Nonlinear control for an optimized grid connection system of renewable energy resources

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ABSTRACT

This paper proposes an integral backstepping based nonlinear control strategy for a grid connected wind-photovoltaic hybrid system. The proposed control strategy aims at extracting the maximum power available while respecting the grid connection standards. The proposed system has a reduced number of power electronic converters, thereby ensuring lower costs and reduced energy losses, which improves the profitability and efficiency of the hybrid system. The effectiveness of the proposed topology and control methodology is validated using the MATLAB/Simulink software environment. The satisfactory results achieved under various atmospheric conditions and in different operating modes of the hybrid system, confirm the high efficiency of the proposed control strategy.

Keywords: Grid connection, Integral backstepping control, Maximum power point tracking, Unity power factor, Wind-PV hybrid system

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proposed as efficient alternatives to conventional MPPT controls [18]-[22]. On another note, grid codes, such as the FERC standard interconnection agreements for wind and other alternative technologies (order No. 661-A), require that a power factor greater than 0.95 be maintained at the point of interconnection. For this purpose, power factor control for grid-connected RPG systems is of paramount importance [23]-[25].

Against this background, the present work proposes an efficient nonlinear control of a low-cost grid-connected PV-wind hybrid configuration. This paper assumes that the grid connection process, as detailed in [26], [27], has already been done. The proposed hybrid system components and their models are presented in the next section, and on the basis of these models nonlinear control laws are developed in the third section. The results of the simulations undertaken to validate and evaluate the proposed control strategy are presented in the fourth section, and a brief conclusion is given in the last section.

2. SYSTEM ELEMENTS AND THEIR MODELS

The proposed hybrid system configuration is illustrated in Figure 1. Using common electronic power converters, this configuration offers considerable savings in initial and operating costs (less energy loss). In fact, DC/DC and DC/AC converters dedicated to the conversion of photovoltaic (PV) energy are eliminated and the double fed induction generator (DFIG) converters will take care of the conversion of PV energy.

![Schematic diagram of the proposed hybrid system and control strategy](image)

Figure 1. Schematic diagram of the proposed hybrid system and control strategy

2.1. Aerodynamic energy conversion

The aerodynamic power, \( P_{aer} \), captured by the turbine used in the proposed system is given by [18]:

\[
P_{aer} = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^2 V_w^3
\]

where: \( C_p \) is the wind turbine power coefficient; \( \rho \) is the air density; \( R \) is the blade radius (in metres); \( V_w \) is the wind speed (in m/s); \( \Omega_i \) is the turbine angular speed (in rad/s); \( \lambda \) is the tip speed ratio and \( \beta \) is the blade pitch angle (in degrees). With \( c_1=0.5176; c_2=116; c_3=0.4; c_4=5; c_5=21 \) and \( c_6=0.0068 \). Figure 2 shows the characteristics of the wind turbine's power coefficient at different values of the blade pitch angle. The pitch control protects the turbine against turbulence and excessive overload, under normal conditions \( \beta=0 \).

2.2. Photovoltaic energy conversion

The mathematical expressions for the single-diode equivalent circuit of the PV cell are given by [19]:

\[
P_{PV} = \frac{V_{oc}}{1 + \frac{1}{\sqrt{3}} \frac{N_{sh}}{V_{oc}}}
\]

where: \( V_{oc} \) is the open-circuit voltage; \( N_{sh} \) is the number of parallel PV cells; \( R_{sh} \) is the shunt resistance; \( I_{sc} \) is the short-circuit current; \( R_s \) is the series resistance; \( I_{ref} \) is the reference current; \( V_{ref} \) is the reference voltage.
\[ I_{\text{cel}} = I_p - I_s \left[ e^{\frac{V_{\text{cel}}}{kT}} - 1 \right] \left( V_{\text{cel}} + I_{\text{cel}} R_{\text{sh}} \right) \]
\[ I_p = \frac{e}{E_{\text{ref}}} \left[ I_{\text{sc}} + K_i (T - T_{\text{ref}}) \right] \]
\[ I_s = I_{rs} \left( \frac{T}{T_{\text{ref}}} \right)^{\frac{3 - q \gamma K T}{E_{\text{ref}}}} \]

