Robust Controllers-Based Power Control of Doubly-Fed Induction Generator for Wind Energy

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Abstract

The large penetration of wind energy intends to increase the capacity of Doubly-Fed Induction Generator (DFIG) wind turbine across the globe. In this paper, a control law is synthesized in order to control the power flow between the stator of DFIG and power system network. The control law is synthesized using three controllers; PI, IMC and RST. The designs of the controllers are presented. The performances of the respective controllers are compared in terms of power tracking, disturbance rejections and robustness against parameter variations.

Keywords: DFIG, IMC, PI, RST, Robustness, Disturbance Rejections.

Introduction

The ever-growing demand of electrical energy can not be fulfilled by the conventional energy sources only because the amounts of fossil fuels are limited. At the same time the use of conventional energy sources causes the environmental degradation like global warming. So, the transition from conventional energy sources to non-energy energy sources became essential.

Wind energy is one of the non-conventional energy sources which are clean, modular & economically viable. Today, the wind projects are large enough to have significant impact on transmission network security, operation, planning and required level of stability [1].

In spite of having other topologies like Synchronous Generator & Induction Generator, the DFIG became much popular in market due to many advantages such as reduced power converter rating, high energy efficiency and decoupled control. A
comparison of variable speed wind turbine using DFIG scheme with alternative schemes is made in [2].

Decoupled control of active and reactive power of DFIG-Based wind turbine is extensively researched [3]-[7]. The use of robust controllers is now encouraging area for variable speed operation. Decoupled control of active and reactive power through robust RST controller to DFIG system for power exchange between stator of DFIG and power system is appreciated in [8]. It is found that design of RST controller is quite cumbersome. At the same time the control system for converters and so called the rotor reference currents is missing. In addition to RST controller, this paper presents the Internal Mode Control (IMC) whose design is simple and performance is superior to that of RST and conventional PI. In this paper, a control law is first synthesized for the rotor side converter (RSC) based on the mathematical modeling of DFIG in d-q reference frame and then the design of RST and IMC are presented for the electrical power exchange between the stator of DFIG and power system network. The performances of respective controllers are compared in terms of active power tracking, disturbance rejections and robustness against the parameter variations.

**Doubly Fed Induction Generator**

Doubly Fed Wound Rotor Induction Machine is an attractive solution for variable speed high power generation. In variable speed constant frequency applications, the so called slip power recovery scheme is common practice where the power due to rotor slip below/above synchronous speed is recovered to /supplied from power source i.e. grid. Electrical power output from the stator is at constant frequency irrespective of the rotor speed. To obtain sub and super synchronous speed operation, the power converters must be able to handle the slip power in both directions using the converters connected to the rotor. Among the three power ports, i.e. stator terminals, rotor terminals and the rotor shaft, rotor terminals act as the energy regulating power port balances the power flow of the entire system. Rotor side converter controls the active power and reactive power whereas grid side converter maintains the constant DC link voltage irrespective of the direction of power flow in the rotor circuit. Configuration of DFIG is shown in figure (1).
Figure 1: Doubly Fed Induction Generator

Modeling of Doubly Fed Induction Generator

The general dynamic model of DFIG same as induction machine in d-q reference frame [9] as follows:

Voltage Equations

\[
V_{ds} = R_s I_{ds} + \frac{d\psi_{ds}}{dt} - \omega_s \psi_{qs}
\]
\[
V_{qs} = R_s I_{qs} + \frac{d\psi_{qs}}{dt} + \omega_s \psi_{ds}
\]
\[
V_{dr} = R_s I_{dr} + \frac{d\omega_s}{dt} - \omega_s \psi_{qr}
\]
\[
V_{qr} = R_s I_{qr} + \frac{d\psi_{qr}}{dt} + \omega_s \psi_{dr}
\]

Flux Equations

\[
\psi_{ds} = L_s I_{ds} + M I_{dr}
\]
\[
\psi_{qs} = L_s I_{qs} + M I_{qr}
\]
\[
\psi_{dr} = L_s I_{dr} + M I_{qs}
\]
\[
\psi_{qr} = L_s I_{qr} + M I_{qs}
\]

Torque Equations

\[
T_e = -P M \frac{L_s}{L_s} (\psi_{qs} I_{dr} - \psi_{ds} I_{qr})
\]

To achieve the active and reactive power control, we choose the d-q reference frame synchronized with the stator flux. By setting the stator flux vector aligned with the d-axis, we have the following expressions:

\[
\psi_{ds} = \psi_s \& \psi_{qs} = 0
\]
\[
T_e = -P M \frac{L_s}{L_s} \psi_{ds} I_{qr}
\]

This is obvious now from above expression that an electromagnetic torque depends on quadrature component of rotor current \( I_{qr} \).

