Optimum Power Point Tracking of Variable Speed Wind Turbine DFIG using Genetic Algorithm

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Abstract - This paper presents Maximum Power Point Tracking (MPPT) controller design of Doubly Fed Induction Generator (DFIG) using Genetic Algorithm (GA). Essential feature of proposed controller is that it is used to trace the maximum power when wind speed is lower than the rated wind speed. Doubly-Fed Induction Generator DFIG has stator terminals are connected directly to the grid. However, the rotor terminals of DFIG are connected to the mains via a partially rated variable frequency ac/dc/ac converter. The ac/dc/ac converter system consisting of a rotor side converter (RSC) and a grid side converter (GSC) are connected back-to-back by a DC-link capacitor. Stator voltage orientation (SVO) is the principle control for RSC controlled by hysteresis current controller. While GSC is controlled by pulse width modulation (PWM). Due to the nature of unpredicted wind speed, determining the optimal tip speed ratio (TSR) is essential to extract the maximum available wind power at any wind speed under rated wind speed. To get the maximum output power under rated wind speed the proposed method must be used. The system under study is simulated using MATLAB/Simulink package. The digital simulation results under different conditions in terms of the variations of the wind turbine generator show that the output power, rotor speed and torque response for step change in wind speed prove the effectiveness and powerful of the proposed GA controller for MPPT.

Keywords – DFIG, MPPT, Pitch Angle, Genetic Algorithm, Wind Turbine Control.

I. INTRODUCTION

Electricity generation from renewable resources, and particularly from the wind, is considered today as a competitive and necessary alternative to fossil resources. Wind turbines can operate with either fixed speed (actually within a speed range about 1 %) or variable speed, Pitch-adjusting variable-speed wind turbines like DFIG which have become the dominating type of yearly installed wind turbines in recent years. Several reasons for choosing DFIG, such as the reduction of both the mechanical structure stresses and the acoustic noise and the possibility to control four quadrant active and reactive power capabilities, have driven the choice for variable speed operation of wind turbines. Doubly fed induction machines inherit all the advantages of a cage induction generator but the fact due to which they are more popular are that the stator of the DFIG is connected directly to the grid and it supplies power from the stator side at grid voltage and frequency. Other than that the control is done from the rotor side. So the power converters used for DFIG control are of less power rating, which reduces the cost as well as the switching losses resulting in enhanced efficiency. In fact, DFIG variable speed operation increases the energetic efficiency and reduces the drive train torque and the energy of generating flow unsteadiness [1]. Control of variable-speed fixed-pitch in the partial load regime generally aims at regulating the power harvested from wind by modifying the electrical generator speed; in particular, the control goal can be to capture the maximum power available from the wind. For each wind speed, there is a certain rotational speed at which the power curve of a given wind turbine has a maximum. There are usually two controllers for the DFIG variable-speed wind turbines which are cross coupled each other [2]. In low wind speed below rated value, the speed controller can continuously adjust the speed of the rotor to maintain the fixed pitch ratio constant at the level which gives the maximum power coefficient and then the efficiency of the turbine will be significantly increased, the generator is controlled by power electronic equipment, which makes it possible to control the rotor speed. In this way the power fluctuations caused by wind variations can be more or less absorbed by changing the rotor speed and thus power variations originating from the wind conversion and the drive train can be reduced. In high wind speed above rated value, pitch angle regulation is necessary where the rotational speed is kept constant. Small changes in pitch angle can have a dramatic effect on the power output. The purpose of the pitch angle control was presented and studied [3-5]. Therefore, control systems for DFIG variable speed wind turbines should continue to evolve towards more and more effective and innovative solutions. Wind energy, even though abundant, varies continually as wind speed changes throughout the day. Amount of power output from a Wind Energy Conversion System WECS depends upon the accuracy with which the peak power points
are tracked by the MPPT controller of the WECS control system irrespective of the type of generator used. The maximum power extraction algorithms researched so far can be classified into three main control methods, namely: 1) tip speed ratio (TSR) control, 2) power signal feedback (PSF) control and 3) hill-climb search (HCS) control [2].

