

Optimal Estimation and Tracking Control for Variable-speed Wind Turbine with PMSG

Farzad Bakhtiari and Jalal Nazarzadeh

Abstract—Designing an optimal tracking controller and system observer is a nonlinear problem in the variable-speed wind energy conversion system (WECS). In this paper, an adjusted feedforward and feedback optimal controller with extended Kalman filter (EKF) is introduced to estimate and control the permanent magnet synchronous generator (PMSG) for the maximum power point tracking (MPPT) with several disturbances of the wind speed. An augmented model of wind turbine and PMSG is expanded, and then the parameters of the optimal controller and estimator are obtained. The dynamic stability of the closed-loop system with feedback-feedforward controller (FFC), EKF and speed controller are analyzed. To compare the dynamic performance of EKF and FFC with the conventional controllers, numerical results are demonstrated with the disturbances of the wind speed and faults in power grid.

Index Terms—Permanent magnet synchronous generator (PMSG), maximum power point tracking (MPPT), extended Kalman filter (EKF), optimal tracking control.

I. INTRODUCTION

RECENTLY, the sensorless permanent magnet synchronous generator (PMSG) has been widely used in wind energy conversion system (WECS) [1]. This system is characterized by the high performance, low inertia, high torque, better network compatibility and relatively low maintenance costs. The maximum power point tracking (MPPT) algorithm calculates the shaft speed of the PMSG based on the current measurements of wind speed and power generation. The implementation of MPPT algorithm in WECS is the control of the power converter by generating a reference signal (shaft speed) for tracking control of PMSGs in order to reach the maximum power output. Thus, adjusting the dynamic performance of wind turbines under variable-speed conditions for tracking control with MPPT algorithm is an essential feature of the WECSs.

The conventional closed-loop system with the proportional-integral (PI) controller and the speed sensor has been commonly applied to WECS for taking MPPT control under variable-speed conditions. In this system, the PI controller provides zero tracking error of the PMSG speed for a constant

reference signal. However, since the PI controller is with low bandwidth, the dynamic performance of the closed-loop system is poor [2]. Reference [3] compares the stability analysis of small and large disturbances in a doubly-fed induction generator and PMSG and shows that the stability margin of PMSG is lower than a doubly-fed induction generator especially after a fault in the system on the grid side.

On the other hand, the speed measurement with mechanical sensors increases the cost, the complexity of the hardware, the delay in time response and the failure rate of the WECS. Moreover, switching by an inverter leads to disturbance effects in measuring the output signals and electromagnetic interference. These effects can be improved by applying a linear and nonlinear perturbation observers to WECS [4], [5]. Also, the wind speed can be estimated by aerodynamic torque and rotor speed so that the wind speed sensor could be omitted [6]. In [7], a robust adaptive control is applied to a WECS for estimating the parameters of WECS. However, the estimations of this observer do not converge to the proper values. A robust nonlinear observer is introduced for handling this problem, which could lead to the saturation and nonlinear system with several derivative operators in the observer [8]. Moreover, in the linear quadratic Gaussian (LQG) procedure, the estimation error appears in the turbine speed with the disturbances of the wind speed [9].

The stability analysis of WECS with PMSG is another critical issue in designing a controller which extracts the maximum energy from the wind turbine [10]. The small-signal stability analysis of WECS with the two-mass model is introduced in [11]. The authors illustrate that the dynamic stability of WECS depends on the torque controller and the response time of the converter. Also, a static synchronous compensator (STATCOM) with a proportion-integration-differentiation (PID) controller can be implemented to improve the dynamic stability in WECS with parallel-operated PMSG connected to a grid. However, despite the improvement in the dynamic stability of the system, the control system needs an external power compensator [12].

The extended Kalman filter (EKF) is a conventional estimator for nonlinear systems with input and output noises to estimate the optimal states of the system at the different operation points [13]. In [14], MPPT algorithm is introduced for WECS with a nonlinear algebraic Riccati equation and EKF. However, the estimation error of EKF is not accept-

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able. In order to resolve this issue, a nonlinear observer such as unscented Kalman filter is recommended in WECS. Therefore, the LQR with EKF cannot be able to provide a stability margin of the closed-loop system with MPPT algorithm in WECS.

In this paper, the dynamic model of a wind turbine and PMSG at the different operation points is developed, and the optimal state estimation is implemented with EKF. Also, a modified LQR controller with feedback and feedforward gains is introduced for tracking the operation points generated by the MPPT algorithm. The feedback gains are constant values. However, the optimal feedforward gains depend on the wind turbine speed. The EKF observer is utilized to adjust the feedforward gains for tracking the operation points from the MPPT algorithm. Finally, the simulation results are illustrated and compared for different types of controllers such as PI, LQG and feedback-feedforward controller (FFC). These results show that the dynamic performance of the optimal FFC effectively improves in comparison to other controllers with variable wind speeds and fault conditions in the WECS on the grid side.

The structure of this paper is organized as follows. Section II presents the nonlinear models of the wind turbine and PMSG and illustrates the closed-loop structure of the proposed system in WECS. In Section III, the optimal design procedures for EKF and FFC are introduced, and the detailed structure of the vector control in WECS with EKF and FFC is described in Section IV. Then, the dynamic stability analysis on WECS is presented and utilized for designing the speed controller in Section V. Finally, Section VI demonstrates the computational and simulation results. Conclusions and topics for future studies are drawn in Section VII.

II. WIND TURBINE AND PMSG IN WECS

For a WECS, the total power generated by the wind turbine P_w can be calculated by [9]:

$$P_w(v_w, \lambda) = \frac{1}{2} \rho \pi R_t^2 v_w^3 C_p(\lambda, \beta) \quad (1)$$

where ρ , R_t , v_w are the air density, rotor radius of the wind turbine and wind speed, respectively; and $C_p(\lambda, \beta)$, β , λ are the turbine power coefficient, turbine blade pitch angle and the tip-speed ratio, respectively.

