Servomechanism based Optimal Control System Design for Maximum Power Extraction from WECS with PMSG

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***Abstract*— The integral servomechanism based linear output feedback control for wind energy conversion systems (WECSs) with permanent magnets synchronous generator (PMSG) has been designed for maximum power extraction. The extended state space equation for given system's error dynamics has been formed. The linear quadratic regulator's optimal control laws are designed and calculated offline. The maximum power extraction from wind energy is achieved via accurate tracking variable reference of the generator's angular shaft speed. The wind is acted as an external disturbance and its speed is estimated with high order disturbance observer (HODO) enhancing reliability of the whole system in case of fault of the anemometer. The simulation results are shown effectiveness of the proposed control system under nominal parameters and some parameters uncertainties, noise, and modelling errors than with traditional disturbance compensation scheme.**

Keywords*— *wind energy conversion system (WECS), permanent magnet synchronous generator (PMSG), linear output feedback controller, integral servomechanism-based control, linear quadratic regulator (LQR), optimal tip speed ratio (TCR), maximum power point tracking (MPPT).

I. INTRODUCTION

The wind energy has demonstrated great potential of growth in energy generation in the last decades. The wind energy conversion systems (WECSs) are differed from kilowatt to megawatt power working in grid-tied to standalone modes. Among them the variable-speed WECS with back-to-back power converters topology are widespread to extract more power via techniques based on regulating tip speed ratio (TCR). The permanent magnet synchronous generator (PMSG) is one of the main components of WECS, therefore its technical characteristics such as high power-density, higher efficiency, and high power-factor are important in choosing complexity of whole system [1-3]. Although the technology of power electronics is advanced in the recent years, the control system's performance is effected from disturbances and other unwanted problems.[3]. Therefore, the robust control system with its disturbance rejection feature can be complex problem.

The performances of the conventional linear approaches such as proportional-integral (PI) and linear quadratic regulator (LQR are sensitive to the parameters perturbations, whereas they are straightforward for implementation due their simplicity. One way to mitigate their negative impacts is use the compensations technique based on disturbance observers like in [4-7] but the control systems become cumbersome and stability of these systems hardly can be guaranteed. In literature, there are many studies about to increase the performance of PMSG and it is so popular [19-23].

In this paper, integral servomechanism based LQR with linear output feedback for the WECS is proposed. The optimal gains are calculated offline therefore the computational burden is not exceeded. The fast-changing wind speed variations are considered as external disturbance. The dynamic equations of the system are simulated numerically in MATLAB. The simulation results are shown effectiveness of the proposed control system under nominal parameters and some parameters uncertainties, noise and modelling errors than with traditional disturbance compensation scheme. The study is based on the assumption that DC-link voltage is controlled accordingly with grid-side power converter and generator-side power converter is controlled with proposed control system.

II. WIND ENERGY CONVERSION SYSTEM

The configuration with a PMSG and full-scale back-to-back (B2B) power converters is widely spread in the wind-turbine market. The WECS equipped with PMSG and back-to-back (B2B) power converter is depicted for demonstration purpose in Figure 1. The full rated B2B power converter is segmented with DC-link capacitor by two, namely generator-side and grid-side. The former extract available power from variable wind energy. Furthermore, it facilitates peak power via defining and tracking reference electromagnetic torque control approach whereas reference for direct axis current is fixed at zero to provide highest torque at least stator current for minimizing loses [8].

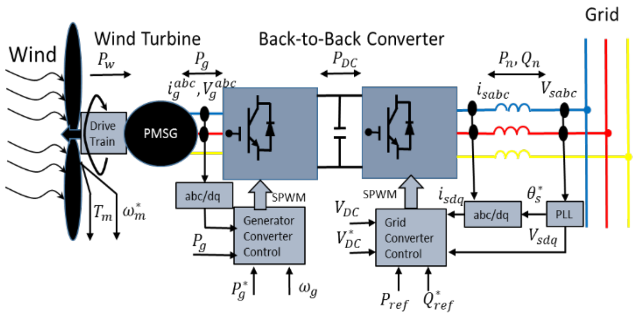

Fig. 1. WECS with PMSG based on Back-to-Back power converter [13]

