Performance Analysis of Unified Nonlinear Controller for Grid Connected PMSG based WECS

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Abstract - In recent years, the need of renewable based power generation is growing exponentially due to high energy demand, depletion of existing fossil fuel deposits and carbon emission issue. Wind based power generation is gaining more interest among the existing renewable based power generation. The doubly-fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG) are the most popular systems for wind energy conversion. The PMSG has attracted more attention due to its advantages of high-power density, high precision, high efficiency and reliability. In this research work, a single nonlinear multi input multi output (MIMO) controller based on feedback linearization method is designed for grid connected PMSG based wind energy conversion system (WECS). The simulation is done using MATLAB/Simulink and the performance of the controller is evaluated for different wind speeds under standalone and grid connected modes. The simulation results show that the developed control strategy provides a good performance.

Key Words: PMSG, wind energy conversion systems, stand-alone and grid-connected systems, nonlinear control, feedback linearization

1. INTRODUCTION

Over the last twenty years, renewable energy sources are attracting more attention because of the price increase, restricted reserves and adverse environmental impact of fossil fuels. In the meantime, technological advancements, cost reduction and governmental incentives have made some renewable energy sources competitive in the market. Among them, wind energy is one of the quickest growing renewable energy sources.

Earlier wind energy has been used for milling grains, pumping water and sailing the seas. In the late nineteenth century, a 12 kW DC windmill generator was developed to generate electricity. It is, however, since the 1980s the technology has become sufficiently mature to supply electricity expeditiously and more reliably. Over the past twenty years, a spread of wind generation technologies is developed, that have improved the conversion potency and reduced the prices for wind energy production. Due to its limited applications, in addition to on-land installations, larger wind turbines are pushed to offshore locations to extract more energy and scale back their impact on land use and landscape.

Wind energy conversion systems (WECS) convert the kinetic energy associated with wind speed into electrical energy for feeding power to the grid. The power output from such wind energy conversion systems depend on the wind speed and the pitch angle of the turbine blades. Doubly fed induction generators (DFIGs) and Permanent magnet synchronous generators (PMSGs) are the most commonly used generators for WECS. PMSG has several advantages which make it very usable for WECS.

Installed capacity of wind power has been progressively growing over the last two decades. The installed capacity of global wind power has increased exponentially from approximately 6 GW in 2001 to 591 GW by 2018. In 2017, annual wind energy production grew 17%, reaching 4.4% of worldwide electric power usage, and providing 11.6% of the electricity in the European Union. This growth has been spurred by the continuous cost increase of classic energy sources, cost reduction of wind turbines, governmental incentive programs, and public demand for cleaner energy sources.

The wind turbines can operate as stand-alone units of small power capacity and supply power to villages, farms, and islands where access to the utility grid is remote or costly. Since the power generated from the wind is variable, other energy sources are normally required in stand-alone systems. A stand-alone wind energy conversion system operates with diesel generators, photovoltaic energy systems, or energy storage systems to form a more reliable distributed generation (DG) system. Stand-alone wind power constitutes only a small fraction of the total installed wind capacity in the world due to its limited applications. The majority of wind turbines operating in the field are grid-connected, and the power generated is directly injected to the grid. As most generators operate at a few hundred volts (typically 690 V), transformers are used to increase the generator voltage to tens of kilovolts, for example, 35 kV, for wind farm substations.

In this work, a single MIMO nonlinear controller is designed for grid connected PMSG based WECS and its performance is analysed in Matlab under varying wind velocities.
2. MATHEMATICAL MODELLING

The schematic diagram of the system is depicted in Fig. 1. It consists of a PMSG driven by a wind turbine, a generator side AC/DC converter, a grid-side DC/AC converter and MIMO controller. The wind turbine converts part of the kinetic energy of the wind into mechanical energy. This energy is converted into electrical energy via the generator. Since the generator output frequency is variable (depends on the wind conditions), a back-to-back converter is used to synchronize its output with the grid frequency [1].

