variables [4, 5]. With the four integral terms $\int \Delta V_L dt$, $\int \Delta V_{dc} dt$, $\iint \Delta V_L dt$ and $\iint \Delta V_{dc} dt$ as the additional state variables, we have the augmented state equations as follows:

$$\begin{aligned} \Delta\dot{x}_a &= A_a.\Delta x_a + B_a.\Delta u \\ \Delta y_a &= C_a \Delta x_a, \end{aligned} \tag{24}$$

where

$$\Delta x_a = \begin{bmatrix} \Delta x \\ \Delta z \end{bmatrix}, \quad \Delta y_a = \begin{bmatrix} \Delta y \\ \Delta z \end{bmatrix},$$

$$\Delta z = [\int \Delta V_L dt, \int \Delta V_{dc} dt, \iint \Delta V_L dt, \iint \Delta V_{dc} dt]^T$$

$$A_a = \begin{bmatrix} A & 0 & 0 \\ C_1 & 0 & 0 \\ C_2 & 0 & 0 \\ 0 & I_{2\times2} & 0 \end{bmatrix}, B_a = \begin{bmatrix} B \\ 0 \end{bmatrix}, \tag{25}$$

$$C_a = \begin{bmatrix} C & 0 \\ 0 & I_{4\times4} \end{bmatrix}.$$

4. Control design

The main objective of the proposed controller is to regulate certain output measurements and drive system states to equilibrium operating points when the wind-driven IG system is subjected to various disturbances under grid connection condition. In this paper, robust controller design using μ-synthesis is presented for study system. For comparison, the simulated results of an output feedback control are presented.

4.1. Output feedback control design

In the design of the output feedback controller, the pole placement approach based on linear quadratic control (LQC) will be used. For the linear system described in Eq. (20a), the linear quadratic state feedback control Δu that minimizes the performance index written as

$$J = \frac{1}{2}\int_0^\infty \left(\Delta x^T Q \Delta x + \Delta u^T R \Delta u\right) dt, \tag{26}$$

where Q is the weighting matrix of the state variable variations and R that of the control effort, is given by [18, 19]

$$\Delta u = -K_s \Delta x \tag{27}$$

The closed-loop system equation with the optimal control $\Delta u(t)$ is

$$\Delta\dot{x} = A_s \Delta x, \quad A_s = A - BK_s = A - SM, \tag{28}$$

where

$$S = BR^{-1}B^T, \quad K_s = R^{-1}B^T M, \tag{29}$$

and M_s is positive semi-definite (stabilizing) solution M of the algebraic Riccati equation (ARE)

$$A^T M + MA + Q - MSM = 0. \tag{30}$$

Since some state variables such as $\Delta\phi_{qr}$, $\Delta\phi_{dr}$, $\Delta\phi_{qs}$ and $\Delta\phi_{ds}$ are not readily measurable, five output variables $\Delta v_l, \Delta v_{dc}, \Delta\omega_r^u, \Delta i_{de}, \Delta i_{qe}$ as listed in Eq. (22) are selected to be the feedback signals. Then, the output feedback control Δu is given by,

$$\Delta u = -K_o \Delta y, \tag{31}$$

where the output feedback gain matrix K_o is related to the state feedback gain matrix K_s as follows:

$$K_o C = K_s. \tag{32}$$

Thus, the output feedback gain matrix K_o can be derived, using K_s and C', the pseudo inverse [13, 20] of the output matrix C, as follows:

$$K_o = K_s C', \tag{33}$$

where

$$C' = C^T (CC^T)^{-1}. \tag{34}$$

4.2. Analysis

For the nominal operating condition, the system eigen-values without controller are obtained (Table 1) using state-space from transfer-function model. Clearly, STATCOM mode presents poor damping.