The stator voltage vector is in quadrature with respect to stator flux vector. Thus, we have

\[
V_{ds} = 0 \& V_{qs} = V_s
\]
The setting of different vectors and transformation angles are represented in figure (2). $\theta_1$ and $\theta_2$ are used in park matrix to convert the stator & rotor two phase rotating variables into two phase fixed variables and vice-versa. The orientation of rotor current vector is realized by tuning of slip frequency $\theta_2$ such that the command signals $I_{qr}$ and $I_{dr}$ can be projected orthogonal and parallel to air gap flux vector respectively.

Now, by choosing this reference, stator voltages and fluxes are written as follows by ignoring the resistances drop.

\[
V_{ds} = 0 \& \ V_{qs} = \omega_s \psi_{ds} = \omega_s \psi_s
\]  

\[
\psi_s = L_s I_{ds} + M I_{dr} \& 0 = L_s I_{qs} + M I_{qr}
\]  

\[
\psi_{dr} = L_r I_{dr} + M I_{ds} \& \psi_{dr} = L_r I_{dr} + M I_{ds}
\]

The stator active & reactive power, the rotor fluxes and voltages can be written in terms of rotor currents.

\[
A.P = -V_s^2 M L_s I_{qr}
\]

\[
R.P = \frac{V_s \psi_s}{L_s} - \frac{V_s M}{L_s} I_{dr}
\]

The above equation states that Active Power ($A.P$) and Reactive Power ($R.P$) are decoupled, where active power is controlled by $I_{qr}$ and reactive power by $I_{dr}$.

\[
\psi_{dr} = \left(\frac{L_r}{L_s} - M^2 \right) I_{dr} + \frac{MV_s}{\omega_s L_s}
\]
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\[
\psi_{qr} = \left(\frac{L_s L_r - M^2}{L_s}\right)I_{qr}
\]  

(19)

\[
V_{dr} = R I_{dr} + \left(\frac{L_s L_r - M^2}{L_s}\right) \frac{dI_{dr}}{dt} - q \left(\frac{L_s L_r - M^2}{L_s}\right) I_{qr}
\]  

(20)

\[
V_{pr} = R I_{pr} + \left(\frac{L_s L_r - M^2}{L_s}\right) \frac{dI_{pr}}{dt} + q \left(\frac{L_s L_r - M^2}{L_s}\right) I_{qr} + \frac{M V_s}{q L_s}
\]  

(21)

The third term of the above equations constitutes cross coupling can be safely ignored because of small influence. Now, the rotor currents are directly related to active & reactive power by constant terms. The block diagram representation for active & reactive power control can be drawn from the equations (17), (18), (21) & (22). Block diagram for active and reactive power is shown in figure (3).

\[
\mathcal{T}(s) = \frac{M V_s}{\left(L_s L_r - M^2\right)s + L_s R_r}
\]  

(22)

Based on the T.F design of RST and IMC are presented in the subsequent sections whereas the conventional PI controller’s design is not focused due to its simplicity.

**Development of Control System**

The q-axis rotor current is used to control active power using maximum power
tracking (MPT). The requirement for the power system network is set to as a power reference, which is compared with the power measured for the reference value of q-axis rotor current. Since the d-axis rotor current controls the reactive power, which is normally set to zero for unity power factor operation of DFIG. The unity power factor operation is possible as the decoupled control of active and reactive power strategy is implemented. The zero reactive power is compared with reactive power measured for the reference value of d-axis rotor current. The control system for the rotor side converter (RSC) is depicted in figure 4.

The objective of grid side converter (GSC) is to maintain the voltage at the DC link between the converters. The RSC already controls the unity power operation and therefore the reference value for the exchange of reactive power between GSC and grid is set to zero. The reference value for the q-axis current is generated by comparing the reference value of DC link voltage and its measured value. In normal operation, GSC is assumed neutral by setting the reference value of d-axis to zero.

