Study on Doubly Fed Induction Generator Control
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Abstract—Due to the recent needs for the expansion of renewable energy as sources of electrical energy, wind energy conversion is receiving much interest all over the world. The variable speed doubly fed induction generator is today the most widely used concept. This paper presents a study of a doubly fed induction generator driven by a wind turbine connected to the grid, and controlled by artificial neural network ANN controller. The behavior of the proposed system is shown without control, and then as controlled by ANN. The effectiveness of the artificial neural network controller is then compared to that of a PID controller.

Index Terms—Artificial Neural Network controller ANN, doubly fed induction generator DFIG, wind turbine.

I. INTRODUCTION

The penetration of wind energy into the electrical grid has increased tremendously in the last 20 years, especially in Denmark and Germany. The standard wind turbine was a simple and highly reliable stall controlled turbine. This type of turbine was designed to produce electricity whenever the wind speed was high enough and the grid was stable [1]. The construction and performance of fixed-speed wind turbines as shown in Fig. 1 depends on the characteristics of mechanical sub-circuits, e.g., pitch control time constants, etc.

Fig. 1 fixed speed wind turbine with directly grid connected squirrel-cage induction generator.

The response time of these mechanical circuits may be in the range of tens of milliseconds. As a result, each time a gust of wind hits the turbine, a fast and strong variation of electrical output power can be observed. These variations in electric power generated not only require a stiff power grid to enable stable operation, but also require a strong mechanical design to absorb high mechanical stresses, which leads to expensive mechanical construction, especially at high-rated power [4-5].

A way to make more controllable turbines is variable speed turbines. Variable speed turbines have become the most dominating type of the yearly installed wind turbines [2-3]; as they can store some of the power fluctuations due to turbulence by increasing the rotor speed, pitching the rotor blades, these turbines can control the power output at any given wind speed [1].

Fig. 2 shows a variable speed turbine connected to a Squirrel-Cage Induction Generator SCIG. Although these direct-on-line systems have been built up to 1.5 MW, but presence of power inverter causes lots of disadvantages such as:

- This power converter, which has to be rated at 1 p.u. of total system power, is expensive.
- Converter efficiency plays an important factor in total system efficiency over the entire operating range [4-5].

Another system is presented using Doubly Fed Induction Generator DFIG, as shown in Fig. 3. It consists of a stator connected directly to grid and a rotor – via slip rings – is connected to grid through four-quadrant ac-to-ac converter based on insulated gate bipolar transistors (IGBTs) [4-5].

This system offers the following advantages:

- Reduced inverter cost, because inverter rating is typically 30% of total system power.
- Improved system efficiency.
- Power-factor control can be implemented at lower cost.
- It has a complete control of active and reactive power.

The doubly fed induction generator with a power converter – shown in Fig. 3 – is a simple and highly controllable way to transform the mechanical energy from the variable speed rotor to a constant frequency electrical utility grid.

The main reason for the popularity of the doubly fed wind induction generators connected to the national networks is their ability to supply power at constant voltage and frequency while the rotor speed varies.

High performance variable speeds drive systems using induction machines have gained more and more popularity during the last decade due to the rapid development of power electron-
ics and microprocessors. The complex control problems, which arise in these variable speed drives, are solved using fast microprocessors and DSPs and new control techniques are added each year [5].

There are two main control technique tendencies: the vector-control VC and the direct torque control DTC used for high performance applications. Based on the induction machines, the VC of AC machines have become the most adopted control technique worldwide [5-6].

VC Topology has three types:
- Stator Flux Oriented (only used with DFIG) [7-8].
- Rotor Flux Oriented (used with both SCIG & DFIG) [9].
- Magnetizing Flux Oriented.

For a doubly-fed machine its stator windings are directly connected to the grid (as shown in Fig. 3), so the stator voltage equations will result simpler as well as the stator-flux-oriented control scheme than the rotor-flux oriented one. Moreover, the stator active and reactive power are controlled directly [5]. In a previous paper, a rotor current control strategy is applied on a doubly-fed induction generator (DFIG)-based wind generation system operating under unbalanced network conditions. A DFIG system model in the positive and negative synchronous reference frames is presented. Variations of stator active and reactive powers and generator torque are fully defined in the presence of negative sequence voltage and current. This control was based on positive and negative (d-q) reference frames is applied used to provide precise control of the rotor positive and negative sequence currents [14].

Another paper discussed the voltage control of the DFIG wind farm. It presents the design methodology of a stator side controller of the DFIG, which produces the terminal voltage control in addition to the DC link voltage regulation [15]. In this paper, a detailed model for representation of DFIG connected to a variable speed wind turbine is presented. Matlab/Simulink tool is used for this dynamic simulation study [12]. A new control topology is applied on the system using ANN (artificial neural network) in order to enhance the response of connecting a DFIG driven by a wind turbine to the electric grid. It consists of three layers: input layer, Hidden layer and output layer, each layer contains random number of neurons forming non linear equations for ANN system.