The TSR control method regulates the rotational speed of the generator in order to maintain the TSR to an optimum value at which power extracted is maximum. This method requires both the wind speed and the turbine speed to be measured or estimated. Fig. 1 shows the block diagram of a WECS with TSR control [2].

In PSF control, it is required to have the knowledge of the wind turbine’s maximum power curve, and track this curve through its control mechanisms. The maximum power curves need to be obtained via simulations or off-line experiment on individual wind turbines. In this method, reference power is generated either using a recorded maximum power curve or using the mechanical power equation of the wind turbine where wind speed or the rotor speed is used as the input. Fig. 2 shows the block diagram of a WECS with PSF controller for maximum power extraction [2].

The HCS control algorithm continuously searches for the peak power of the wind turbine. It can overcome some of the common problems normally associated with the other two methods. The tracking algorithm, depending upon the location of the operating point and relation between the changes in power and speed, computes the desired optimum signal in order to drive the system to the point of maximum power. Fig. 3 shows the principle of HCS control [2].

II. OPERATING REGION AND AERODYNAMICS OF THE WIND TURBINE

A. Operating Region of the Wind Turbine

The wind turbine operates, with different dynamics, from the cut-in wind speed (usually 4 m/s, for modern wind turbines) to the cut-out wind speed (around 24 m/s), as shown in Fig. 4. Three distinct wind speed points can be noticed in this power curve [6]:

1) \( V_{wind\,\,cut-in} \): The lowest wind speed at which wind turbine starts to generate power.
2) \( V_{wind\,\,rated} \): Wind speed at which the wind turbine generates the rated power, which is usually the maximum power wind turbine can produce.
3) \( V_{wind\,\,cut-out} \): Wind speed at which the turbine ceases power generation and is shut down (with automatic brakes and/or blade pitching) to protect the turbine from mechanical damage.

B. Aerodynamic of the Wind Turbine

The energy conversion in a wind turbine can be described by the nonlinear equations [7], [8]:

\[
P_m = 0.5 \rho A V_w^3 C_p
\]

(1)

Where \( P_m \) is the mechanical power (Watt), \( \rho \) is the air density (kg/m\(^3\)), \( A = \pi R^2 \) is area covered by turbine blades (m\(^2\)), \( R \) is Rotor radius (m), \( V_w \) (m/sec) is the velocity of available wind and \( C_p \) is the coefficient of power. The power captured by the wind turbine depends highly on \( C_p \) for a given wind speed and the relationship of \( C_p \) with \( \lambda \) and \( \beta \) represents output characteristics of the wind turbine as in (2):
\( C_p(\lambda, \beta) = 0.5176 \left( \frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{-\frac{21}{\lambda_i}} + 0.0068\lambda \) 
(2)

Where \( \lambda \) is tip speed ratio, a variable expressing the linear speeds of blade tip to speed of wind and \( \beta \) is the pitch angle, \( \lambda \) and \( \frac{1}{\lambda_i} \) can be expressed as in (3) and (4), respectively.

\[
\lambda = \frac{w_t}{V_w}
\]
(3)

Where \( w_t \) is rotational turbine speed (rad/sec).

\[
\frac{1}{\lambda_i} = \frac{1}{\lambda} + 0.0006\beta \quad \beta^2 + 1
\]
(4)

By using (2), the typical \( C_p \) versus \( \lambda \) curve at different pitch angle \( \beta \) is shown in Fig. 5. As aforementioned, there is an optimum value of \( \lambda \) that leads to maximum power coefficient \( C_{p,\text{max}} \). The maximum theoretical value of \( C_p \) is approximately 0.59 [9].

Fig. 5 Power coefficient \( C_p(\lambda, \beta) \) versus \( \lambda \) for various values of pitch angle \( \beta \).

So in the mode of MPPT which is between cut in wind speed and rated wind speed, if \( \lambda \) is maintained constantly at its optimal value corresponding to \( C_{p,\text{max}} \), this ensures that the energy extracted is in its maximum operating point.

