A fuzzy logic supervisor for active and reactive power control of a variable speed wind energy conversion system associated to a flywheel storage system

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ARTICLE INFO

Article history:
Received 13 June 2007
Received in revised form 4 February 2008
Accepted 16 December 2008
Available online 31 January 2009

Keywords:
WECS
DFIG
Flywheel Energy Storage System (FESS)
Fuzzy logic supervisor
Powers smoothing

ABSTRACT

In this paper, we propose a Wind Energy Conversion System (WECS) at variable speed using a Doubly Fed Induction Generator (DFIG) controlled on the rotor side through converters. A Flywheel Energy Storage System (FESS) is connected to the studied wind generator at the DC bus in order to evaluate its capacity to participate to the ancillary services. We study the improvement of the active and reactive power quality produced by the wind generator and its effect on the load voltage regulation connected to the wind generator. For that, a fuzzy logic supervisor is established to control the FESS operation and the DC bus voltage in order to smooth the active power fluctuations due to the random wind speed variations. A control law is also described to smooth the reactive power at the connection node to the grid.

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1. Introduction

In order to increase the penetration rate of the wind generators in the power electric system dispatching, it is necessary to incorporate them in the ancillary services such as voltage or frequency control and reactive power compensation. The association of an Energy Storage System (ESS) to these renewable sources has a significant role in the power system stability. In fact, an ESS can contribute to the energy balance between the production and the consumption. It provides the energy in case of consumption deficiency and accumulates it at high wind speeds for which the energy request is reduced. An ESS offers also the possibility of the power regulation supplied as well as the load voltage control connected to the wind generator.

Barton and Infield [1] have developed probabilistic methods to evaluate the energy storage capacity to increase the penetration of the intermittent embedded renewable generation (ERG) on the power system. The interest was concerted to the wind generator connections to the locations where the ERG level is limited by the voltage rise. Various storage technologies associated with their principal applications are then developed [1,2]. Therefore, a comparative study permits to classify them according to their time scales and their storage capacities. The FESS can be adopted for this production type which requires a storage capacity of a few minutes [3–5]. This is due to its important characteristics to ensure a high dynamic, a long lifespan and a good efficiency.

In Ref. [6], a variable speed WECS using a permanent magnet synchronous generator was adopted. A FESS is associated to the wind generator to smooth the fluctuated powers injected to grid. Different control laws and fuzzy supervision were elaborated in order to control the FESS operation, to regulate the DC bus voltage and to improve the powers quality provided for an operated mode coupled to the power electric system or to an isolated load.

Others [7,8] propose also an energy conversion structure with a variable speed generator based on a DFIG associated to a super capacitor. This storage element has the capability to compensate enough real power to the system for smoothing instantaneous wind fluctuations. It also ensures the system transient stability and improves the voltage quality supplied on the generator level.

In this paper, a method has been developed to reduce output power fluctuations of a DFIG with an energy storage system using a FESS. We are interesting on the study of the power quality improvement produced by the wind generator due to random wind speed variations and its effect on the load voltage control connected to the wind generator. A supervisor based on a fuzzy logic was elaborated to control the FESS operation in order to smooth the active power fluctuating. A control laws were also applied allowing the regulation of the DC bus voltage as well as the reactive power enhancement satisfying the load flow.

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2. Description of the studied WECS

The WECS adopted here is shown in Fig. 1. It consists of a DFIG driven by a wind turbine and controlled on the rotor side through the power converters which ensuring a variable speed operating. The stator is connected to the power electric system through a transmission line and supplying a load. The FESS coupled to DC bus, is constituted of an induction machine. The main purpose is the control of the active and reactive power transit in the system and its effect on the load voltage regulation.

3. DFIG control

To obtain the state model of the DFIG, we adopt the hypotheses of the oriented constant stator flux and we neglect the stator resistor, then we have:

\[ \dot{\psi}_{sd} = 0, \quad \frac{d}{dt} \psi_{qd} = 0, \quad v_{sd} = 0 \quad \text{and} \quad v_{dq} = -V_s \]  

where \( V_s \) is the stator voltage magnitude.