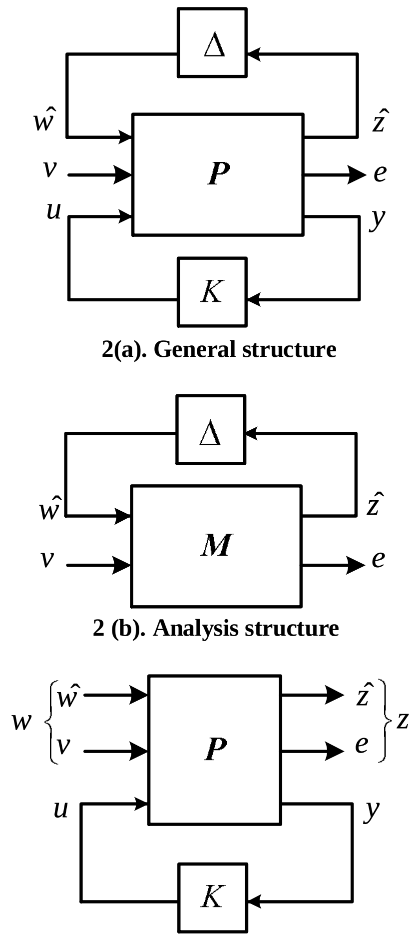
Table 1. System eigen-values without and with output feedback controller

Modes	Without controller	With output feedback controller
Generator Dynamics	-121.5±J2345 -5.5±J8.2 -11.2	-123.5±J2352 -8.6±J5.8 -7.4
STATCOM Dynamics	-43.6±J376.3 -0.067	-96.3±J552 -578

System eigen-values with output feedback are shown in Table 1. As can be seen STATCOM mode has good damping when as compared with the no-controller situation, where damping of generator mode is reduced.

4.3. Robust control design

General structure of robust control problems is shown in Fig. 2(a), where Δ indicates system uncertainty, P is generalized system model containing nominal system model and weighting functions for uncertainty and performance and K is the controller. In this figure, v is the disturbance input vector (contains reference inputs, noise and disturbance) and e is error signals which we want to regulate. u and y are control inputs and measured output vector (sensor output), respectively. In controller analysis problems, K is considered as part of the main system where it could be composed with certain part of P to make the unique system M, as shown in Fig. 2(b). In this figure, M is the results of generalized system P and K controller as follows [20-25]:



2(a). General structure

2 (b). Analysis structure

2 (c). Design structure

Fig.2. General robust control structure

$$M = F_l(P, K) = P_n + P_{12}K(I - P_{22}K)^{-1}P_{21}, \tag{35}$$

where M is:

$$\begin{bmatrix} z \\ y \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \begin{bmatrix} w \\ u \end{bmatrix} \tag{36}$$

also, generalized system model can be described by state space, as follows:

$$\begin{aligned} \dot{x} &= Ax + B_1 w + B_2 u \\ z &= C_1 x + D_{11} w + D_{12} u \\ y &= C_2 x + D_{21} w + D_{22} u \end{aligned} \tag{37}$$

In design problems, the aim is the K stable controller design so z outputs shown in Fig. 2(c) can be minimized.

4.4. Robust control based on μ-synthesis

Using normal singular values for analysis and design of control systems to confront the structured uncertainties lead to conservative results and increased control efforts. To mitigate this problem, μ-synthesis method was employed. The main property of μ is stability conditions and robust performance for any kind of uncertainty. The main basis for definition of μ is as union feedback system with $M-\Delta$ structure according to Fig. 3 with stable $M(s)$ and $\Delta(s)$ [20-23].

If $\underline{\Delta}$ defined as follows:

$$\underline{\Delta} = \{diag[\delta_1 I_{r1},...,\delta_s I_{rs},\Delta_1,...,\Delta_f\]:\delta_i \in C,\Delta_j \in C^{mj\times mj}\} \quad (38)$$

The structured singular values μ is:

$$\mu_{\Delta}(M) = \begin{cases} 0 & \det(I-M\Delta)\neq 0 \\ \left[\min\limits_{\Delta\in\underline{\Delta}}\{\bar{\sigma}(\Delta)\perp\det(I-M\Delta)=0\}\right]^{-1} & \det(I-M\Delta)=0 \end{cases} \quad (39)$$

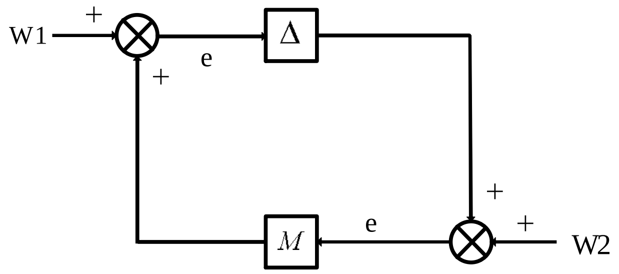


Fig.3. *M-Δ* structure with feedback

Note that the P includes the nominal plant, the weighting functions and scaling factor so that $\Delta_u \in B\Delta$.

