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Control of Doubly Fed Induction Generator Based Wind Energy Conversion Systems Using Feedback Linearization

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ABSTRACT
Wind energy based electricity generation is becoming economical with the advancement in power electronic technology and efficient control methods. Wind energy is expected to share around 25% of global electricity generation by the year 2030. Wind is inherently variable and interconnection of the electricity generated using such a varying source to the grid is quite challenging. Variable speed turbines, permanent magnet synchronous generators and connection to the grid using power electronic converters helped in extracting more energy from wind and delivering it to the grid with better stability. Doubly Fed Induction Generators (DFIG) with back to back converters offers a decoupled control of grid and the turbine, so DFIG is preferred for high power grid connected wind energy conversion systems. Since the system dynamics of a DFIG based grid connected generating units are nonlinear with multiple input and multiple output, design of controllers is a tough task. Feedback linearization technique offers a linear control for nonlinear systems through transformation and it is successfully used in permanent magnet synchronous machine drives. This paper presents a controller design for DFIG based wind energy conversion systems using feedback linearization. The proposed control is simulated on a 1.5kW system using Matlab-Simulink tool.

KEYWORDS: Wind Energy, DFIG, back to back converters, Controller design, Feedback linearization

INTRODUCTION

Electricity generation from wind energy is one of the fast growing renewable energy conversion technique as they are less polluting and becoming economical compared to the unit cost of electricity generated from fossil fuel. Power capture with variable speed turbines coupled to Doubly Fed Induction Generators (DFIG) are become popular for high capacity wind power generation plants, as the scheme possess higher conversion efficiency, low capital requirement and with flexibility in control. [1] The power generated is directly connected to the grid through the stator of the DFIG and the rotor of DFIG is connected to the grid through a set of converters. Only exciting current of the DFIG is transferred through the converters, which offer better control and low investment for converters. [2]. The rotor side converter help in controlling generator speed with wind speed by keeping tip speed ratio of the generator at optimum power capture. The DC link capacitor voltage is maintained constant through the grid side converter. The performance of the wind energy generation systems based on DFIG so depends on the converter and their efficient control. Vector control method for the DFIG is proposed as a better method for real and reactive power control in [3]. Wind speed is inherently variable and the generator speed has to be controlled to extract the maximum power continuously.

Dynamic equations of the converters are nonlinear and deriving a simple controller is a tough task [4] and a few techniques were used to remove the nonlinearity [5]. Some researches were done in Permanent Magnet Synchronous Generator based wind generation control by using feedback linearization [6-9]. Feedback linearization offers a control law through change of variables, so that linear control techniques can be applied. In

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DFIG based power generation systems, the control become more complex due to the presence of two converters and the two windings of the generator.

This paper attempt to develop a control strategy for a DFIG based wind energy conversion system using feedback linearization. The dynamics of the system is developed based on state space analysis and a linear controller is developed. The proposed strategy is tested using simulation on a Matlab-Simulink platform.

Modeling Of The System:

A grid connected DFIG based wind energy conversion system consists of a variable speed wind turbine, which is coupled to the generator through a gear box. The stator of the DFIG directly connected to the grid, whereas its rotor windings are connected to the grid through a grid side converter, a DC link and a rotor side converter as shown in Fig. 1

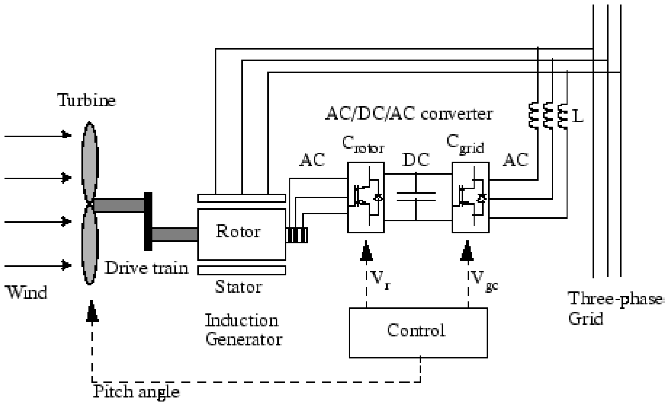

Fig. 1: A DFIG based wind energy system

The back to back converters enable to decouple the grid frequency from the generator rotor frequency, so the system can capture power at various speeds independent of the grid frequency. The converter control help in controlling the power flow to the grid, whereas the pitch control help to control the turbine speed at various incoming wind speeds. Since the turbine is operated between cut in speed and rated speed, pitch controller is not considered here.