The interconnection of DFIG to an existing power system network should be done in three steps. The first step is the regulation of stator voltage with the network voltage; second step is the stator connection to the network after cross-checking the phase sequence and synchronization and the third step is the topic of paper, which is nothing but the power regulation between the DFIG and network.

**IMC-Based Robust Controller**

The Internal Model Control (IMC): This control strategy has the general structure depicted in figure (5). In fact, the process-model mismatch is common which is shown in above diagrams by comparing the output of the process and its model resulting a signal \( \hat{d}(s) \). In this diagram, \( d(s) \) is unknown disturbance affecting the system? The manipulated input \( U(s) \) is applied to both the process and its model.
Figure 5: IMC Block diagram

If \( d(s) \) is zero then \( \hat{d}(s) \) is a measure of the difference in behavior between the process and its model. If \( G_p(s) = \hat{G}_p(s) \) then \( \hat{d}(s) \) is equal to unknown disturbance. Thus \( \hat{d}(s) \) may be regarded as the information that is missing in the model \( \hat{G}_p(s) \) and can therefore be used to improve the control. This is done by subtracting \( \hat{d}(s) \) from set point \( R(s) \) which is very similar to affecting a set point trim.

The resulting control signal equations are given below.

\[
\hat{d}(s) = [G_p(s) - \hat{G}_p(s)] U(s) + d(s) \tag{23}
\]

\[
U(s) = [R(s) - \hat{d}(s)] G_c(s) \tag{24}
\]

Thus,

\[
U(s) = \frac{[R(s) - d(s)] G_c(s)}{1 + [G_p(s) - \hat{G}_p(s)] G_c(s)} \tag{25}
\]

As \( Y(s) = G_p(s) U(s) + d(s) \) \( \tag{26} \)

So, the closed loop transfer function for IMC scheme is expressed below

\[
Y(s) = \frac{G_c(s) G_p(s) R(s) + [1 - G_c(s) \hat{G}_p(s)] d(s)}{1 + [G_p(s) - \hat{G}_p(s)] G_c(s)} \tag{27}
\]

We can see that if \( G_c(s) = \frac{1}{\hat{G}_p(s)} \) and \( G_p(s) = \hat{G}_p(s) \) then perfect set point tracking and disturbance rejection is achieved. This is also to be noted that even if \( G_p(s) \neq \hat{G}_p(s) \), perfect disturbance rejection can still be realized provided \( G_c(s) = \frac{1}{\hat{G}_p(s)} \).
Additionally, the process model mismatch should be minimized to improve the robustness. Since the discrepancies between the process and model behavior usually occur at the high frequency end of the system’s frequency response so, a low pass filter \( G_f(s) \) is usually added to attenuate the effects of process-model mismatch. Thus, the internal model controller is usually designed as the inverse of the process model in series with a low pass filter i.e. \( G_{IMC}(s) = G_r(s)G_f(s) \). Proper value of \( G_r(s)G_f(s) \) is selected for the order of filter to prevent the differential control action. Now, the resulting closed loop becomes

\[
Y(s) = \frac{G_{IMC}(s)G_p(s)R(s) + [1 - G_{IMC}(s)\hat{G}_p(s)]Y(s)}{1 + [G_p(s) - \hat{G}_p(s)G_{IMC}(s)]}
\]  

(28)

(A) IMC-Based PI Controller: The IMC strategy can also be used to generate the settings for conventional PI controllers. The IMC block-diagram of above figure can be reduced to a conventional closed loop structure by re-arranging to the following form as shown in figure (6).

Thus,

\[
G_{PI}(s) = \frac{G_{IMC}(s)}{1 - G_{IMC}(s)\hat{G}_p(s)}
\]  

(29)

(B) IMC-Based Design of DFIG-Based Wind Power Plant: The process may be with time-delay or without time-delay. The process with time-delay is usually designed by Pade approximation. In this paper, the process without time-delay/time-delay free process is selected; therefore the filter designed is presented for time-delay free process only. The use of IMC filter to DFIG appeared in papers [10-12].

Step1: Given process model \( \hat{G}_p(s) \) is expressed as a product of two components, called invertible and non-invertible components.

\[
\hat{G}_p(s) = \hat{G}_p^+(s)\hat{G}_p^-(s)
\]
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Step 2: Choose non-invertible component \( \hat{G}_p(s) \) contains positive zeros and time-delay. Inverting the non-invertible component would lead the system to instability & realisability problems.