The effectiveness of the artificial neural network controller is then compared with that of a PID controller. Simulation results are performed and analyzed under the same operating conditions.

II. MATHEMATICAL MODEL OF THE DOUBLY FED INDUCTION GENERATOR DFIG

For the development of induction machine model, the d-q arbitrary reference frame model of induction machine is transformed into stationary reference frame [10]. Using d-q component of the stator currents ($i_{sd}$ and $i_{sq}$) and rotor currents ($i_{rd}$ and $i_{rq}$) as state variables, starting of voltage equations of the induction machine the following differential equations are derived [5]:

\[
\begin{align*}
\psi_s &= L_m i_ms + L_{ss} i_{sx} + L_{mr} i_{rx} + L_{sr} i_{ry} \\
0 &= L_{ss} i_{sy} + L_{mr} i_{rx} + L_{sr} i_{ry}
\end{align*}
\]

Where $i_{ms}$ is the stator magnetizing current. Then, from equations 4 & 5 we find that:

\[
\begin{align*}
i_{sx} &= \frac{L_m}{L_{ss}} (i_{ms} - i_{rx}) \\
i_{sy} &= -\frac{L_m}{L_{ss}} i_{ry}
\end{align*}
\]
Thus, the governing equations for the rotor currents are as follows:

\[
T_r \frac{di}{dt} + i_r = \frac{V_x}{R_r} + (\omega_x - \omega_r)T_t i_r - (\sigma_r - T_r) \frac{di_{ms}}{dt} \tag{8}
\]

\[
T_r \frac{di}{dt} + i_r = \frac{V_y}{R_r} + (\omega_x - \omega_r)(T_t i_r + (\sigma_r - T_r)i_{ms}) \tag{9}
\]

Where:

\[T_r = \frac{D}{R_r l_{ss}}\]

is the rotor time constant, and \(\sigma_r = \frac{l_{rr}}{l_{rs}}\).

Considering that the x-axis component of the stator voltage is zero, the general expression of the active and reactive power in synchronous reference frame is:

Since \(p_s = \frac{3}{2} V_{sy} i_{sy} \) & \(q_s = \frac{3}{2} V_{sy} i_{sx}\)

Then \(\dot{p}_s = 3\frac{V_{sy}}{2l_{ss}} V_{sy} i_{ry}\)

& \(\dot{q}_s = \frac{3}{2} V_{sy} \frac{\lambda_m}{l_{ss}} i_{ms} - i_{rx}\)

\[
\dot{p}_s = \frac{3\lambda_m V_{sy}}{2l_{ss}} i_{ry} \tag{10}
\]

\[
\dot{q}_s = \frac{3}{2} V_{sy} \frac{\lambda_m}{l_{ss}} i_{ms} - i_{rx} \tag{11}
\]

III. THE ROTOR CURRENT CONTROLLER

Starting from the complete linearized 8th order system [5] a multiple input/multiple output (MIMO) system, which describes the induction machine and the drive-train model, can be build using the specific functions from Control System Toolbox [13]. Then, the desired transfer function between each input/output pair can be extracted as shown in Fig.: 5.

\[H_{ij}(s)\]

\[I_{ref} \rightarrow H_{pi}(s) \rightarrow \delta_i \rightarrow \delta_{ref} \rightarrow i_{ref} \rightarrow H_{cy}(s) \rightarrow V_{y} \rightarrow V_{ref} \rightarrow \delta_{ref} \rightarrow \delta_i \rightarrow H_{pi}(s) \rightarrow I_{ref}
\]

In the controllers design will be considered the following transfer functions:

- Transfer functions between the stator voltage and the rotor currents:

\[H_{vry-irx,y}(s)\]

- Transfer functions between the rotor voltages and the rotor currents which is considered in our study as the system shown in Fig.: 6.

\[H_{vrx,y-irx,y}(s)\]

The system under control shown in Fig.: 6 includes DFIG machine rotor model, converter model, PI controller model and filter model.

A converter \(H_c(s)\) can be modeled in synchronous reference frame in terms of its fundamental components neglecting the harmonics. So, the transfer function associated with the fundamental component for a voltage source converter is:

\[H_{c_x,y}(s) = \frac{1}{1 + sT_c delay} \tag{13}\]

Since this time delay is very small the converter transfer function will be neglected in analysis.

A first-order filter \(H_f(s)\) is used for the feedback signals. The transfer function for this filter is given by:

\[H_{f_{x,y}}(s) = \frac{1}{1 + sT_f} \tag{14}\]

Depending on the modulation strategy this time constant can have different values in order to eliminate the ripple in the measured currents. In the design of the rotor current controllers a value of 0.5 msec has been considered.

