Research Article

Performance Analysis of Savonius Rotor Based Hydropower Generation Scheme with Electronic Load Controller

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1. Introduction

Of late, distributed generation schemes are becoming popular in developed as well as developing countries to augment the existing power scenario. Induction generators are best suited for such applications due to their many advantages over other generators available [1]. The conventional sources of energy from coal, oil, natural gas, and uranium are observed to pollute air and water and produce ecological imbalances and, therefore, are hostile to both human beings and other plants and animals in the long run. Therefore, alternative sources of energy, like wind, solar, hydro, tidal, geothermal, and so forth, need to be explored to bring about a change in the energy scenario, in terms of both capacity and quality. Hydropower schemes generate a clean and environment friendly form of energy. However, large hydropower plants with generating capacity above 25 MW are often considered to endow with drawbacks such as high initial cost and environmental impacts [2]. Therefore, distributed generation scheme with run-of-river scheme is considered to be a benign source of energy. The recent survey conducted by Energy Next (EN) in collaboration with the Ministry of New and Renewable Energy (MNRE), Govt. of India, in April 2015 reveals that the States of Arunachal Pradesh, Himachal Pradesh, and Uttarakhand alone have small hydropower (SHP) potential of 5447.16 MW with harnessed capacity of 917.63 MW [3]. This figure may go up with installation of more run-of-river schemes in these areas. In smaller capacity hydropower plants, use of uncontrolled turbines is preferred, thus allowing the water flow as it comes and driving the turbine-generator set. Use of costly governors in such applications is unwise; thus use of load control mechanism is usually adopted. In this paper, a mechanism is evolved to regulate the consumer’s load by diverting additional load to a dump load, thereby maintaining the power output of the machine by the use of an electronic load controller (ELC).

The use of ELC in the proposed scheme is realized by incorporating an AC-DC-AC converter similar to that of a wind energy conversion system, which produces a constant voltage and constant frequency from variable water velocity. Once a stable voltage and frequency are achieved, the total output power remains constant and hence the power switching between the main load and the dump load becomes feasible.

The turbine selected in the present study is a vertical axis Savonius rotor, which is commonly used as wind turbines...
2. System Configuration

In the proposed scheme, a Savonius rotor coupled with a 7.5 kW, 3-phase, 415 V, 14.5 A, 50 Hz, Y-connected, 4-pole, squirrel cage induction machine is employed. The excitation of the AG is achieved by means of a delta connected capacitor bank of 140 μF. The dimension of Savonius rotor so selected is given in the appendix.

The power output from Savonius turbine is given by

\[ P = 0.5 C_p A \rho V^3, \]  

where \( P \) is power output (W), \( \rho \) is the density of water (kg/m³), \( A \) is the swept area of rotor (m²), \( V \) is the velocity of water (m/s), and \( C_p \) is the power coefficient.

Tip speed ratio is given by

\[ \text{TSR} = \frac{\omega D}{2V}, \]  

where \( \omega \) is the angular velocity and \( D \) is rotor diameter (m). Coefficient of torque \( C_t \) is given by

\[ C_t = \frac{C_p}{\text{TSR}}. \]  

Shaft torque \( T_{sh} \) is given by

\[ T_{sh} = \frac{p}{\omega} = \frac{0.5 C_p A \rho V^3}{2\pi N/60}. \]  

The generated voltage and frequency of the machine are likely to vary with the varying velocity of river water. This, in turn, would result in unbalanced voltage and frequency at the load end. Thus, for uncontrolled turbine with varying input power, it is essential to determine the real and reactive power requirements of the generating machine in order to arrest the changes in terminal voltage and frequency. To maintain the rated voltage and frequency at the load end therefore, an AC-DC-AC converter realized with the help of an uncontrolled rectifier and insulated gate bipolar transistor (IGBT) based current controlled voltage source inverter (CC-VSI) is used. The triggering pulses to the three-legged IGBTs are varied in accordance with the varying input power.