a) Modelling of Wind Turbine:

The power conversion in wind turbine depends on the wind speed and its interaction with the turbine blades. The extractable power from the wind is given by [10]

$$P_w = \frac{1}{2}\rho A v^3 C_p \tag{1}$$

Whereas ρ is density of air, A is area swept by blades, and v is incoming wind velocity and C_p power coefficient. Power coefficient depends on the tip speed ratio$\lambda = \frac{\omega R}{v}$ and the angle of attack α. The mechanical torque developed can be calculated as $T_m = \frac{P_w}{\omega}$.

b) Modelling of DFIG:

DFIG is a wound rotor type induction machine, its stator consisting of three phase distributed windings. The rotor circuit converters enable a DFIG to decouple the electrical grid behavior from the variable speed turbine. The feedback control loop ensure the independent electrical dynamics from mechanical dynamics.[11] For the modeling of DFIG in the synchronously rotating frame of reference we have to represent the two phase of stator and that of rotor circuit variable in a synchronously rotating (d-q) frame of reference.

c) Modelling of Grid Side Converter:

Dynamic equations of grid side converters in d-q reference frame can be written as [2]

$$\begin{bmatrix} \dot{i_{sd}} \\ \dot{i_{sq}} \\ \dot{v_{dc}} \end{bmatrix} = \begin{bmatrix} \frac{v_{sd}}{L_s} - \frac{R_s}{L_s} i_{sd} + \omega i_{sq} \\ \frac{v_{sq}}{L_s} - \frac{R_s}{L_s} i_{sq} + \omega i_{sd} \\ \frac{3 v_{sq} i_{sq}}{2 C v_{dc}} - \frac{i_i}{C} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{-1}{L_s} \\ 0 \end{bmatrix} v_{iq} + \begin{bmatrix} \frac{-1}{L_s} \\ 0 \\ 0 \end{bmatrix} v_{id} \tag{2}$$

Where v_{sd},v_{sd},i_{sd} and $i_{sq}$are grid side direct axis and quadrature axis voltages and currents, R_s and L_s are resistance and inductances on grid side, v_{dc} is the DC link voltage across the capacitor C connected, v_{id}, v_{iq} and

i_i the injected voltage and currents.The grid side converter is nonlinear with multiple input and multiple output, so design of a controller with conventional methods are difficult.

Feedback linearization:

Feedback linearization is the technique to transform nonlinear systems into linear ones, so that linear control techniques can be applied. This technique is possible through change of variables and by selecting a suitable control input. Consider a multi-input multi-output system with state space relations

$$\dot{x} = f(x) + g(x)u \tag{3}$$
$$y = h(x) \tag{4}$$

Where x is the state vector with size nx1, u is the control input vector of size mx1, y is the output vector of size mx1, g is a nxm matrix, f and h are smooth vector fields. The input-output linearization can be obtained through successively differentiating output until the input appear.