Then the filter transfer function will be as follows:

\[H_{f_{x,y}}(s) = \frac{2 \times 10^3}{(s + 2 \times 10^3)} \tag{15}\]

A PI controller \(H_{pi}(s)\) is given by:

\[H_{pi}(s) = \frac{k_p s + 1}{s T_i + 1} \tag{16}\]

The integration time constant of the PI controller is selected at 0.005 sec in order to obtain a bandwidth of 200Hz.

Selecting for \(k_p\) a value of 10, the rotor current controller parameters are [5]:

\(k_p = 0.28\) & \(T_i = 0.005 \text{ sec}\)

Therefore the PI Controller Transfer Function will be as follows:
\[ H_{PI}(s) = \frac{0.28(s + 200)}{(s + 20)} \quad (17) \]

IV. THE ROTOR MODEL

Closed Loop Analysis:
The closed loop transfer function will be as follows:
\[ T.F. (s) = \frac{H_{F(s)} H_{x,y}(s)}{1 + H_{F(s)} H_{x,y}(s) H_{F(s)} H_{x,y}(s)} \quad (18) \]

Where that:
\[ H_{F(s)} = \frac{2.695(s + 19120)(s + 5141)(s + 17.62)(s + 11 + j158)(s + 11 + j158)(s + 12.4 - j313)(s + 12.4 + j313)}{(s + 1991)(s + 236 - j148)(s + 236 + j148)(s + 206 + j427)(s + 206 - j427)} \]
\[ H_{x,y}(s) = \frac{2\times10^3}{(s + 2\times10^3)} \]
\[ H_{F(s)} = \frac{0.28(s + 200)}{(s + 20)} \]
Then T.F. (s) = \[ \frac{0.7546(s + 19120)(s + 5141)(s + 2000)(s + 18)}{(s + 1991)(s + 236 - j148)(s + 236 + j148)(s + 206 + j427)(s + 206 - j427)} \quad (19) \]

Therefore, from the last equation we can get the following results:

<table>
<thead>
<tr>
<th>Eigen Values</th>
<th>Damping</th>
<th>Frequency (rad/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-235.5±j147.81</td>
<td>0.847</td>
<td>278</td>
</tr>
<tr>
<td>206±j426.6</td>
<td>-0.434 (refused)</td>
<td>473.7</td>
</tr>
</tbody>
</table>

Applying Zero-Pole cancellation, we get the approximated transfer function as follows:
\[ T.F. (s) = \frac{0.7546(s + 19120)(s + 5141)(s + 2000)}{(s + 1991)(s + 236 - j148)(s + 236 + j148)(s + 206 + j427)(s + 206 - j427)} \]
\[ = \frac{0.8s^3 + 19817s^2 + 110788802s + 1.5\times10^{11}}{s^4 + 2462s^3 + 1015280s + 153944120} \quad (20) \]

Behavior of the closed loop Transfer function is shown as follows:

- **Step Response:**
The behavior of the system if a step input is applied to it is shown in Fig.: 7, it is clear that the system will reach steady state after about 0.02 seconds.

- **Bode Plot Diagram:**
The bode plot diagram of the system is shown in Fig.: 8, it is clear that the system is stable.

- **Root Locus:**
The root locus of the system is shown in Fig.: 9, by zooming to the graph in Fig.: 10 the location of poles and zeroes is more clear. Stability of the system is clear in the diagram.

V. CONTROL STRATEGIES

A) The PID Controller
The proportional plus derivative plus integral (PID) controller is one of the famous controllers used in a wide range in the
industrial applications. The output of the PID controller in time domain is defined by the following equation:

$$v_c(t) = k_p e(t) + k_d \frac{d(e)}{dt} + k_i \int_0^t e(t)dt$$  \hspace{1cm} (22)$$

Where $v_c(t)$ is the output of the PID controller, $k_p$ is the proportional gain, $k_d$ is the derivative gain, $k_i$ is the integral gain and $e(t)$ is the instantaneous error signal. The main advantage of adding the derivative part to the proportional controller is to fasten the output response of the system and a small integral gain value is added to eliminate the noise in the signal.

Designing a PID Controller to the system as shown in Fig. 11, assume that Maximum percentage over shoot for the system is 16%, settling time is 16msec and $k_i = 0.01$ then we get $\xi = 0.5$, and $w_n = 475$ then $k_p = 196534.5879$ & $k_d = 5.1683$.