Fig. 6 shows turbine mechanical power as a function of turbine speed by substituting (2), (3) and (4) in (1) at various wind speed and tip speed ratio \( \lambda \). The power for a certain wind speed is maximum at a certain value of rotor speed called optimum turbine speed \( W_{t,\text{opt}} \). This is the speed which corresponds to optimum tip speed ratio \( \lambda_{\text{opt}} \) and maximum power coefficient \( C_{p,\text{max}} \). In order to have maximum possible power, the turbine should always operate at \( \lambda_{\text{opt}} \). This is possible by controlling the rotational speed of the turbine so that it always rotates at the optimum speed of rotation.

III. MPPT BASED ON TIP SPEED RATIO \( \lambda \)

For MPPT the optimal tip speed ratio \( \lambda_{\text{opt}} \) is determined at maximum power coefficient \( C_{p,\text{opt}} \) and zero pitch angle \( \beta \) by using (2), Equation (2) is optimized for different \( \lambda \) using optimization technique called Genetic Algorithm (GA) in present work. The next section will describe the GA method.

IV. GENETIC ALGORITHM OPTIMIZATION

A. Principles of Genetic Algorithm

A genetic algorithm (GA) is a robust optimization technique based on natural selection [10-13]. The basic goal of GA is to optimize functions called fitness functions. GA-based approaches differ from conventional problem-solving methods in several ways. First, GA works with a coding of the parameter set rather than the parameters themselves. Second, GA search from a population of points rather than a single point. Third, GA use payoff objective function information, not other auxiliary knowledge. Finally, GA use probabilistic transition rules, not deterministic rules. These properties make GA robust, powerful, and data-independent. A simple GA starts with a population of solutions encoded in one of many ways. Binary encodings are quite common and are used in this report. The GA determines each string’s strength based on an objective function and performs one or more of three genetic operators on certain strings in the population. GA concepts could be adapted into the form that is suitable for computer implementation. Fig. 7 shows the flowchart of GA.

1) The Initialization generates an initial random population consisting of individuals whose characteristics are coded by the string of zeros and ones (Encoding the variables into binary strings).

2) The Elitism given a fitness function based on a suitable performance criterion; calculate a fitness value for each string within the population (Evaluation).

3) The Reproduction based on a probability basis; choose pairs of individuals to breed offspring strings, where individuals with a higher fitness value will be selected than those with a lower fitness value (Best fitness).
4) The Crossover divides the binary coding of each parent into two or more segments and then combines to give a new offspring string that has inherited part of its coding from each parent (The crossover used here is one cut point method).

5) The Mutation inverse bits in coding of the offspring with a low probability.

6) If search goal is achieved, or an allowable generation is attained, stop. Otherwise return to step (2).

The object function used here is given as in (5):

\[ F_{unction} = C_p(\lambda) = 0.5176 \left( \frac{116}{\lambda_1} - 5 \right) e^{-\frac{31}{\lambda_1}} + 0.0068\lambda \] (5)

Where \( \frac{1}{\lambda} = \frac{1}{\lambda} - 0.035 \) at \( \beta = 0 \). Then, the above equation is entered in the genetic algorithm under mentioned conditions and the result value obtained after number of generations (Iterations) of power coefficient using genetic algorithm GA is \( C_{p,max} = 0.48 \) as shown in Fig. 8. The tip speed ratio \( \lambda \) corresponding to \( C_{p,max} \) is \( \lambda_{opt} = 8.1 \) is shown in Fig. 9.

From Fig. 5 it is clear that the values of \( \lambda_{opt} \) and \( C_{p,max} \) are exact values at \( \beta = 0 \). Then, by using (6):

\[ \lambda_{opt} = \frac{\omega_p}{\omega_r} \] (6)

It is necessary to get the value of \( \omega_p \) which is corresponding to \( \lambda_{opt} \) at different wind speed at specified \( \omega_r \) corresponding to the maximum power that can be obtained using (1) as shown in Fig. 6 and Table 2. The maximum power points curve is obtained as shown in Fig. 10.