where: \( I_{\text{cel}} \) is the current crossing the PV cell; \( V_{\text{cel}} \) is the PV cell voltage; \( I_p \) is the photocurrent; \( I_s, I_{rc} \) and \( I_r \) are the cell saturation current, the reverse saturation current and the short-circuits current; \( q \) is the electron charge; \( R_s \) and \( R_{\text{sh}} \) are the intrinsic parallel and series resistors; \( K \) is the Boltzmann constant; \( \gamma \) is the diode ideality factor; \( E \) is the solar irradiance; \( E_{\text{ref}} \) is the reference irradiance (1 kW/m²); \( T \) is the temperature on absolute scale; \( T_{\text{ref}} \) is the reference temperature (298.15K); \( K_i \) is the short-circuit current temperature coefficient and \( E_{\text{bc}} \) is the band-gap energy of the cell. Therefore, with a photovoltaic generator (PVG) consisting of \( Np \) strings in parallel, each string consists of \( Ns \) cells in series, the expression of the PVG current \( (I_{pv}) \) as a function of its voltage \( (V_{pv}) \) can be derived as follows:

\[
\begin{align*}
V_{pv} &= Ns V_{cel} \\
I_{pv} &= Np I_{cel} \Rightarrow I_{pv} &= Np I_{ph} - Np I_{s} \left[ e^{(q Np I_{pv} + Np I_{rs} R_{sh}) / kT} - 1 \right] - \frac{Np V_{pv} + Np I_{pv} R_{sh}}{Np R_{sh}}
\end{align*}
\]

In this paper, a PVG made up of seventeen SM55 panels connected in series is considered. Electrical specifications for one panel are given in [21]. The Power-Voltage characteristics of the PVG under solar irradiance change are shown in Figure 3. The coordinates of the maximum power points shown in the zoomed-in parts of Figures 2 and 3 will be used to verify the simulation results.

**2.3. State space representation**

All measured 3-phase quantities are transformed into the stator-flux oriented dq-reference frame as shown in Figure 1. The DC-bus voltage, which is also the PVG voltage \( V_{pv} \), is governed by the following equation:

\[ \frac{dV_{pv}}{dt} = \frac{1}{C} \left( K_{dg} I_{dg} + K_{ag} I_{ag} + I_{pv} - I_{rc} \right) \]

where \( C \) is the DC-bus capacitor; \( I_{rc} \) is the DC-current absorbed by the rotor side converter (RSC); \( I_{dg} \) and \( I_{ag} \) are the d-axis and q-axis components of the current absorbed by the grid side converter (GSC); \( K_{dg} \) and \( K_{ag} \) are the GSC control signal components in d-q frame.

In the synchronous d-q-frame, the stator flux vector is aligned on the d-axis. Assuming that the stator flux magnitude is constant and the small drop in the stator resistance voltage is negligible, the stator voltage vector is also considered practically aligned on the q-axis of the d-q-frame [27]-[29]. According to (4) and [18] an overall state space representation of the hybrid system under consideration is given by:

\[
\begin{align*}
\frac{dI_{dr}}{dt} &= \omega I_{qr} - \frac{R_{ds}}{L_{ds}} I_{dr} + \frac{V_{pv}}{L_{ds}} K_{dr} \\
\frac{dI_{qr}}{dt} &= -\omega I_{dr} - \frac{R_{qs}}{L_{qs}} I_{qr} - \frac{R_{qg}}{L_{qg}} I_{qg} + \frac{V_{pv}}{L_{qs}} K_{qr} \\
\frac{dI_{dg}}{dt} &= \omega I_{ag} - \frac{R_{ds}}{L_{ds}} I_{dg} - \frac{V_{pv}}{L_{ds}} K_{dg} \\
\frac{dI_{ag}}{dt} &= -\omega I_{dg} - \frac{R_{qs}}{L_{qs}} I_{ag} + \frac{V_{pv}}{L_{qs}} K_{ag} \\
\frac{dV_{pv}}{dt} &= \frac{1}{C} \left( K_{dg} I_{dg} + K_{ag} I_{ag} + I_{pv} - I_{rc} \right)
\end{align*}
\]

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where \( I_{dr} \) and \( I_{qr} \) are the rotor current components; \( L_s \) and \( L_r \) are the stator and rotor inductances; \( R_r \) is the resistance of rotor windings; \( \theta_s(\theta_r) \) are the angular position of the d-q frame with respect to the reference frame attached to the stator (rotor); \( M \) is the stator-rotor magnetizing inductance; \( \sigma \) is the leakage coefficient (\( \sigma = 1 - M^2/L_sL_r \)); \( K_{dr} \) and \( K_{qr} \) are the RSC control signal components; \( R_f \) and \( L_f \) are the resistance and the inductance of the L-filter; \( V_q \) is the q-axis component of the stator voltage; \( V_f \) is the quadrature component of the transformer \((T_r)\) secondary voltage, see Figure 1, with \( V_f = mV_q \); \( m \) is the transformation ratio of \( T_r \). The electromagnetic torque is expressed in the synchronous frame as:

\[
T_{em} = -\frac{M}{L_s} \varphi_q I_{qr}
\]  

(6)

where \( p \) is the number of pole pairs per phase in the DFIG stator windings; \( \varphi_d \) is the d-axis component of the stator flux.

