USE OF A CONFIGURABLE TORQUE–SPEED DEPENDENCE FOR POWER MAXIMIZATION OF SQUIRREL-CAGE-INDUCTION-GENERATOR-BASED WIND ENERGY CONVERSION SYSTEM

BY

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Abstract. The aim of this paper is to propose controllable torque–speed dependence for power maximization of squirrel-cage-induction-generator–based wind energy conversion system. It uses a vector control scheme and allows imposing both the slope and the zero-torque point of a generator forced mechanical characteristic. A better dynamic, along with extended domain of stable operation and controllable generator torque variations, is thus obtained. Through numerical simulation, closed-loop dynamics and stability analysis are performed for the proposed control method.

Key words: wind energy conversion systems, wind turbine control, optimization methods, stability, asynchronous machine field-oriented control.

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1. Introduction

Variable-speed wind energy conversion system (WECS) is a highly nonlinear time-variant system excited by stochastic inputs which significantly affect its reliability and lead to non negligible variations in the dynamic behaviour of the system over its operating range. This is a reason for which variable speed wind turbines control has not yet converged to a classical widely-accepted solution. Usually the WECS control deals with a multicriteria
objective, with various components, expressing energy and performance optimization problems, such as wind turbine power limitation in full-load operating mode, the alleviation of wind-turbulence-generated mechanical fatigue, maximization of captured energy in partial-load mode, the reduction of mean squared error between the actual operating point and the optimal power regime etc. [1], [2], [3]. The WECS control aiming at reducing the mechanical fatigue due to generator torque variations along with minimizing the mean squared error of the operating point around the optimal regime characteristic, ORC, is still a problem of significant interest. It can be stated as a dynamic optimization problem with the following performance criterion [5], [7]:

\[
I = E \left[ \alpha \cdot (\lambda - \lambda_{opt})^2 + \Delta T_{em}^2 \right].
\]

where: \( E \) is the statistical average; \( \lambda \) – the tip speed ratio defined as ratio between the peripheral speed of the blades and the wind speed; \( \lambda_{opt} \) – the optimal tip speed ratio that grants captured power maximization; \( \Delta T_{em} \) – the electromagnetic torque variation; \( \alpha \) – a weighting coefficient.

In this paper, the case of a high-power SCIG-based WECS, operating in the partial-load regime, is considered. The wind turbine is controlled to extract maximum power available in the wind. An improved control method is proposed that overcomes the main drawback of the classical control solution: slow dynamic response with accentuated overshoot [12]. The proposed method allows imposing both the slope and the zero-torque point of the SCIG mechanical characteristic. In this way good dynamic with acceptable electromagnetic torque variations is ensured. The presented results allow a comparison with the classical vector-controlled system.

This paper is structured as follows. Section 2 presents the statement of the improved control method. Section 3 presents the basic wind conversion system modelling; Section 4 presents the vector control principle, the block defining the desired torque-versus-rotational-speed dependence within the proposed method, the closed-loop analysis and some design issues. For the classical control and for the improved control, in Section 5 a closed-loop stability analysis is presented using Matlab Symbolic Math toolbox and in Section 6 Matlab®/Simulink® simulation results are presented. Section 7 presents the main conclusion regarding the obtained results.

2. Control Problem Statement

A large horizontal-axis wind turbine with a back-to-back converter and a vector-controlled SCIG has a slow dynamic. Its output energy efficiency is given by the first term of the performance criterion (1), whose minimization
reflects good dynamic behavior. However, the two terms of the performance criterion have to be reasonably traded-off, to ensure system reliability also [5]. In the following, different possibilities of driving the SCIG generator at variable speed will be analyzed.

Using a scalar control, one can control generator speed in a wide range by varying the stator voltage and the frequency such as their ratio to be kept constant [6]. The generator mechanical characteristics in this case are presented in Fig. 1, case (a). The mechanical time constant of the system linearized around a typical operating point is [4]:

(2)

\[
T = J_h \left( \frac{\partial T_{em}}{\partial \Omega_h} - \frac{\partial T_w}{\partial \Omega_h} \right).
\]

where \( T_{em} \) is the induction generator torque, \( T_w \) is the wind turbine torque, and \( J_h \) and \( \Omega_h \) are the high-speed shaft turbine inertia and rotational speed.