Consider the general structure shown in Fig. 2(a). For K controller design, two conditions of robust stability and robust performance should be satisfied as mentioned in the above structure, and it should be re-designed according to Fig. 4 by standard $M-\Delta$ structure. In which $\hat{\Delta}$ and block M defined by Eqs. (38) and (39), respectively

$$\hat{\Delta}_P =: \left\{\begin{bmatrix}\Delta & 0\\ 0 & \Delta_P\end{bmatrix} : \Delta\in B\Delta, \Delta_p \in c^{nv\times ne}\right\} \quad (40)$$

μ-Synthesis problem is contained to find K stabilizing controller for generalized system which minimize the below equation [9, 20-22]:

$$\min_k \inf_\omega (\|M\|_\mu) \quad (41)$$

Ideally, based on the μ-theory, the robust stability and performance holds for a given *M*-Δ configuration if and only if:

$$\inf_K \|M\|_\mu \leq 1 \quad (42)$$

In the other words, the performance and stability assessment of the closed-loop system M is a μ test over frequency range and for the given uncertainty structure Δ. Using the performance robustness condition and the well-known upper bound for μ, the robust synthesis problem to be solved is reduced to the following [23]:

$$\min_K \inf_D \sup_\omega \bar{\sigma}(DM(j\omega)D^{-1}), \quad (43)$$

or equivalently:

$$\min_K \inf_D \|DF_L(P,K)D^{-1}\|_\infty .$$

By iteratively, solving for *D* and *K* (*D-K* iteration algorithm). Here *D* is any positive definite symmetric matrix with appropriate dimension and $\bar{\sigma}(.)$ denotes the maximum singular value of a matrix.

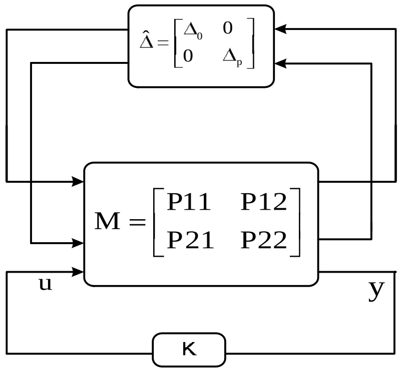


Fig.4. Standard *M-Δ* structure for μ controller design

4.5. Weighting functions selection

4.5.1. Uncertainty weights selection

For robust control design, an open-loop system is represented by nominal plant model Pnom(s) and the uncertainty set which covers the differences between Pnom(s) and reality of the physical system. Unstructured uncertainty was represented using frequency-domain bounds on transfer functions. Typically the bounds grow with frequency owing to greater likeliness of high frequency modeling errors. A power system can possess a large number of topological configuration and steady-state operating points. Variation of these operating points can be viewed as a source of unstructured uncertainty in the nominal linear plant model. The percentage of model uncertainty is represented by the weight Wu which corresponds to the frequency variation of the model uncertainty. Often, first order transfer function is selected for simplicity in obtaining the controller. Therefore, weighting function is chosen to cover the maximum uncertainty as follows:

$$W_u = \frac{0.05s}{2s+0.01} \quad (44)$$

4.5.2. Performance weights selection

The selection of WP entails a trade-off among different performance requirements, particularly good regulation versus peak control action. The weight on the output error, WP, must be close to an integrator at low frequencies in order to get zero steady-state error, good tracking and disturbances rejection. On the other hand, an important issue with regard to selection of these weights is degree for achieving performance objectives. Moreover, in order to keep the controller complexity low, the order of selected weights should be kept low. Based on the above discussion, therefore, a suitable first order performance weighting function is chosen as follows:

$$W_P = \frac{(s/20+0.6)}{(s+0.001\times 0.6)} \quad (45)$$

4.6. μ-Controller design

The robust synthesis problem is obtained in terms of the μ-theory and the μ-analysis. Synthesis toolbox of MATLAB is used to obtain optimal controller [26]. In summery the synthesis procedure for the proposed strategy is:

1. *Formulate the WECS and identify the state space model.*
2. *Identify the uncertainty blocks and associated weighting functions according to dynamic model, practical limits and performance requirements.*
3. *Obtain M-Δ configuration to formulate the desired level of robust performance.*
4. *Use D-K iteration algorithm by μ-synthesis toolbox to obtain the optimal controller.*
5. *Reduce the order of the resulting controller by using the standard model reduction techniques and apply μ-analysis to the closed-loop system with reduced controller to check whether or not the upper bound of μ remains less than one.*

The controller K(s) is found at the end of the second D-K iteration, yielding the value of about 0.99 on the upper bound on μ. Thus, the robust performance is guaranteed. The resulting controller is of dynamic type and has a high order (32^{th}). The controller is reduced to a 14^{th} order with no performance degradation using the standard Henkel norm approximation. Eigen-values of system with μ-controller are shown in Table 2. It can be observed that the damping of STATCOM and generator modes have improved compared to the output feedback controller.

