A Feedback Linearization Control Scheme for the Integration of Wind Energy Conversion Systems into Distribution Grids

Federico Delfino, Member, IEEE, Fabio Pampararo, Renato Procopio, Member, IEEE, and Mansueto Rossi

Abstract—This paper focuses on the development of a control strategy for the integration of wind energy conversion systems (WECS) into the electrical distribution networks. The paper addresses the combined provision of energy and ancillary services, which is the main focus of the distribution networks. Typically, a WECS is composed of a variable speed wind turbine coupled with a direct driven permanent magnet (DDPM) synchronous generator. This configuration offers a considerable flexibility in design and operation of the power unit, as its output is delivered to the grid through a fully controlled frequency converter. Here, a new control scheme is proposed to regulate electrical and mechanical quantities of such a generation unit, aimed both at reaching optimal performances in terms of power delivered to the grid and at providing the voltage support ancillary service at the point of common coupling. The control scheme is derived resorting to the feedback linearization (FBL) technique, which allows both decoupling and linearization of a non-linear multiple input multiple output system. Numerical simulations are then performed in order to show how the flexibility of the DDPM wind generator can be fully exploited, thanks to the use of the FBL approach, which assures independent control of each variable and significant simplifications in controller synthesis and system operation, thus making it easier to integrate WECS into modern day smart grids.

Index Terms—Direct drive, feedback linearization, permanent magnet synchronous generator, wind power.

I. INTRODUCTION

THE INCREASED penetration of renewable energy conversion systems (WECS) into the electrical distribution networks is facing climate changes and at the same time, compact and low-speed triggered systems, suitable for residential use.

Among the different kinds of wind generation systems, those based on direct driven permanent magnet (DDPM) are gaining attention and growing developments in gearless energy transmission with power-electronic interfaces providing the opportunity to integrate WECS into modern day smart grids.

A. Control

Wind turbine for large-sized power plants (on shore and off-shore) and, at the same time, compact and low-speed triggered systems, suitable for residential use.

However, many utilities are reluctant to install significant wind capacity because of the intermittent nature of the resource, which prevents wind power to be controlled in the same way as conventional “bulk” units. Thus, research in the field of wind power integration is gaining momentum, mainly through the development of suitable control strategies for integrating WECS into the grid, in order to perform a voltage support at the point of common coupling (PCC). The DDPM machine, jointly with new power-electronic equipment and new controllers, has thus become an important and very employed technique, as the possibility of reducing maintenance costs and increasing reliability of the wind mill and reducing maintenance can be eliminated.

In the light of this state-of-the-art, the aim of this paper is to develop a new control scheme for integrating WECS into the grid, in order to perform a voltage support at the point of common coupling (PCC). The control scheme is derived resorting to the feedback linearization (FBL) technique, which allows both decoupling and linearization of a non-linear multiple input multiple output (MIMO) system. Numerical simulations are then performed in order to show how the flexibility of the DDPM wind generator can be fully exploited, thanks to the use of the FBL approach, which assures independent control of each variable and significant simplifications in controller synthesis and system operation, thus making it easier to integrate WECS into modern day smart grids.

B. System Operation

The DDPM machine, which works at minimal speed ratio to the value that maximizes aerodynamic efficiency, offers a considerable gain in the same way as conventional fossil fuel “bulk” units. Among the different kinds of wind generation systems, those based on direct driven permanent magnet (DDPM) are gaining attention and growing developments in gearless energy transmission with power-electronic interfaces providing the opportunity to integrate WECS into modern day smart grids.

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multiple-inputs, multiple-outputs system to a number of single input, single output linear systems, without resorting to mathematical approximations (like the small signal analysis); this makes it easier to design the regulators transfer functions and allows a decoupled (independent) control of each regulated variable.