Knowing that the induction generator characteristic slope, \( \left( \frac{\partial T_{em}}{\partial \Omega_h} \right) \), is always larger than the wind turbine characteristic slope, \( \left( \frac{\partial T_w}{\partial \Omega_h} \right) \), the time constant will always be positive and the system will always be stable. The major drawback of a scalar control is that the variations of the generator torque cannot be limited in absence of a torque control loop. Hence, the drive train mechanical loads cannot be conveniently controlled.

Using a torque vector control, the generator characteristics obtained for a constant torque set-point are presented in Fig. 1, case (b). This intrinsically overcomes the drawback of the scalar control, but has other disadvantages. As the generator characteristics slopes are zero, the system is stable only on the
descending side of the wind turbine characteristic. The stability may be obtained by employing an outer speed control loop. The other drawback is a large time constant (eq. (2)).

This paper proposes a new control method that combines the advantages of the two above-presented methods. Based on the torque vector control, the generator mechanical characteristic is forced to have a controllable slope.

3. WECS Modeling

The case of a back-to-back 2 MW rigid-drive-train SCIG-based WECS is considered in this paper. The average turbine (wind) torque is given by the expression:

\[ T_w = 0.5 \pi \rho \cdot v^2 R^3 C_T(\lambda) . \]

where: \( v \) is the wind speed, \( R \) – the blade length, \( \rho \) – the air density, and \( C_T(\lambda) \) – the torque coefficient, which depends on the wind turbine tip speed ratio, \( \lambda \). This dependence can be approximated by a polynomial and gives the wind torque shapes in Fig. 1. The tip speed ratio is given below:

\[ \lambda = R \cdot \Omega_h / (i \cdot v) . \]

where: \( i \) is the drive train multiplication ratio.

The rigid drive train, with the parameter values given in Appendix, is characterized by the following motion equation [8]:

\[ J_h \frac{d \Omega_h}{dt} = \frac{T}{l}(\Omega_h, v) - T_{em}(\Omega_h, \Omega_c) . \]

where: \( J_h = J_g + J_w / i^2 \) is the high-speed shaft inertia, \( J_g \) and \( J_w \) – the generator and turbine rotor inertias respectively.

The studied machine is a 2-pole-pairs SCIG. The generator feeds a power grid via a back-to-back converter [6]. The converter has two inverters decoupled by a DC-link. The grid-side inverter is dedicated to the DC-link power transfer to the grid. In order to achieve this target, it maintains the DC-link voltage constant. The machine-side inverter is employed for the SCIG speed control. It allows the turbine operation at variable speed. Based on the DC-link constant voltage, this power structure allows fast SCIG torque adjustment using the vector control scheme [6].
4. WECS Control

4.1. Vector Control

The generator torque control is achieved by considering a SCIG modeling in the rotor (d,q) frame [6]. The associated vector control structure separately drives the machine flux and torque, as they correspond to axis $d$ and $q$, respectively. This control structure will be not further detailed as it is beyond the scope of this paper. Their dynamic performances are very good as the torque settling time is usually rated at hundred of milliseconds for the considered machine. Therefore, this low-level electrical dynamic is neglected in relation to the mechanical dynamic exhibited by the rotational speed evolution.

4.2. Speed Control and Torque-Speed Dependence Block (TSDB)

Wind turbines speed control is essential as it allows not only captured power control, but also over-speed protection and mechanical loads alleviation. The speed control in this paper is ensured by a PI controller. This configuration is classical, being employed in the majority of wind turbine control applications. Considering a measure of the wind speed, the rotational speed set-point corresponding to the optimal tip speed (maximum power capture) is given by the following relation:

$$\Omega_{h}^\ast (t) = \left( k_{opt} \cdot i / R \right) \cdot v(t) = k_{\lambda} \cdot v(t).$$

The PI controller parameters influence on the controlled system dynamics will be analyzed in the following section. As already stated in [12], the wind speed has a double influence on the system. Beside of imposing the rotational speed set-point, it also influences directly the plant by changing the wind torque and consequently the rotational speed. Thus, if the PI controller is tuned to ensure a good tracking, then the closed-loop system dynamic behavior results far from being optimal, having an important overshoot, as described in [12].