Table 2. System eigen-values with μ-controller

Generator Dynamics	-125.8±J2362.8 -20.4±J8.6 -14.2
STATCOM Dynamics	-265±J528 -585

5. Simulation results

In this section different comparative cases (with robust and output feedback controller) are examined to show the effectiveness of the proposed μ-based controller. These cases are evaluated by time domain nonlinear simulation, through the usage of MATLAB software package.

The dynamic performances of robust and output feedback controllers for the WECS, following the wind speed change in Fig. 5, were compared under disturbance. The results are depicted in Figs. 6-10. The disturbance of a wind gust started at t = 53.0 s, reaching the peak wind speed of 19.9 m.s^{-1} at t = 54.5 s and finally the wind speed dropped to 16.45 m.s^{-1} at t = 55.3 s. For the sake of clarity, the effects of wind shear and tower shadow were ignored. It is obvious that the rotor would accelerate as a result of the increasing mechanical power caused by increasing wind speed if the pitch angle was fixed. However, as demonstrated in Fig. 6, the robust controller generated a pitch angle command as soon as the wind speed began to increase.

The second disturbance of a three-phase short circuit at the infinite bus at t = 30 s (after system response is reached to steady state) was chosen to compare the performance of two controllers. The response of closed loop system under this disturbance is shown in Figs. 11-14. The bus voltage and DC-capacitor voltage were returned to its reference value in very short time and swings amplitude with proposed controller is less than output feedback controller.

As can be seen, the proposed robust method significantly damp power system oscillations compared to output feedback controller.

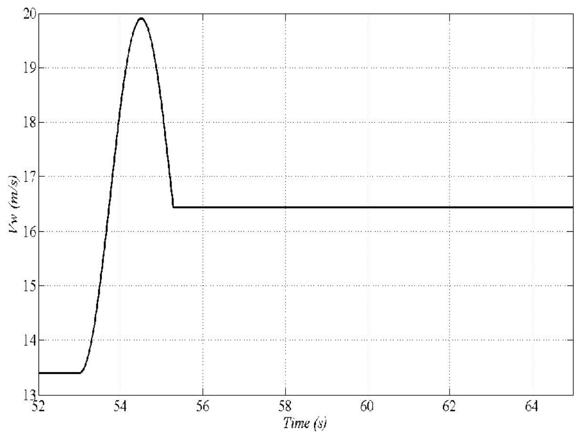


Fig.5. Wind speed curve

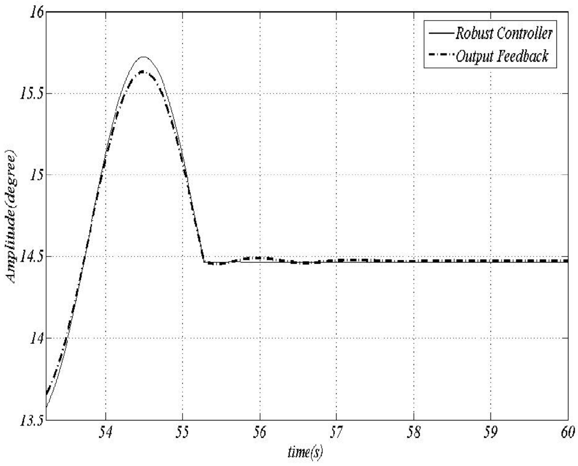


Fig.6. Deviation of turbine blade pitch angle with output feedback and robust controller