![Schematic diagram of PMSG based WECS](image)

2.1 Modelling of Wind Turbine

The wind turbine retrieves only a fraction of the wind’s kinetic power. This power is determined by the area swept by the blades, $S_{\omega} (S_{\omega} = \pi R^2)$, the wind speed, $v_\omega$, the air density, $\rho$, and the power coefficient, $C_p$ which characterizes each turbine. Hence, the generated mechanical power, can be expressed as follows:

$$P_m = \frac{1}{2} \pi \rho C_p (\lambda \beta) R^2 v_\omega^2$$  \hspace{1cm} (1)

$$\lambda = \frac{\omega_m R}{v_\omega}$$  \hspace{1cm} (2)

where $R$ is the radius of the turbine, $C_p$ is the power coefficient which is a function of $\lambda$, the tip speed ratio and $\beta$, the pitch angle. $\omega_m$ is the turbine angular speed. Neglecting the friction forces, the dynamic equation of the wind turbine is given by

$$\frac{d\omega_m}{dt} = \frac{P}{J} (T_m - T_g)$$  \hspace{1cm} (3)

where $\omega_m$ is the rotating speed of the blade, $P$, the number of pole pairs, $J$, the moment of inertia of the generator, $T_m$, the torque developed by the turbine and $T_g$, the torque due to load which in this case is the generator electromagnetic torque.

2.2 Modelling of PMSG

The PMSG converts the mechanical energy obtained from the wind turbine to electrical energy. In order to simplify its analysis, the three-phase PMSG is modelled in the dq reference frame. It is given by

$$u_{ds} = R_s i_{ds} + L_d \frac{di_{ds}}{dt} - \omega_r L_q i_q$$  \hspace{1cm} (4)

$$u_{qs} = R_s i_{qs} + L_q \frac{di_{qs}}{dt} + \omega_r L_d i_{ds} + \omega_r \lambda_r$$  \hspace{1cm} (5)

$$T_g = \frac{3P}{2} \left[ \lambda_r i_{qs} - (i_{ds} - L_q i_{ds}) i_{ds} i_{qs} \right]$$  \hspace{1cm} (6)

where $u_{ds}$, $u_{qs}$ and $i_{ds}$, $i_{qs}$ are the generator stator dq-axis voltages (V) and currents (A), respectively; $R_s$ is the stator winding resistance (Ω); $L_d$ and $L_q$ are the stator d-axis and q-axis self-inductances (H); $\omega_r$ is the rotor electrical angular speed (rad/s); and $\lambda_r$ is the rotor flux (Wb) generated by the permanent magnets. Non-salient (or round) rotor PMSG is considered in this study, the d- and q-axis magnetizing inductances are therefore equal ($L_d = L_q$).

2.3 Modelling of Back-to-Back Converter

The back-to-back (B2B) converter consists of two identical voltage source converters (VSC) and a capacitor which is connected in between them. The generator-side VSC converts the three-phase generator AC output signal into DC voltage, whereas the grid-side VSC converts the DC voltage into the load input three-phase AC voltage. The load voltage will be controlled through the grid-side VSC. Its dq reference frame output voltage model is given by

$$u_{di} = L_f \frac{di_{di}}{dt} - \omega_x L_q i_{qi} + u_{di}$$  \hspace{1cm} (7)

$$u_{qi} = L_f \frac{di_{qi}}{dt} + \omega_x L_d i_{di} + u_{qi}$$  \hspace{1cm} (8)

where $u_{di}$, $u_{qi}$ and $i_{di}$, $i_{qi}$ are the grid-side converter output dq-axis voltages (V) and currents (A), respectively; $u_{di}$ and $u_{qi}$ are the load dq-axis voltage (V); $L_f$ and $\omega_x$ are the grid side filter inductance (H) and the grid electrical angular speed (rad/s), respectively.

2.4 Modelling of Grid side circuit

The grid-side circuit is composed of a RL load, a filter, $L_p$, the line inductance, $L_g'$ and the grid when the system operates in the grid-connected mode. For the sake of simplicity, the transformer leakage inductance is included in $L_g'$. One of the advantages of the proposed control system is that the voltage of the load is constantly controlled in grid-connected mode and stand-alone mode. It is therefore not necessary to use a capacitor in the output filter of the converter.