The variation in the DC link capacitor voltage presents the direct-axis component of current from the machine. The peak value of the line-to-line voltage from the machine is computed and compared with the reference peak value (415√2 V). The difference between these two quantities is the reactive power required by the machine or is the amount of quadrature-axis component of current to be supplied to the machine. These two axes reference currents, namely, \( I_{ds} \) and \( I_{qs} \), are converted into three-phase form by inverse Park’s transformation. The “\( \cos(\omega t) \)” and “\( \sin(\omega t) \)” terms needed for Park’s transformation are derived with the help of a phase locked loop (PLL) which is fed with unit templates of line voltages from the machine. The three-phase reference currents thus obtained are compared with the actual load currents in a hysteresis current controller to yield the firing signals for the six devices in the voltage source inverter (VSI). The fluctuation in capacitance voltage is due to power consumed by the devices in the VSI and filter resistances.

2.1. Generation of Unit Voltage Templates. The line voltages \( (V_{ab}, V_{bc}, \text{and } V_{ca}) \) of the generator terminals are considered sinusoidal and therefore, their amplitudes are computed as

\[ V_{\text{actual(peak)}} = \sqrt{\frac{2}{3}} (V_{ab}^2 + V_{bc}^2 + V_{ca}^2). \]
The unit template voltages are derived as

\[
\begin{align*}
    u_a &= \frac{V_{ab}}{V_{\text{actual \(peak\)}}}, \\
    u_b &= \frac{V_{bc}}{V_{\text{actual \(peak\)}}}, \\
    u_c &= \frac{V_{ca}}{V_{\text{actual \(peak\)}}},
\end{align*}
\]

where \(V_{\text{actual \(peak\)}}\) is the peak value of the three-phase ac voltage being sensed at the generator terminal at the \(n\)th instant. The output of the PI controller \((I_{qs}^*)\) for maintaining the ac terminal voltage constant at the \(n\)th instant is expressed as

\[
I_{qs}^* = I_{qs(n-1)} + K_{pa} \left( V_{\text{err}(n)} - V_{\text{err}(n-1)} \right) + K_{as} V_{\text{err}(n)},
\]

where \(K_{pa}\) and \(K_{as}\) are the proportional and integral gain constants of the PI controller, \(V_{\text{err}(n)}\) and \(V_{\text{err}(n-1)}\) are voltage errors in the \(n\)th and \((n-1)\)th instants, and \(I_{qs(n-1)}^*\) is the amplitude of quadrature component of the reference source current at the \((n-1)\)th instant.

2.2. Quadrature-Axis Component of Reference Source Currents. The ac voltage error \(V_{\text{err}(n)}\) at the \(n\)th sampling instant is given by

\[
V_{\text{err}(n)} = V_{\text{ref}(peak)(n)} - V_{\text{actual \(peak\)}(n)},
\]

where \(V_{\text{ref}(peak)(n)}\) is the peak value of the three-phase ac voltage being sensed at the generator terminal at the \(n\)th instant.

2.3. Direct-Axis Component of Reference Source Currents. The error in dc bus voltage \(V_{\text{derr}(n)}\) of the VSI at the \(n\)th sampling instant is given by

\[
V_{\text{derr}(n)} = V_{\text{derr}(n)} - V_{\text{d\(actual\)}(n)},
\]

where \(V_{\text{derr}(n)}\) is the reference dc voltage and \(V_{\text{d\(actual\)}(n)}\) is the DC link voltage of the VSI being sensed at the \(n\)th instant. The output of the PI controller \((I_{ds}^*)\) for maintaining dc bus voltage at the \(n\)th instant is expressed as

\[
I_{ds}^* = I_{ds(n-1)} + K_{pd} \left( V_{\text{derr}(n)} - V_{\text{derr}(n-1)} \right) + K_{id} V_{\text{derr}(n)}.
\]

where \(I_{ds(n)}^*\) is considered as the amplitude of active source current at the \(n\)th instant while \(K_{pd}\) and \(K_{id}\) are the proportional and integral gain constants of dc voltage PI controller.