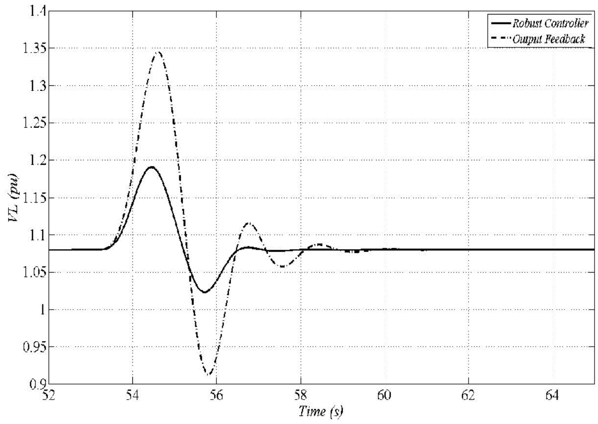


Fig.7. Deviation of bus voltage following wind speed variation with output feedback and robust controller

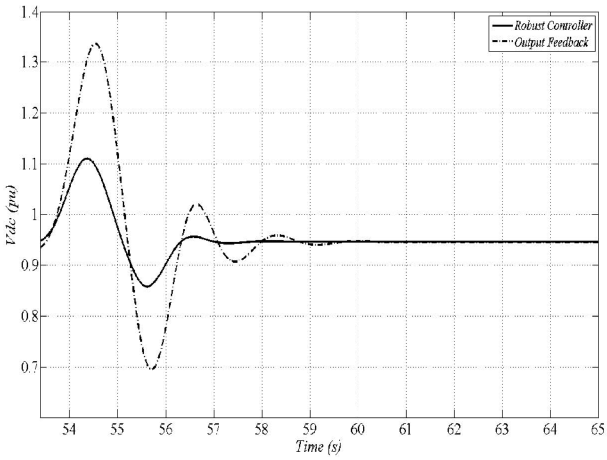


Fig.8. Deviation of DC-capacitor voltage following wind speed variation with output feedback and robust controller

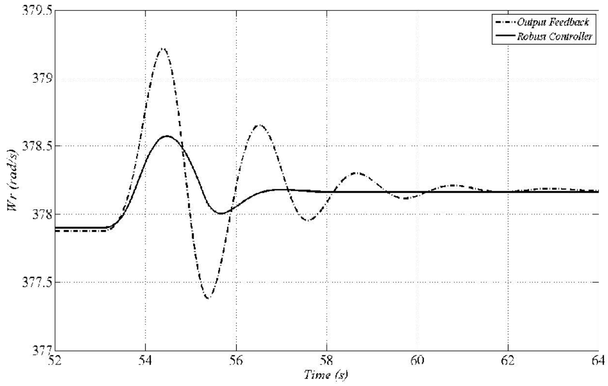


Fig.9. Deviation of rotor angular speed following wind speed variation with output feedback and robust controller

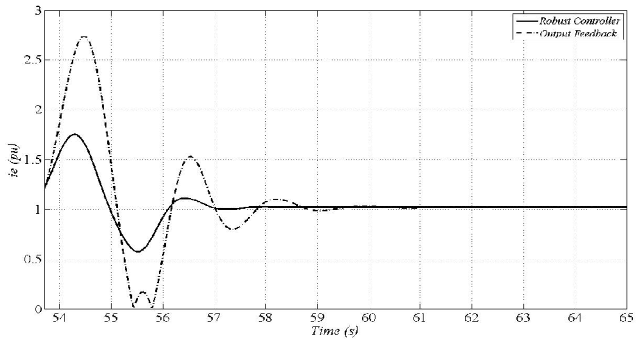


Fig.10. Deviation of STATCOM current following wind speed variation with output feedback and robust controller

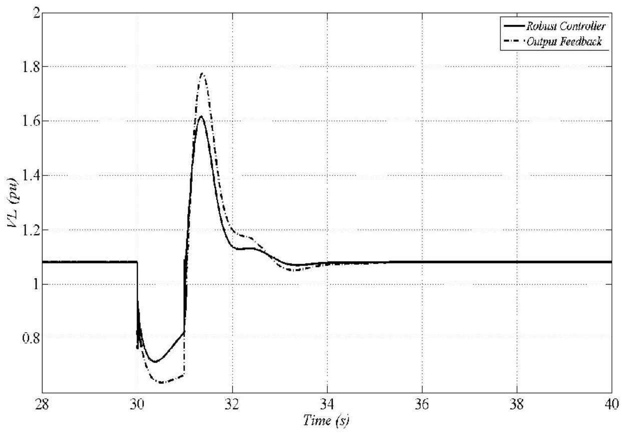


Fig.11. Dynamic response of bus voltage for short circuit with output feedback and robust controller

6. Conclusion

In this paper, robust controller design for wind energy conversion system with STATCOM was discussed. Different disturbance effects in dynamic performance of the system were simulated. Results revealed that the proposed controller in bus voltage regulation and improvement in damping of power system oscillations was very effective.