3. DESIGN OF HYBRID SYSTEM CONTROLLERS

The grid voltage is assumed to be stable, and the stator flux is estimated as:

\[
\dot{\varphi}_s = \int (v_s - R_s i_s) dt ; \quad i \in \{a, b, c\}
\]  

(7)

The angular frequency \( (\omega_s) \) and the phase angle \( (\theta_s) \) of the synchronous d-q frame are generated using a three-phase phase-locked loop (PLL), as shown in Figure 4 \([18, 21]\).

![Figure 4. Block diagram of the PLL](image)

The RSC controller is designed to track the maximum power point (MPP) of the wind turbine and to inject the stator power with near unity power factor (UPF). The GSC controller is designed to track the MPP of the PVG and to maintain the reactive power injected by the GSC close to zero in Figure 1.

3.1. Designation of the hybrid system outputs and their references

The DFIG rotor dynamics obey Newton’s second law for rotational dynamics, thus:

\[
J \frac{d\Omega_r}{dt} = T_{a/r} + T_{em} - F \Omega_r
\]  

(8)

where \( J \) and \( F \) are the total inertia and total viscosity coefficient (turbine and DFIG), \( T_{a/r} \) is the aerodynamic torque applied to DFIG rotor, \( T_{em} \) is the algebraic value of the DFIG electromagnetic torque and \( \Omega_r \) its rotor speed. Operating the wind turbine at the maximum power point (i.e. \( \lambda = \lambda_{opt} \) and \( C_p = C_{p_{max}} \)) means that:

\[
P_{aer} = P_{aer_{max}} \quad \Rightarrow \quad P_{aer_{max}} = \frac{1}{2} C_{p_{max}} \rho \pi R^2 (V_w)^3 = \frac{1}{2} C_{p_{max}} \rho \pi R^2 \left( \frac{\Omega R}{\lambda_{opt}} \right)^3
\]  

(9)

Then, the optimal aerodynamic torque, \( T_{a/r, opt} \), is such that:
\[ T_{a/r, opt} = \frac{P_{\text{ars} max}}{\Delta r} \quad \Rightarrow \quad T_{a/r, opt} = K_{\text{opt}} \Omega_r^2 \quad (10) \]

where \( K_{\text{opt}} = \frac{\rho R K^3 c_{p, max}}{2 G^3 \alpha_{\text{opt}}^2} \), \( G \) is the gearbox ratio and \( \Omega_r \) is the DFIG rotor speed. The optimal electromagnetic torque \( (T_{\text{em, opt}}) \) and then the reference of the first output (q-axis rotor current; \( I_{qr} \)) are derived as:

\[ \Rightarrow T_{\text{em, opt}} = F \Omega_r - T_{a/r, opt} \quad (11) \]

\[ \Rightarrow I_{qr \text{ref}} = \frac{I_a}{p \mu \phi_y} \left( K_{\text{opt}} \Omega_r^2 - F \Omega_r \right) \quad \Rightarrow \frac{dI_{qr \text{ref}}}{dt} = \frac{I_a}{p \mu \phi_y} \frac{d \Omega_r}{dt} (2K_{\text{opt}} \Omega_r - F) \quad (12) \]

The reactive powers are expressed as a function of \( I_d \) and \( I_q \) (second and third outputs) as [18]:

\[ \begin{align*}
Q_s &= \frac{V_s^2}{u} I_d - M V_s I_d \frac{d \theta}{dt} \\
Q_g &= V_g I_d 
\end{align*} \quad (13) \]

where \( Q_s \) is the reactive power injected by the DFIG stator; \( Q_g \) is the reactive powers injected by the GSC. In order to operate the hybrid system at or near UPF, the references of the direct currents are derived as:

\[ \begin{align*}
Q_{s, \text{opt}} &= \frac{V_s^2}{u} I_d \text{ref} - M V_s I_d \text{ref} = 0 \\
Q_{g, \text{opt}} &= V_g I_d \text{ref} = 0 
\end{align*} \quad \Rightarrow \quad \frac{dI_d \text{ref}}{dt} = \frac{V_s}{M} \frac{d \theta}{dt} \quad \text{and} \quad \frac{dI_q \text{ref}}{dt} = \frac{dI_d \text{ref}}{dt} = 0 \quad (14) \]