In order to improve the WECS behavior, this paper proposes the employment of a so-called torque-speed dependence block, TSDB, who generates the electromagnetic torque reference as a linear dependence of the high-speed shaft rotational speed. Thus, by forcing the dependence between the electromagnetic torque and its rotational speed, the generator mechanical characteristic $T_{em}(\Omega_{h})$ can be rotated with an arbitrarily imposed angle.

In this way, a supplementary degree of freedom is added to the system as its dynamic can be conveniently modified. This is done by changing the generator characteristic slope:
The equation that generates the linear dependence is:

\[ T_{em} = m \cdot (\Omega_h - \Omega_c). \]

where: \( \Omega_c \) is the zero-torque rotational speed. This point is outputted by the PI speed controller, where the slope \( m \) is given as a user-supplied value. According to (2), a large value of \( m \) will speed up the plant.

The proposed control structure is given in Fig. 2. One can remark the wind speed double influence over the system and the TSDB presence that affects the electromagnetic torque reference.

\[ J \frac{d}{dt} \Delta \Omega_h = \frac{\partial T_w}{\partial \Omega_h} \Delta \Omega_h + \frac{\partial T_w}{\partial v} \Delta v - \frac{\partial T_{em}}{\partial \Omega_c} \Delta \Omega_c - \frac{\partial T_{em}}{\partial \Omega_h} \Delta \Omega_h. \]

The following notations are used next. The wind torque and electromagnetic torque variation with rotational speed are denoted as \( \frac{\partial T_w}{\partial \Omega_h} = k \) and \( \frac{\partial T_{em}}{\partial \Omega_c} = m \) respectively, while the wind torque variation with respect to the wind speed is noted as \( \frac{\partial T_w}{\partial v} = k_v \). The generator torque variation with the control input, \( \Omega_c \), is denoted by \( \frac{\partial T_{em}}{\partial \Omega_c} = -m \). Note that \( k \) and \( k_v \) depend on the steady-state operating point.

Simple algebra leads to the rotational speed variation dependence on the wind speed and control input variations:

\[ \Delta \Omega_h = k_v \cdot P \cdot \Delta v - m \cdot P \cdot (\Delta \Omega_h - \Delta \Omega_c). \]
where:

\[(11)\]
\[P = \frac{1}{J_h \cdot s - k}.
\]

In closed loop, the rotational speed variation is (Fig. 3):

\[(12)\]
\[
\Delta \Omega_h = k_v \cdot P \cdot \Delta v - m \cdot P \left[ \Delta \Omega_h - H_{pf} \cdot \left( \Delta \Omega_h^* - \Delta \Omega_h \right) \right].
\]

where: \(H_{pf} = K_p \left( 1 + \frac{1}{sT} \right)\) is the controller transfer function.

![Block structure of the controlled system.](image)

Further, one can extract the rotational speed dependence on the wind speed:

\[(13)\]
\[
\frac{\Delta \Omega_h}{\Delta v} = \frac{k_v \cdot P + m \cdot P \cdot H_{pf} \cdot k_v}{1 + m \cdot P \cdot \left( 1 + H_{pf} \right)}.
\]

One aims at obtaining system dynamic performance of the maximum power tracking. This can be translated in good tracking of the wind speed variations. Thus, the rotational speed response to wind speed variations is imposed as being a standard second-order response:

\[(14)\]
\[
\frac{\Delta \Omega_h}{\Delta v} = \frac{T_1 s + 1}{T_0 s^2 + 2 \xi T_0 s + 1}.
\]

where: the closed-loop time constant, \(T_0\), the damping, \(\xi\), and the system’s zero time constant, \(T_1\), depend on the generator torque slope, \(m\), through the following equations:
\[
T_0 = \frac{T_f \cdot J_h}{K_p \cdot m}, \quad \xi = \frac{m(1 + K_p) - k}{2} \sqrt{\frac{T_f}{K_p \cdot m \cdot J_h}}.
\]

\[
T_1 = T_f \left( k_v / (K_p \cdot m \cdot k_v) + 1 \right).
\]

### 4.4. Design Issues

As it has already been seen, the generator torque slope determines the closed-loop system dynamic behavior. An increased value of \( m \) leads to a decrease in both \( T_0 \) and \( T_1 \) time constants and an increase of the damping, \( \xi \), Fig. 4. This implies faster settling time of the wind turbine rotational speed together with lower overshoot.