This work was supported by the Scholarship Programme from the Islamic Development Bank (ID 2021-588606)

The extracted aerodynamic power from wind turbine can expressed as [2]

$$P_a = \frac{1}{2}\rho\pi R^2 C_p(\lambda,\beta)v^3 \tag{1}$$

Where, ρ, R, WT, v, $C_p(\lambda,\beta)$ symbolized air density, rotor radius, wind speed, power coefficient depends capacity of the wind turbine, respectively.

The WT should operate at maximum power coefficient C_p^{MAX} to facilitate maximum power extraction which depends on the tip-speed ratio (TCR) λ and pitch angle β [9].

The power coefficient will mainly depend on TCR if the pitch angle will be fixed at zero degrees for all blades, where TCR relation is

$$\lambda = \frac{\omega_t R}{v} \tag{2}$$

where ω_t is angular shaft speed of the WT.

The reference angular shaft speed of variable speed WECS under partial load condition can be facilitated with defining λ_{opt} . However, the pitch regulation should be applied to reduce the power from exceeding wind speed or even shut down WT.

$$\omega_{t,d} = \frac{\lambda_{opt} v}{R} \tag{3}$$

The wind speed is function of aerodynamic torque and shown in Eq.4.

$$T_a = \frac{P_a}{\omega_t} = \frac{1}{2}\rho\pi R^3 C_q(\lambda,\beta)v^2 \tag{4}$$

Where, $C_q(\lambda,\beta)$ shows torque coefficient and derived from power coefficient by using $C_q(\lambda,\beta) = C_p(\lambda,\beta)/\lambda$.

In this study, the model equations of PMSG in the synchronous reference frame.

$$\begin{cases} \frac{d\omega}{dt} = \frac{1}{Jn_{gb}}T_a - \frac{B}{J}\omega - \frac{1}{J}T_e \\ \frac{dT_e}{dt} = -PK\omega i_d - \frac{R_s}{L}T_e - \frac{\psi_m PK}{L}\omega + \frac{K}{L}V_q + d_q \\ \frac{di_d}{dt} = \frac{1}{L}V_d - \frac{R_s}{L}i_d + \frac{P}{K}\omega T_e + d_d \end{cases} \tag{5}$$

where angular shaft speed of PMSG, i_d is d-axis stator current, and V_d and V_q present the stator voltages in d-axis and q-axis, respectively; R_s is stator resistance; L is stator inductance; B is viscous friction coefficient; ψ_m denotes magnetic flux linkage; J presents rotor inertia; P is pole pairs, and T_e is electromagnetic torque.

The electromagnetic torque is function of q-axis stator current, i_q [8]

$$T_e = Ki_q \tag{6}$$

where $K = 3/2(\psi_m P)$.

The terms d_q and d_d represent the lumped disturbances associated with parameters uncertainty, noise and modeling errors in the system (5)

$$d_q = \left(\frac{R_s}{L} - \frac{R_s+\Delta R_s}{L+\Delta L}\right)T_e + \left(\frac{1}{L} - \frac{1}{L+\Delta L}\right)\psi_m PK\omega + \left(\frac{1}{L} - \frac{1}{L+\Delta L}\right)Kv_q + d_{qn} \tag{7}$$

$$d_d = \left(\frac{R_s}{L} - \frac{R_s+\Delta R_s}{L+\Delta L}\right)i_d + \left(\frac{1}{L} - \frac{1}{L+\Delta L}\right)v_d + d_{dn} \tag{8}$$

where ΔR_s and ΔL_s are varied parameters of the PMSG's stator resistance and inductance due to impact of ambient temperature, and d_{qn} and d_{dn} include the noise and modeling errors usually come from sensors and apparatus which are difficult to model.

III. DESIGN OF LINEAR CONTROL

A. The integral servomechanism based linear quadratic control (ISLQRC)

The proposed ISLQRC law is presented in this section.