We deduce the following reduced state model as:

\[
\begin{align*}
\dot{i}_{rd} &= \sigma L_s \frac{d}{dt} i_{rd} + r_r i_{rd} - \left( \omega_s - \Omega_{mech} \right) \sigma L_s i_{rq} \\
\dot{i}_{rq} &= \sigma L_s \frac{d}{dt} i_{rq} + r_r i_{rq} + \left( \omega_s - \Omega_{mech} \right) \sigma L_s i_{rd} + \frac{M}{L_s} \phi_{sd} \left( \omega_s - \Omega_{mech} \right)
\end{align*}
\]  

where \( v_{rd} \) and \( v_{rq} \) are the \( d \) and \( q \) components of the rotor voltage, respectively; \( v_{sd} \) and \( v_{sq} \) are the \( d \) and \( q \) components of the stator voltage, respectively; \( i_{rd} \) and \( i_{rq} \) are the \( d \) and \( q \) components of the rotor current, respectively; \( \phi_{rd} \) and \( \phi_{rq} \) are the \( d \) and \( q \) components of the stator flux, respectively; \( \omega_s \) and \( \Omega_{mech} \) are the synchronous pulsation and the aero generator speed, respectively; \( r_r \) is the rotor resistor; \( L_s \), \( L_r \) and \( M \) are the stator, the rotor and the mutual inductance, respectively; \( \sigma \) is a leakage parameter such as \( \sigma = 1 - \frac{M^2}{L_s L_r} \).

Usually, the DFIG control is ensured by a vector control of the rotor currents [9–11]. The maximum power point tracking (MPPT) is ensured by the converter 1 (Conv1) in the rotor side. The MPPT, which depends on the aerodynamic power and the wind speed turbine, is carried out in some work by using fuzzy rules [12] or by an artificial neuronal network [13].

4. DC bus voltage control

The converter 2 (Conv2) in the grid side ensures the DC bus voltage control as well as the exchanged active and reactive powers between the generator, the load, the power system and the FESS. Each converter exerts its influence on the DC bus by his injected current.

In power terms, and by neglecting the converter losses, the DC bus equation can be written as following:

\[
\frac{d}{dt} V_C^2 = \frac{2}{C} (P_r - P_f - P_{st})
\]  

where \( P_r \) is the active power in the rotor side, \( P_f \) is the \( P_f \) one transmitted through the filter and \( P_{st} \) is the FESS power (stored/restored).

The filter is used to attenuate the generated harmonics by the Conv2. By neglecting the filter resistor and taking into account the hypothesis defined in Eq. (1), we obtain [14]:

\[
\begin{align*}
V_{fd} &= -L_f \omega_s i_{fd} \\
V_{fq} &= L_f \omega_s i_{fq} - V_s
\end{align*}
\]

where \( i_{fd} \) and \( i_{fq} \) are the \( d \) and \( q \) components of the filter current, respectively; \( V_{fd} \) and \( V_{fq} \) are the \( d \) and \( q \) components of the modulated average voltage in the filter side, respectively.

The active and reactive powers transmitted into the grid through the filter are given by:

\[
\begin{align*}
P_f &= \frac{V_f}{L_f \omega_s} V_{fd} \\
Q_f &= -\frac{V_f}{L_f \omega_s} (V_{fq} + V_s)
\end{align*}
\]  

The two expressions (6) and (7) show that the powers \( P_f \) and \( Q_f \) can be separatedly controlled by \( V_{fd} \) and \( V_{fq} \), respectively. Consequently, it would be possible to regulate the DC bus voltage by \( V_{fd} \).