![Fig. 4 - Closed-loop time constant, \( T_0 \), damping, \( \xi \) and the system's zero time constant \( T_1 \) versus the generator torque slope, \( m \).](image)

The curves represented exhibit some kind of “saturation”, meaning that large values of \( m \) will not significantly influence the system dynamics. Also, when \( m \) increases, the electromagnetic torque variations induced by the wind speed tracking process increase also.

Using the transfer function from the wind speed to the electromagnetic torque given below (Fig. 3):

\[
\frac{\Delta T_{em}}{\Delta v} = m \cdot \frac{\Delta \Omega_h}{\Delta v} + m \cdot H_{pf} \cdot \left( \frac{\Delta \Omega_h}{\Delta v} - k_h \right) = m \frac{\Delta \Omega_h}{\Delta v} + \left( k_h - k_v \right) \frac{\Delta T_0}{\Delta v} + \frac{T_f^2}{T_f^2 s^2 + 2 \xi T_0 s + 1}.
\]
and applying the final value theorem, one can estimate more accurately the torque variations dependence on parameter \( m \), when a step variation of the wind speed is considered, i.e., \( \Delta v(s) = 1/s \):

\[
\Delta T_{em\_st} = \lim_{s \to 0} \Delta T_{em}(t) = \lim_{s \to 0} \varepsilon \Delta T_{em}(s) = m \cdot k_c \left[ 1 + \left( \frac{K_p}{T_i} \right) \left( 2 \xi T_0 - T_1 \right) \right].
\]

Eq. (18) shows that the torque amplitude is proportional with the value of \( m \).

Now, one can analyze the transfer function from the wind speed to the tip speed ratio variations. Starting from eq. (4), one can obtain by differentiation around the optimal operating point (determined by \( \lambda_{opt} \)):

\[
\Delta \Omega_b = \left( \frac{v \cdot i}{R} \right) \Delta \lambda + \left( \frac{\lambda}{i} \right) \Delta v.
\]

Then, \( \frac{\Delta \lambda}{\Delta v} = \frac{R}{v \cdot i} \cdot \frac{\Delta \Omega_b}{\Delta \lambda} = \frac{\lambda_{opt}}{v} \), and if employing (14), one obtains:

\[
\frac{\Delta \lambda}{\Delta v} = \frac{\lambda_{opt}}{v} \left( \frac{T_i s + 1}{T_o s^2 + 2 \xi T_o s + 1} \right).
\]

This latter relation shows that the tip speed variations will be reduced as the closed-loop system time constant becomes smaller (the term in the brackets approaches zero).

To conclude, the user-supplied parameter \( m \) significantly affects the closed-loop system dynamical behavior. It can be seen as a trade-off parameter between the tracking fidelity of the wind speed variations (power maximization purpose) and the alleviation of the electromagnetic torque high-frequency components (reliability purpose). From this point of view it plays the role of the weighting parameter \( \alpha \) introduced in (1).

5. Stability Analysis

Vector control ensures the wind turbine stability only on the descending side of the wind torque characteristic. The stable operating region can be extended towards low rotational speed values by using an outer rotational speed loop, usually built around a PI controller.

Analysis is performed for two cases. First, the classical control structure with speed loop and vector control, when the generator characteristic slope is zero, has been approached. Secondly, the control structure including the torque-
speed dependence bloc (TSDB), when the generator characteristic slope can be changed, has been analyzed.