This paper is organized in six parts. In Section II the whole system model is derived, considering separately wind turbine, synchronous generator, machine side pulse-width modulation (PWM) inverter, DC link, network side PWM inverter and grid, while in Section III the theory necessary to apply the FBL and to synthesize the control is outlined. The next two sections present simulations results aimed at highlighting the system behavior both in normal operating conditions and in the event of faults. In particular, Section IV is devoted to a simulation campaign, performed in order to test the WECS response to wind speed fluctuations and reference variations, showing also its ability to deliver reactive power to the grid when the generated active power is low. Beside this latter kind of ancillary services, utilities and transmission system operators (TSOs) are becoming more demanding in terms of the kind prescribed by E.ON Netz GmbH [16]. Finally, in Section VI some conclusions are drawn.

II. WIND ENERGY CONVERSION SYSTEM

The considered WECS consists of a permanent magnet synchronous generator driven by a wind turbine, a machine side PWM inverter, an intermediate DC circuit, and grid side PWM inverter, as indicated in Fig. 1. In the the mathematical models used to represent each component will be outlined.

A. Wind Turbine Model

The output mechanical power $P$ of the turbine is given by

$$P = \frac{1}{2} \rho \cdot \frac{V_{w}}{\gamma} \cdot \omega_{mec},$$

where $\rho$ (kg/m$^3$) is the air density, $V_{w}$ (m/s) is wind speed, $\gamma$ (°) the tip speed coefficient, $\omega_{mec}$ (rad/s) the mechanical angular frequency of the machine ($\omega_{mec} = \frac{\Phi_{1p}}{L_{sq} \cdot R_{s}}$)

Therefore, $\omega_{mec}$ can be approximated

$$\omega_{mec} = \omega_{opt} \cdot e^{-0.17 \gamma}$$

$\omega_{opt}$ is obtained by solving

$$\frac{d \omega}{d \gamma} = \frac{1}{2} \left[ 1.952 - 0.17 \cdot \gamma \right] e^{-0.17 \gamma} = 0.$$  \hspace{1cm} (4)

Once (4) is solved, in the variable $\gamma$, $\gamma_{opt} = 11.48$, one can insert the solution into [2] and then compute the optimal machine angular frequency $\omega_{opt}$ by using the following expression:

$$\omega_{opt} = \frac{2 \cdot V_{ph} \cdot p}{11.48}$$

where $p$ is the pole pair of the generator ($\omega_{opt} = p \cdot \omega_{ph}$).

If the active power or the mechanical speed becomes greater than their rated value, the pitch control mode ($\beta\Phi_0$) is activated as a limiter for those quantities.

B. PMSG Model

The PMSG dynamic equations are expressed in the “d-q reference” frame. The model of the machine d-q axes voltages $v_{eq}$ in terms of the machine d-q axes voltages $v_{eq}$ is formulated with the maximum active power extraction from the wind. The value of $\gamma$ that maximizes the coefficient $c_{\gamma}$ for each pitch angle $\beta$ is obtained by solving

$$\frac{dc_{\gamma}}{d\beta} = \frac{1}{2} \left[ 1.952 - 0.17 \cdot \gamma \right] e^{-0.17 \gamma} = 0.$$  \hspace{1cm} (4)

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Equations (11) and (12) do not take into account the inverter losses; a simple way to consider these losses in the first harmonic model is to add an “equivalent resistance,” whose value is heuristically set to four thirds of the static switch resistance, $R_{sw}$ [18]. This way, and using the definitions (13) and (14), (11) and (12) have to be modified as follows:

$$v_{sd} = \sqrt{3/2}V_{d} - 4/3 R_{pwm} \dot{i}_{d}$$  

$$v_{sq} = \sqrt{3/2}V_{q} - 4/3 R_{pwm} \dot{i}_{q}. \tag{16}$$

**D. DC Link**

The DC link electrical behavior is described simply by the Kirchhoff’s laws (Fig. 1)

$$V_{DC} = R_{d}i_{d} + L_{d} \dot{i}_{d} + V_{dc} \tag{17}$$

$$V_{DC} = R_{q}i_{q} + L_{q} \dot{i}_{q} + V_{dc} \tag{18}$$

$$i_{d} + i_{q} = 0. \tag{19}$$

**E. Grid Side PWM Inverter**

The equations for the grid side inverter of the machine side inverter

$$v_{md} = \sqrt{3/2}V_{md}$$

$$v_{mq} = \sqrt{3/2}V_{mq} \tag{20}$$

where $U_{md}$, $U_{mq}$, and $U_{q}$, are the grid voltages. This time, the $d$ and $q$ converter phasor angular frequency.