The tip-speed ratio λ is defined by:

$$\lambda = \frac{\omega_t R_t}{v_w} \quad (2)$$

where ω_t is the mechanical shaft speed of the wind turbine.

Normally, for a given blade angle and wind speed, the maximum power can be absorbed by the wind turbine at a specified shaft speed of a turbine. Figure 1 shows the output power and maximum power $P_{\max}(\omega_t)$ of the wind turbine versus ω_t . This figure shows that the operation point of the maximum power received by the turbine can be expressed as a function of shaft speed. Moreover, the state space model of PMSG in a two-axial frame can be expressed as [15]:

$$\begin{cases} \frac{di_d}{dt} = -\frac{1}{L} R_s i_d + \omega_r i_q - \frac{1}{L} (v_d + n_{vd}) \\ \frac{di_q}{dt} = -\frac{1}{L} R_s i_q - \omega_r i_d + \frac{1}{L} \omega_r \psi_f - \frac{1}{L} (v_q + n_{vq}) \\ \frac{d\omega_r}{dt} = \frac{p^2}{4J} \frac{1}{\omega_r} P_w \left(v_w, \frac{2R_t \omega_r}{p v_w} \right) - \frac{3p^2}{8J} \psi_f i_q \end{cases} \quad (3)$$

where v_d and v_q are the direct and quadrature stator input voltages, respectively; i_d and i_q are the direct and quadrature stator currents, respectively; ω_r is the electrical rotational speed of the PMSG, i.e., $\omega_r/\omega_t = p/2$; J and p are the inertia and the pole numbers of the PMSG, respectively; n_{vd} and n_{vq} are the noises of direct and quadrature stator input voltages with co-variance matrix $\tilde{\mathbf{Q}}$, respectively; and L , R_s , ψ_f are the inductance, the resistance of the stator winding and the magnetization flux linkage generated by the permanent magnet, respectively.

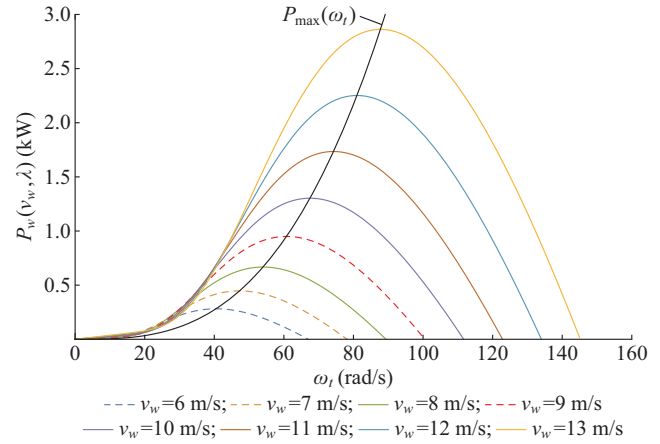


Fig. 1. Output power of wind turbine at different wind and shaft speeds with $R_t = 1.2$ m and $\beta = 0$.

The KCL equation in the DC-link capacitor node according to the switching of the three-phase converter is:

$$c_{dc} \frac{dv_{cc}}{dt} = S_a i_a + S_b i_b + S_c i_c - i_{mg} \quad (4)$$

where S_a , S_b , S_c are the switching signals for each converter legs; and v_{cc} , c_{dc} , i_{mg} are the DC-link voltage, DC-link capacitor and the current of the grid side converter, respectively. Also, the switching signals in the converter produce the output voltages of three phases (as , bs , cs) as v_{as} , v_{bs} , v_{cs} determined by:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = v_{cc} \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \quad (5)$$

The switching signals S_a , S_b , S_c are generated using the compensated pulse-width modulation (PWM) method where the carrier wave is adjusted according to the capacitor voltage for compensating the variations of the DC-link voltage

[16]. Thus, we have:

$$S_k = \text{sign}(v_k - v_{cr}) \quad k = a, b, c \quad (6)$$

where v_{cr} is a triangular carrier wave with amplitude $v_{cc}/2$ and a constant frequency equal to the switching frequency. The park's transformation is used to transfer the controller's output voltage v_d and v_q to the "abc" frame.

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} \cos(\hat{\theta}_r) & -\sin(\hat{\theta}_r) \\ \cos(\hat{\theta}_r - \frac{2\pi}{3}) & -\sin(\hat{\theta}_r - \frac{2\pi}{3}) \\ \cos(\hat{\theta}_r + \frac{2\pi}{3}) & -\sin(\hat{\theta}_r + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix} \quad (7)$$

where $\hat{\theta}_r$ is the simultaneous angle between phase *as* and the field axis in PMSG.

Figure 2 shows the closed-loop structure of the proposed system in WECS. In this system, without using the mechanical speed sensor, the speed and currents of the PMSG are estimated by EKF. Using the reference speed from the MPPT and the estimated speed from EKF, the torque $i_{q,ref}$ and flux $i_{d,ref}$ of PMSG are tuned by PI controller. Another optimal controller (FFC) is utilized to track the currents of PMSG to desired values. Also, voltage decoupling terms are needed for independently controlling of PMSG. These decoupling and control signals depend on the currents and PMSG speed. Thus, FFC should be adjusted by the estimated speed.

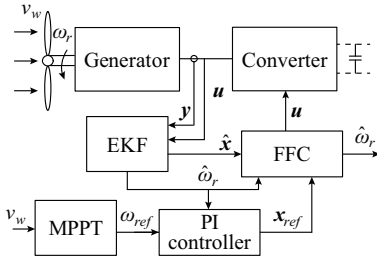


Fig. 2. Closed-loop structure of WECS.