Since the PVG characteristics have a single extremum, as shown in Figure 3, the derivative of the PVG power with respect to its voltage \( \left( \frac{\partial P_{pv}}{\partial V_{pv}} \right) \) was chosen as the fourth output of the system with a reference value of zero:

\[ \left( \frac{\partial P_{pv}}{\partial V_{pv}} \right) \text{ref} = 0 \quad (15) \]

3.2. Elaboration of RSC control laws

Let us define the first error \( \varepsilon_1 \) and a first lyapunov function candidate (LFC) \( V_1 \) as:

\[ \varepsilon_1 = I_{qr} - I_{qr \text{ref}}; \quad V_1 = \frac{1}{2} \varepsilon_1^2 + \frac{1}{2} \sigma_1^2 \quad (16) \]

where \( \sigma_1 = c_1 \int \varepsilon_1(\tau) \, d\tau, c_1 \) is the design parameter of the integral action. \( V_1 \) time-derivative is as:

\[ \frac{dV_1}{dt} = \varepsilon_1 \left( \frac{d\varepsilon_1}{dt} + \sigma_1 \right) \quad \Rightarrow \quad \frac{dV_1}{dt} = \varepsilon_1 \left( c_1 \epsilon_1 - \omega_1 I_d \frac{d \theta}{dt} - \frac{M V_s}{\omega_1 L_q} I_q + \frac{K_{\text{opt}} \varepsilon_1}{L_q} - \frac{dI_{qr \text{ref}}}{dt} \right) \quad (17) \]

The q-axis component of RSC control signal, \( K_{qr} \), is chosen as:

\[ K_{qr} = \frac{I_{qr \text{ref}}}{V_{pv}} \left( -c_1 \varepsilon_1 - c_1 \sigma_1 + \omega_1 I_d \frac{d \theta}{dt} + \frac{M V_s}{\omega_1 L_q} I_q + \frac{K_{\text{opt}} \varepsilon_1}{L_q} + \frac{dI_{qr \text{ref}}}{dt} \right) \quad (18) \]

where \( c_1 \) is a strictly positive design parameter. \( V_1 \) time derivative of the closed-loop system becomes:

\[ \frac{dV_1}{dt} = -c_1 \varepsilon_1^2 \quad (19) \]

Similarly, the error between \( I_{dq} \) and its desired value, and a second LFC are defined as follows:

\[ \varepsilon_2 = I_{dq} - I_{dq \text{ref}}; \quad V_2 = \frac{1}{2} \varepsilon_2^2 + \frac{1}{2} \sigma_2^2 \quad (20) \]

where \( \sigma_2 = c_2 \int \varepsilon_2(\tau) \, d\tau, c_2 \) is the design parameter of the integral action. \( V_2 \) time-derivative is as:
\[ \frac{dV_2}{dt} = \varepsilon_2 \left( \frac{dx_2}{dt} + c_2 \sigma_2 \right) \quad (5) \]

(21)

Then, the d-axis component of RSC control signal is chosen such that:

\[ K_{dr} = \frac{I_r \sigma}{V_p} \left( -c_2 \varepsilon_2 - c_2 \sigma_2 + \frac{R_f}{L_f} I_{dr} - \omega_r I_{qr} \right) \quad (22) \]

where \(c_2\) is a strictly positive design parameter. With the above choice, \(V_2\) time derivative becomes:

\[ \frac{dV_2}{dt} = -c_2 \varepsilon_2^2 \quad (23) \]

### 3.3. Elaboration of GSC control laws

The error \( \varepsilon_3 \), between \( I_{dq} \) and its desired value, and a third LFC are defined as:

\[ \varepsilon_3 = I_{dq} - I_{dq_{ref}} \]

\[ V_3 = \frac{1}{2} \varepsilon_3^2 + \frac{1}{2} \sigma_3^2 \quad (24) \]

where \(\sigma_3 = c_{sl} \int_0^t \varepsilon_3(t) \, dt\); \(c_{sl}\) is the design parameter of the integral action. So, \(V_3\) time-derivative is as:

\[ \frac{dV_3}{dt} = \varepsilon_3 \left( \frac{dx_3}{dt} + c_3 \sigma_3 \right) \quad (5) \]

\[ \frac{dV_3}{dt} = \varepsilon_3 \left( \frac{dx_3}{dt} + c_3 \sigma_3 \right) \]

(25)

Then, the d-axis component of GSC control signal is chosen as:

\[ A_1 K_{dg} + A_2 K_{qg} = B_4 \quad (26) \]

where:

\[ A_1 = \frac{V_p}{L_f}; \quad A_2 = 0; \quad B_4 = c_4 \varepsilon_4 + c_4 \sigma_4 + \omega_q I_{qg} - \frac{R_f}{L_f} I_{dq}; \]

with \(c_4\) is a strictly positive design parameter.