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**B. Genetic Algorithm Controller for MPPT Mode**

The genetic algorithm controller is used in the region between the cut in speed and the rated wind speed to find the maximum power at different wind speeds. To find and track the MPP, you should get the optimal value of \( \lambda \) at maximum power coefficient and this is done by genetic algorithm to solve (2) at different values of \( \lambda \). Noting that the pitch angle in this region is zero. The object function used here is one variable equation then it is very important to define constrains and the other parameters of genetic algorithm as the following:

- \( 0 < \lambda < 13 \)
- \( \lambda_{min} = 0 \) and \( \lambda_{max} = 13 \)

The parameters used for genetic algorithm are given in Table 1.

**Table 1**

<table>
<thead>
<tr>
<th>Parameters of GA</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genetic Algorithm property</td>
<td>Value</td>
</tr>
<tr>
<td>Chromosome Length</td>
<td>16</td>
</tr>
<tr>
<td>Population Size</td>
<td>200</td>
</tr>
<tr>
<td>No. of iterations (Generations)</td>
<td>150</td>
</tr>
</tbody>
</table>
The objective of the MPPT operation mode is to maximize power extraction at low to medium wind speeds by following the maximum value of the wind power coefficient \((C_{p,\text{max}})\) and \(\lambda\) obtained by GA with \(\beta=0\) as depicted in Fig. 10.

![Fig. 10 Wind turbine mechanical power output and MPP versus turbine speed at different wind speed](image)

### Table 2

<table>
<thead>
<tr>
<th>(v_w) (m/sec)</th>
<th>(\lambda_{\text{opt}}) By GA</th>
<th>(\omega_{\text{rated}}) By GA</th>
<th>(C_{p,\text{max}}) By GA</th>
<th>((0.5^<em>a^</em>\lambda^*\omega)^{0.5})</th>
<th>(P_{\text{rated}}) (Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>8.1</td>
<td>1.0568</td>
<td>0.48</td>
<td>867.616</td>
<td>0.0555</td>
</tr>
<tr>
<td>6</td>
<td>8.1</td>
<td>1.5853</td>
<td>0.48</td>
<td>867.616</td>
<td>0.1874</td>
</tr>
<tr>
<td>8</td>
<td>8.1</td>
<td>2.1137</td>
<td>0.48</td>
<td>867.616</td>
<td>0.4442</td>
</tr>
<tr>
<td>10</td>
<td>8.1</td>
<td>2.6422</td>
<td>0.48</td>
<td>867.616</td>
<td>0.8676</td>
</tr>
<tr>
<td>12</td>
<td>8.1</td>
<td>3.1706</td>
<td>0.48</td>
<td>867.616</td>
<td>1.4992</td>
</tr>
</tbody>
</table>

The above equations used to track the maximum power point based on proposed genetic algorithm are simulated using Matlab/Simulink as shown in Fig. 11.

![Fig. 11 Block diagram of tracking curve in Matlab/Simulink](image)

The wind turbine parameters used here in this paper is shown in Table 3.

### Table 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value and Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air density</td>
<td>(\rho)</td>
<td>1.225 Kg/m^3</td>
</tr>
<tr>
<td>Rotor radius</td>
<td>(R)</td>
<td>30.6657 m</td>
</tr>
<tr>
<td>Number of blades</td>
<td>(N_{\text{blades}})</td>
<td>3</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>(v_{\text{rated}})</td>
<td>12 m/sec</td>
</tr>
</tbody>
</table>

**VI. DFIG MODEL FOR WECS**

The DFIG-based WECS is shown in Fig. 12. The dynamics of the DFIG is represented by a fourth-order state space model using the synchronously rotating reference frame (\(q-d\)-frame) as given in (7)-(10) [14]. Where \(V_{qs}\), \(V_{ds}\), \(V_{q}\), and \(V_{d}\) are the q and d-axis stator and rotor voltages, respectively. \(I_{qs}\), \(I_{ds}\), \(I_{qr}\), and \(I_{dr}\) are the q and d-axis stator and rotor currents, respectively. \(\lambda_{qs}\), \(\lambda_{ds}\), \(\lambda_{qr}\), and \(\lambda_{dr}\) are the q and d-axis stator and rotor fluxes, respectively.