III. OPTIMAL OBSERVER AND TRACKING CONTROL IN WECS

Using the inputs and outputs of the system, an optimal estimation of the system variables can be obtained at the operation point by EKF. Besides, to force the direct and quadrature currents of the PMSG to track the reference values $\mathbf{x}_{ref} = [i_{d,ref}, i_{q,ref}]^T$ with zero steady-state error, it is necessary to remove the effect ψ_f from the system and estimator responses. For this purpose, the input control of the system in (3) is given by:

$$\begin{cases} \mathbf{u} = -\mathbf{B}_\omega \psi_f + \mathbf{u}_c \\ \mathbf{B}_\omega = [0 \quad \hat{\omega}_r]^T \end{cases} \quad (8)$$

where $\hat{\omega}_r$ is the estimation of the electrical rotational speed; and $\mathbf{u}_c$ is the vector of the controller output signals. Also, the linear approximation of the system around the operation point is considered at any time. Thus, EKF for the dynamical system in (3) with the input control (8) is [17]:

$$\frac{d}{dt} \hat{\mathbf{x}} = \mathbf{A} \hat{\mathbf{x}} + \mathbf{B} \mathbf{u}_c + \mathbf{K}(\mathbf{y} - \hat{\mathbf{y}}) \quad (9)$$

where $\mathbf{K}$ is the Kalman filter gain; and $\mathbf{A}$ and $\mathbf{B}$ are the input Jacobin matrices of the system expressed as:

$$\mathbf{A} = \begin{bmatrix} -\frac{R_s}{L} & \hat{\omega}_r & \hat{i}_q \\ -\hat{\omega}_r & -\frac{R_s}{L} & -\hat{i}_d \\ 0 & -\frac{3p^2\psi_f}{8J} & \frac{\delta p}{\delta \omega_r} \bigg|_{\hat{\omega}_r} \end{bmatrix} \quad (10)$$

$$\mathbf{B} = \frac{-1}{L} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}^T \quad (11)$$

Also, the vectors of $\hat{\mathbf{x}}$, $\mathbf{u}_c$, $\mathbf{y}$ and $\hat{\mathbf{y}}$ are defined as:

$$\begin{cases} \hat{\mathbf{x}} = [\hat{i}_d \quad \hat{i}_q \quad \hat{\omega}_r]^T \\ \hat{\mathbf{y}} = \mathbf{C} \hat{\mathbf{x}} = [\hat{i}_d \quad \hat{i}_q]^T \\ \mathbf{u}_c = [v_{dc} \quad v_{qc}]^T \\ \mathbf{y} = [i_d + n_{id} \quad i_q + n_{iq}]^T \end{cases} \quad (12)$$

where $\hat{i}_d$ and $\hat{i}_q$ are the estimations of the direct and quadrature currents, respectively; $\mathbf{C}$ is the constant matrix; v_{dc} and v_{qc} are the direct and quadrature input controls without the permanent flux effect in PMSG, respectively; and n_{id} and n_{iq} are the noises of the direct and quadrature measurement output signals with covariance matrix $\tilde{\mathbf{R}}$, respectively.

The power variations of the turbine with respect to the turbine speed can be obtained from (1) as:

$$\frac{\delta p}{\delta \omega_r} = \frac{p^2}{4J} \frac{\partial}{\partial \omega_r} \frac{1}{\omega_r} P_w \left(v_w, \frac{2R_t \omega_r}{p v_w} \right) \quad (13)$$

The Kalman filter gain in (9) can be obtained from:

$$\mathbf{K} = \mathbf{P} \mathbf{C}^T \tilde{\mathbf{R}}^{-1} \quad (14)$$

where $\mathbf{P}$ is the covariance matrix of the estimation errors, which can be determined from:

$$\frac{d}{dt} \mathbf{P} = \mathbf{A} \mathbf{P} + \mathbf{P} \mathbf{A}^T + \tilde{\mathbf{Q}} - \mathbf{P} \mathbf{C}^T \tilde{\mathbf{R}}^{-1} \mathbf{C} \mathbf{P} \quad (15)$$

In this equation, the constant matrix $\mathbf{C}$ is considered as:

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \quad (16)$$

On the other hand, if the wind turbine is directly connected to a PMSG, the shaft speed of the wind turbine can be adjusted to the MPPT method by setting the torque of the permanent machine [5]. Due to the high inertia of the wind turbine, the speed rate of the wind turbine is lower than the rate of the direct and quadrature currents in (3). Therefore, the dynamics of these currents in (3) with using (8) can be obtained by optimal estimation of the machines speed $\hat{\omega}_r$. As a result, we have:

$$\begin{cases} \frac{d}{dt} \mathbf{x}_i = \mathbf{A}_i \mathbf{x}_i + \mathbf{B}_i \mathbf{u}_c \\ \mathbf{x}_i = [i_d \quad i_q]^T \end{cases} \quad (17)$$

The matrices of this relation are:

$$\begin{cases} \mathbf{A}_i = \begin{bmatrix} -\frac{R_s}{L} & \hat{\omega}_r \\ -\hat{\omega}_r & -\frac{R_s}{L} \end{bmatrix} \\ \mathbf{B}_i = -\frac{1}{L} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \end{cases} \quad (18)$$

The input control of the PMSG for tracking the state vector of PMSG to the reference vector $\mathbf{x}_{ref}$ based on the estimator output vector $\hat{\mathbf{y}}$ is given by:

$$\mathbf{u}_c = \mathbf{K}_r \mathbf{x}_{ref} - \mathbf{K}_f \hat{\mathbf{y}} \quad (19)$$

