Advance Electronic Load Controller for Micro Hydro Power Plant

Dipesh Shrestha, Ankit Babu Rajbanshi, Kushal Shrestha and Indraman Tamrakar
Department of Electrical Engineering, Institute of Engineering, Tribhuvan University, Lalitpur 1915, Nepal

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Abstract: Most of the MHP (micro hydro power) plants use ELC (electronic load controller) for speed control. Various types of ELC have been developed so far. A dummy ballast load is connected across each phase of generator terminals and ELC controls the power consumed by the ballast load to result in constant speed operation. The ELC developed so far uses thyristor switches in each phase to control ballast load power. The ELC senses the system frequency and comparing it with reference frequency, it generates a common value of firing angle for all three thyristor pairs of each phase. The performance of such ELC is not perfect for unbalanced consumers load connected in each phase, which overloads the generator. This paper presents an advanced type of ELC which senses frequency as well as consumer’s load current of each phase and fires the thyristor pairs with different value of firing angles for different phases. This solves the problem of overloading of the generator with unbalanced consumer’s load. Simulink model is developed to perform transient analysis of the proposed scheme and the prototype of hardware is also fabricated. The simulation results and experimental results are presented.

Keywords: MHP, ELC, current balancing, thyristor.

1. Introduction

MHP (micro hydro power) is one of the most economical and environmental friendly technology of energy supplement in rural area. MHP fulfills the electrical energy demand in rural area which is not served from national grid due to the higher cost of transmission line. So, all the MHP plants are operated in isolated mode. MHP designers always try to design the MHP at a lower possible cost. Therefore, ELC (electronic load controller) is used instead of oil pressure governor in order to reduce the high cost of governor. MHP is run off river type plant without reservoir at headrace and turbine is operated at constant head and discharge. The plant capacity is designed for minimum discharge available at dry season. So, there is no meaning of saving the water during light load period.

Frequency variation of ±2% and terminal voltage variation of ±5% from their nominal rated values are acceptable in MHP scheme as reported in Ref. [1].

An ELC is an electronic device that keeps the speed of synchronous generator constant at varying load conditions. The generator is driven by unregulated turbine with constant power output and a dummy ballast load is connected across the generator terminals to dump the excess of power generated. When the consumers load change, frequency of generated voltage changes. The frequency is sensed and compared with the reference frequency and the error signal that obtained is utilized to control power consumed by ballast load so that generator always operates at its full rating, which results to constant speed as reported in Ref. [2]. Various types of electronic load controller so far developed are reported in Ref. [3]. Most of the reported electronic load controllers are based on controlled and uncontrolled rectifier with DC (direct current) chopper. In Refs. [4, 5], the modeling and design of ELC based...
on rectifier and DC chopper are reported for the transient analysis of the performance of SEIG (self-excited induction generators). Singh et al. [6] have described the mathematical modeling of self-excited induction generators with ELC (improved electronic load controller) for micro hydro applications supplying variety of loads. The ELC developed so far works on frequency balance technique in which the ballast of each phase is fired with same firing angle. So, all ballast loads consume equal power resulting to overloading of synchronous generator for unbalanced loads. Therefore, it is usual practice to select an oversized generator to overcome this problem and overloading of the generator increases the overall cost of the plant.

This paper deals with the frequency and phase current balance technique of ELC to reduce the overloading of the generator. In the proposed scheme, anti-parallel connected thyristor pair is used to control the power consumed by ballast of each phase and the change in load in one phase does not affect the dummy power consumption of other phases. The scheme is simulated using Matlab Simulink and the simulation results are presented. Moreover, the prototype hardware is also fabricated and the experimental results are presented, too.

2. Proposed Scheme

Fig. 1 shows the schematic diagram of the proposed scheme. The synchronous generator has an exciter, which controls the voltage variation due to changing load. It is driven by unregulated turbine with constant power output of 1 p.u.. The generator supplies power to the three phase resistive consumer load. The proposed ELC with resistive ballast load in each phase is connected in parallel to the load. If the consumers load of a phase changes, the load current of respective phase change and frequency of generated voltage changes. The frequency and load currents of each phase are sensed. Then the firing angles for the thyristor of respective phases are calculated. After firing the thyristor pairs with calculated firing angles, it results to constant frequency and balance generator terminal currents, too.

3. Modeling of the Proposed Scheme

3.1 Modeling of Synchronous Generator

The synchronous machine model available in the Matlab Simulink is used for performing the transient analysis of the proposed scheme. The d-q equivalent circuit model of the synchronous machine is used in the simulation model, which takes care of dynamics of stator, field and damper windings. This model has considered the effect of magnetic saturation which is reported in Ref. [7]. Stator windings of synchronous generator are assumed to be connected in star with grounded neutral. A 1.2 KVA synchronous generator model with terminal voltage of 230 V is chosen for simulation study.

