



# Robust Optimal Controller Design for Induction Generator Driven by Variable-Speed Wind Turbine with STATCOM Using Immune Algorithm

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**Abstract**— this paper presents the modelling, controller design and a steady-state analysis algorithm for a wind-driven induction generator system. An output feedback linear quadratic controller is designed for the static synchronous compensator (STATCOM) and the variable blade pitch in a wind energy conversion system (WECS) in order to reach the voltage and mechanical power control under both grid-connection and islanding conditions. A two-reference-frame model is proposed to decouple the STATCOM real and reactive power control loops for the output feedback controller. To ensure zero steady-state voltage errors for the output feedback controller, the integrals of load bus voltage deviation and dc-capacitor voltage deviation are employed as the additional state variables. Pole-placement technique is used to determine a proper weighting matrix for the linear quadratic controller such that satisfactory damping characteristics can be achieved for the closed-loop system. Effects of various system disturbances on the dynamic performance have been simulated, and the results reveal that the proposed controller is effective in regulating the load voltage and stabilizing the generator rotating speed for the WECS either connected with or disconnected from the power grid. In addition, proper steady-state operating points for an isolated induction generator can be determined by the proposed steady-state analysis algorithm. Constant output frequency control using the derived steady-state characteristics of the isolated induction generator is then demonstrated in this paper.

**Keywords**— Induction generator (IG), static synchronous compensator (STATCOM), voltage regulation, wind energy conversion system (WECS), wind turbine

## I. INTRODUCTION

Induction generators 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 everchanging wind speed on power quality, coupled with the need of excitation current for induction generator (IG), make the mechanical power control and voltage regulation indispensable to the wind-driven induction generator system. By far, the most effective way of controlling the mechanical power captured by the wind turbine is to adjust the rotor blade pitch angle. Blade pitch is analogous to the throttle valve in conventional steam turbines, except that the speed of control is much faster than the governor control in a steam turbine [1], [2]. It can be employed to regulate mechanical power input and real power output of the WECS. However, the reactive power required by the IG can be provided by a shunt

capacitor bank, but it may cause excessive overvoltage during disconnection. Moreover, the amount of capacitance required for excitation varies with the generator speed [3]. Thus, if a fixed shunt capacitor is connected across the terminals of the IG, the terminal voltage will vary with generator speed. To achieve continuous voltage

Regulation under varying system conditions, static synchronous compensators (STATCOMs), have been employed in the literatures. The basic principle of a STATCOM installed in a 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.

An application of the linearized multivariable output feedback technique to the design of a voltage and mechanical power regulator for a wind turbine-induction

generator around a specific operating point was given in. Nevertheless, for the WECS, it is impractical and uneconomical to fix the generator output power (or rotor speed) at a specific operating point since the wind speed changes all the time. Besides, the controller design based on the constant output power (or rotor speed) considerations under grid-connection condition would fail in islanding operation.

In this paper, an output feedback controller is designed to regulate system voltage and mechanical power under both grid-connection and islanding conditions. The major features of the proposed output feedback controller are summarized as follows.

1) A systematic approach based on pole placement technique has been applied to determine proper weighting matrix for the linear quadratic controller such that the eigenvalues for the closed-loop system can be shifted to desirable locations. As a result, satisfactory transient excursion suppression in system voltages and generator speed can be reached by the controller when the WECS is subjected to major disturbances.

2) The integrals of load bus voltage deviation and dc-capacitor voltage deviation are employed as additional state variables to eliminate the steady-state voltage errors for the output feedback controller.

3) A control scheme with two reference frames is proposed to reach the decoupled control for the STATCOM real and reactive power control loops in case of voltage fluctuations, no matter what kind of disturbances may take place.

4) A simple algorithm is developed to determine proper steady-state operating points for an isolated IG. Using the relationship between the generator speed and the output power at various frequencies, a proportional-integral controller is proposed to achieve constant frequency control for an isolated IG with sufficient mechanical power.

## II. SYSTEM MODELS

Fig. 1 depicts the one-line diagram of an induction generator driven by a variable-speed wind turbine and connected to a grid through a transmission line. An output feedback controller is utilized to control the wind turbine mechanical power and the system reactive power through the variable blade pitch and the STATCOM, respectively. 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. Note that a constant impedance load is assumed in Fig. 1.