**F. G-Reference**

A finite bus $r_{ref}$, and the angular parameters, $\omega$, and the grid voltages $v_{grid}$, and the quantities defined in the previous section is the following:

$$v_{rd} = R_{rd} + L_{rd} \dot{i}_{rd} + v_{grid}, \tag{21}$$

$$v_{rq} = R_{rq} + L_{rq} \dot{i}_{rq}. \tag{22}$$

The $d$-q reference frame can be identified as follows:

$$x = [u_{rd}, u_{rq}, v_{dc}, i_{rd}, i_{rq}]^T. \tag{23}$$

As a consequence, considering the equations derived in the previous sections, and defining

$$L_{rd} = L_{rd} + L_{lin} \tag{24}$$

$$L_{rq} = L_{rq} + L_{lin} \tag{25}$$

$$R_{rs} = R_{rs} + (4/3) R_{pwm}. \tag{26}$$

The DC link model reduces to a power balance between the grid and the DC link capacitor (thus $L_{q}$).
The article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

\[ f(x) \text{ and } g(x) \text{ can be written in the following forms:} \]

\[
f(x) = \begin{bmatrix}
-R_{el}I_{rad} - \alpha_{th}E_{rad}I_{rad} \\
-R_{el}I_{rad} + \alpha_{th}E_{rad}I_{rad}
\end{bmatrix}
\]

\[
g(x) = \begin{bmatrix}
\frac{V_{in}/I_{rad}}{0} \\
0 \\
0
\end{bmatrix}
\]

(31)

As system output variables, we chose the following quantities:

\[
h(x) = \left[\begin{array}{c}
\alpha_{th} \\
I_{rad} \\
I_{eq} \\
V_{DC}
\end{array}\right].
\]

(32)

This way, we can directly control the machine angular frequency (in order to set its value to the optimal one), the DC link voltage and the reactive power delivered to the grid [according to (25)], by regulating \( I_{eq} \), while, by acting on \( I_{rad} \), we can minimize the machine current.

The goal of the feedback linearization is to obtain a transformed system whose states are the output variables and, eventually, some of their derivatives. This structure is achieved by considering each one of the outputs and, repeatedly, applying to it the Lie derivatives [10] along the vector \( f \) and along the vector \( g \), until at least one input variable appears in the last as an example, for the output \( h_1 = \alpha_{th} \), we have to compute

\[
\begin{align*}
\left\{ L_{f,h_1} = (\nabla h_1, f) = \right. \\
\left\{ L_{g,h_1} = (\nabla h_1, g) = \right.
\end{align*}
\]

(33)

where the symbol \( (\nabla \cdot) \) represents the scalar gradient with respect to state \( \nu \).

Since in the last expression \( \nu \) is explicitly (actually, the expression \( \nu \))

\[
\left\{ L_{f,h_1} = (\nabla h_1, f) = \right. \]

\[
\left\{ L_{g,h_1} = (\nabla h_1, g) = \right.
\]

\[
\frac{\partial}{\partial x} \frac{\delta f}{\delta x} \left. \right|_{x_0}
\]

(35)

As a result, we have

\[
\frac{\partial}{\partial x_0} \frac{\delta f}{\delta x} \left. \right|_{x_0}
\]

(36)

So, the first order derivative.