Step 3: Set \( G_c(s) = \frac{1}{G_p^+(s)} \) and then \( G_{mc}(s) = G_c(s)G_f(s) \)

Step 4: \( G_f(s) \) is a low pass filter; \( G_f(s) = \frac{1}{(1 + \lambda_f s)^n} \)

Here, \( \lambda_f \) is the filter tuning parameter and \( n \) is the order of the filter.

Step 5: Adjust the filter tuning parameter \( \lambda_f \) to shape the both set point tracking and disturbance rejection response. Choosing the desired value of \( \lambda_f \) as a tradeoff between performance & robustness. If the \( \lambda_f \) is small, the closed loop system is fast and if the \( \lambda_f \) is large, the close loop system is more robust (insensitive to model error).

RST Controller
The control design aims to compute the value of R, S & T polynomials to achieve certain required performance for regulation & tracking.

Figure 7: Block Diagram of RST Controller

The system is having transfer function \( B/A \) with \( Y_{ref} \) as an input and \( Y \) as an output, shown in figure (7).

The transfer function of the regulated system is

\[
Y = \frac{BT}{AS + BR} Y_{ref} + \frac{BS}{AS + BR} Y
\]  

(30)
Applying the Bezout equation. More details of RST are found in [13-14].

\[ D = AS + BR = CF \]  \hspace{1cm} (31)

Where, \( C \) is the command polynomial and \( F \) is the filtering polynomial. In order to have good adjustment accuracy, we require choosing a strictly proper regulator. So, if \( A \) is a polynomial of \( n \) \([\text{deg} \ (A) = n]\) degree then we must have the degree of polynomials like below:

\[
\begin{align*}
\deg (D) &= 2n + 1 \\
\deg (S) &= \deg (A) + 1 \\
\deg (A) &= \deg (R)
\end{align*}
\]

In this case:

\[
\begin{align*}
A &= a_1 p + a_0 \\
R &= r_1 p + r_0 \\
B &= b_0 \\
S &= s_2 p^2 + s_1 p + s_0 \\
D &= d_3 p^3 + d_2 p^2 + d_1 p + d_0
\end{align*}
\]

To find the coefficients of polynomials \( R \) and \( S \), the robust pole placement method is adopted with \( T_c \) as control horizon and \( T_f \) as filtering horizon. We have:

\[
p_c = -\frac{1}{T_c} & \text{ and } p_f = -\frac{1}{T_f}
\]

Here, \( p_c \) is the pole of \( C \) and \( p_f \) is the double pole of \( F \). The pole \( p_c \) must accelerate the system and is generally chosen three-five times greater than the pole of \( A \). In The pole \( p_f \) is usually three times smaller than \( p_c \).

To obtain good disturbance rejections and good stability in steady state the term \( \frac{BS}{AS + BR} \) must tend towards zero.

The Bezout equation leads to four equations with four unknown terms where the coefficients of \( D \) are related to the coefficients of polynomials \( R \& S \) by the Sylvester Matrix.

\[
\begin{pmatrix}
    d_3 \\
    d_2 \\
    d_1 \\
    d_0
\end{pmatrix} =
\begin{pmatrix}
    a_1 & 0 & 0 & 0 \\
    0 & a_1 & 0 & 0 \\
    0 & a_0 & b_0 & 0 \\
    0 & 0 & 0 & b_0
\end{pmatrix}
\begin{pmatrix}
    s_2 \\
    s_1 \\
    r_1 \\
    r_0
\end{pmatrix}
\]  \hspace{1cm} (32)

In order to determine the coefficients of \( T \), we should consider that \( Y \) must be
equal to $Y_{ref}$ in steady state case. So, the term $\frac{BT}{AS + BR}$ equal to one.