The Lie derivative of $h(x)$ along $f(x)$is given by

$$L_f h(x) = \frac{dh(x)}{dx} f(x) \tag{5}$$

and Lie derivative of $h(x)$ along $g(x)$is given by

$$L_g h(x) = \frac{dh(x)}{dx} g(x) \tag{6}$$

Then time derivative of output

$$\dot{y} = \frac{dh(x)}{dt} = \frac{dh(x)}{dx}\dot{x} = \frac{dh(x)}{dx} f(x) + \frac{dh(x)}{dx} g(x)u \tag{7}$$

$$\dot{y} = L_f h(x) + L_g h(x)u \tag{8}$$

Continuously differentiating y

$$y_i^{r_i} = L_f^{r_i} h_i(x) + \sum_{j=1}^{m} \{L_{gj} L_f^{r_i-1} h_i(x)\} u_j \tag{9}$$

If $L_{gj} L_f^{r_i-1} h_i(x) \neq 0$ for at least one value of j, then the input u will be directly related in the derivatives. By finding the derivatives of all the outputs, it can be written as

$$\begin{bmatrix} y_1^{r_1} \\ y_2^{r_2} \\ \cdot \\ \cdot \\ y_m^{r_m} \end{bmatrix} = \begin{bmatrix} L_f^{r_1} h_1(x) \\ L_f^{r_2} h_2(x) \\ \cdot \\ \cdot \\ L_f^{r_m} h_m(x) \end{bmatrix} + E(x)u \tag{10}$$

where the mxm decoupling matrix $E(x)$ is defined as

$$E(x) = \begin{bmatrix} L_{g1} L_f^{r_1-1} h_1(x) & \ldots\ldots & L_{gm} L_f^{r_1-1} h_1(x) \\ L_{g1} L_f^{r_2-1} h_2(x) & \cdots\cdots & L_{gm} L_f^{r_2-1} h_2(x) \\ \vdots & \vdots\,\vdots & \vdots \\ L_{g1} L_f^{r_m-1} h_m(x) & \cdots\cdots & L_{gm} L_f^{r_m-1} h_m(x) \end{bmatrix} \tag{11}$$

If the decoupling matrix is singular, the input transformation can be found by

$$u = -E^{-1}(x) \begin{bmatrix} L_f^{r_1} h_1(x) \\ L_f^{r_2} h_2(x) \\ \cdot \\ \cdot \\ L_f^{r_m} h_m(x) \end{bmatrix} + E^{-1}(x) \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \cdot \\ \cdot \\ \alpha_m \end{bmatrix} \tag{12}$$

α_1, α_2, ..$\alpha_m$are the new input, from that the output can be written as

$$\begin{bmatrix} y_1^{r_1} \\ y_2^{r_2} \\ \cdot \\ \cdot \\ y_m^{r_m} \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \cdot \\ \cdot \\ \alpha_m \end{bmatrix} \tag{13}$$

This offers a linear relation and input and output is totally decoupled.

Controller Design

Applying feedback linearization technique can give a linear control with decoupling. Considering i_{sd} and v_{dc} as the outputs

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} i_{sd} \\ v_{dc} \end{bmatrix} \tag{14}$$

Differentiating output y_1

$$\dot{i_{sd}} = \frac{v_{sd}}{L_s} - \frac{R_s}{L_s} i_{sd} + \omega i_{sq} - \frac{1}{L_s} v_{id} \tag{15}$$

Here $L_f h(x)$=0 and $u_1 = v_{id}$

Differentiating the second output y_2

$$\dot{v_{dc}} = \frac{3 v_{sq} i_{sq}}{2 C v_{dc}} - \frac{i_i}{C} \tag{16}$$

Taking second derivative

$$\ddot{v_{dc}} = \frac{3 v_{sq}}{2 C v_{dc}} \left(\frac{v_{sq}}{L_s} - \frac{R_s}{L_s} i_{sq} + \omega i_{sd} - \frac{-1}{L_s} v_{iq} \right) - \frac{3 v_{sq} i_{sq}}{2 C {v_{dc}}^2} \left(\frac{3 v_{sq} i_{sq}}{2 C v_{dc}} - \frac{i_i}{C} \right) - \frac{i_i}{C} \tag{17}$$