3.2 Modeling of Electronic Load Controller

ELC is used to consume the excess of power delivered by the synchronous generator. The ELC proposed in the scheme consumes power in such a way that the excessive power of particular phase is dissipated in the ballast of the respective phase so that the generator is not overloaded. In case of no load condition, the ELC can dissipate all active power generated in the ballast load. Fig. 2 shows the basic circuit diagram and the control strategy of the proposed ELC.

In this scheme, the three phase generator is connected to a three phase varying load. The frequency of the generated voltage and the load currents of all
phases are sensed.

Fig. 3 shows the logic behind the firing angle generation for the ballast of each phase. The frequency of the generated voltage is compared with the reference frequency, i.e., 50 Hz. The error obtained is fed to the PI-controller [8]. The PI-controller generates firing angle to balance the frequency of the generated voltage. Moreover, the load current of each phase is fed to the microcontroller. Inside the microcontroller, each phase load current is compared with the rated phase current of generator, i.e., 1.73 A for 1.2 KVA generator with terminal voltage of 230 V. This error current of each phase should flow through the ballast of respective phase to balance the generator terminal currents. In order to flow this desired current through the ballast, the firing angle is calculated inside the microcontroller using Eq. (3). Eqs. (1) and (2) give the output voltage and current of the chopped waveform for different values of firing angle for the resistive ballast load as reported in Ref. [9]. Using data of output chopped current and firing angle obtained from Eq. (2), Eq. (3) has been derived using regression method. Eq. (3) gives the value of firing angle “$\alpha$” for a particular value of current. In this way, the microcontroller generates the firing angle for the ballast of each phase using Eq. (3) which balances the phase current of the generator. Finally, the firing angle generated by microcontroller for each phase is added with the firing angle generated by the PI-controller. The firing angle that obtained for each phase fires the ballast of respective phase. In this way, both the generator terminal currents and frequency are balanced without causing overload to the generator even in unbalanced load condition.

$$V_o = V_s \left[1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}\right]^{1/2}$$ (1)

$$I_o = \frac{V_o}{R_{ballast}} = \frac{V_s}{R_{ballast}} \left[1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}\right]^{1/2}$$ (2)

$$\alpha = p_1 \times i_b^4 + p_2 \times i_b^3 + p_3 \times i_b^2 + p_4 \times i_b + p_5 \quad (3)$$

where,

$V_o =$ output rms voltage of the chopped waveform;
$I_o$ = output rms current of the chopped waveform;
$\alpha$ = firing angle for the thyristor;
$V_s$ = input rms voltage;
$R_{\text{ballast}}$ = resistance of ballast;
$i_b$ = current to be flown through ballast;
$p_1 = 0.2552$;
$p_2 = -1.054$;
$p_3 = 1.455$;
$p_4 = -102.1$;
$p_5 = 180.1$.

The detail parameters of the synchronous machine model of matlab are given in the Appendix. The required value of ballast load resistance is calculated as follows:

- Line to line voltage (VL) = 400 V;
- Generator full load current (Iphase) = $\frac{\text{kVA}}{\sqrt{3}V_L} = \frac{1.2}{\sqrt{3} \times 400} = 1.73$ A;
- Generator maximum output power per phase (Pphase) = 333 W;
- Ballast resistance per phase (Rballast) = $\frac{P_{\text{phase}}}{I_{\text{phase}}} = \frac{333}{1.73} = 111.1 \Omega \approx 110 \Omega$.

4. Simulation Results

The complete simulation model of proposed scheme is shown in Fig. 4. Fig. 5 shows the detail of ELC block. The scheme consists of a 1.2 KVA synchronous generator. The rating of ballast load chosen is able to consume all the power generated by the generator at no-load case. The excitation voltage $V_f$ of synchronous generator is limited to 2.1 p.u., which is just sufficient to produce 1 p.u. of stator terminal voltage at full resistive load.

The model is simulated with the varying loads. First, the model is operated with load of 333 W in each phase. After 3 seconds, the load of R-phase is disconnected. After 6 seconds, the load of Y-phase is also disconnected. After 9 seconds, the loads of all phases are disconnected from the system. After 12 seconds,
the loads of all phases are again switched ON. This switching pattern of loads is shown in Table 1.