The above choice guarantees the closed-loop negativity of the \(V_3\) time-derivative, which would become:

\[ \frac{dV_3}{dt} = -c_4 \varepsilon_4^2 \quad (27) \]

The PV-MPPT error \( \varepsilon_4 \) and a fourth LFC, \(V_4\), are defined as:

\[ \varepsilon_4 = \frac{\partial \dot{p}_p}{\partial p_p} - \left( \frac{\partial \dot{p}_p}{\partial p_p} \right)_{ref} = \frac{\partial \dot{p}_p}{\partial p_p} = I_p + V_p \frac{\partial \dot{p}_p}{\partial P_p}; \quad V_4 = \frac{1}{2} \varepsilon_4^2 + \frac{1}{2} \sigma_4^2 \quad (28) \]

where \(\sigma_4 = c_{si} \int_0^t \varepsilon_4(t) \, dt\); \(c_{si}\) is the integral action design parameter. \(\varepsilon_4\) derivative can be formulated as:

\[ \frac{d\varepsilon_4}{dt} = f \frac{dV_4}{dt} = \frac{f}{c} \left( K_{dg} I_{dq} + K_{qg} I_{qg} + I_p - I_r \right) \quad (29) \]

where \(f = V_p \frac{\partial^2 \dot{p}_p}{\partial P_p \partial p_p} + 2 \frac{\partial \dot{p}_p}{\partial p_p}\). The time-derivative of \(V_4\) is deduced as:

\[ \frac{dV_4}{dt} = \varepsilon_4 \left( \frac{dx_4}{dt} + c_4 \sigma_4 \right) \]

\[ \varepsilon_4 = \frac{\partial \dot{p}_p}{\partial p_p} - \left( \frac{\partial \dot{p}_p}{\partial p_p} \right)_{ref} = \frac{\partial \dot{p}_p}{\partial p_p} = I_p + V_p \frac{\partial \dot{p}_p}{\partial P_p}; \quad \sigma_4 = c_{si} \int_0^t \varepsilon_4(t) \, dt \]

(30)

Then, \(K_{dg}\) and \(K_{qg}\) are chosen in such a way that they satisfy:

\[ A_1 K_{dg} + A_2 K_{qg} = B_4 \quad (31) \]

Then, the GSC control signals, \(K_{dg}\) and \(K_{qg}\), are calculated using (26) and (31):

\[
\begin{bmatrix} K_{dg} \\ K_{qg} \end{bmatrix} = \begin{bmatrix} A_1 & A_2 \\ A_3 & A_4 \end{bmatrix}^{-1} \begin{bmatrix} B_1 \\ B_2 \end{bmatrix}
\]

(33)
3.4. Overall stability analysis

Let us define an overall Lyapunov function candidate \( V_T \) such as:

\[
V_T = \sum_{i=1}^{4} V_i = \sum_{i=1}^{4} \frac{e_i^2}{2} + \sum_{i=1}^{4} \frac{\sigma_i^2}{2}
\]  

(34)

According to (19), (23), (27) and (32), \( V_T \) time-derivative of the closed-loop system is:

\[
\frac{dV_T}{dt} = \sum_{i=1}^{4} \frac{dV_i}{dt} = -\sum_{i=1}^{4} c_i e_i^2
\]  

(35)

Thus, \( V_T \) is a positive definite function and has a negative definite derivative, therefore the tracking errors are asymptotically stable and converge to zero in Lyapunov’s approach.

4. SIMULATION RESULTS

The closed-loop hybrid system is modeled in MATLAB-Simulink software in order to assess the performance of the designed controllers. The main parameters used for the simulation are summarized in Table 1. Figure 5 shows Matlab/Simulink diagram for the hybrid system. The solar radiation and wind velocity profiles shown in Figure 6 are used to perform this assessment.