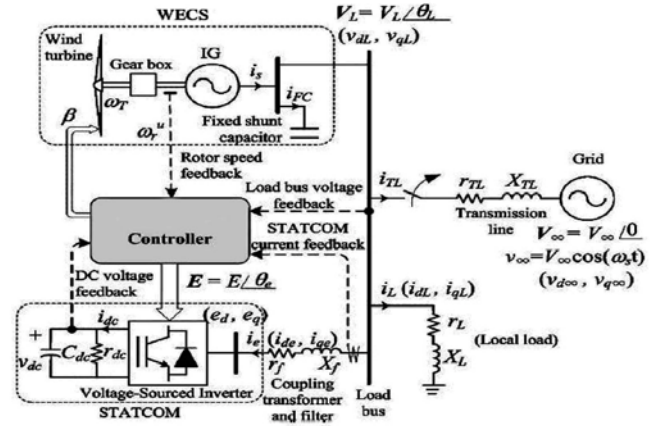


Fig. 1. System configuration

### A. Induction Generator Model

The per unit ux-linkages for the stator and rotor circuits of the induction generator described in d- and q-axes are as follows [3]:

$$\dot{\phi}_{qs} = \omega_b (v_{qL} + r_s i_{qs}) - \omega_s \phi_{ds} \quad (1)$$

$$\dot{\phi}_{ds} = \omega_b (v_{dL} + r_s i_{ds}) + \omega_s \phi_{qs} \quad (2)$$

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

$$\dot{\phi}_{dr} = \omega_b (v_{dr} - r_r i_{dr}) + (\omega_s - \omega_r) \phi_{qr} \quad (4)$$

Where a synchronous reference frame rotating at the electrical angular speed corresponding to the fundamental frequency of the grid voltage, herein denoted as  $s$ , is adopted. The electromechanical torque in per unit can be written in terms of stator ux linkages and currents as

$$T_e = \phi_{ds} i_{qs} - \phi_{qs} i_{ds} \quad (5)$$

The per unit rotor acceleration is given by

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

Where  $T_m$  is the per unit mechanical torque of the wind turbine, and  $H_T$  and  $D_T$  are the equivalent inertia constant and the equivalent damping constant of the wind turbine-induction generator system, respectively.

### B. Wind Turbine Model

The mechanical power output of a wind turbine can be written as [1]

$$P_m = \frac{1}{2} \rho A C_p V_w^3 \quad (7)$$

Where  $\rho$  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 wind turbine.

The power coefficient  $C_p$  varies with the wind speed, the rotational speed of the turbine, and the turbine blade parameters. The MOD-2 wind turbine model with the

following closed-form approximate relationship for  $C_p$  is used:

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

The tip speed ratio is defined as

$$\gamma = \frac{\omega_T R}{V_w} \quad (9)$$

here  $\omega_T$  is the rotating speed of the wind turbine. mechanical torque are the Wind turbines can obtain the following equation

$$T_m = \frac{1}{2} \rho \pi R^3 V_w^2 \frac{C_p}{\gamma} \quad (10)$$

It is observed from (9)–(10) that the mechanical power output of a wind turbine is related to the turbine speed  $\omega_T$ , wind speed  $V_w$ , and the pitch angle  $\beta$ . An increase in the pitch angle, which results in a decrease in the power coefficient  $C_p$ , is efficient to control the mechanical power of the wind turbine.

### C. STATCOM Model

For 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 [3]

$$\dot{i}_{de} = \frac{\omega_b r_f}{X_f} i_{de} + \omega_s i_{qe} + \frac{\omega_b}{X_f} (V_{dL} - e_d) \quad (11)$$

$$\dot{i}_{qe} = \frac{\omega_b r_f}{X_f} i_{qe} - \omega_s i_{de} + \frac{\omega_b}{X_f} (V_{qL} - e_q) \quad (12)$$

Where  $i_{de}$ ,  $i_{qe}$ ,  $e_d$ ,  $e_q$  are current and voltage axis d and q STATCOM. and  $V_{dL}$ ,  $V_{qL}$  are bus voltages at the axes d and q.

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:

$$V_{dc} i_{dc} = e_d i_{de} + e_q i_{qe} \quad (13)$$

The per unit dc-side circuit equation is

$$\dot{V}_{dc} = \frac{1}{C_{dc}} \left( i_{dc} - \frac{V_{dc}}{r_{dc}} \right) \quad (14)$$

Where  $r_{dc}$  is used to represent the inverter switching loss.