For the zero steady-state error (i.e., $\hat{\mathbf{y}} = \mathbf{x}_i = \mathbf{x}_{ref}$), the feedforward gain $\mathbf{K}_r$ can be determined from (17) and (19) as:

$$\mathbf{K}_r = \mathbf{K}_f - \mathbf{B}_i^{-1} \mathbf{A}_i \quad (20)$$

Also, the feedback gain $\mathbf{K}_f$ can be determined by applying the optimal control of linear quadratic regulator as [14]:

$$\mathbf{K}_f = \mathbf{R}^{-1} \mathbf{B}_i^T \mathbf{S} \quad (21)$$

where the matrix $\mathbf{S}$ may be obtained from the algebraic matrix Riccati equation as:

$$\mathbf{A}_i^T \mathbf{S} + \mathbf{S} \mathbf{A}_i - \mathbf{S} \mathbf{B}_i \mathbf{R}^{-1} \mathbf{B}_i^T \mathbf{S} + \mathbf{Q} = \mathbf{0} \quad (22)$$

In (21) and (22), $\mathbf{R}$ and $\mathbf{Q}$ are the weighted matrices for input control and state variables of the system, respectively. If these weighted matrices are considered as the diagonal matrices whose diagonal elements are equal to r and q , the feedback and feedforward gain matrices $\mathbf{K}_f$ and $\mathbf{K}_r$ can be determined by:

$$\begin{cases} \mathbf{K}_f = \begin{bmatrix} R_s - \Delta & 0 \\ 0 & R_s - \Delta \end{bmatrix} \\ \mathbf{K}_r = \begin{bmatrix} -\Delta & L\hat{\omega}_r \\ -L\hat{\omega}_r & -\Delta \end{bmatrix} \end{cases} \quad (23)$$

where $\Delta = \sqrt{q/r + R_s^2}$.

IV. VECTOR CONTROL IN WECS

To achieve optimal tracking control for WECS, the vector control has been used by designing the optimal feedback and feedforward gains. In the closed-loop WECS, the reference speed obtained from MPPT is firstly compared with the rotor speed which is estimated from (9). The speed error passes through the speed controller and generates the reference torque signal of PMSG. Therefore, the airgap torque T_{ag} in PMSG could be calculated as:

$$T_{ag} = \frac{3}{4} p i_q \psi_f \quad (24)$$

To produce this airgap torque, we can adjust the quadrature current to $i_{q,ref}$ as:

$$i_{q,ref} = \frac{4T_{e,ref}}{3p\psi_f} \quad (25)$$

Also, to track the speed of PMSG regarding to MPPT, a suitable speed controller such as PI has been used in WECS. Under this condition, $T_{e,ref}$ can be adjusted by the

output of PI speed controller with output saturation.

$$T_{e,ref} = K_p e_\omega + K_i \int e_\omega dt \quad (26)$$

where K_i and K_p are the integral and proportional gains of PI controller, respectively; and e_ω is the tracking speed error of PMSG. Thus, the dynamic equation for PI controller can be written as:

$$\frac{d}{dt} \zeta = K_i e_\omega = K_i (\omega_{r,ref} - \hat{\omega}_r) \quad (27)$$

where ζ is the output of the integrator in PI controller as shown in Fig. 3. On the other hand, for producing unit power factor, the direct current should be adjusted to zero, i.e., $i_{d,ref} = 0$ [5]. Therefore, the direct and quadrature stator currents should be regulated to track the reference values $i_{d,ref}$ and $i_{q,ref}$ by the optimal FFC. The structure of the vector control in WECS with EKF and optimal FFC is shown in Fig. 3.

V. DYNAMIC STABILITY OF WECS

The small signal disturbance of the state vector in Fig. 3 at the operation point can be used to analyze the dynamic stability of WECS. Therefore, the dynamics of the small deviation for the state vector of the estimator and PI controller ($\tilde{\mathbf{x}}_e = \hat{\mathbf{x}} - \mathbf{x}_o$ and $\tilde{\zeta} = \zeta - \zeta_o$) which are close to the operation point ($\mathbf{x}_o = [i_{do}, i_{qo}, \omega_{ro}]^T$, ζ_o and v_{wo}), are expressed by substituting (12) and (19) into (9) as:

$$\frac{d}{dt} \tilde{\mathbf{x}}_e = \mathbf{K}_s \mathbf{C} \tilde{\mathbf{x}} + (\mathbf{A}_o - \mathbf{M} - \mathbf{K}_s \mathbf{C}) \tilde{\mathbf{x}}_e + \mathbf{N} \tilde{\zeta} \quad (28)$$

where $\tilde{\mathbf{x}}$ is the small deviation of the state vector of PMSG and $\tilde{\mathbf{x}} = \mathbf{x} - \mathbf{x}_o$, $\mathbf{x}$ is the state vector of PMSG, i.e., $\mathbf{x} = [i_d, i_q, \omega_r]^T$. Also, $\mathbf{M}$ and $\mathbf{N}$ are two constant matrices expressed as:

$$\begin{cases} \mathbf{M} = \begin{bmatrix} \frac{1}{\tau} & 0 & \gamma(\zeta_o - K_p \omega_{ro}) \\ 0 & \frac{1}{\tau} & i_{do} - \frac{\psi_f}{L} + \frac{\Delta}{L} K_p \gamma \\ 0 & 0 & 0 \end{bmatrix} \\ \mathbf{N} = \begin{bmatrix} \gamma \omega_{ro} \\ -\frac{\Delta}{L} \gamma \\ 0 \end{bmatrix} \end{cases} \quad (29)$$

where γ , τ and ζ_o are considered as:

$$\begin{cases} \gamma = \frac{4}{3p\psi_f} \\ \tau = \frac{L}{R_s - \Delta} \\ \zeta_o = \frac{1}{K_i \gamma} i_{qo} \end{cases} \quad (30)$$

Also, in (28), $\mathbf{K}_s$ is determined by the steady-state solution of covariance matrix ($d\mathbf{P}/dt = \mathbf{0}$) in (14) and (15), and $\mathbf{A}_o$ is the system matrix of the estimator at the operation point. This matrix can be obtained from (10) as:

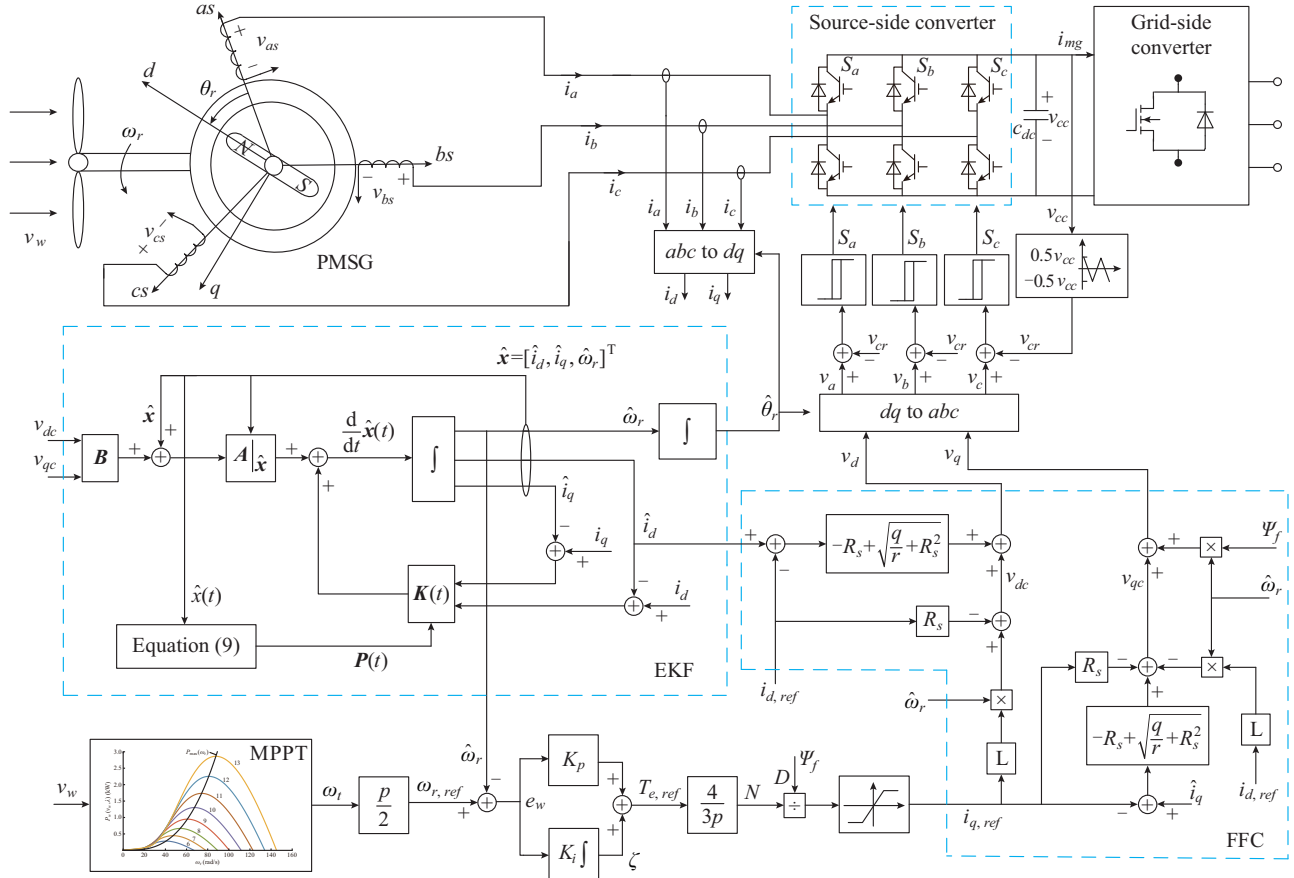


Fig. 3. Structure of the vector control in WECS with EKF and optimal FFC.

$$A_o = \begin{bmatrix} -\frac{R_s}{L} & \omega_{ro} & i_{qo} \\ -\omega_{ro} & -\frac{R_s}{L} & \frac{\psi_f}{L} - i_{do} \\ 0 & -\frac{3p^2\psi_f}{8J} & \left. \frac{\delta p}{\delta \omega_r} \right|_{\omega_{ro}} \end{bmatrix} \quad (31)$$

Similarly, for the system dynamics in (3) and (27), we can obtain:

$$\frac{d}{dt} \tilde{\mathbf{x}} = \mathbf{A}_o \tilde{\mathbf{x}} + \mathbf{M} \tilde{\mathbf{x}}_e + \mathbf{N} \tilde{\boldsymbol{\zeta}} \quad (32)$$

$$\frac{d}{dt} \tilde{\boldsymbol{\zeta}} = [\mathbf{0} \quad \mathbf{0} \quad -\mathbf{K}_i] \tilde{\mathbf{x}}_e + \mathbf{D} \tilde{\mathbf{x}}_e \quad (33)$$

Using (28), (32) and (33), the augmented model of WECS can be determined as:

$$\frac{d}{dt} \begin{bmatrix} \tilde{\mathbf{x}} \\ \tilde{\mathbf{x}}_e \\ \tilde{\boldsymbol{\zeta}} \end{bmatrix} = \begin{bmatrix} \mathbf{A}_o & \mathbf{M} & \mathbf{N} \\ \mathbf{K}_s \mathbf{C} & \mathbf{A}_o - \mathbf{K}_s \mathbf{C} + \mathbf{M} & \mathbf{N} \\ \mathbf{0}_{1 \times 3} & \mathbf{D} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \tilde{\mathbf{x}} \\ \tilde{\mathbf{x}}_e \\ \tilde{\boldsymbol{\zeta}} \end{bmatrix} \quad (34)$$

The eigenvalues of the augmented matrix can be used for obtaining the dynamic stability of the closed-loop system and designing the speed controller of WECS.

VI. NUMERICAL ANALYSIS

The parameters of WECS with PMSG and optimal EKF

and FFC are illustrated in Table I.