5.1. Classical Case: Speed Loop and Vector Control

For analyzing purposes, one replaces the nonlinear system structure with a linearized one, for easily applying the linear stability analysis methods. The classical system is characterized by the following motion equation:

\[
J_h \frac{d\Omega_h}{dt} = \frac{T_m}{i}(\Omega_h, v) - T_{em}.
\]  

(21)

By differentiating eq. (21) around a steady-state operation point one obtained:

\[
J_h \frac{d\Delta \Omega}{dt} = \frac{\partial T_m}{\partial \Omega_h} \Delta \Omega_h + \frac{\partial T_m}{\partial v} \Delta v - \Delta T_{em}.
\]  

(22)

Using the same notation from section 4.3. and after some algebra one obtains:

\[
\Delta \Omega_h = \frac{k_v}{J_h \cdot s - k} \Delta v - \frac{1}{J_h \cdot s - k} \Delta T_{em}.
\]  

(23)

Because it cannot be adjusted through the control law, the first term of (23) can be neglected. Therefore (23) becomes:

\[
\frac{\Delta \Omega_h}{\Delta T_{em}} = -\frac{1}{J_h \cdot s - k}.
\]  

(24)

The generator torque dynamic follows the stator quadrature current dynamic that can be imposed by vector control as a first-order transfer function. Hence, the generator torque dynamic can be described by \( H_s(s) = 1/(Ts+1) \), with the time constant \( T \) imposed by control design.

Knowing that the PI speed controller transfer function is \( H_{pi}(s) = k_p \left( 1 + 1/(Ts) \right) \), then the equivalent linear structure of the classical system (without TSDB) in closed loop is given in Fig. 5, with:

\[
k_p = \left( \frac{\lambda_{opt} \cdot i}{R} \right).
\]  

(25)
Fig. 5 − Classical speed control loop.

The closed-loop transfer function of the system in Fig. 5 is:

\[
\frac{\Delta \Omega_h}{\Delta v} = \frac{-k_p (T_i s + 1) k_h}{J_h T_i T_s^3 + T_i (J_h - k \cdot T) s^2 - T_i (k + k_p) s - k_p}.
\]

from which one obtains the characteristic equation:

\[
J_h T_i T_s^3 + T_i (J_h - k \cdot T) s^2 - T_i (k + k_p) s - k_p = 0.
\]

Considering eq. (27), one can apply the Routh-Hurwitz criterion for stability analysis. The first requirement of this criterion is that all coefficients to have the same sign, which implies the following conditions for the controller parameters:

\[
T_i > 0, \quad k_p < -k, \quad k_p < 0.
\]

The second requirement implies the computation of the Hurwitz determinant and leads to the following condition for the integral time constant, \(T_i\):

\[
T_i < \frac{J_h T \cdot k_p}{(J_h - k \cdot T)(k + k_p)}.
\]

The curve \(T_i(k_p)\) given by expression (29) is represented in plane for two situations:

a) when \(k = k_{\text{pos}}\);

b) when \(k = k_{\text{neg}}\),

where: \(k_{\text{pos}}\) and \(k_{\text{neg}}\) are the wind turbine characteristic slopes on the ascending and respectively descending side, at the inflexion points (i.e., the largest slopes – Fig. 6).
By imposing the three Routh parameters conditions (28), the stability domains are limited to the second quadrant. The graphical representation of function $T_i(k_p) = \frac{J_s T \cdot k_p}{(J_h - k \cdot T)(k + k_p)}$ for both values of $k$ is composed of the curves in Fig. 7.

According to the condition obtained from the Hurwitz determinant the system stability domains are localized above these curves (see shaded regions from Fig. 7).

One can remark that the domains intersection, gives the global stability domain, doubly shaded, for the slope $k$ being either negative or positive. The thin dotted straight lines represent the vertical and horizontal asymptotes, given by the expressions specified on Fig. 7.

5.2. TSDB Case

For the second case when TSDB is present, the initial structure changed as shown in Fig. 8.
The motion equation changed also, as is shown in (5). By differentiating (5) around a steady-state operation point one obtains:

\[
J_h \frac{d}{dt} \Delta \Omega_h = \frac{\partial T_w}{\partial \Omega_h} \Delta \Omega_h + \frac{\partial T_w}{\partial \nu} \Delta \nu - \frac{\partial T_{em}}{\partial \Omega_h} \Delta \Omega_h - \frac{\partial T_{em}}{\partial \Omega_c} \Delta \Omega_c .
\]

where: \( \frac{\partial T_w}{\partial \Omega_h} = k \), \( \frac{\partial T_w}{\partial \nu} = k_v \), \( \frac{\partial T_{em}}{\partial \Omega_h} = m \), \( \frac{\partial T_{em}}{\partial \Omega_c} = -m \) have the same meaning as above.