\[
V_{qs} = R_s I_{qs} + \omega_e \lambda_{ds} + \frac{d}{dt} \lambda_{qs} \tag{7}
\]

\[
V_{ds} = R_s I_{ds} - \omega_e \lambda_{qs} + \frac{d}{dt} \lambda_{ds} \tag{8}
\]

\[
V_{qr} = R_r I_{qr} + (\omega_s - \omega_e) \lambda_{dr} + \frac{d}{dt} \lambda_{qr} \tag{9}
\]

\[
V_{dr} = R_r I_{dr} - (\omega_s - \omega_e) \lambda_{qr} + \frac{d}{dt} \lambda_{dr} \tag{10}
\]

\(\omega_e\) is the angular velocity of the synchronously rotating reference frame. \(\omega_s\) is the rotor electrical angular speed. \(R_s\) and \(R_r\) are the stator and rotor resistances, respectively.

The flux linkage equations are given as in (11)-(14):

\[
\lambda_{qs} = L_s I_{qs} + L_m I_{qr} \tag{11}
\]

\[
\lambda_{ds} = L_s I_{ds} + L_m I_{dr} \tag{12}
\]

\[
\lambda_{qr} = L_r I_{qr} + L_m I_{qs} \tag{13}
\]

\[
\lambda_{dr} = L_r I_{dr} + L_m I_{ds} \tag{14}
\]

Where \(L_s\), \(L_r\), and \(L_m\) are the stator, rotor, and mutual inductances, respectively, with \(L_s = L_{ls} + L_m\) and \(L_r = L_{lr} + L_m\); \(L_{ls}\) and \(L_{lr}\) are the stator and rotor self inductance, respectively.

All the equations above are induction motor equations. When the induction motor operates as a generator, current direction will be opposite.
active and reactive power outputs from stator and rotor side are given as in (15)-(16):

\[ P_s = \frac{1}{2} (V_{sq} I_{q} + V_{dq} I_{d}) \]  
(15)

\[ Q_s = \frac{1}{2} (V_{qr} I_{d} - V_{dr} I_{q}) \]  
(16)

\[ P_r = \frac{1}{2} (V_{qr} I_{q} + V_{dr} I_{d}) \]  
(17)

\[ Q_r = \frac{1}{2} (V_{qr} I_{d} - V_{dr} I_{q}) \]  
(18)

The total active and reactive power generated by DFIG are given as in (19)-(20):

\[ P_{\text{total}} = P_s + P_r \]  
(19)

\[ Q_{\text{total}} = Q_s + Q_r \]  
(20)

If total \( P_{\text{total}} \) and/or total \( Q_{\text{total}} \) is negative, DFIG is supplying power to the power grid, else it is drawing power from the grid. The electromagnetic torque \( \tau_e \) generated by the machine which can be written in terms of flux linkages and currents is given as in (21):

\[ \tau_e = \frac{3}{2} P (\lambda_{ds} I_q - \lambda_{dq} I_d) \]  
(21)

Where \( P \) is the number of the pole pairs.

VII. CONTROL OF DFIG WECS FOR MPPT

Control of the DFIG is achieved by control of the variable frequency converter, which includes control of the RSC and control of the GSC as the following:

A. Design of the Rotor Side Converter RSC Controller

In DFIG wind energy systems, the stator of the generator is directly connected to the grid, and its voltage and frequency can be considered constant under the normal operating conditions. It is therefore, convenient to use stator voltage oriented control (SVOC) for the DFIG [15]. The stator voltage oriented control is achieved by aligning the d-axis of the synchronous reference frame with the stator voltage vector \( V_s \). The resultant d- and q-axis stator voltages are: \( V_{sd} = 0 \) and \( V_{dq} = V_{s} \). This DFIG control scheme is a rotor side control scheme where the stator reactive power is controlled by the direct current axis loop and the active power is controlled by the quadrature current axis loop. In the active power control loop the rotor electrical angular speed is compared with the reference rotor electrical angular speed obtained by MPPT and the error is fed to a conventional PI (Speed Regulator) controller to generate the reference quadrature axis current. Similarly, the stator side reactive power is calculated and is compared with the reference stator reactive power (\( Q_{s, \text{ref}} = 0 \)) and the error is fed to another PI (Var Regulator) controller to generate the reference direct axis current. Then both the direct and quadrature axis reference currents are converted from d-q axis reference frame to a-b-c frame. Then, the three phase reference currents are compared with three phase rotor actual currents and the error is the input to hysteresis current controller and the output of this controller is the switch control signal to the firing gates of RSC. The band widths of the controllers are set at 5% of the rated current values. The hysteresis controller output gives the PWM switching pulses for the rotor side bidirectional converter control as shown in Fig. 13. The whole control scheme is simulated using Matlab/Simulink as shown in Fig. 14. The stator voltage vector angle \( \theta_s \) is measured as shown in Fig. 15 and the rotor position angle \( \theta_r \) is measured by an encoder mounted on the shaft of the generator. The slip angle \( \theta_{sl} \) for the reference frame transformation can be obtained as the following (\( \theta_{sl} = \theta_s - \theta_r \)) as shown in Fig. 15.
bus voltage which is controlled by the direct current axis loop and the quadrature current axis which is kept at zero for unity power factor. The actual DC-bus voltage is compared with the reference DC-bus voltage and the error is fed to a conventional PI (DC Voltage Regulator) controller and the output of PI controller is control signal of direct axis voltage of GSC. Similarly, the quadrature axis reference current of GSC is compared to the actual quadrature axis current of GSC and the error is fed to another conventional PI (Current Regulator) controller and the output of PI controller is control signal of quadrature axis voltage of GSC. Then, the control signals of direct and quadrature axis voltages are the input to PWM controller (Space Vector Modulator) and the output of this controller is the switch control signals (Pulses) to the firing gates of the GSC as shown in Fig. 16.

**GSC Control System**

![Fig. 16 Block diagram of GSC in Matlab/Simulink.](image)

**C. PI Controllers Design**

The output signal of a PI controller can be obtained by using (22):

\[ U = K_p \cdot e + K_i \cdot \int e \cdot dt \]  

(22)

Where \( e \) is the error signal, \( K_p \) and \( K_i \) are the proportional gain and integral gain, respectively. Choosing the appropriate control parameters of RSC and GSC is very important to gain good performance although the whole system might be able to work for a wide range of parameters. The most important objective is to maintain the system stability by selecting appropriate control parameters. And then those parameters can be tuned up corresponding to the specified performance requirement. There are some methods that can be used to determine the system parameters that can keep the whole system in the stable region. One of the methods is by using Butterworth polynomial to optimize the closed loop eigen value locations [16]. The Butterworth method locates the eigen values uniformly in the left-half s-plane on a circle with radius \( \omega_p \), with its center at the origin as shown in Fig. 17.

![Fig. 17 Location of poles for second order Butterworth polynomial.](image)

The Butterworth polynomial for a transfer function with a second order denominator is given as in (23):

\[ p^2 + \sqrt{2} \cdot \omega_p \cdot p + \omega_p^2 = 0 \]  

(23)

Where \( p = \frac{d}{dt} \). The PI parameters are determined by comparing the coefficients in (23) with the denominators of the corresponding transfer functions and then choosing appropriate \( \omega_p \). Where \( \omega_p \) is the bandwidth of the controller, which depends upon the design value. The system used has a significant advantage for the protection of the DFIG. It can naturally protect the system from over-current since current limiters can be easily inserted in the control system as shown in Fig. 14 and Fig. 16. The values of the parameters of each PI controller used in controlling of DFIG are shown in Table 4.