### D. Transmission line model

The per unit ux-linkages for the Transmission line described in d- and q-axes are as follows[4]

$$\dot{i}_{dTL} = -\frac{w_b r_{TL}}{X_{TL}} i_{dTL} + w_s i_{qTL} + \frac{w_b}{X_{TL}} (V_{dL} - V_{d\infty}) \quad (15)$$

$$\dot{i}_{qTL} = -\frac{w_b r_{TL}}{X_{TL}} i_{qTL} - w_s i_{dTL} + \frac{w_b}{X_{TL}} (V_{qL} - V_{q\infty}) \quad (16)$$

Where  $V_{q\infty}$ ,  $V_{d\infty}$  are per unit voltage at the axes q and d

### E. Fixed a shunt capacitor model

The per unit ux-linkages for the Fixed a shunt capacitor described in d- and q-axes are as follows [4]

$$\dot{V}_{dL} = w_s V_{qL} + w_b X_c i_{dfc} \quad (17)$$

$$\dot{V}_{qL} = -w_s V_{dL} + w_b X_c i_{qfc} \quad (18)$$

### F. Load model

The per unit ux-linkages for the load described in d- and q-axes are as follows[4]

$$\dot{i}_{dL} = -\frac{w_b r_L}{X_L} i_{dL} + w_s i_{qL} + \frac{w_b}{X_L} V_{dL} \quad (19)$$

$$\dot{i}_{qL} = -\frac{w_b r_L}{X_L} i_{qL} - w_s i_{dL} + \frac{w_b}{X_L} V_{qL} \quad (20)$$

## III. LINEARIZATION EQUATIONS THE POWER SYSTEM UNDER STUDY

To determine the appropriate control signal for STATCOM, Dynamic equations of system under study can be Linearization as follows.

$$\begin{aligned} \Delta \dot{x} &= A \Delta x + B \Delta u \\ \Delta y &= C \Delta x \end{aligned} \quad (21)$$

$$\begin{aligned} \Delta x &= [\Delta v_{dL}, \Delta v_{qL}, \Delta i_{dL}, \Delta i_{qL}, \Delta w_r^u, \Delta v_{dc}, \Delta \varphi_{qr}, \\ &\Delta \varphi_{dr}, \Delta \varphi_{ds}, \Delta \varphi_{qs}, \Delta i_{dTL}, \Delta i_{qTL}, \Delta i_{de}, \Delta i_{qe}]^T \end{aligned} \quad (22)$$

Where  $\Delta x$ ,  $\Delta u$ ,  $\Delta y$  are state vectors respectively, input and output system.

Mode input vector equations expressed in (23)

$$\Delta u = [\Delta e_d, \Delta e_q, \Delta \beta]^T \quad (23)$$

and output as vector is defined as (24)

$$\Delta y = [\Delta v_L, \Delta v_{dc}, \Delta w_r^u, \Delta i_{de}, \Delta i_{qe}]^T = C \Delta x \quad (24)$$

Where output matrix  $C$ , is as as follow

$$C = [C_1^T, C_2^T, C_3^T, C_4^T, C_5^T]^T \quad (25)$$

The  $C_1$ ,  $C_2$ ,  $C_3$ ,  $C_4$ , and  $C_5$  are sub matrix as follow

$$\Delta v_{dc} = C_2 \cdot \Delta x, \quad \Delta v_L = C_1 \cdot \Delta x$$

$$\Delta i_{de} = C_4 \cdot \Delta x, \quad \Delta w_r^u = C_3 \cdot \Delta x$$

$$\Delta i_{qe} = C_5 \cdot \Delta x$$

## IV. IMMUNE EVOLUTIONARY ALGORITHM

Having computers that automatically solve problems without being explicitly programmed to be the main goal of Artificial Intelligence [5].

Recently, interest in using techniques inspired by principles and mechanisms of the immune system has increased. And the systems currently in a variety of issues

such as computer security, information analysis, classification, template matching and parametric optimization is used [6, 7].

Clooney selection and placement antibodies with low degree of similarity is as follows.

1. Initialize: the initial set (population), called AB, the n number of antibody (Ab),  $i = 1, \dots, n$  is created.

2. Assessment: an antigen, Ag for the issue to be considered with all antibodies to be compared, as well as their degree of similarity  $f_i$  which the antigens are determined.

3. Placement: The probability of a certain pr new antibody is produced and placed a new set, so that parameter pr is the probability of placement.

Similarity degree is proportional to the antigen. In short, each antibody with probability pc, and clones are placed in a new set of parameter pc is likely to be cloned.

4. Clone: when a new antibody in the previous step does not produce an antibody (Ab) from the current set is selected. Likely to choose a direct antibody

5. super shoot: If the antibody with a high degree of similarity of selected clones in the previous step is not part super shoot is sent, super shoot antibodies selected for each element of its corresponding string with mutation probability pm mutations occurred. The probability of similarity degree images antibody with antigen is.

6. Repeat - Category: Repeat steps 3 to 5 until a new set of size n AB be created.

7. Repeat algorithm: The new collection is produced and stage 2 (assessment) is sent, the process repeats until a stop condition continues.

Flowchart continued safety, given the algorithm, details of which form (2) is given.