Simple calculus shows that the high-speed shaft rotational speed variation in closed loop is:

\[
\Delta \Omega_h = \frac{k_v}{J_h \cdot s - k} \Delta \nu - \frac{m}{J_h \cdot s - k} (\Delta \Omega_h - \Delta \Omega_c)
\]

Like in the first case, the first term in (31) is neglected and the obtained expression is:

\[
\Delta \Omega_h = -\frac{m}{J_h \cdot s - k} (\Delta \Omega_h - \Delta \Omega_c)
\]

The closed-loop transfer function of the system is:

\[
\frac{\Delta \Omega_h}{\Delta \nu} = m k_p (T_i s + 1) k_h .
\]

\[
\frac{1}{J_h T_i T_s^3 + T_i (J_h - k \cdot T) s^2 + T_i \left[ (m - k) + m k_p \right] s + m k_p}
\]

and the associated characteristic equation is:

\[
J_h T_i T_s^3 + T_i (J_h - k \cdot T) s^2 + T_i \left[ (m - k) + m k_p \right] s + m k_p = 0
\]

Like in the first case, by applying the Routh-Hurwitz criterion, one obtains the following conditions for PI speed controller parameters:

\[
T_i > 0 ; k_p > 0 ; k_p > \frac{k}{m} - 1
\]

\[
T_i > \frac{m J_h T \cdot k_p}{(J_h - k \cdot T) \left[ (m - k) + m k_p \right]}
\]
Fig. 9 – Stability domain for speed closed loop with TSDB: $a$ – for $m > k_{pos}, m > k_{neg}$; $b$ – for $m > k_{pos}, m > k_{neg}$.

The curve $T_i(k_p)$ given by expression (36) is represented in plane for four situations:

a) when $k = k_{pos}$
   
   a.1) $m > k_{pos}$ ($m = 600$)
   
   a.2) $m < k_{pos}$ ($m = 100$)

b) when $k = k_{neg}$
   
   b.1) $m > k_{neg}$ ($m = 600$)
   
   b.2) $m > k_{neg}$ ($m = 100$)

where: $k_{pos}$ and $k_{neg}$ have the same values as in the first case. Also, like in the first case, by applying Routh conditions (35), the stability domains are limited to the first quadrant and by applying the Hurwitz criterion the stability domains are localized above the curves derived from (36), for the indicated situations of choosing $m$ and $k$ (Figs. 9 $a$ and 9 $b$).

The doubly shaded domains in Fig. 9 are the global stability domains, in the $T_i - k_p$ plane, obtained from the stability domains intersection derived for the above indicated situations of choosing $m$ and $k$.

One can observe that the global stability margin is smaller as the generator characteristic slope is diminished (Fig. 9 $b$).

To conclude, for a fixed plant ($i.e., k_{pos}$ and $k_{neg}$) and fixed control parameters ($i.e., k_p$ and $T_i$), the first (classic) case gives a fixed stability domain. The second case gives an adjustable stability domain by employing...
different values of \( m \), in the same conditions.

For two points considered from both global stability domains (for classical speed loop (1500,1.2) and for improved speed loop (10,1.5), when \( m=600 \)) one can see, as it is shown in Fig. 10, that stability is achieved irrespective of the sign of the wind turbine characteristic slope.

![Stability analysis over the high-speed shaft behavior](image)

**Fig. 10** − Stability analysis over the high-speed shaft behavior:

\( a \) − when \( k = k_{\text{neg}} \); \( b \) − when \( k = k_{\text{pos}} \).

### 6. Simulation Results

The controlled WECS behavior is analyzed by numerical simulation using Matlab®/Simulink® software. The simulation block diagram corresponds to Fig. 2.