In a similar way, for the control \( v \) we have

\[
\begin{align*}
\left\{ L_{f,h_1} = (\nabla h_1, f) = \right. \\
\left\{ L_{g,h_1} = (\nabla h_1, g) = \right.
\end{align*}
\]

(37)

and for the control output

\[
\begin{align*}
\left\{ L_{f,h_1} = (\nabla h_1, f) = \right. \\
\left\{ L_{g,h_1} = (\nabla h_1, g) = \right.
\end{align*}
\]

(38)

Taking into account that \( \nu = 1 \)

(39)

For input variables \( V_i \) (i.e., \( i = 1, 2, ..., 4 \)), we have

\[
\left\{ L_{f,h_1} = (\nabla h_1, f) = \right. \\
\left\{ L_{g,h_1} = (\nabla h_1, g) = \right.
\]

(40)

so that the fictitious inputs can be derived and the system can be re-written in state space form. Thanks to this result, the very simple control scheme of Fig. 2 can be applied, where \( R_{ii} \) are the regulators.

In order to employ this scheme, a relation between the actual and the fictitious inputs is needed. So, if we rewrite (40) as

\[
\left\{ L_{f,h_1} = (\nabla h_1, f) = \right. \\
\left\{ L_{g,h_1} = (\nabla h_1, g) = \right.
\]

(41)

or

\[
E(x) \cdot u = T_h(x)
\]

(42)
The peculiarities of the proposed control strategy if compared with conventional ones can be highlighted as follows.

Traditional controls usually adopt some sort of multi-level architecture like the one proposed in [19]; an external level (corresponding to a number of outer control loops with their P or PI regulators) is responsible for maintaining the wind turbine at the optimum speed, making at the same time the grid side converter deliver the desired reactive power and the active power corresponding to the mechanical one produced by the wind turbine (or, as an alternative to the former, performing voltage regulation). The outputs of this outer level are the reference signals for the converter axis currents, controlled by inner loops (equipped with another set of PI regulators), and constituting an intermediate control level whose outputs are the converter parameters $U_{dref}$, $U_{qref}$, $U_{dref}$, and $U_{qref}$. In [19], a third level, named “internal,” is identified as the one responsible for producing, on the basis of these latter parameters, the actual control signals to the converters switches; furthermore, another control loop is used to regulate the DC link voltage. So, from an “architectural” point of view, a first difference between traditional schemes and the one proposed in this paper can be identified in the fact that this latter does not need a “hierarchical” structure, treating the system as a whole requiring in principle only a regulator per each control channel.

Furthermore, in traditional control schemes, a decoupling, for instance, of active and reactive power delivered to the grid is usually obtained by the regulators (and of the related proportional and integral gains); as an example, in [19], the reference currents $i_{d*}$ and $i_{q*}$ are calculated according to the following expressions

$$i_{d*} = \frac{\Delta P}{\mu}$$

$$i_{q*} = \frac{\Delta Q}{\Phi_1}$$

where the matrix $E$ depends only on the system parameters (e.g., $J$, $C_{dc}$, and so on) and $x$, then the required relationship is

$$[U_{dref} \ U_{qref} \ U_{dref} \ U_{qref}]^T = E^{-1}(x) \cdot T_C(x). \tag{43}$$

We verified that the matrix $E(x)$ is invertible; this check is not reported here for brevity.

As anticipated, among the reference values in Fig. 2, that referring to $\omega_{ref}$ is chosen in order to minimize the stator current module (and then the generator Joule losses), for each value of the electrical torque $C_e$.

The choice of regulators types and their proportional and integral gains settings. This task is accomplished by an heuristic procedure, perhaps by refining and error through several simulations, as outlined in [20] for the grid side converter. An “architectural” point of view, we first look at the related gain of this controller until borderline stability is reached, i.e., 25% of this “limit” gain (Fig 4).

The integral gain term was then chosen as the 10% of 4. The integral gains settings. This task is usually accomplished by an heuristic procedure, perhaps making use of trial and error techniques.