![Matlab/Simulink diagram for the hybrid system](image)

Figure 5. Matlab/Simulink diagram for the hybrid system

| Table 1. Parameters of controlled system |
|-----------------------------------------|
| **DFIG rated power** | \( P_n = 1kW \) | **Air density** | \( \rho = 1.22 \) kg/m\(^3\) |
| **Line to line voltage** | \( U_s = 190V \) | **Viscous coefficient** | \( \zeta_p = 8.13 \) |
| **DFIG pole pair number** | \( p = 3 \) | **Gearbox ratio** | \( G = 1.3 \) |
| **Maximal power coefficient** | \( C_{p,max} = 4.8 \) | **Switching frequency** | \( f_s = 10kHz \) |
| **Optimal Tip speed ratio** | \( \lambda_{opt} = 8.13 \) | **DC-bus capacitor** | \( C = 100\mu F \) |
| **Controllers** | | **Filter resistance** | \( R_f = 0.5655 \Omega \) |
| \( c_1 = 7 \times 10^5 \); \( c_{11} = 7 \times 10^4 \); \( c_2 = 6 \times 10^4 \); \( c_{31} = 7 \times 10^2 \); \( c_3 = 36 \times 10^4 \); \( c_{33} = 20 \times 10^5 \); \( c_4 = 10^5 \); \( c_{44} = 50 \times 10^5 \) | | | |

A PI controller has been proposed in [29] for controlling the same hybrid system proposed in this paper and the MPPT algorithm “perturb and observe” (including the PVG power limitation to avoid GSC overload) was used to adjust the PVG voltage. In order to provide a good idea of the proposed control performance, the simulation results obtained using the control strategy proposed in [29] are also presented (as the algorithm for tracking the maximum power of the turbine has not been specified in [29], the q-axis rotor current reference established in this paper has been used in order to provide MPPT control of the wind turbine).

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The first simulation result, Figure 7, clearly shows that the PLL has successfully met its objective (q-axis stator flux is almost zero), and that its outputs are more accurate when used with the integral backstepping control. Figure 8 shows that the d-axis component of the stator voltage (which has been neglected in the design of the controllers) is indeed practically zero; its value does not exceed 0.2V with the proposed controller and ± 0.6V with the PI controller. Figure 9 shows the tracking efficiency of the q-axis rotor current reference provided by the proposed RSC controller, which results in very good tracking performance of the optimal electromagnetic torque, as shown in Figure 10. Figure 11 shows that the power coefficient of the wind turbine has been kept close to its maximum value regardless of variations in wind speed. Figure 12 shows that the d-axis rotor current was kept close to its reference value (with a tracking error of less than 0.5A) and hence the stator reactive power was kept close to zero, as shown in Figure 13. Moreover, the proposed GSC controller has been proven more efficient in controlling the reactive power injected by the GSC close to zero, as shown in Figure 14.

Figure 6. Environmental conditions, (a) solar radiation profile, (b) wind velocity profile

Figure 7. DFIG stator flux

Figure 8. DFIG stator voltage

Figure 9. q-axis rotor current

Figure 10. DFIG electromagnetic torque

The total injected power, shown in Figure 15, reveals that the total reactive power is near zero and the active power injected using the proposed controller is greater than that generated using the PI controller. The wind speed profile in Figure 6 was used to evaluate the hybrid system during different operating modes of the DFIG, as can be seen in Figure 16. In the sub-synchronous mode, the power of the PVG is routed through both the GSC and the RSC. Therefore, the active power injected by the GSC becomes lower than that produced by the PVG, as can be seen in the zoomed-in portion of Figure 14.
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5. CONCLUSION

A nonlinear control strategy for a grid-connected PV-wind hybrid system has been presented. The main control objectives are to guarantee the maximum extraction of locally available renewable energy and to operate the grid-connected hybrid system near unity power factor. The control laws have been developed in the stator-flux oriented reference frame on the basis of Lyapunov's stability theory. The soundness of the proposed control strategy has been confirmed by numerical simulations and its performance was compared to that obtained with a previously proposed one. The results obtained highlight the performance of the proposed nonlinear controller. Future work will concentrate on experimental testing of the proposed control strategy, as well as on improving the control of other renewable energy systems.

REFERENCES

[1] B. Dursun, C. Gokcol, I. Umut, E. Ucar, and S. Kocabey, "Techno-Economic Evaluation of a Hybrid PV-Wind Power Generation System," International Journal of Green Energy, vol. 10, pp. 117-136, 2013, doi: 10.1080/15435075.2011.641192.

[2] Z. Othman, S. I. Sulaiman, I. Musirin, A. M. Omar, and S. Shaari, "Hybrid Stand-alone Photovoltaic Systems Sizing Optimization Based on Load Profile," Bulletin of Electrical Engineering and Informatics (BEEI), vol. 7, no. 2, pp. 153-160, 2018, doi: 10.11591/eei.v7i2.1171.