The main idea behind this modelling approach is to represent the grid and the load by an equivalent Thevenin...
model. This model will be connected in series with $L_f$ at A as illustrated in Fig. 2. If $Z_i = R_i + j \omega g L_i$ denotes the load impedance and $u_g = u_{dG} + j u_{qG}$ represents the grid voltage, then the Thevenin voltage and impedance in the grid-connected mode are given respectively by

\[
E_{th} = \frac{(R_i + j \omega g L_i)(u_{dG} + j u_{qG})}{R_i + j \omega g (L_i + L_f)}
\]

\[
Z_{th} = \frac{\omega g L_i (R_i + j \omega g L_i)}{R_i + j \omega g (L_i + L_f)}
\]

Note that $R_i$ and $L_i$ are obtained from the active and reactive power supplied to the load as follows

\[
R_i = \sqrt{3} \frac{u_{ll}^2 P_i}{P_i^2 + Q_i^2}
\]

\[
L_i = \sqrt{3} \frac{u_{ll}^2 Q_i}{P_i^2 + Q_i^2}
\]

where $u_{ll}$ is the load line-to-line RMS voltage. $P_i$ and $Q_i$ are the load active and reactive power of the system, respectively. They can be obtained from the load current and voltage

\[
P_i = \frac{3}{2} (u_{q1} i_{q1} + u_{d1} i_{d1})
\]

\[
Q_i = \frac{3}{2} (u_{q1} i_{q1} - u_{d1} i_{d1})
\]

Fig. 2: Grid-side circuit and the respective Thevenin equivalent circuit

When the grid is not available (in the stand-alone mode), the Thevenin voltage and impedance are respectively given by

\[
E_{th} = 0 \quad \text{and} \quad Z_{th} = Z_i
\]

The grid-side circuit is assumed in a quasi-static mode, therefore, the following relationships are valid

\[
u_{d1} = R_{ch} i_{d1} - \omega q L_{ch} i_{q1} + E_{thd}
\]

\[
u_{q1} = R_{ch} i_{q1} + \omega d L_{ch} i_{d1} + E_{thq}
\]

where $R_{ch}$ and $\omega q L_{ch}$ are real and imaginary parts of the Thevenin impedance, respectively ($Z_{th} = R_{ch} + j \omega q L_{ch}$).

3. FEEDBACK LINEARIZATION

Feedback linearization is a method for nonlinear control design which has attracted a great deal of research interest in recent years. The central idea of this method is to algebraically transform the nonlinear dynamics of a system into a (fully or partly) linear one, so that linear control techniques can be applied [6].

Fig. 3: MIMO controller structure

The controller is designed using the input-output feedback linearization method. The MIMO controller will calculate and generate the appropriate control signals for each converter.

The control objectives are:
1) keep the wind turbine operating at its maximum power by controlling $\omega_p$
2) achieve a linear relationship between the stator current and the electromagnetic torque by controlling the stator d-axis current,$i_{ds}$
3) meet load voltage requirement by controlling both load d-axis and q-axis voltages, $u_{d1}$ and $u_{q1}$ respectively.

In this study, $i_{ds}, i_{qs}, \omega_p, i_{d1}, i_{q1}$ are taken as state variables, $u_{ds}, u_{qs}, i_{d1}, u_{q1}$ are taken as input variables and $\dot{i}_{ds}, \dot{i}_{qs}, \dot{i}_{d1}, \dot{i}_{q1}$ are considered as output variables.

\[
\begin{align*}
\tilde{x} &= [i_{ds}, i_{qs}, \omega_p, i_{d1}, i_{q1}]^T \\
\tilde{u} &= [u_{ds}, u_{qs}, i_{d1}, u_{q1}]^T \\
\tilde{y} &= [i_{ds}, i_{qs}, i_{d1}, i_{q1}]^T
\end{align*}
\]

where

\[
\begin{align*}
\tilde{\tau}_{ds} &= \int (i_{ds} - i_{ds}) \, d\xi \\
\tilde{\tau}_{qs} &= \int (\omega_p - \omega_p) \, d\xi \\
\tilde{u}_{d1} &= \int (u_{d1} - u_{d1}) \, d\xi \\
\tilde{u}_{q1} &= \int (u_{q1} - u_{q1}) \, d\xi
\end{align*}
\]

To ensure zero steady state error and to increase the robustness of the controller when the system structure changes, integral actions are added into the control-loop. This happens, for instance, when the system switches from the stand-alone mode to the grid connected mode. The input output feedback linearization control design method is used.
to linearize and decouple this nonlinear model. Each output is differentiated therefore until at least one input appears. However, it can be noted that each controlled variable has been differentiated twice, before a control input emerges, except for $\omega_d$, which has been differentiated three times.