This gives a relation with input $u_2 = v_{iq}$

From these two derivatives

$$\begin{bmatrix} \dot{y_1} \\ \ddot{y_2} \end{bmatrix} = \begin{bmatrix} \dot{i_{sd}} \\ \ddot{v_{dc}} \end{bmatrix} = \begin{bmatrix} \frac{v_{sd}}{L_s} - \frac{R_s}{L_s} i_{sd} + \omega i_{sq} \\ \frac{3 v_{sq}}{2 C v_{dc}} \left(\frac{v_{sq}}{L_s} - \frac{R_s}{L_s} i_{sq} + \omega i_{sd} \right) - \frac{3 v_{sq} i_{sq}}{2 C {v_{dc}}^2} \left(\frac{3 v_{sq} i_{sq}}{2 C v_{dc}} - \frac{i_i}{C} \right) - \frac{i_i}{C} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_s} & 0 \\ 0 & \frac{-3 v_{sq}}{2 C v_{dc} L_s} \end{bmatrix} \begin{bmatrix} v_{id} \\ v_{iq} \end{bmatrix} \tag{18}$$

Where,

$$\begin{bmatrix} v_{id} \\ v_{iq} \end{bmatrix} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{19}$$

This is in the form of

$$\begin{bmatrix} y_1^{r_1} \\ y_2^{r_2} \\ \cdot \\ \cdot \\ y_m^{r_m} \end{bmatrix} = \begin{bmatrix} L_f^{r_1} h_1(x) \\ L_f^{r_2} h_2(x) \\ \cdot \\ \cdot \\ L_f^{r_m} h_m(x) \end{bmatrix} + E(x) u \tag{20}$$

With

$$E(x) = \begin{bmatrix} \frac{1}{L_s} & 0 \\ 0 & \frac{-3 v_{sq}}{2 C v_{dc} L_s} \end{bmatrix} \tag{21}$$

From inspection it can be seen that *E(x)* is non-singular with

$$E^{-1}(x) = \begin{bmatrix} -L_s & 0 \\ 0 & \frac{-2 C v_{dc} L_s}{3 v_{sq}} \end{bmatrix} \tag{22}$$

So the new control law can be written as

$$\begin{bmatrix} v_{id} \\ v_{iq} \end{bmatrix} = \begin{bmatrix} -L_s & 0 \\ 0 & \frac{-2 C v_{dc} L_s}{3 v_{sq}} \end{bmatrix} \left\{ \begin{bmatrix} \frac{v_{sd}}{L_s} - \frac{R_s}{L_s} i_{sd} + \omega i_{sq} \\ \frac{3 v_{sq}}{2 C v_{dc}} \left(\frac{v_{sq}}{L_s} - \frac{R_s}{L_s} i_{sq} + \omega i_{sd} \right) - \frac{3 v_{sq} i_{sq}}{2 C {v_{dc}}^2} \left(\frac{3 v_{sq} i_{sq}}{2 C v_{dc}} - \frac{i_i}{C} \right) - \frac{i_i}{C} \end{bmatrix} + \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} \right\} \tag{23}$$

For tracking control

$$\begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} \dot{y_1} - k_{11}(y_1 - y_{1ref}) \\ \ddot{y_2} - k_{21}(\dot{y_2} - \dot{y_{2ref}}) - k_{22}(y_2 - y_{2ref}) \end{bmatrix} \tag{24}$$

The output errors can be calculated from

$$(y_1 - \dot{y_{1ref}}) - k_{11}(y_1 - y_{1ref}) = 0 \tag{25}$$

$$(\ddot{y_2} - \ddot{y_{2ref}}) - k_{21}(\dot{y_2} - \dot{y_{2ref}}) - k_{22}(y_2 - y_{2ref}) = 0 \tag{26}$$

The gains $k_{11}, k_{21}$and k_{22} can be selected as positive as they offer stable tracking control.[12]

To avoid the tracking errors during the parameter variations, integral control can be added to the tracking control. [13] In this paper the gains are found by trial and error method during simulation to minimize the error.