2.4. Reference Source Currents. The reference source currents \((I_{as}^*, I_{bs}^*, \text{and } I_{cs}^*)\) are obtained with the help of inverse Park's transformation as shown in

\[
I_{d\phi} = T I_{abc}
\]

\[
= \begin{bmatrix}
    \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\
    \sin(\omega t) & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\
    \sqrt{\frac{2}{3}} & \sqrt{\frac{2}{3}} & \sqrt{\frac{2}{3}}
\end{bmatrix}
\begin{bmatrix}
    I_a \\
    I_b \\
    I_c
\end{bmatrix}.
\]

2.5. Current Controller. The load currents \((I_a, I_b, \text{and } I_c)\) are compared with the reference source currents \((I_{as}^*, I_{bs}^*, \text{and } I_{cs}^*)\) and error signals are passed through hysteresis band to generate the firing pulses, which are operated to produce output voltage in manner to reduce the current error. Figure 3 shows the three-phase CC-VSI with hysteresis current controller.

The output of the current controller decides the switching patterns to be given to the IGBTs in the VSI. The current errors are computed as

\[
\begin{align*}
    I_{a\text{err}} &= I_{as}^* - I_a, \\
    I_{b\text{err}} &= I_{bs}^* - I_b, \\
    I_{c\text{err}} &= I_{cs}^* - I_c.
\end{align*}
\]

3. Design and Control of ELC

Although the input power is varying, with the help of AC-DC-AC converter, the generator terminal voltage and frequency are observed to be constant. Thus, the total power generated remains constant; so a power diverter circuit such as an ELC may be connected in parallel to the main load. This circuit diverts the unused power to an auxiliary load or dump load thus helping in achieving balance of the power system. The ELC is designed using IGBT based chopper switch.

![Figure 3: Schematic diagram of control scheme.](image-url)
For feeding reactive power in case of 0.8 pf lagging reactive load it is found that AGs require 130%–160% of rated generated power [10–12]. Therefore, for 7.5 kW generators the VAR rating of the controller should be around 9.975 kVAR (133%).

Then, the apparent power $S$ is given by

$$S = \sqrt{7.5^2 + 9.98^2} = 12.48 \text{kVA.}$$

So the current rating of the converter is

$$3V_L = 12.48,$$

$$I_c = 17.36 \text{A.}$$

Now, average current flowing through ELC can be taken as 90% of converter rms current, considering the worst case of load unbalancing:

$$I_{(\text{average})} = 0.90 \times 17.36 = 15.62 \text{A.}$$

Considering voltage ripple in $V_{dc}$ in the order of 2% then

$$V_{dc(\text{ripple})} = 2\% \text{ of } 560 = 11.2 \text{ V.}$$

Taking the values of $V_{dc(\text{ripple})}$, $I_{(\text{average})}$, and $\omega = 314 \text{ r/s}$, we have

$$C_{dc} = \frac{I_{(\text{average})}}{2\omega V_{dc}} = 2220.7 \mu \text{F} \approx 3000 \mu \text{F.}$$

3000 $\mu \text{F}$ is selected which is available in market.

Rating of dump load is

$$R_{dp} = \frac{V_{dc}^2}{P_R} = \frac{560^2}{7500} = 48 \Omega \approx 50 \Omega.$$ 

Value of $R_{dp}$ is selected as 50 $\Omega$ for giving wide range of control to the controller, where $R_{dp}$ is resistance of dump load and $P_R$ is rated power of generator.

The control signal for chopper is generated through the error signal generated by comparing voltage across DC capacitor and the reference voltage of 560 V. Chopper regulations maintain the machine terminal voltage constant by feeding additional load to dump load.

The output power of the AG is held constant at varying consumer loads. Thus, the generated power is given by

$$P_{gen} = P_{ELC} + P_{Load},$$

where $P_{gen}$ is generated power by the AG, $P_{Load}$ is consumer’s load, and $P_{ELC}$ is the power absorbed by the ELC [13].

### 4. Results and Discussion

A complete hydropower generation scheme consisting of a Savonius rotor, asynchronous machine, and AC-DC-AC converter connected to three-phase load is modeled and simulated in MATLAB/Simulink environment. Varying water velocities ranging from 1.96 m/s to 2.02 m/s are considered. Table 1 shows the variation of active power with the velocity of water.
Table 1: Variation of output power with velocity of water.