Then the system give the following response shown in Fig. 12:

For enhancing the response of PID Controller, a mathematical calculations are made to get $P_D$ & $k_D$ as accurate results. Comparing the T.F. of the model with the general 2nd order system model, and assuming maximum percentage over shoot is 5% and put $k_i = 0.01$, then $\xi = 0.7$ and $w_n = 300$ then we get the values of $P_D$ & $k_D$ as follows $k_p = 168036.0456$ & $k_d = 3.84309568$.

and the behaviour of the system becomes as shown in Fig. 13:

B) Artificial Neural Network (ANN) Control

In classical control systems, knowledge of the controlled system (plant) is required in the form of a set of algebraic and differential equations, which analytically relate inputs and outputs. However, these models can become complex, rely on many assumptions, may contain parameters which are difficult to measure or may change significantly during operation as in the case of the rotor flux oriented control (RFOC) induction motor drive. Classical control theory suffers from some limitations due to the assumptions made for the control system such as linearity, time-invariance, etc. These problems can be overcome by using artificial intelligence-based control techniques, and these techniques can be used, even when the analytical models are not known. Such control systems can also be less sensitive to parameter variation than classical control systems.

The main advantages of using artificial intelligence-based controllers and estimators are [11]:

- Their design does not require a mathematical model of the plant.
- They can lead to improved performance, when properly tuned.
- They may require less tuning effort than conventional controllers.
- They may be designed on the basis of data from a real system or a plant in the absence of necessary expert knowledge.

ANN is an approximator with free approximators, have no mathematical model [11]. It consists of three layers as shown in Fig.:14, Input layer, Hidden layer, Output layer. Each layer got a random number of neurons; these neurons are multiplied and summed with weight functions according to the following equation.

$$y = \sum_{j=1}^{n} w_M X_j = wM_1X_1 + wM_2X_2 + ... wM_nX_n$$ \hspace{1cm} (23)$$

This equation can be represented by network shown in Fig.:14. There are $n$ input nodes in the input layer, $M$ hidden nodes in the hidden layer.
Neurons are used to enhance the error signal came out from the system and input new signal to the system to give better response.

The Current is controlled by Artificial Neural Network Controller and the results are compared with PID Controller. The system under study is shown in Fig.: 15, applying a step input with initial value Zero and final value one, step time is one second.

As shown in Fig.: 15 the Artificial Neural Network (ANN) controller is designed using Trial & Error Method, it consists of three inputs in the input layer; the first input is the step function, second input is feedback from the system, and third input is feedback from the controller.

It contains one hidden layer, with 6 neurons. Tan sigmoid function is used at the input of the hidden layer and a Linear Transfer Function is used at its output.

Simulating the results of the system we get the following figure:

As shown in Fig.: 17, the system response with ANN is more efficient than the two versions of the PID controllers. Maximum percentage overshoot in case of ANN is a very small value if compared with the PID’s. Accordingly, the rise time in case of PID controller is slightly smaller than the ANN’s controller, while Settling Time of ANN is lower than that of PID Controller

This paper has proposed a new method of machine control by using artificial neural network (ANN) for a doubly fed induction generator (DFIG) connected to a variable speed wind turbine. The validity of the proposed method has been evaluated by computer simulations. From the comparative study between the proposed controller and the conventional PID controller, it has been shown that the proposed ANN is very effective on the stabilization of the system. Therefore the proposed method can contribute to expand wind energy utilization.
VIII. APPENDIX

A) Doubly fed induction generator data

Table 1 showing DFIG data

<table>
<thead>
<tr>
<th>Parameters at rated speed</th>
<th>DFIG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power [MW]</td>
<td>2</td>
</tr>
<tr>
<td>Stator Resistance [Ω]</td>
<td>0.001</td>
</tr>
<tr>
<td>Stator Leakage Inductance [mH]</td>
<td>0.07</td>
</tr>
<tr>
<td>Rotor Resistance [Ω]</td>
<td>0.0013</td>
</tr>
<tr>
<td>Rotor Leakage Inductance [mH]</td>
<td>0.08</td>
</tr>
<tr>
<td>Magnetizing Inductance [mH]</td>
<td>3</td>
</tr>
<tr>
<td>Number of pole pairs</td>
<td>2</td>
</tr>
<tr>
<td>Moment of Inertia [kgm²]</td>
<td>90</td>
</tr>
<tr>
<td>Rated Speed [rpm]</td>
<td>1512</td>
</tr>
</tbody>
</table>

B) Wind turbine data

Table 2 Wind Turbine data

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment of inertia of the wind turbine rotor [kgm²]</td>
<td>90 x 10e005</td>
</tr>
<tr>
<td>Equivalent spring constant indicating the torsional stiffness of the shaft [Nm/rad]</td>
<td>120 x 10e006</td>
</tr>
<tr>
<td>Equivalent damping coefficient of the shaft</td>
<td>3.6 x 10e005</td>
</tr>
<tr>
<td>Gear box ratio</td>
<td>100</td>
</tr>
</tbody>
</table>

IX. REFERENCES