The control diagram of the DC bus voltage \( V_C \) is shown in Fig. 2. The proportional integral regulator PI was introduced into the regulation loop to make null the regulation error and to eliminate the \( P_r \) and \( P_{st} \) effect considered as perturbations.

![Fig. 1. WECS under consideration.](Image 1)

![Fig. 2. Control of the DC bus voltage.](Image 2)
5. Power assessment

The active and reactive power assessment in the load connection node to the wind generator is given by:

\[ P_g = P_f + P_l - P_1 = P_m - P_l \]  
\[ Q_e = Q_f + Q_q - Q_l = Q_m - Q_l \]

where \( P_s \) and \( Q_s \) are the active and reactive powers provided by the wind generator in the stator side, respectively; \( P_l \) and \( Q_l \) are the active and reactive powers in the filter side, respectively; \( P_f \) and \( Q_f \) are the active and reactive powers of the load, respectively; \( P_m \) and \( Q_m \) are the active and reactive powers of the wind generator at the connection node, respectively.

The DFIG is coupled to the power system through a transmission line in the stator side. Thus, by neglecting the line resistor, we can write in steady state the following equations:

\[ \begin{align*}
V_{gd} - L_1 \omega_s i_{gd} &= 0 \\
V_{gs} + V_s + L_1 \omega_s i_{gd} &= 0
\end{align*} \]

with \( i_{gd} \) and \( i_{gs} \) are the \( d \) and \( q \) components of the transmission line current, respectively; \( V_{gd} \) and \( V_{gs} \) are the \( d \) and \( q \) components of the grid voltage, respectively; \( L_1 \) is the line inductance.

Eq. (10) permit to deduce the \( P_s \) and \( Q_s \) expressions, which are given by:

\[ P_g = \frac{V_s V_{gd}}{L_1 \omega_s} \quad (11) \]

and

\[ Q_s = \frac{V_s}{L_1 \omega_s} (V_{qs} + V_s) \quad (12) \]

In the same way, the computation of the stator voltage variations \( \Delta V_s \) gives:

\[ \Delta V_s = \frac{2 L_1 \omega_s (V_s^2 - L_1 \omega_s Q_s)}{2 V_s^2 - 2 L_1 \omega_s Q_s - 1} \Delta Q_m - \frac{2 L_1^2 \omega_s^2 P_s}{2 V_s^2 - 2 L_1 \omega_s Q_s - 1} \Delta P_m \quad (13) \]

Eq. (13) shows the relation between the stator voltage variations \( \Delta V_s \) according to the active and reactive powers of the wind generator in the connection node.

Since the aerodynamic power is proportional to the cube of the wind speed \([13]\), its random variations have a great influence on the powers quality of the DFIG and consequently on the quality of the whole electric parameters at the grid node. Therefore, in order to ensure a constant and smooth voltage \( V_s \), it is preferred to impose a null reactive power \( Q_s \) injected into the grid ensuring a unit power factor. It is also necessary to approve a perfect DC bus voltage control. As it is defined previously, if \( P_m \) is the active power in the connection node, which corresponds to the aerodynamic power \( P_{aero} \) decreased by the machine losses, \( P_{reg} \) is the desired one injected to the grid, then the reference power of the FESS control \( P_{st} \) is determined by:

\[ P_{st} = P_{reg} - P_m \quad (15) \]

The reference value \( P_{st} \) is added to the DC bus controller output. The integration of this expression gives the total power \( E_{fw} \) stored in the flywheel, so we have:

\[ E_{fw} = E_{fw0} + \int P_{st} \, dt \quad (16) \]

where \( E_{fw0} \) is the initially flywheel stored energy.

While this energy depends on the flywheel speed \( \Omega_{fw} \) by:

\[ E_{fw} = \frac{1}{2} j_{fw} \Omega_{fw}^2 \quad (17) \]

then, we deduce the flywheel speed as following:

\[ \Omega_{fw} = \sqrt{\frac{2 E_{fw}}{j_{fw}}} \quad (18) \]

where \( j_{fw} \) is the flywheel inertia.