Two situations have been analyzed: first, when the electromagnetic torque reference is obtained directly as output of the PI speed controller (classical WECS speed control structure) and a second one, when the electromagnetic torque is imposed by the above-presented dependence block (TSDB − Fig. 2).

Concerning the first situation, the PI speed controller has been tuned around the optimal operating point at 9 m/s. Its parameters, \( K_p = 733 \) and \( T_s = 2 s \), correspond to a closed-loop time constant of about 2 sec.

The corresponding operating point trajectory on the \( T(\Omega_h) \) plane indicates, first, a motoring regime. Then, when the generation regime is reached, the operating point evolves towards ORC. Fig. 11 b contains the detailed system response to a positive step change in the wind speed (of 0.5 m/s). The dynamic response lasts for about 10 sec − Fig. 11 c. One can note the quite large generator torque variations that correspond to significant control effort − Fig. 11 d.
Fig. 11 − Simulation results for a classical speed control structure with a vector controlled SCIG: 
a − trajectory of the operating point; 
b − zoom of a around ORC; 
c − high-speed shaft rotational speed; 
d − electromagnetic torque variation. 
Dynamic closed-loop responses for slopes m=200 and m=600: 
e − high-speed shaft rotational speed; 
f − electromagnetic torque.

Now, let us consider the second situation, when the speed controller output is passed through the TSDB, as indicated in Fig. 2.
Two values of the characteristic slopes, $m = 200$, and $m = 600$, have been chosen. Because $m$ parameter strongly influences the system dynamics, the parameters values of the PI speed controller have to be changed in order to obtain the same dynamic response. The new values for the speed controller are: $K_p = 1.2$ and $T_i = 0.8$.

The results are shown for the same operating point as in the first situation (positive wind speed step transition from 9 m/s to 9.5 m/s). As the system is nonlinear, for negative wind speed steps, the response differs slightly. One can see that the obtained dynamic is better as the slope is larger (Fig. 11 e), but the inconvenient is the increase of electromagnetic torque variation (Fig. 11 f). The overshoot is also significantly reduced. These results are coherent with the discussion in Section 4.4.

Fig. 12 shows the system response to stochastic wind speed. The turbine is fed with a stationary band-limited wind signal [9].

![Fig. 12](image_url)

**Fig. 12** – System response to stochastic wind speed for slopes $m = 200$ and $m = 600$: 
- **a** – high-speed shaft rotational speed; 
- **b** – electromagnetic torque.

Large slope values lead to smaller variance of the speed error (better wind speed tracking performance) – Fig. 12 a. Large slopes also lead to large SCIG torque variations, therefore to larger mechanical stress. This shows that the slope parameter $m$ can be effectively used as a trade-off parameter between energy efficiency and mechanical stress alleviation.

Furthermore, for $m$ values larger than 600, the generator torque variations become so large that the system operates in saturation. An upper limit value of $m$ should be identified in order to avoid nonlinear behaviour of the controlled system.

### 7. Conclusions

This paper deals with dynamic power optimization and stability analysis for high-power WECS with a vector-controlled SCIG.

1. To ensure faster dynamics, the electromagnetic torque is linked to the
rotational speed by a linear dependence, similar to the one exhibited by the SCIG natural characteristic. This is achieved by passing the speed controller output through a torque-speed dependence block. The main difference with respect to the classical control structure is that the speed controller output is not the electromagnetic torque reference, but the zero-torque speed of the generator mechanical characteristic [10].

2. The influence of the torque-speed slope on the closed-loop dynamics has been thoroughly studied. Numerical simulations show that the controlled system dynamics can be conveniently adjusted using a single parameter: the torque-speed slope. It not only diminishes the speed overshoot, but also provides a mean of achieving simply a trade-off between the energy efficiency and mechanical efforts in the wind turbine partial-load region. The user-supplied value of the torque-speed slope can be conveniently adjusted corresponding to the wind speed value and turbulence. Small values can be provided by a supervisor that is concerned with the wind turbine reliability. Although high torque-speed slope values ensure faster turbine response, one must ensure their limitation in order to avoid excessive motoring regimes or too strong nonlinear behavior.