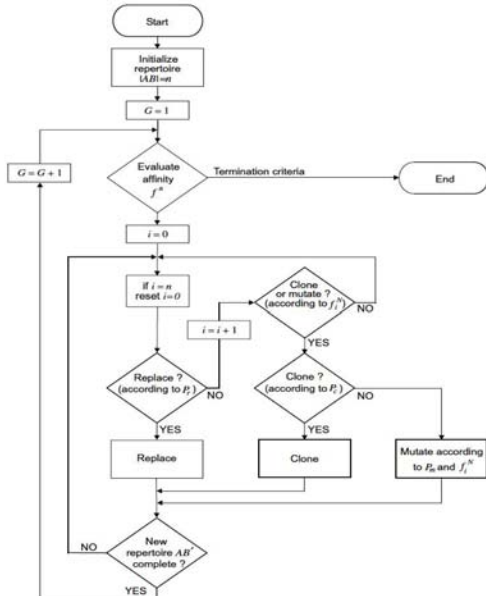


Fig2: flowchart Immune Algorithm

## V. LQG CONTROLLER DESIGN

Now LQG controller design for the system being studied are paid. LQG controller block diagram form the figure (3) is:

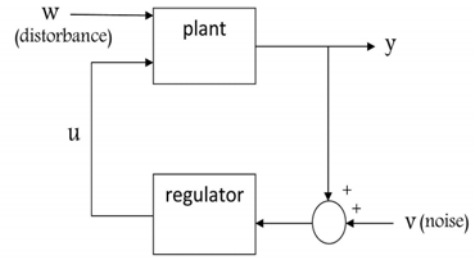


Fig 3 LQG controller block diagram

In this figure target is set output ( $y$ ) of the zero point.

State equation as relations (26) and (27) are:

$$\dot{x} = Ax + Bu + Gw \quad (26)$$

$$\bar{y} = Cx + Du + Hw + v \quad (27)$$

Where  $w$  and  $v$  are white noise model. LQG controller includes an optimal state feedback using a Kalman state estimate is nasty.

That the two sections independently, as explained below are designed.

### A. Using State Feedback

In control, measurement by displaying second form of relation (28) is calculated.

$$J(u) = \int_0^{\infty} \{x^T Qx + 2x^T Nxu + u^T Ru\} dt \quad (28)$$

Weight matrices  $Q$  and  $N$  and  $R$  by the efficiency and precision control are defined and determined.

The first step is to design a feedback  $u = -Kx$  that the minimum cost function  $J(u)$ , the search will be.

Coefficient matrix using the  $k$  to the minimum, using algebraic equations is obtained Rykaty. The coefficient of interest, using optimal LQ call.

If  $A, B, C$  and  $D$  matrix system under study and  $Q, R$  and  $N$  weight matrices are obtained, then use the coefficient  $K$ , gain of the LQ, relationship (29) is obtained.

$$K = lqr(A, B, Q, R, N) \quad (29)$$

### B. Estimator State Kalman

State feedback LQ in relation  $U = -Kx$ , on the poles placement is not applicable unless all conditions measured are considered. This applies if the estimate of a state, as derived variables are therefore related (30) we have:

$$U = -K\hat{x} \quad (30)$$

In orther to solve the Output feedback problem, or the remaining optimal state estimation by Kalman filter, which created the relation (31) is calculated.

$$\frac{d}{dt} \hat{x} = A\hat{x} + Bu + L(\bar{y} - C\hat{x} - Du) \quad (31)$$

With input  $u$  (controller) and the (measured) can be expressed.

Noise covariance information as relations (32) to (34) has been considered.

$$E(vv^T) = R_n \quad (32)$$



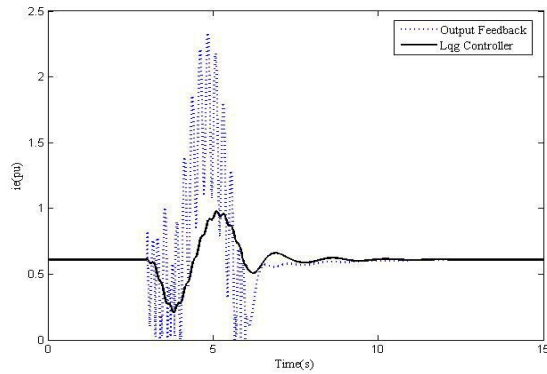


Fig 8: STATCOM current

Same as that of the Find (5) to (8) is visible, provided LQG control design, the voltage regulation and load fluctuations also improved the damping system was very effective and provided feedback to the control output results with appropriate can be.

## VII. SUMMARY

In this article, provided optimal control based method lqg, for the system under study was designed, the effects of changes in wind speed on the dynamic performance of building systems like and the results indicate that the control visitors' comment on the case terminal voltage

regulation and improved damping system oscillations has been very effective.

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