With this control law, the FESS does not contribute to the DC bus voltage control, which is ensured by the converter 2 (Conv2) in the grid side. If the wind generator will be coupled to the isolated load, the FESS control strategy must be modified. In fact, a new term will be added in Eq. (15) so that \([6]\):

\[ P_{st} = P_{reg} - P_m - \Delta P \quad (19) \]

with \( \Delta P \) is the needed power to control the DC bus.

This term permits to regulate the DC bus voltage through a PI regulator and it is incorporated in the speed control loop of the FESS certified by the converter 3 (Conv3). Consequently, the converter 2...
(Conv2) will ensure the frequency and voltage regulation applied to the isolated load.

8. FESS fuzzy supervisor

The power desired from the coupling flywheel-wind generator $P_{reg}$ depends really on two parameters. The first one is the flywheel speed, which must be always preserved between the operation limits. The second one is the wind power accessibility associated to the weather conditions. For that, a fuzzy logic supervisor is established [18] to generate the adequate regulation power value $P_{reg}$ according to the flywheel speed $\Omega_{fw}$ and the filtered wind power generated $P_{aerof}$ as it is shown in Fig. 4.

The fuzzy system consists of $\Omega_{fw}$ and $P_{aerof}$ inputs. Thus, three membership functions are proposed for each one defined as following: small (S), medium (M) and large (L) shown in Fig. 5.

According to the flywheel state and the wind speed evolution, the FESS must store or restore electrical power compared to the reference value. So, if the flywheel speed is too small, storage is favoured. Most of the generated power is so used to flywheel charge. If this speed becomes too high, the restitution is selected. Then, if the speed is middling, the system operates normally. Nine fuzzy rules are then defined which consequences are summarized in Table 1.

By adopting a Sugeno fuzzy inference system of 0 order, which not requiring a defuzzification stage, the fuzzy supervisor output is calculated as following:

$$P_{reg} = \frac{\sum_{i=1}^{9} \alpha_i y_i}{\sum_{i=1}^{9} \alpha_i}$$  \hspace{1cm} (20)

Fig. 5. Membership functions of input variables.

Table 1
Fuzzy inference table.

<table>
<thead>
<tr>
<th>$\Omega_{fw}$ (pu)</th>
<th>$P_{aerof}$ (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>S</td>
</tr>
<tr>
<td>Medium</td>
<td>M</td>
</tr>
<tr>
<td>Large</td>
<td>BM</td>
</tr>
</tbody>
</table>

where $y_i$ is the consequence of the fuzzy rule $i$ which represents the smoothed desired power value.

$\alpha_i$ is such as:

$$\alpha_i = \prod_{j=1}^{3} \mu_j(\Omega_{fw}) \mu_j(P_{aerof}), \quad i = 1 \ldots 9$$  \hspace{1cm} (21)

with $\mu_j(\Omega_{fw}), \mu_j(P_{aerof})$ are the membership degree of the variables $\Omega_{fw}$ and $P_{aerof}$, respectively.

Fig. 6 shows the evolution of the desired regulation power delivered by the fuzzy supervisor $P_{reg}$ according to the flywheel speed $\Omega_{fw}$ and the filtered aerodynamic power $P_{aerof}$.

9. Simulation results and interpretations

All simulations are run with the 300 s duration with the same wind variation shown in Fig. 7. Wind speed model varies within
the 6–12 m/s speed range. Fig. 8 shows the power curves forwarded into DC bus. The flywheel reference power $P_{st}$ is positive where it is stored and negative if it is generated by the FESS. The powers $P_r$ and $P_f$ change sign according to the sub or super synchronous operating showing the bidirectional power transfer between rotor and power system. The curve given by Fig. 9 shows the effectiveness of the control law elaborated to stabilise the DC link voltage significantly relating to the reference value chosen here equal to 1 pu. We notice that the flywheel rotational speed remains between the acceptable limits fixed on the membership functions as it is shown in Fig. 10.