The simulations have been performed on a real system, whose electrical parameters are listed in Table I.

### Table I: Modeled System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_m$</td>
<td>Rated generator power</td>
<td>250 kW</td>
</tr>
<tr>
<td>$V_{dc}$</td>
<td>Rated generator voltage (L to L)</td>
<td>835 V</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of pole pairs</td>
<td>11</td>
</tr>
<tr>
<td>$J$</td>
<td>Moment of inertia</td>
<td>2.525 x 10^5 kg m^2</td>
</tr>
<tr>
<td>$L_{sd}$</td>
<td>Stator d-axis inductance</td>
<td>0.278 H</td>
</tr>
<tr>
<td>$L_{sq}$</td>
<td>Stator q-axis inductance</td>
<td>0.250 H</td>
</tr>
<tr>
<td>$R_e$</td>
<td>Stator resistance</td>
<td>0.015 Ω</td>
</tr>
<tr>
<td>$L_{gd}$</td>
<td>Filter inductance</td>
<td>33 mH</td>
</tr>
<tr>
<td>$R_L$</td>
<td>Filter resistance</td>
<td>0.074 Ω</td>
</tr>
<tr>
<td>$L_{gd}$</td>
<td>Inductance between grid side conv. and grid</td>
<td>0.025 H</td>
</tr>
<tr>
<td>$R$</td>
<td>Resistance between grid side conv. and grid</td>
<td>0.086 Ω</td>
</tr>
<tr>
<td>$C_{dc}$</td>
<td>DC link capacitance</td>
<td>100 μF</td>
</tr>
</tbody>
</table>

As previously stated, one of the main advantages of this method is the complete decoupling of each control channel; as a matter of fact, the step variations imposed to $i_{d*}$ at $t = 30$ s or $i_{q*}$ at $t = 5$ s (Figs. 3, 8, 3, respectively) to minimize the machine current in order to decrease the generator losses and to regulate the reactive power at the grid side, do not affect the machine speed (Fig. 6). This means that after the beginning of the simulation, the machine speed is set at the optimum speed value which guarantees maximum power extraction for the actual wind speed magnitude (performance coefficient $C_p$ close to its maximum value), until the wind rises...
Fig. 3. Reactive power and its reference at the grid-side.

at $t = 10$ s, without being affected by modification of $h_3$. Since the new $V_3$ would make both generated power and rotor speed exceed their rated values, the pitch angle is increased (Fig. 5) in order to limit the rotor speed.

As anticipated, the variation of $h_2$ at $t = 30$ s does not affect the machine speed, which remains constant till the wind decreases to 5 m/s ($t = 80$ s), the pitch angle is set back to zero and the speed control loop regulates $\omega_m$ in order to reach the new optimal value. Fig. 7 shows that both the active power $P_m$ generated by the machine and that delivered to the grid $P_n$ follow the behavior of $\omega_m$ as expected.

As far as the behavior of the reactive power delivered to the grid is concerned (Fig. 3), since the regulator is purely proportional and the transfer function between $V_3$ and $h_3 = i_{nq}$ is an integrator, the response of the control loop (the third one in Fig. 2) is that of a simple pole, whose time constant can be tuned by varying the regulator proportional gain; this means that the closed-loop response of this control channel is "shaped" in a very straightforward way. Similar considerations could be done for the other control channels, but the feature is of particular interest for this one, as the reactive power, being an important ancillary service, is subjected to stringent regulations by system operators [17], [18], especially in terms of the system response time when given reference variations are considered; the developed control scheme can help the designer in fulfilling these requirements at the control synthesis stage.

Most importantly, by comparing Figs. 3 and 7, it is evident that every variation of the active power delivered to the grid has no effect (not even transient) on the reactive power (and vice versa); when, after about 80 s, the active power falls below 0.2 MW (i.e., below the 10% of the rated power), the system continues to inject into the grid the same value of the reactive power till $t = 100$ s when, in response to a reference variation, the reactive power exchanged with the grid becomes negative. This latter result highlights the system ability to generate or absorb the required value for the reactive power, even if the active power is low.