[3] G. R. Prudhvi Kumar, D. Sattianadan, and K. Vijayakumar, "A survey on power management strategies of hybrid energy systems in microgrid," International Journal of Electrical and Computer Engineering (IJECE), vol. 10, pp. 1667-1673, 2020, doi: 10.11591/ijece.v10i2.pp1667-1673.
[4] A. Fathy, K. Kaaniche and T. M. Alanazi, "Recent Approach Based Social Spider Optimizer for Optimal Sizing of Hybrid PV/Wind/Battery/Diesel Integrated Microgrid in Aljouf Region," in IEEE Access, vol. 8, pp. 57630-57645, 2020, doi: 10.1109/ACCESS.2020.2982805.

[5] S. M. M. Aval, and A. Ahadi, "Reliability Evaluation of Wind Turbine Systems’ Components," Bulletin of Electrical Engineering and Informatics, vol. 5, no. 2, pp. 160-168, 2016, doi: 10.11591/eei.v5i2.525.

[6] M. Nurunnabi, N. K. Roy, E. Hossain and H. R. Pota, "Size Optimization and Sensitivity Analysis of Hybrid Wind/PV Micro-Grids- A Case Study for Bangladesh," in IEEE Access, vol. 7, pp. 150120-150140, 2019, doi: 10.1109/ACCESS.2019.2945937.

[7] I. Sofimieari, M. W. B. Mustafa, and F. Obite, "Modelling and analysis of a PV/wind/diesel hybrid standalone microgrid for rural electrification in Nigeria," Bulletin of Electrical Engineering and Informatics (BEEI), vol. 8, no. 4, pp. 1498-1477, 2019, doi: 10.11591/eei.v8i4.1608.

[8] W. K. Ahmed, "Aspects in Formulating Mathematical Model of Wind Turbine," Bulletin of Electrical Engineering and Informatics (BEEI), vol. 2, no. 2, pp. 88-94, 2013, doi: 10.11591/eei.v2i2.210.

[9] P. Cheng, H. Nian, C. Wu and Z. Q. Zhu, "Direct Stator Current Vector Control Strategy of DFIG Without Phase-Locked Loop During Network Unbalance," in IEEE Transactions on Power Electronics, vol. 32, no. 1, pp. 284-297, Jan. 2017, doi: 10.1109/TPEL.2016.253368.

[10] Ali Rahnamaei, and Mahdi Salimi, "A Novel Grid Connected Photovoltaic System," Bulletin of Electrical Engineering and Informatics (BEEI), vol. 5, no. 2, pp. 133-143, 2016, doi: 10.11591/eei.v5i2.523.

[11] A. Merabet, K. Tawfiq Ahmed, H. Ibrahim, R. Beguenane and A. M. Y. M. Ghas, "Energy Management and Control System for Laboratory Scale Microgrid Based Wind-PV-Battery," in IEEE Transactions on Sustainable Energy, vol. 8, no. 1, pp. 145-154, Jan. 2017, doi: 10.1109/TSTE.2016.2587828.

[12] A. Mahammed, A. Kouzou, A. Hafaifa, and B. Talbi, "A new technique for a good efficiency of photovoltaic system under fast changing solar irradiation," in Electrotechnica, Automatica, Electronic (EEA), vol. 67, no. 67, pp. 12-19, 2019.

[13] A. Raj and S. S. Dash, "Grid connected hybrid energy system with Maximum power point tracking technique," 2013 International Conference on Energy Efficient Technologies for Sustainability, 2013, pp. 338-342, doi: 10.1109/ICEETS.2013.6533406.

[14] S. Mahjoub, M. Ayadi, F. Masmoudi, and N. Derbel, "Control of Hybrid Renewable Energy System Based on MPPT Strategy Technique," 2018 15th International Multi-Conference on Systems, Signals & Devices (SSD), 2018, pp. 1280-1286, doi: 10.1109/SSD.2018.8570450.

[15] B. Madaci, R. Chenni, E. Kurt, and K. E. Hemsas, "Design and control of a stand-alone hybrid power system," International Journal of Hydrogen Energy, vol. 41, no. 29, pp. 12485-12496, 2016, doi: 10.1016/j.ijhydene.2016.01.117.