TABLE I
PARAMETERS OF WECS

Parameter	Description	Value
R_s	Resistance of PMSG	0.135 Ω
L	Inductance of PMSG	4 mH
ψ_f	Permanent magnet flux	0.5 V·s
J	Inertia of PMSG	1.168 kg/m ²
B	Friction of PMSG	0 N·m·s
p	Pole pairs of PMSG	8
ρ	Air density	1.225 kg/m ³
R_l	Rotor radius	1.2 m

For numerical simulation analyses, the wind speed is first considered as 12 m/s, and when $t = 4$ s, the wind speed reduces to 10 m/s. After that, the wind speed is increased to 14 m/s when $t = 8$ s and finally decreased to 12 m/s when $t = 12$ s.

To evaluate the dynamic responses of the closed-loop system in Fig. 3, three controllers PI, LQG [9] and FFC are implemented. The electrical and mechanical parameters of WECS in Fig. 3 are taken from [2], [18]. These parameters are illustrated in Table I. According to the wind speed, the shaft speed for the maximum power conversion in the wind turbine is determined, and using (3) and (25), we can deter-

mine the DC operation points of the system for desired shaft speed. The operation points for $v_w=12$ m/s and $\psi_f=0.5$ V·s are $i_{d0}=0$, $i_{q0}=9.26$ A and $\omega_{ro}=324$ rad/s, respectively. By replacing the parameters of WECS in (10), (11) and (18), the matrices of the system at the operation point are obtained as:

$$\begin{cases} \mathbf{A}_o = \begin{bmatrix} -33.75 & 324 & 9.26 \\ -324 & -33.75 & 125 \\ 0 & -10.27 & -0.29 \end{bmatrix} \\ \mathbf{B} = -\begin{bmatrix} 250 & 0 & 0 \\ 0 & 250 & 0 \end{bmatrix} \end{cases} \quad (35)$$

$$\begin{cases} \mathbf{A}_i = \begin{bmatrix} -33.75 & 324 \\ -324 & -33.75 \end{bmatrix} \\ \mathbf{B}_\omega = \begin{bmatrix} 0 \\ 324 \end{bmatrix} \end{cases} \quad (36)$$

To design EKF, the input and measurement covariance matrices in (8) and (9) at the starting operation point are given as:

$$\tilde{\mathbf{Q}} = \text{diag}(0.1, 0.1, 0.1) \quad (37)$$

$$\tilde{\mathbf{R}} = \text{diag}(0.1, 0.1) \quad (38)$$

The rates of the Kalman filter gains in the closed-loop system shown in Fig. 3 are obtained by (14) and (15). The results are depicted in Fig. 4. The steady-state values of the Kalman filter gains for $v_w=12$ m/s are:

$$\mathbf{K}_s = 10^{-2} \times \begin{bmatrix} 1.50 & -0.26 \\ -0.26 & 4.00 \\ 9.24 & -89.07 \end{bmatrix} \quad (39)$$

Also, FFC gains in (23) for $r=1$ and $q=100$ can be determined as:

$$\begin{cases} \mathbf{K}_f = \begin{bmatrix} -9.866 & 0 \\ 0 & -9.866 \end{bmatrix} \\ \mathbf{K}_r = \begin{bmatrix} -10.001 & 0.004\hat{\omega}_r \\ -0.004\hat{\omega}_r & -10.001 \end{bmatrix} \end{cases} \quad (40)$$

For the stability analysis of the system in the vicinity of the operation points, the augmented matrix of this system can be determined by obtaining $\mathbf{M}$ and $\mathbf{N}$ from (29) as:

$$\begin{cases} \mathbf{M} = 100 \times \begin{bmatrix} -24.66 & 0 & -1.73 \\ 0 & -24.66 & 12.28 \\ 0 & 0 & 0 \end{bmatrix} \\ \mathbf{N} = \begin{bmatrix} 108 \\ -833.41 \\ 0 \end{bmatrix} \end{cases} \quad (41)$$

The locus of the dominated complex eigenvalues of the augmented system $\mathbf{A}_a$ in s-plane with a variation of the proportional and integrator gains K_p and K_i is shown in Fig. 5. In this figure, the integrator gain is considered ($K_i=1, 2, \dots, 5$), but the proportional gain varies from zero to ten. Also, the closed-loop system is a FFC controller with $v_w=12$ m/s.

In Fig. 5, to obtain the acceptable overshoot and settling time of the system, we can set the integrator and proportion-

al gains of the speed controller to $K_i=5$ and $K_p=1.623$, respectively.

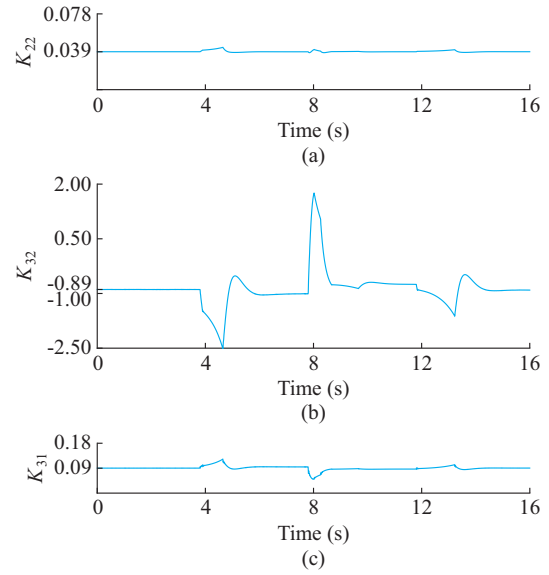


Fig. 4. Elements of K_{22} , K_{32} and K_{31} of Kalman filter gains for EKF in WECS. (a) K_{22} . (b) K_{32} . (c) K_{31} .