The state equation is

$$
\begin{bmatrix}
\frac{\dot{x}_{ds}}{\dot{x}_{d}} \\
\omega_r \\
\frac{\dot{x}_{dl}}{\dot{x}_{q}}
\end{bmatrix} =
\begin{bmatrix}
A_1 & A_2 & A_3 \\
A_4 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
x_{ds} \\
x_{dl} \\
x_{dq}
\end{bmatrix}
+ \begin{bmatrix}
\frac{1}{L_d} & 0 & 0 \\
0 & \frac{2\pi f L_q}{R_{th}} & 0 \\
0 & 0 & \frac{R_{th}}{L_f}
\end{bmatrix}
\begin{bmatrix}
u_{ds} \\
u_{dl} \\
u_{dq}
\end{bmatrix}
$$

(4.8)

Where,

$$
A_1 = -\frac{R_g}{L_d} x_{ds} + \frac{L_s}{L_d} \omega_r x_{qs},
$$

$$
A_2 = -\frac{3p^2}{2fL_q} \omega_r (-L_d \omega_r x_{ds} - R_s x_{qs} - \lambda_r \omega_r),
$$

$$
A_3 = \frac{2K_{pm} \omega_r}{f^2} \left( \frac{3p^2}{2} \omega_r - \frac{K_{pm} \omega_r^2}{p} \right) x_{qs} - \frac{K_{pm} \omega_r^2}{p} x_{qs},
$$

$$
A_4 = R_{th} \left( \omega_g x_{dq} \right) - \frac{u_{qd}}{L_f} - \omega_q L_c \left( -\omega_g x_{dl} - \frac{u_{dl}}{L_f} \right) + E_{thd},
$$

$$
A_5 = R_{th} \left( -\omega_g x_{dl} \right) + \omega_q L_c \left( \omega_g x_{dq} - \frac{u_{dq}}{L_f} \right) + E_{thq}
$$

The control law has the following form

$$
\vec{u} = 3(\hat{x})^{-1}[-A(\hat{x}) + \hat{v}]
$$

(4.9)

By choosing $u$ as in Eqn. (23), the nonlinearities in Eqn. (22) are cancelled and the following linear relationship between the new outputs $\vec{y}_d(\hat{x})$ and the new inputs, $\hat{v}$, is obtained.

$$
\vec{y}_d(\hat{x}) = \hat{v}
$$

(4.10)

Where,

$$
\vec{y}_d(\hat{x}) = [\vec{x}_{ds}, \vec{x}_{dl}, \vec{u}_{dl}, \vec{u}_{dq}]^T
$$

$$
\hat{v} = [v_1, v_2, v_3, v_4]^T
$$

Note that the total relative degree ($r = 7$) is equal to the order of the system $n (n = 7)$. Therefore, the linearization is complete and there is no internal dynamics. A state feedback controller is used. It has the following equation:

$$
v_p = -k_p e_p
$$

(4.11)

where $k_p (p \in \{1,2,3,4,5,6\}$ and $q \in \{1,2,3\}$) is the feedback gain matrix and $e_p$ represents the errors between the outputs variables ($\vec{x}_{ds}$, $\vec{x}_{dl}$, $\vec{u}_{dl}$, and $\vec{u}_{dq}$) and the reference signals. These references are equal to zero. Therefore, the expressions of $v_p (p \in \{1,2,3,4,5,6\})$ are as follows:

$$
v_1 = -k_{11} x_{ds} - k_{22} v_{ds}
$$

$$
v_2 = -k_{31} \dot{x}_{dl} - k_{32} \dot{v}_{dl}
$$

$$
v_3 = -k_{41} \dot{u}_{qd} - k_{42} \dot{u}_{dq}
$$

$$
v_4 = -k_{51} \dot{u}_{qi} - k_{52} \dot{u}_{q1}
$$

(4.12)

Where, $k_{ij}$ is the feedback gain matrix [1]. The reference signals, such as $i_{ds}$, $\omega_r$, $u_{dl}$, $u_{q1}$ are chosen considering the following points.

1) $i_{ds}$ is set to zero to realize the zero d-Axis current (ZDC) control scheme. This control scheme is employed to achieve a linear relationship between the stator current and the electromagnetic torque.

2) $\omega_r$ is generated by the MPPT with optimal tip speed ratio.

3) $u_{dl}$ is aligned with the grid voltage vector to achieve voltage-oriented control (VOC). Therefore, $u_{dl}$ is equal to the grid voltage magnitude. Hence $u_{q1}$ is equal to zero.