Finally, Fig. 9 shows the effective reduction of machine current ($-6\%$) comparing a control which would impose $i_{md} = 0$ and the proposed approach. The picture is related to the generator working point at $t = 50$ s. The red line is the hyperbole defined by (9), that can be seen as a constraint ($i_{md}$ and $i_{mq}$ values must ensure the required electromagnetic torque), while the blue line is the circle that represents the current absolute value. As a matter of fact, the curves corresponding to constant absolute values of the machine current are circles in the $i_{md}, i_{mq}$ plane; among them, the one identifying the allowable minimum for the current module is the one tangent to (9); this is because the function gradient and the constraint gradient have to be parallel in the minimum point. As a consequence, the couple ($i_{md}, i_{mq}$) that minimizes the machine current, providing at the same time the required electromagnetic torque, is the one identified by the label "new working point" in Fig. 9. Figs. 8 and 10 show how, in response to the step imposed to $h_2 = i_{md}$ at $t = 30$ s, $i_{mq}$, after a transient, reaches the "optimum" value corresponding to this point.

V. BEHAVIOR DURING FAULT RIDE THROUGH

Fault ride through capabilities is nowadays demanded by a number of TSO grid codes [15], [16] both for conventional and renewable generation units. Prescriptions differ considerably in terms of the shape of the limit curves for the voltage [17] (which identify the severest voltage drop the generation unit must withstand) and also in terms of the behavior the generator must comply with during the fault (essentially, the active and reactive currents to be injected into the grid).

Here, the voltage limit curve (Fig. 11, V_{PCC}) and the prescription about the reactive current to be delivered as indicated
As illustrated in Fig. 11, the fault ride through transient takes place at $t = 0$ s; the grid voltage drops to zero and in response, the control system raises the reference for $I_{nq}$ from the pre-fault value to the rated one (Fig. 15). The actual value of $I_{nq}$ follows its reference with a time behavior given by the third control loop sketched in Fig. 2. The resulting voltage support action can be appreciated in Fig. 11; as can be seen, the PCC experiences a voltage drop less severe than the one affecting the grid.

Reactive and active powers delivered to the grid during the fault are shown in Figs. 13 and 14, respectively; it can be observed that the reactive power fed to the grid does not
vanish, thanks to the just highlighted voltage support at PCC.

After 150 ms, the grid voltage starts rising linearly and, when the 0.5 pu value is reached, the reactive current is decreased as prescribed by (44); in the same time interval, the active power increases and, after a transient, finally reaches the pre-fault value. On the contrary, the final values of both reactive power and $I_{nq}$ differ from the pre-fault ones as, according to the prescribed limit $\epsilon$ the fault is lower than 0.9 pu and $\epsilon$ must continue to deliver reactive power.

The cited constraints $\epsilon$ of 20 ms can represent a transient behavior $\epsilon$ simplicity of the system in Fig. 2, $\epsilon_{eq}$ closed.

VI. Conclusion and Perspectives of Future Work

This paper discussed issues related to the management of wind renewable energy in distribution networks. The presented control scheme, together with the mathematical model needed for its implementation, offers the possibility of a fully decoupled control of the main variables which characterize WECS...
operation, allowing to regulate the reactive power injected into the grid independently from the maximum power point tracking and maintaining, at the same time, the DC link voltage at its rated value and the generator at its maximum power factor. Moreover, the very simple system structure resulting from the application of the FBL greatly simplifies the regulators synthesis, thus making it easier to meet regulatory constraints on control loop dynamic behavior. It should be underlined that such features can help integrating wind distributed generation resources in modern smart grids, in view of their ever growing application both for active power production and ancillary services provision [21].

Future research activities will be devoted to the extension of the presented approach to systems equipped with short-term storage for power smoothing applications.

REFERENCES

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