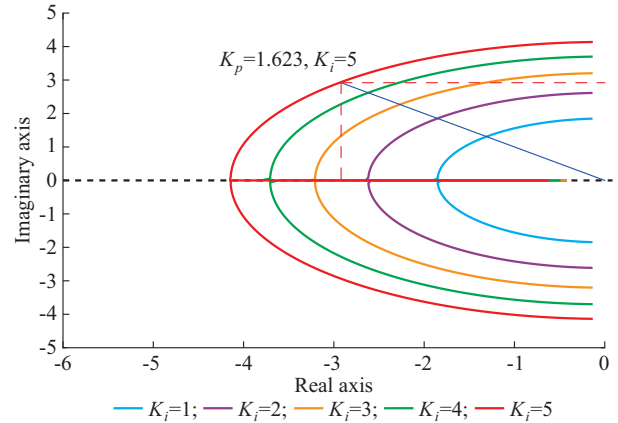


Fig. 5. Locus of the dominated complex eigenvalue of WECS for FFC with $v_w=12$ m/s.

Besides, we compare the dominated complex eigenvalues of the closed-loop system for two wind speeds and different controllers in Table II. The wind speed for obtaining LQG gain is $v_w=12$ m/s, and the eigenvalues of EKF/FFC are equal to LQG. In contrast to LQG, EKF/FFC updates its filter gains according to the wind speed. Thus, the eigenvalues of the system for $v_w=10$ m/s are not equal. This table shows that the stability margin of EKF/FFC in a wide range of wind speeds is acceptable.

The estimation of the state variables with the reference and actual signals in Fig. 3 is depicted in Fig. 6.

Also, the system performance under the transient conditions with different controllers such as PI, LQG and FFC is evaluated and compared. The results are presented in Figs. 7-9. The structure of the PI controller for WECS is given without decoupling signals for i_d and i_q [19]. This structure is similar to the FFC and LQG. Also, the gains of the PI cur-

rent controllers are given as $K_p=5$ and $K_i=5$, and the gains of the PI speed controller is the same as the FFC and LQG controller. Figures 7 and 8 show that by variation of the wind speed when $t=4$, 8 and 12 s, the quadrature currents of PMSG effectively track their reference currents by all controllers. However, the LQG and PI controllers have not acceptable responses for tracking the direct current. To compare the responses of the three controllers for MPPT, the variations of the electrical shaft speed is illustrated in Fig. 9. For wind speed change when $t=4$ s, the PI controller can track the reference speed from MPPT, but for the increased wind speed when $t=8$ s, a high overshoot with the low transient response is produced by PI controller. Also, the steady-state tracking error appears in the LQG controller to track the reference speed. However, the reference speed is smoothly tracked by EKF/FFC at different wind speeds.

TABLE II
DOMINATED COMPLEX EIGENVALUES OF WECS WITH FFC, LQG AND PI CONTROLLERS

Controller	Eigenvalue	
	$v_w = 10$ m/s	$v_w = 12$ m/s
FFC	$-2.905 \pm j2.954$	$-2.929 \pm j2.929$
LQG	$-2.894 \pm j2.963$	$-2.929 \pm j2.929$
PI	$-0.981 \pm j0.046$	$-0.979 \pm j0.055$

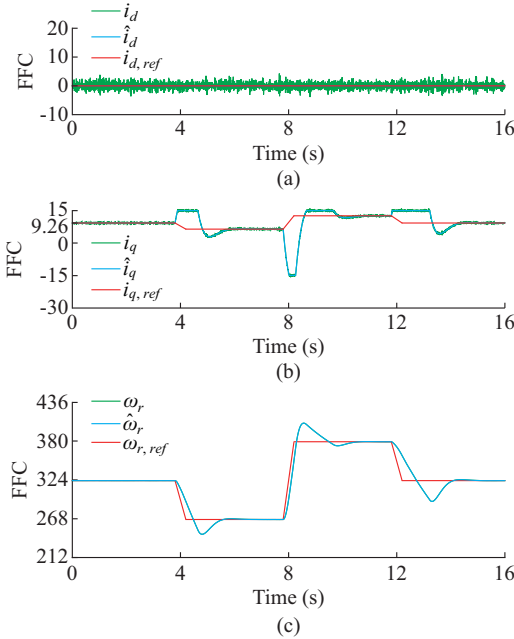


Fig. 6. Dynamical response of EKF/FFC in WECS. (a) Direct current. (b) Quadrature current. (c) Electrical rotational speed.

The dynamic behavior of the model described in this paper is investigated by applying a large disturbance such as three-phase short circuit in the grid for 40 ms, and the simulation results of the capacitor voltage and compensated PWM signals are shown in Fig. 10. Initially, the capacitor voltage is increased but it grows less after the network reaches the normal conditions. Figure 11 shows that the compensated PWM modulation technique can decouple the dynamic of the source-side converter from the large disturbance on

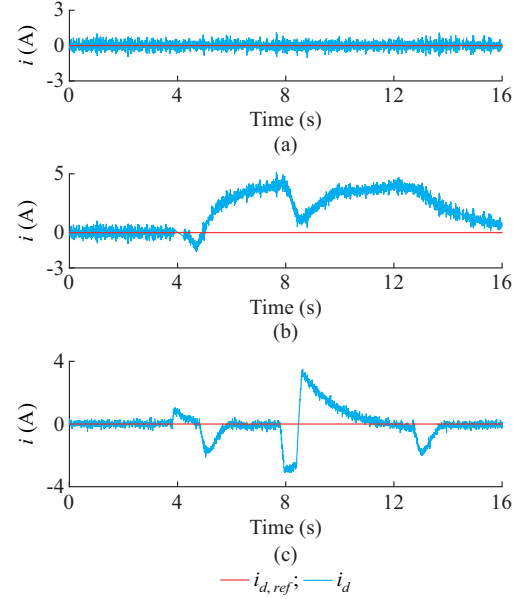


Fig. 7. Direct current of PMSG with FFC, LQG and PI controllers. (a) FFC. (b) LQG. (c) PI.