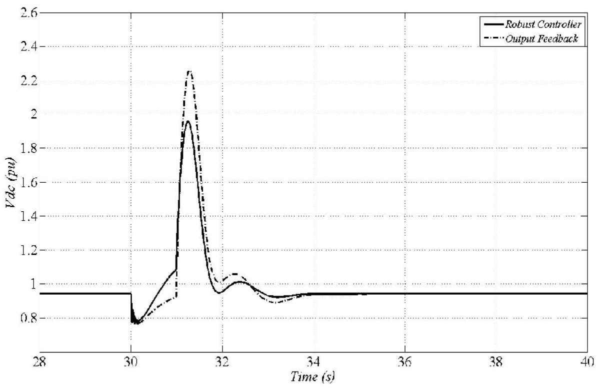


Fig.12. Dynamic response of DC-capacitor voltage for short circuit with output feedback and robust controller

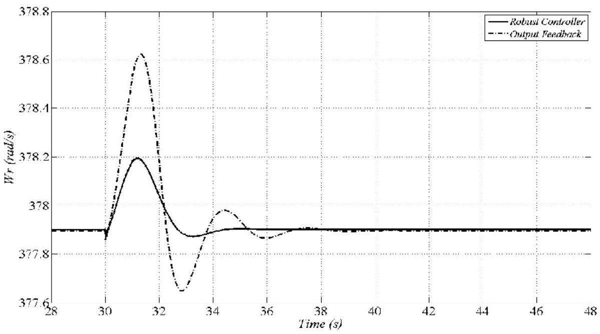


Fig.13. Dynamic response of rotor angular speed for three phase short circuit with output feedback and robust controller

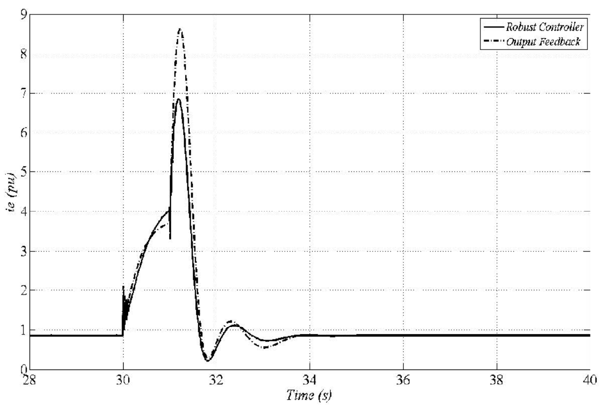


Fig.14. Dynamic response of STATCOM current for three phase short circuit with output feedback and robust controller

Furthermore, it was found that system performance with the proposed controller was fairly satisfactory in spite of disturbances and various uncertainties involved. The time domain simulation results also showed good performance on damping and improved stability under variable wind speed and short circuit as a large disturbance.

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Appendix A

Table A.1. Simulation parameters

Induction generator (2.5 MW, 4 poles, 4.16 kV,60 Hz)		
Stator resistance	r_s	0.0025 pu
Rotor resistance	r_r	0.0025 pu
Stator leakage reactance	X_s	0.0196 pu
Rotor leakage reactance	X_r	0.0196 pu
Magnetizing reactance	X_m	1.63 pu
Voltage-sourced inverter		
Series line resistance	r_f	0.02 pu
Series line reactance	x_f	0.14 pu
DC-link capacitance	c_{dc}	0.0028 F
Switching loss resistance	r_{dC}	500 pu
Transmission line		
Line resistance	r_{tl}	0.015 pu
Line reactance	x_{tl}	0.21 pu
Infinite-bus voltage	V_{dinf}	1 pu
Load model		
Nominal power at nominal voltage	Pl/Ql	0.15/0.6
Wind turbine [11], [12]		
Equivalent inertia constant	H_t	18.711 s
Equivalent damping constant	D_t	0.010125 pu
Rotor radius	R	150 ft
Gear ratio	GR	102.56
System base setting		
System MVA	S_b	2.5 MVA
Induction generator voltage base	V_{acb}	$\sqrt{(2/3)} \times 4.16kV$