[16] Y. Errami, M. Ouassaid, and M. Maaroufi, "A performance comparison of a nonlinear and a linear control for grid connected PMSG wind energy conversion system," International Journal of Electrical Power & Energy Systems, vol. 68, pp. 180-194, 2015, doi: 10.1016/j.ijepes.2014.12.027.

[17] B. Housseini, A. F. Okou and R. Beguenane, "Performance comparison of variable speed PMSG-based wind energy system control architecture," 2017 Twelfth International Conference on Ecological Vehicles and Renewable Energies (EVER), 2017, pp. 1-10, doi: 10.1109/EVER.2017.7935923.

[18] A. El Malah, A. B. Razzaq, E. Abdelmounim, and M. Madark, "Robust Nonlinear Sensorless MPPT Control with Unity Power Factor for Grid Connected DFIG Wind Turbines," International Review on Modelling and Simulations, vol. 11, no. 5, pp. 313-324, 2018, doi: 10.18566/irr.v11i5.15018.

[19] M. Madark, A. B. Razzaq, E. Abdelmounim and M. E. Malah, "Nonlinear Controller of Solar PV System for Water Pumping and Irrigation Applications," 2019 International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS), 2019, pp. 1-6, doi: 10.1109/WITS.2019.8723736.

[20] F. Maida, O. Barambones, S. Lassad, and A. Fleh, "A robust MPP tracker based on sliding mode control for a photovoltaic based pumping system," International Journal of Automation and Computing, vol. 14, no. 4, pp. 489-500, 2016, doi: 10.1007/s11633-016-0982-6.

[21] M. El Malah, A. B. Razzaq, M. Guissier, E. Abdelmounim, and M. Madark, "Backstepping based power control of a three-phase Single-stage Grid-connected PV system," International Journal of Electrical and Computer Engineering (IJECE), vol. 9, no. 6, pp. 4738-4748, 2019, doi: 10.11591/ijece.v9i6.pp4738-4748.

[22] N. Priyadarshini, K. R. Ramachandaramurthy, S. K. Padmanaban, F. Azam, A. K. Sharma and J. P. Kesari, "An ANN Based Intelligent MPPT Control for Wind Water Pumping System," 2018 2nd IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES), 2018, pp. 443-448, doi: 10.1109/ICPEICES.2018.8897287.

[23] S. -H. Dong, Y. Wang and S. -W. Shu, "A novel Unity Power Factor control strategy based on flux re-orientation for PMSG based wind turbine," 2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), 2014, pp. 1-4, doi: 10.1109/ITEC-AP.2014.6941171.

[24] S. Amuthameena, G. Amuthan, L. Ganesan, "Comparative analysis of utility power factor grid-connected PV system with PI and fuzzy-based controllers," International Journal of Power Electronics, vol. 8, no. 2, pp. 159-177, 2017, doi: 10.1504/IJPELEC.2017.082939.

[25] T. Laagoubi, M. Bouzi, and M. Benchagra, "MPPT and Power Factor Control for Grid Connected PV Systems with Fuzzy Logic Controllers," International Journal of Power Electronics and Drive Systems (IJPEDS), vol. 9, pp. 105-113, 2018, doi: 10.11591/ijpeds.v9i1.pp105-113.
[26] S. Gallardo, J. M. Carrasco, E. Galvan and L. G. Franquelo, "DSP-based doubly fed induction generator test bench using a back-to-back PWM converter," 30th Annual Conference of IEEE Industrial Electronics Society, 2004. 
IECON 2004, 2004, pp. 1411-1416 Vol. 2, doi: 10.1109/IECON.2004.1431785.

[27] J. A. Cortajarena, J. De Marcos, P. Alvarez, F. J. Vicandi and P. Alkorta, "Start up and control of a DFIG wind turbine test rig," IECON 2011 - 37th Annual Conference of the IEEE Industrial Electronics Society, 2011, pp. 2030-2035, doi: 10.1109/IECON.2011.6119620.

[28] M. Bouderbala, B. Bossoufi, A. Lagrioui, M. Taoussi, H. A. Aroussi, and Y. Ihedrane, "Direct and indirect vector control of a doubly fed induction generator based in a wind energy conversion system," International Journal of Electrical and Computer Engineering (IJECE), vol. 9, no. 3, pp. 1531-1540, 2019, doi: 10.11591/ijece.v9i3.pp1531-1540.

[29] R. G. Wandhare and V. Agarwal, "Novel Integration of a PV-Wind Energy System With Enhanced Efficiency," in IEEE Transactions on Power Electronics, vol. 30, no. 7, pp. 3638-3649, July 2015, doi: 10.1109/TPEL.2014.2345766.

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