The minimization function of the performance index assuming autonomous, infinite-horizon, linear regulator situation in shown in Eq.9.

$$\mathrm{Min}\, J(u) = \frac{1}{2}\int_0^\infty x^T Q x + u^T R u \, dt \tag{9}$$

Where Q≥0 and R>0 for all x

In order to implement the servomechanism technique [10], the state-space system is shown in Eq.11 is extended by getting the integral of angular shaft speed error shown in Eq.10.

$$\dot{\tilde{x}} = \tilde{A}\tilde{x} + \tilde{B}u \tag{10}$$

Where extended state and control matrices will be as following

$$\tilde{A} = \begin{bmatrix} 0 & I \\ A & 0 \end{bmatrix}, \tilde{B} = \begin{bmatrix} 0 \\ B \end{bmatrix} \tag{11}$$

Where states vector is $\tilde{x}^T = [\int \tilde{\omega} dt \quad \tilde{\omega} \quad \tilde{T}_e \quad i_{ds}]$.

Introducing following error dynamics

$$\tilde{\omega} = \omega - \omega_d, \omega_d = \omega_{t,d} \cdot n_{gb} = \frac{\lambda_{opt}}{R}\vartheta \cdot n_{gb},$$

$$\tilde{T}_e = T_e - T_{ed},\ T_{ed} = \frac{1}{n_{gb}}T_a - B\omega_d - J\dot{\omega}_d \tag{12}$$

The control variables consist of only linear feedback parts

$$V_{qs} = u_{fbq},\ V_{ds} = u_{fbd} \tag{13}$$

where u_{fbq} and u_{fbd} are q axis and d axis components of linear output feedback control system, respectively.

The PMSG's error dynamics is defined as

$$\begin{cases} \frac{d\tilde{\omega}}{dt} = -\frac{B}{J}\tilde{\omega} - \frac{1}{J}\tilde{T}_e \\ \frac{d\tilde{T}_e}{dt} = -PL\tilde{\omega} i_d - \frac{R_s}{L}\tilde{T}_e - \frac{\psi_m PK}{L}\tilde{\omega} + \frac{K}{L}V_q \\ \frac{di_{ds}}{dt} = \frac{1}{L}V_d - \frac{R_s}{L}i_d + \frac{PL}{K}\tilde{\omega}\,\tilde{T}_e \end{cases} \tag{14}$$

The constant states and control matrices can be extracted from it and nonlinear terms eliminated

$$A(x) = \begin{bmatrix} -\frac{B}{J} & -\frac{1}{J} & 0 \\ -\frac{\psi_m PK}{L} & -\frac{R_s}{L} & 0 \\ 0 & 0 & -\frac{R_s}{L} \end{bmatrix}, B = \begin{bmatrix} 0 & 0 \\ \frac{K}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix} \tag{15}$$

The integral servomechanism based extended states and control matrices according to the equation (11) is

$$\tilde{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{B}{J} & -\frac{1}{J} & 0 \\ 0 & -\frac{\psi_m PK}{L} & -\frac{R_s}{L} & 0 \\ 0 & 0 & 0 & -\frac{R_s}{L} \end{bmatrix}, \tilde{B} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{K}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix} \tag{16}$$

The algebraic Riccati equation (ARE) for the extended LQ problem is

$$\tilde{A}^T\tilde{P}+\tilde{P}\tilde{A}-\tilde{P}\tilde{B}R^{-1}\tilde{B}^T\tilde{P}+\tilde{Q}=0 \qquad (17)$$

Where $\tilde{P}$ is positive definite matrix is the solution of ARE which drive the cost function (9) to minimum.
The integral servomechanism based optimal control law is

$$u=-R^{-1}\tilde{B}^T\tilde{P}\tilde{x}=-\tilde{K}\tilde{x} \qquad (18)$$

To enhance the reliability of the WECS, high order disturbance observer (HODO) can estimate the wind speed which is cubic of aerodynamic torque acted as external disturbance. The fact that HODO does not require first derivative to be zero and other derivatives to be bounded is advantageous to estimate fast-varying wind speed [10]. Moreover, the accuracy of the estimation is proved in the studies listed in the reference list.