3. The stability analysis performed shows that the classical speed loop cannot be deduced from the improved speed loop with the TSDB, by customizing parameter $m$ at zero value [11]. It has a different structure for which the stability domain changes from the second quadrant to the first quadrant in the plane of controller’s parameter (gain versus integral time constant). The range of the PI proportional gain is reduced and the desired values are near to zero, whereas for the classical system a large negative value is used. Global stability domain is larger and can change as the torque-speed slope is changed depending on user needs. In this way, one obtains significant flexibility over the dynamic stability domain.

Future work will aim at finding a suitable gain scheduling law for the torque-speed curve slope with respect to the wind speed variation and user requirements. The influence of this parameter on the power regulation loop in full-load regime should also be studied.

Appendix

Blade length $R = 45$ m, rotor inertia $J_w = 9 \cdot 10^6$ kg m$^2$, rated wind speed 10.5 m/s, air density $\rho = 1.25$ kg/m$^3$, optimal tip speed ratio $\lambda_{opt} = 7$, SCIG rated power 2MW, maximal torque 17000Nm, $J_g = 135$ kg m$^2$, multiplier ratio $i = 100$.

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UTILIZAREA UNEI DEPENDENȚE VITEZĂ-CUPLU CONFIGURATĂ PENTRU MAXIMIZAREA PUTERII UNUI SISTEM DE CONVERSIE A ENERGIEI EOLIENE CU GENERATOR ASINCRON CU ROTORUL ÎN SCURT CIRCUIT

(Rezumat)

Lucrarea propune o metodă de maximizare a puterii unui sistem eolian de mare putere bazat pe un generator asincron cu rotorul în scurt circuit. Metoda constă în
sinteza unui bloc de dependență, controlabilă, a cuplului funcție de viteză de rotație. Sistemul studiat este o turbină eoliană de 2 MW cu un mecanism de transmisie fix și un generator asincron cu rotorul în scurt circuit.

Analiza dinamicii sistemului se bazează pe faptul că se cunosc caracteristicile generatorului și turbinei eoliene, atât în cazul comenzii vectoriale, cât și în al celei scalare, precum și expresia constantei de timp mecanice, obținută pe baza liniarizării ecuației de mișcare a sistemului în jurul unui punct de funcționare. Analiza a scos în evidență posibilitatea utilizării unei comenzii vectoriale în cadrul sistemului, datorită avantajului de a avea un control asupra variațiilor de cuplul electromagnetic, dar cu o înclinare a caracteristicii generatorului obținute la o pantă controlabilă, funcție de nevoile utilizatorului. Aceasta permite îmbunătățirea dinamicii sistemului și diminuarea variațiilor de cuplu. Panta controlabilă a caracteristicii generatorului este generată printr-o dependență între cuplul generatorului și viteză de rotație la arborele rapid, dependență numită **TSDB – Torque-Speed Dependence Bloc**.

S-a observat că pentru o valoare mare a pantei dinamica sistemului s-a îmbunătățit, cu dezavantajul unor variații mari ale cuplului la arborele generatorului, iar pentru o valoare mică efectul este invers, în sensul reducerii variațiilor de cuplul în defavoarea unei dinamici mai lente a sistemului. S-a ajuns astfel la concluzia că această pantă, notată cu \( m \), poate fi comparată cu un coeficient de ponderare al unui criteriu de performanță liniar pătratic, care are rolul de a pondera eforturile funcție de nevoile utilizatorului. Se poate spune că s-a creat un nou grad de libertate, și anume panta caracteristicii \( m \).

Simulările au arătat că peste o anumită valoare dată pantei caracteristicii generatorului comportamentul sistemului este nelinear. Deci valoarea acestuia nu poate fi oarecare. Din analiza stabilității asupra sistemului inițial, cu buclă de viteză pentru optimizare (maximizarea puterii) și control vectorial, precum și asupra sistemului îmbunătățit prin dependență creată între cuplu și viteză la arborele rapid (TSDB), s-a remarcat că panta oferă o flexibilitate asupra marjii de stabilitate în funcție de ce performanțe sunt impuse sistemului.

O direcție viitoare de cercetare o constituie analiza influenței pantei caracteristicii generatorului asupra comportamentului sistemului atunci când acesta funcționează în zona de sarcină totală.