**Table 4**

<table>
<thead>
<tr>
<th>Parameters of PI Controllers</th>
<th>( \omega_p ) (rad/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RSC</strong></td>
<td><strong>Speed Regulator</strong></td>
</tr>
<tr>
<td></td>
<td>( k_{p,r} )</td>
</tr>
<tr>
<td></td>
<td>( k_{i,r} )</td>
</tr>
<tr>
<td></td>
<td><strong>Var Regulator</strong></td>
</tr>
<tr>
<td></td>
<td>( k_{p,v} )</td>
</tr>
<tr>
<td></td>
<td>( k_{i,v} )</td>
</tr>
<tr>
<td><strong>GSC</strong></td>
<td><strong>DC Voltage Regulator</strong></td>
</tr>
<tr>
<td></td>
<td>( k_{p,d} )</td>
</tr>
<tr>
<td></td>
<td>( k_{i,d} )</td>
</tr>
</tbody>
</table>

**VIII. RESULTS OF MPPT USING GENETIC ALGORITHM CONTROLLER**

The DFIG control structure is modeled and simulated in Matlab/Simulink and the overall model is shown in Fig. 18. The simulation is carried out under different conditions as the following:

1) Step change in wind speed.
2) Changing the value of generator inertia.
3) Changing the value of rotor resistance.
A. Effect of Changing Wind Speed

The simulation is carried out for a 1.5 MW DFIG-based WECS to verify the effectiveness of above described control system under varying wind speed. The DFIG parameters are shown in Table 5. The wind speed varies as shown in Fig. 19. The variation of wind speed causes change of operation mode in the wind turbine system from subsynchronous to supersynchronous. When the wind speed is less than rated speed ($V_r = 12 \text{ m/sec}$), the wind turbine is operating in MPPT mode so the steady state value of $C_p$ is 0.48 and $\lambda$ is 8.1 at $\beta = 0$. Fig. 20 and 21 show the time response of $C_p$ and $\lambda$ due to wind speed variation, respectively. When the wind speed varies, the rotor speed, the mechanical torque, the mechanical power, stator power and rotor power of generator response also varies as shown in Fig. 22, 23, 24, 25 and 26, respectively. Noting that Fig. 26 indicates the transfer operation from subsynchronous to supersynchronous according to the variation in wind speed. Also, the total active power output response of DFIG varies accordingly as shown in Fig. 27 and verifies the values shown in Table 2 but the stator reactive power response is always regulated to zero as shown in Fig. 28 and achievement of unity power factor operation for both RSC and GSC as shown in Fig. 28 and 29, respectively. By doing so, the power factor of the overall DFIG wind turbine system can be regulated according to the requirement as shown in Fig. 30. During the entire operation period of the wind turbine, GSC maintains the DC-link voltage response in back to back converter of the DFIG to a constant value as shown in Fig. 31.
Fig. 23 Mechanical torque of generator response during the variation of wind speed in Matlab/Simulink.

Fig. 24 Mechanical power of generator response during the variation of wind speed in Matlab/Simulink.

Fig. 25 Stator power response during the variation of wind speed in Matlab/Simulink.

Fig. 26 Rotor power response during the variation of wind speed in Matlab/Simulink.

Fig. 27 Total active power response generated by DFIG during the variation of wind speed in Matlab/Simulink.

Fig. 28 Regulation of reactive power response during the variation of wind speed in Matlab/Simulink.

Fig. 29 The quadrature current axis response responsible for unity power factor during the variation of wind speed in Matlab/Simulink.

Fig. 30 Unity power factor by using DFIG for Phase A.
Fig. 31 The DC link voltage response during the variation of wind speed in Matlab/Simulink.