IV. SIMULATION RESULTS

The simulation results of PMSG based WECS with parameters listed in Table 1 is presented in the section. The proposed ISLQRC's parameters are listed in Table 2. To evaluate the efficiency of the proposed control pitch angle has been fixed at zero and with λ_{opt}, the maximum power coefficient is 0.411. The fast-varying wind speed is presented in Figure 2 with mean value of 12.13 m/s. The parameters of the PMSG, R_s and L are extended by 20% and 1% respectively. This emulated the model uncertainty due to increase of ambient temperature in the WT [11]. The modelling errors and noise have presented with the $d_{qn}=10^5\sin(t)$ and $d_{dn}=10^3\sin(t)$ associated with sensors and power electronics.

TABLE I. WECS PARAMETERS

Symbol	Quantity	Value	[Unit]
P_{rated}	Rated power	5	kW
R_s	Stator resistance	0.3676	Ω
L	Stator inductance	3.55	mH
ψ_m	Magnet flux linkage	0.2867	V·s/rad
J	Mechanical inertia	7.856	kg·m^2
P	Pole pairs	14	-
B	Viscous friction coefficient	0.002	kg·m^2/s
R	Rotor radius	1.84	m
ρ	Air density	1.25	kg/m^3

By solving extended ARE equations (17) the optimal gains matrix (18) can be obtained.

The simulations of the proposed integral servomechanism based LQR control system for improving tracking performance of the PMSG's angular shaft speed in the WECS has been evaluated under nominal parameters and model uncertainty, noise and external disturbance and compared with lumped disturbance compensation approach based LQR control system presented in [4-7].

TABLE II. PARAMETERS OF CONTROLLER

Parameters	Values
Tuning gains	Q=diag([1 10000 1000 1]), R=diag([0.0005 0.0005])
HODO's observer gains	L_1=500, L_2=100, L_3=20

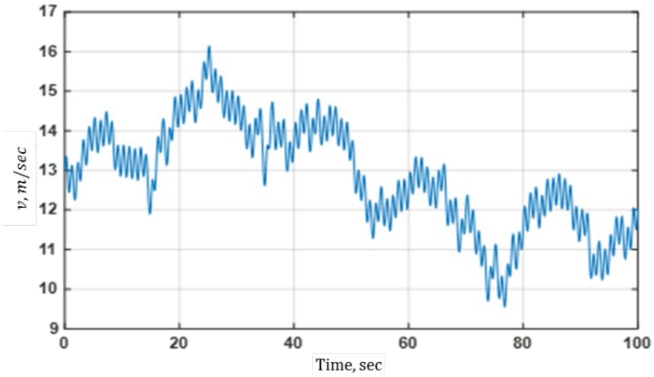

Fig. 2. Wind speed, v profile with mean value of 12.13, m/sec.

The performance of the proposed ISLQRC system are presented in Table 3. The mean absolute percentage error (MAPE) is used to show the performance of controller with $|\tilde{\omega}|$ and $|\tilde{T}_a|$ are shown in Fig.3 and Fig.4, respectively. Also, performance of the proposed ISLFC performance is compared with traditional LQRC with lumped disturbance compensation technique under distributions, uncertainties and modelling errors in the WECS. The performance of the proposed controller under scenario 2 are demonstrated in Figures 5 and 6.