**Results and Discussion**

The performances of the three controllers IMC, RST and PI for the dynamic response of active power of 5 MW at 0.4 seconds are illustrated in figures 8.1, 8.2 and 8.3 respectively. Similarly the response of reactive power at the same time is also shown in figures 9.1, 9.2 and 9.3. This is clearly understood that IMC robust controller gives better performance especially in terms of disturbance rejections.
Figure 9.2: Reactive power_RST

Figure 9.3: Reactive power_PI

Figure 10.1: Active power_IMC (Parameter variation)

Figure 10.2: Active power_RST (Parameter variation)

Figure 10.3: Active power_PI (Parameter variation)
We have seen that there are three polynomials to be evaluated in case of RST; two parameters for PI and only one parameter i.e. filter tuning parameter for IMC. Choosing only one parameter makes the IMC to simple one. The many times simulations are done to select the filter tuning parameter for better disturbance rejections and tracking. There is an uncertainty in selecting the poles of command polynomial and filtering polynomial in RST controller for accurate tracking and better disturbance rejections. This uncertainty is reduced in IMC due to tuning of only one parameter which serves the both purposes.

This is observed that the good performances of robust controllers like RST and IMC are achieved at the expense of reduction in the magnitude of signals during the process. Therefore, the gain ‘K’ is provided in the control system block diagram. This ‘K’ can be assumed analogous to the modulation index for the PWM generators. Many times the simulations are done to set the value of ‘K’ for the pulses of converters which are configured as voltage controlled sources.

The response of active power for the changed parameter \( M / L_s = \beta \) value is now shown in figures 10.1, 10.2 and 10.3 for all three controllers. Now, compare the figures 8 and 10 corresponding to their respective controller, it is observed that the performances of IMC and RST do not change much whereas appreciable change is seen in performance of PI controller for the change in \( \beta \) value.

**Conclusion**

The mathematical equation in d-q reference frame that governs the modeling of DFIG is presented. The control system is synthesized in order to control the power flow between the stator of DFIG and power system network. Generations of rotor reference currents are described. The designs of the controllers ‘IMC & RST’ are presented. It is found that the IMC is simple robust technique. The performances of controllers are compared in terms of power tracking, disturbance rejections and robustness against parameter variations. The performance of IMC is found superior to that of PI and RST especially for disturbance rejections. Good power tracking is also observed. The robustness is validated against the parameter \( \beta \) variance. Ignoring the cross coupling terms in the transfer function is safely accepted. Many times the simulations are performed to set the value filter tuning parameter and gain. It is expected that the robust controllers would be the better replacement of conventional PI controller especially for variable speed operation.
Appendix

Notations used and Parameter’s values

<table>
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<tr>
<th>S.N</th>
<th>Parameter</th>
<th>Values</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Capacity</td>
<td>9 MW</td>
</tr>
<tr>
<td>2</td>
<td>$V_s$ = Stator Voltage, frequency</td>
<td>575 V, 60 Hz</td>
</tr>
<tr>
<td>3</td>
<td>$P$ = No. of Poles</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>$R_s$ = Stator Resistance (in per unit)</td>
<td>0.00706</td>
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<tr>
<td>5</td>
<td>$L_{sl}$ = Stator Leakage Inductance (in per unit)</td>
<td>0.171</td>
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<tr>
<td>6</td>
<td>$R_r$ = Rotor Resistance (in per unit)</td>
<td>0.005</td>
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<tr>
<td>7</td>
<td>$L_{rr}$ = Rotor Leakage Inductance (in per unit)</td>
<td>0.156</td>
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<tr>
<td>8</td>
<td>$M$ = Magnetizing Inductance (in per unit)</td>
<td>2.9</td>
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<tr>
<td>9</td>
<td>$T_e$ = electromagnetic torque</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>$\psi_{qs}$ = quadrature axis stator flux linkage</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>$\psi_{ds}$ = direct axis stator flux linkage</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>$L_s = L_{qs} + L_m = stator inductance$</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>$L_r = L_{qr} + L_m = rotor inductance$</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>$I_{ds}$ = direct axis rotor current</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>$I_{qr}$ = quadrature axis rotor current</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>$V_{ds}$ = direct axis stator voltage</td>
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<tr>
<td>17</td>
<td>$V_{qs}$ = quadrature axis stator voltage</td>
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<tr>
<td>18</td>
<td>$I_{ds}$ = direct axis stator current</td>
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</tr>
<tr>
<td>19</td>
<td>$I_{qs}$ = quadrature axis stator current</td>
<td></td>
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<tr>
<td>20</td>
<td>$\omega_r$ = rotor speed</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>$\omega_s$ = synchronous speed</td>
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</tbody>
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References


Biographical Note

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