The exact control for the system now

$$\begin{bmatrix} v_{id} \\ v_{iq} \end{bmatrix} = \begin{bmatrix} -v_{sd} - R_s i_{sd} + \omega L_s i_{sq} - L_s \alpha_1 \\ (v_{sq} - R_s i_{sq} + \omega L_s i_{sd}) + \frac{L_s i_{sq}}{v_{dc}} \left(\frac{3 v_{sq} i_{sq}}{2 C v_{dc}} - \frac{i_i}{C} \right) + \frac{2 C v_{dc} L_s}{3 v_{sq}} \frac{i_i}{C} + \frac{2 C v_{dc} L_s}{3 v_{sq}} \alpha_2 \end{bmatrix} \quad (27)$$

Simulation and Results:

To verify the effect of feedback linearization technique, this control strategy simulated on a 1.5kW wind energy conversion system based on DFIG on Matlab-Simulink platform.

The simulation done for a 575 V, 60 Hz grid connected DFIG with a DC link voltage of 1150V. The resistance and inductance of the grid side converter is taken as 18mH and 0.3Ω. DC link capacitor value is 2000µF. The gain values of the converter selected as $k_{11} = 1000, k_{21} = 5000$ and k_{22}=20000.

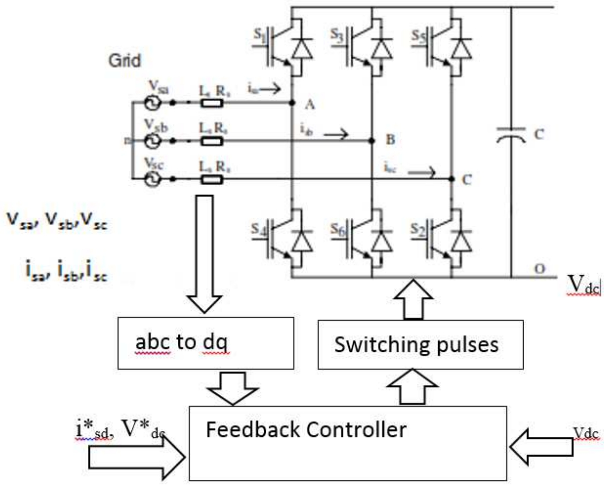

Fig. 2: Control scheme Simulation results are shown below.

Fig. 3: Grid Voltage in pu

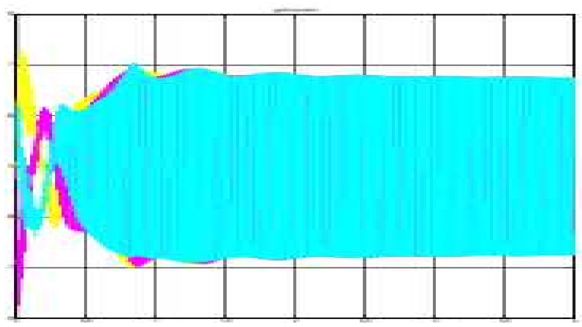

Fig. 4: Grid current

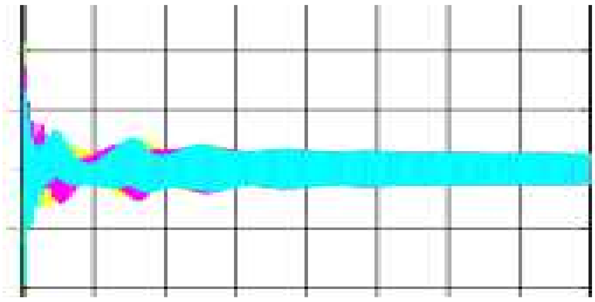

Fig. 5: Grid Side converter current

Conclusion:

Grid interconnection of wind energy based generators are a technical challenge as the wind is variable and grid has strict restrictions for changes in voltage and frequency. Successful power injection to the grid depends on the effective control of the power electronic controllers. DFIG offer a decoupled control during the interconnection and becoming as a popular choice for wind energy conversion. Control of power converters are inherently nonlinear in DFIG based systems and feedback linearization offer an easier control design as it can transform a nonlinear system to a linear system without approximations and assumptions. In this paper controller design of a DFIG is discussed and it is verified by using a computer simulation. This technique can be extended to other physical systems with coupling and nonlinearity in their dynamics.

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