TABLE III. THE SERVOMECHANISM BASED LQR CONTROL PERFORMANCE FOR WECS APPLICATION WITH PMSG

Criteria and cases		Scenario 1	Scenario 2	Improved by, %
Mean absolute percentage error of angular shaft speed, $|\tilde{\omega}|$	LQR with compensation	0.7249	0.7246	-
	LQR with Servomechanism	0.2084	0.2099	71.25%/ 71.03%
Aerodynamic torque estimation errors, $|\tilde{T}_a|$	LQR with compensation	0.0748	0.0735	-
	LQR with Servomechanism	0.0694	0.0690	7.22%/6.12%

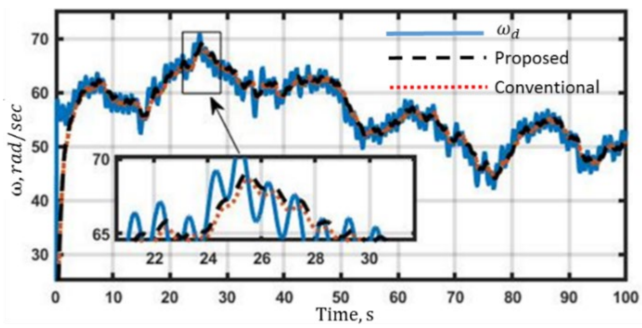

Fig. 3. The angular shaft speed tracking the reference under proposed control (scenario 1) and conventional LQR control

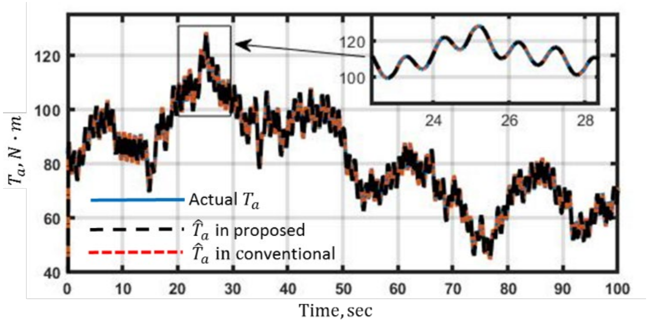

Fig. 4. The aerodynamic torque estimation with HODO under proposed control (scenario 1) and conventional LQR control

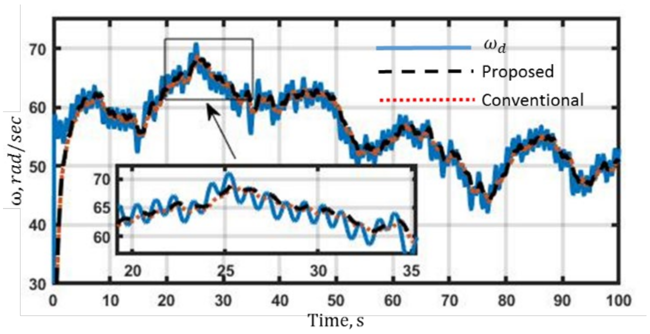

Fig. 5. The angular shaft speed tracking the reference under proposed control (scenario 2) and conventional LQR control

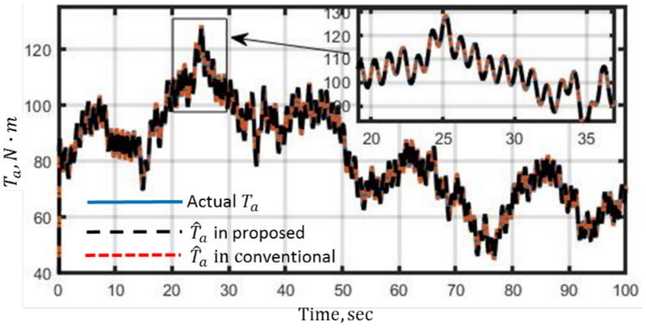

Fig. 6. The aerodynamic torque estimation with HODO under proposed control (scenario 2) and conventional LQR control

V. CONCLUSION

In this study, the variable speed WECS with controlling the power converter of PMSG-side to improve power extraction from wind energy. To enhance its performance with obtaining the optimal gains of extended LQ problem by using minimization function and MARE are presented The performance of the proposed linear output feedback controller shows its robustness regardless under various sources of disturbances.

The proposed control shows superior performance than the lumped disturbances compensation based traditional LQRC system under fast-varying external disturbance, model uncertainty, modelling errors and noise. The HODO is utilized for wind speed estimation via aerodynamic torque, which enhances the reliability of whole system when there is fault with wind sensors.

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