In the system without any storage, Fig. 11 shows the $P_m$ power fluctuating following the wind speed variations. Thus, the storage system permits to enhance the power quality by reducing the fluctuations. It is seen that the variations of the active power is comparatively smoother than the system without storage arrangement. This makes it possible to provide a smooth active power to the load which consumes an active power $P_l = 1.2$ pu.

Fig. 12 shows the reactive power curves produced by the wind generator. The power smoothing is carried out around 0.2 pu which corresponding to the load consumption $Q_l = 0.2$ pu. Consequently, the reactive power injected into the grid will be null ensuring a unit power factor at the connection node.

Expression (13) shows the relation between the load voltage variations and the active and reactive powers produced by the wind generator. The expression is given by:

$$V_L = V_L^{ref} + K_{P_l} P_l + K_{Q_l} Q_l$$

where $V_L$ is the load voltage, $V_L^{ref}$ is the reference voltage, $P_l$ is the load active power, $Q_l$ is the load reactive power, $K_{P_l}$ and $K_{Q_l}$ are the gain coefficients.

![Fig. 8. Power curves $P_r$, $P_f$ and $P_{st}$.](image8)

![Fig. 9. DC bus voltage curve.](image9)

![Fig. 10. Flywheel speed $\omega_{fw}$.](image10)

![Fig. 11. Active powers generated by the wind generator $P_m$ at the connection node ($P_l = 1.2$ pu).](image11)

![Fig. 12. Reactive powers generated by the wind generator $Q_m$ at the connection node ($Q_l = 0.2$ pu).](image12)
generator. For that, the powers quality affects greatly the voltage level on the connection node. The curves of the load voltage are shown in Fig. 13. It is noticed that the load voltage variations are reduced for an important active and reactive power smoothing. This shows the significant improvement related to the powers quality and their effect on the load voltage connected to the wind generator.

The wind profile shown at Fig. 7 reveals three zones: weak wind lower than 8 m/s, middling wind around 8 m/s corresponding to the nominal operating of the wind generator and high wind superior than 8 m/s. The active power in the rotor side \(P_{m}\) is proportional to the rotor slip pulsation, thus it is positive in the under synchronised operation for which the wind speed is less than 8 m/s as it is shown in Fig. 8. It becomes negative if the wind speed increases and the mechanical speed will be greater than the synchronous one. The active power through the filters \(P_{f}\) changes also according to the wind speed. The FESS power \(P_{e}\) is stored in the flywheel for the high wind which involves acceleration in the flywheel speed illustrated in Fig. 10. The flywheel is then slowed if the wind speed decreases what proves that \(P_{e}\) will be restored as shown in Fig. 8. In consequence, the FESS has an important purpose to provide an extra power supply available according to the wind speed variations.

10. Conclusion

In this paper, powers smoothing capability of the DFIG associated to a FESS in the DC bus link is investigated. The FESS control based on a fuzzy logic supervisor is able to reduce the active power fluctuations due to the random wind speed variations and to produce more clean power to the grid. Reactive power control is ensured to provide a smooth reactive power to the load supplied by the wind generator. The results show the enhancement of the powers quality and its contribution to improve and to reduce the load voltage variations in the connection node.

Acknowledgements

This study, achieved in the research unit "Advanced Control and Energy Management" ACEM of the National School of Engineering of Sfax, enters in the setting of the research project federated "Systèmes Eoliens" sustained by the State Secretariat to the Scientific Research and Technology and coordinated by the National Management Energy Agency. We thank the ENIS, the SERST and the ANME.

Appendix A

<table>
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<th>DFIG</th>
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<td>Rotor resistor (r_r=)0.0043</td>
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References

[12] Z. Chen, S. Gomez, M. Mc Cormick, A fuzzy logic controlled power electronic system for variable speed wind energy conversion systems, Power