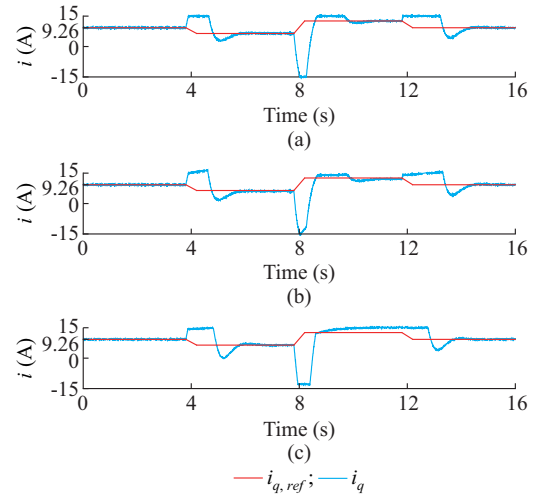


Fig. 8. Quadrature current of PMSG with FFC, LQG and PI controllers. (a) FFC. (b) LQG. (c) PI.

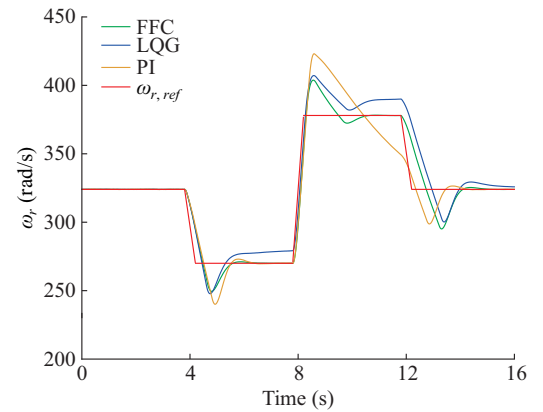


Fig. 9. Comparison of rotation speed for MPPT with FFC, LQG and PI controllers.

the grid side.

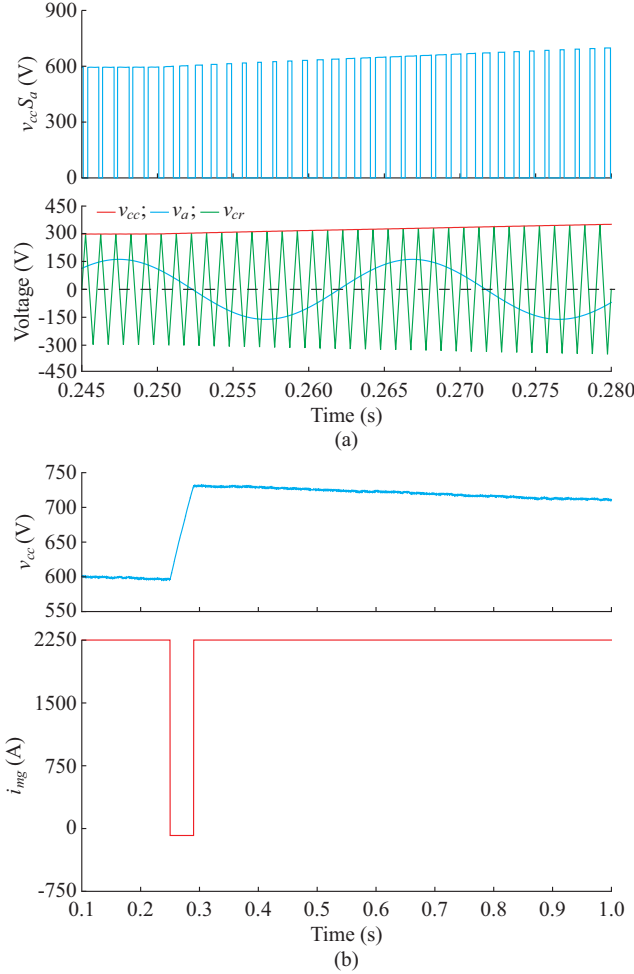


Fig. 10. PWM signals and capacitor voltage under fault condition. (a) PWM signals. (b) Capacitor.

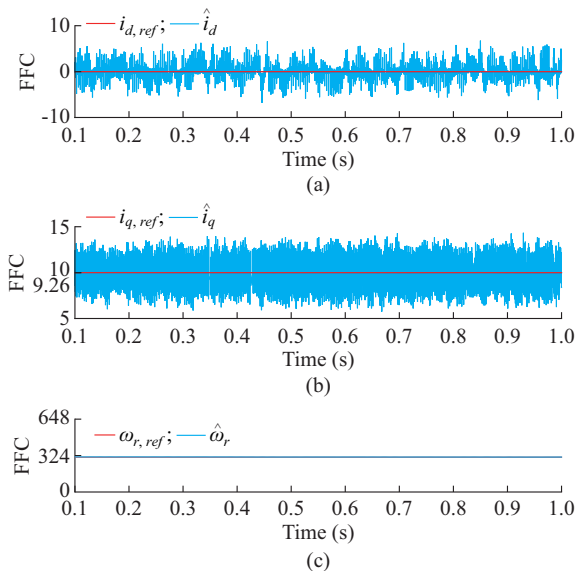


Fig. 11. State variable of FFC under fault condition. (a) Direct current. (b) Quadrature current. (c) Electrical rotational speed.

VII. CONCLUSION

In this paper, the detailed design procedure of the EKF and FFC for MPPT has been introduced. The design procedures of EKF and FFC are straightforward techniques and simple to implement. Also, the stability analysis on the WECS is presented and utilized for designing the speed controller. Moreover, the simulation results have illustrated that the PI controller has a low dynamic response with the high overshoot. Furthermore, a tracking error appears in the LQG controller under the steady-state conditions, whereas, the dynamic performances of the EKF and FFC have been tracked the reference speed for different wind speeds. The consideration of the saturation effect in design procedure and the disturbance on the input voltage of the converter are some other topics for future studies.

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