The synchronization to the grid is done by using a PLL (Phase-locked Loop). Therefore, in the grid connected mode, the grid frequency ($\omega_g$) which is used in the dq-abc coordinate transformation is generated by the PLL.

4. RESULTS AND DISCUSSION

The simulation is carried out using Matlab. The system consider for simulation comprises 2.45 MW variable speed non-salient pole PMSG generator is employed and the respective parameters are shown in Table -1 [5].

Case 1: System under standalone mode

The Simulink Model of PMSG based WECS under standalone mode is shown in fig.3. The inputs to the turbine are wind speed, pitch angle and generator speed. The output torque of the wind turbine is given to the PMSG as input. To analyze the behavior of PMSG under varying wind speed, three wind speeds are considered. For simulation, initial wind speed is taken as 12m/s and it falls to 8m/s at 1.5 time units and then reduces to 5m/s at 2.5-time units. The torque output of wind turbine is shown in fig.4. The torque is found to be negative since the Permanent Magnet Synchronous machine act as Generator.

The rotor speed of PMSG varies according to wind speed.

The output voltage and current of PMSG for varying wind speed are measured. It shows that the generated voltage and current are high when the wind speed is high and vice versa.

The simulated waveforms of the rotor speed, generator output power $P_m$ show that the PMSG output power depends on wind speed.
Fig -3: Simulink Model of PMSG based WECS under standalone mode

Table -1: Parameters of the system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rated Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_m$</td>
<td>2.5 MW</td>
</tr>
<tr>
<td>$\omega_m$</td>
<td>4.3 rad/s</td>
</tr>
<tr>
<td>$\lambda_r$</td>
<td>28 wb</td>
</tr>
<tr>
<td>$P$</td>
<td>8</td>
</tr>
<tr>
<td>$J$</td>
<td>4000 kgm$^2$</td>
</tr>
<tr>
<td>$R_g$</td>
<td>24.21 m$\Omega$</td>
</tr>
<tr>
<td>$L_{ds}, L_{qs}$</td>
<td>9.81mH</td>
</tr>
<tr>
<td>$v_m$</td>
<td>15 m/s</td>
</tr>
<tr>
<td>$u_d$</td>
<td>4kV</td>
</tr>
<tr>
<td>$u_{dc}$</td>
<td>8 kV</td>
</tr>
<tr>
<td>$C_{dc}$</td>
<td>1657 $\mu$F</td>
</tr>
<tr>
<td>$L_f$</td>
<td>16.884 mH</td>
</tr>
<tr>
<td>$L_g$</td>
<td>1.6884 $\mu$H</td>
</tr>
<tr>
<td>$u_{II}$</td>
<td>4kV</td>
</tr>
</tbody>
</table>

Fig -4: Torque output of Wind turbine

Fig -5: Rotor speed and output power of PMSG

Fig -6: Output Voltage and current waveforms of PMSG

Case 2: Grid connected system

The Simulink Model of PMSG based WECS under grid connected mode is shown in fig-6. The inputs to the turbine are wind speed, pitch angle and generator speed. The output torque of the wind turbine is given to the PMSG as input. The output of PMSG is given to the back to back converter to synchronize the variable frequency of PMSG with the grid frequency. The load is connected between back to back converter and the grid.
The Simulink Model of MIMO Controller for grid connected PMSG based WECS is shown in fig-8. The synchronization to the grid is done by using a PLL (Phase-locked Loop). Therefore, in the grid connected mode, the grid frequency which is used in the dq-abc coordinate transformation is generated by the PLL. The Controller is designed based on the equations (4.8) to (4.12). The controller gains are considered from [1].

The reference rotor speed is calculated by using MPPT with optimal tip speed ratio. The measured wind speed $v_w$ is used to produce the generator speed reference $\omega_r$ according to the optimal tip speed ratio $\lambda_{opt} = 8.1$. The MIMO controller is able to calculate and generate the required PWM pulses for Generator and Grid side converters. The output pulses are shown in fig-9. The control pulses are generated by controlling the output variables, rotor speed, stator direct axis current and dq components of load voltage.

The Simulink Model of MIMO Controller for grid connected PMSG based WECS is shown in fig-8. The synchronization to the grid is done by using a PLL (Phase-locked Loop). Therefore, in the grid connected mode, the grid frequency which is used in the dq-abc coordinate transformation is generated by the PLL. The Controller is designed based on the equations (4.8) to (4.12). The controller gains are considered from [1].
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