<table>
<thead>
<tr>
<th>S/number</th>
<th>Velocity of water (m/s)</th>
<th>Active power output (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>1.8</td>
<td>1.35</td>
</tr>
<tr>
<td>4</td>
<td>1.96</td>
<td>2.0</td>
</tr>
<tr>
<td>5</td>
<td>2.0</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Figure 6: Variation of consumer power and dump load power.

Three-phase resistive loads are switched in at different instants; three-phase loads of 1 kW, 2.5 kW, and 1 kW, respectively, are connected and then disconnected at 1.0 s and 1.5 s, 1.5 s and 2.0 s, and 2.5 s and 3.0 s, respectively, as shown in Figure 6. As seen from the figure, the rated terminal voltage is maintained while the machine is loaded and there is a precise load sharing between the main load and the dump load. The generator is operated to produce a maximum power output of 2.5 kW. When the consumer’s load is zero, the dump load takes the total generated power. On the other hand, when the consumer’s load is equal to the maximum generator output, no power is diverted to dump load. This act of power switching between the two ensures a constant total power output from the machine at constant terminal voltage.

The Fast Fourier Transforms (FFT) analysis of load current at full load indicates a total harmonic distortion (THD) of 2.93%. This is shown in Figure 7. The ELC starts working at 0.5 s when the voltage across the DC link capacitor builds up to 560 volts. Figures 8 and 9 show the system frequencies and DC link voltages of AC-DC-AC converter and ELC while Figure 10 shows the MATLAB/Simulink model of the
complete system. In this paper, variable water velocity is considered, as the analysis becomes easier when the input power remains constant, which means velocity of water remains the same, but in actual practice, it will never be constant; hence the use of dual converters plays a vital role here.

5. Conclusions

The work presented in this paper demonstrates a successful power switching between the main load and the dump load while maintaining a constant terminal voltage. The performance of ELC is satisfactory. The AC-DC-AC converter performs satisfactorily with independent control of active and reactive power thus giving a constant voltage and frequency output at the machine terminal. The proposed system may be adopted in rural areas where distributed power generation is a suitable option and the consumers are less. The power diverted to the dump load may also be gainfully utilized in battery charging and supplying power to some auxiliary circuit or equipment.

Appendices

A. Machine Parameters

Three-phase generating unit was as follows: 7.5 kW, 415 V, 14.5 A, 50 Hz, Y-connected, 4-pole, squirrel induction machine:

\[ R_s = 0.9 \, \Omega, \quad R_r = 0.66 \, \Omega, \quad X_{ls} = X_{lr} = 1.437 \, \Omega, \quad \text{and} \quad X_{ml} \text{ (sat.)} = 35.74 \, \Omega. \]

B. Controller Parameters for AC/DC/AC Controller

Consider \( C_{dc} = 2000 \, \mu F, \quad K_{pa} = 0.0118, \quad K_{ia} = 0.0018, \quad K_{pd} = 0.036, \quad \text{and} \quad K_{id} = 0.0008. \)

C. Savonius Rotor Parameters

The Savonius rotor parameters are as follows: \( D_r \) (rotor diameter) = 2 m, \( H_r \) (rotor height) = 2 m, \( C_p \) (power coefficient) = 0.25, \( \rho \) (water density at 25\(^\circ\)C) = 997.0479 kg/m\(^3\), and inner diameter = 1.8 m, with thickness = 100 mm, no overlapping.

D. LCL Filter Parameters

Consider \( L_f = 80 \, \text{mH}, \quad C_f = 40 \, \mu F, \quad R_f = 30 \, \Omega. \)

E. ELC Parameters

The ELC parameters are as follows: current rating = 17.36 A, DC capacitor rating (selected) = 3000 \( \mu F \), rating of dump load (selected) = 50 \( \Omega \), controller parameter, \( K_p = 0.5 \), and \( K_i = 8. \)
Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References