Table 5
DFIG Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Mechanical Power</td>
<td>1.5 MW</td>
</tr>
<tr>
<td>Rated Stator Line-to-line Voltage</td>
<td>690 V (rms)</td>
</tr>
<tr>
<td>Rated Stator Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Rated Rotor Speed</td>
<td>1750 rpm</td>
</tr>
<tr>
<td>Number of Pole Pairs</td>
<td>2</td>
</tr>
<tr>
<td>Rated Mechanical Torque</td>
<td>8.185 kN-m</td>
</tr>
<tr>
<td>Stator Winding Resistance, Rs</td>
<td>2.65 mΩ</td>
</tr>
<tr>
<td>Rotor Winding Resistance, Rr</td>
<td>2.63 mΩ</td>
</tr>
<tr>
<td>Stator Leakage Inductance, Ls</td>
<td>0.1387 mH</td>
</tr>
<tr>
<td>Rotor Leakage Inductance, Lr</td>
<td>0.1337 mH</td>
</tr>
<tr>
<td>Magnetizing Inductance, Lm</td>
<td>5.4749 mH</td>
</tr>
<tr>
<td>Shaft inertia</td>
<td>20 J kg·m²</td>
</tr>
<tr>
<td>DC link voltage</td>
<td>1200 V</td>
</tr>
<tr>
<td>DC link capacitor</td>
<td>90 mF</td>
</tr>
</tbody>
</table>

B. Effect of Changing Inertia of Generator

For the same wind speed as mentioned above the system is studied and simulated for two values of generator inertia compared to the mentioned generator inertia above in order to indicate the effect of changing generator inertia on MPPT by displayed the next figures for tip speed ratio λ and power coefficient $C_p$. The first case for generator inertia $J = 30 \text{ Kg} \cdot \text{m}^2$, the system is simulated and the results of $C_p$ and λ response are shown in Fig. 32 and 33, respectively. It is clear from this case that the tip speed ratio and the power coefficient need a time to reach steady state value compared to results obtained at $J = 20 \text{ Kg} \cdot \text{m}^2$.

The second case for generator inertia $J = 15 \text{ Kg} \cdot \text{m}^2$, the system is simulated and the results of $C_p$ and λ response are shown in Fig. 34 and 35, respectively. It is clear from this case that the tip speed ratio and the power coefficient are almost similar to the results obtained at $J = 20 \text{ Kg} \cdot \text{m}^2$.

C. Effect of Changing Rotor Resistance

For the same wind speed as mentioned above the system is studied and simulated for two values of rotor resistance in order to indicate the effect of changing rotor resistance on MPPT by displayed the next
figures for tip speed ratio \( \lambda \) and power coefficient \( C_p \).

The first case for \( R_r = 0.263 \, \text{m} \Omega \), the system is simulated and the results of \( C_p \) and \( \lambda \) response are shown in Fig. 36 and 37, respectively.

\[ \text{Fig. 36 Power coefficient } C_p \text{ response during the changing of rotor resistance } R_r = 0.263 \, \text{m} \Omega \text{ in Matlab/Simulink.} \]

\[ \text{Fig. 37 Tip speed ratio } \lambda \text{ response during the changing of rotor resistance } R_r = 0.263 \, \text{m} \Omega \text{ in Matlab/Simulink.} \]

The second case for rotor resistance for \( R_r = 26.3 \, \text{m} \Omega \), the system is simulated and the results of \( C_p \) and \( \lambda \) response are shown in Fig. 38 and 39, respectively.

\[ \text{Fig. 38 Power coefficient } C_p \text{ response during the changing of rotor resistance } R_r = 26.3 \, \text{m} \Omega \text{ in Matlab/Simulink.} \]

\[ \text{Fig. 39 Tip speed ratio } \lambda \text{ response during the changing of rotor resistance } R_r = 26.3 \, \text{m} \Omega \text{ in Matlab/Simulink.} \]

The results displayed above show that the DFIG has the ability to track and find the maximum power at different values of rotor resistance for step change in wind speed.

IX. CONCLUSIONS

In this paper, artificial intelligence of genetic algorithm has been used for the operation and control of MPPT of the wind turbine. The GA has been used in MPPT mode to get the optimal value of \( \lambda_{opt} \) and maximum power coefficient \( C_{p_{max}} \). When the wind speed changes, this designed controller can track the maximum power under different conditions when the wind speed is lower than the rated wind speed. The two cases subsynchronous and supersynchronous are carried out using Matlab/Simulink and the results show that the intelligent controllers of DFIG give good performance.

REFERENCES