Fig. 6a shows the speed of the generator which is nearly constant and equal to 1 p.u. Fig. 6b shows the average power generated $P_{gen}$ by the generator which is also nearly constant and nearly equal to 1.18 KW. Fig. 6c shows the average active power consumed by the consumer $P_{load}$ which is changing with different load switching. Fig. 6d shows the average active power consumed by the ballast $P_{ballast}$. From Figs. 6b-6d, it is clear that the average active power generated by the generator at any instant is equal to the sum of active power consumed by the consumer and respective ballast at any instant. Table 2 shows the speed and average active power generated by generator and consumed by consumer and ballast load. Table 3 shows the currents at different time intervals during the simulation period. The simulation results show that the total power generated by the generator is always constant and equal to the sum of power consumed by the ballast load and consumer load resulting in constant speed and the generator terminals currents are balanced.

The simulation results show that there are some transients because of switching on and off of loads at the interval of 3 seconds. The current, power and frequency during the transient periods are within the acceptable range. The generator current reaches at most to the value of 1.92 A during the time of 6-9 seconds when the load at two phases are zero as shown in Table 3. This is the worst case where the overloading of the generator is maximum and equal to 10.98%.

Table 1  Loads at different time interval.

<table>
<thead>
<tr>
<th>Phase</th>
<th>0-3 s</th>
<th>3-6 s</th>
<th>6-9 s</th>
<th>9-12 s</th>
<th>12-15 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>333 W</td>
<td>0.1 W</td>
<td>0.1 W</td>
<td>0.1 W</td>
<td>333 W</td>
</tr>
<tr>
<td>Y</td>
<td>333 W</td>
<td>333 W</td>
<td>0.1 W</td>
<td>0.1 W</td>
<td>333 W</td>
</tr>
<tr>
<td>B</td>
<td>333 W</td>
<td>333 W</td>
<td>333 W</td>
<td>0.1 W</td>
<td>333 W</td>
</tr>
</tbody>
</table>
Fig. 6  (a): Speed response of generator; (b) Average active power generated by generator; (c): Active power consumed by consumer load; (d): Average active power consumed by ballast load; (e): Response of generator terminal currents; (f): Zoomed views of generator terminal currents; (g): Response of ballast load current; and (h): Zoomed views of ballast load current.
Table 2 Speed and power results at different time intervals.

<table>
<thead>
<tr>
<th>Variables</th>
<th>0-3 s</th>
<th>3-6 s</th>
<th>6-9 s</th>
<th>9-12 s</th>
<th>12-15 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{gen}} ) (W)</td>
<td>1,180</td>
<td>1,180</td>
<td>1,180</td>
<td>1,180</td>
<td>1,180</td>
</tr>
<tr>
<td>( P_{\text{load}} ) (W)</td>
<td>1080</td>
<td>780</td>
<td>455</td>
<td>0</td>
<td>1,080</td>
</tr>
<tr>
<td>( P_{\text{ballast}} ) (W)</td>
<td>100</td>
<td>400</td>
<td>725</td>
<td>1,180</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 3 Current at different intervals.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Generator current (A)</th>
<th>0-3 s</th>
<th>3-6 s</th>
<th>6-9 s</th>
<th>9-12 s</th>
<th>12-15 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>1.71</td>
<td>1.86</td>
<td>1.92</td>
<td>1.80</td>
<td>1.70</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>1.70</td>
<td>1.58</td>
<td>1.69</td>
<td>1.80</td>
<td>1.73</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1.71</td>
<td>1.62</td>
<td>1.69</td>
<td>1.80</td>
<td>1.68</td>
<td></td>
</tr>
</tbody>
</table>

5. Experimental Results

Fig. 7 shows the overall hardware circuit diagram of Advance ELC. It consists of a frequency sensor, three zero crossing detectors, offset and triac firing circuits. The overall programming is done in ATMEGA32 microcontroller. The frequency sensor senses the frequency of the generated voltage by synchronous generator. The zero crossing detector circuit detects the zero crossing points of ac voltage of each phase which is used as reference point for gate signal for firing triac.

The microcontroller can measure voltage only but not current. So the consumers’ load current is measured with the help of transducer called current probe which converts alternating current to equivalent AC voltage. This ac voltage cannot be directly fed to microcontroller. The offset circuit offsets the AC voltage obtained from the current probe and converted to DC signal and by using root mean square formula the current is calculated by microcontroller. Finally, the microcontroller generates the firing angle “\( \alpha \)” by using the technique used in simulation and fires the triac so that the extra power generated are dumped in the ballast load of respective phases.

Fig. 8 shows the overall system setup for testing Advance ELC. The three phase synchronous generator of 1.2 KVA capacities is driven by a DC motor of 2 KW capacities. The speed of DC motor is set manually to a constant value by controlling the voltage across armature of motor so that the setup can be realized as generator driven by a turbine with constant flow of water. The output terminals of synchronous generator are connected to three resistive rheostats in each phase which act as consumers’ load. The resistive ballast loads are also connected across each phase of generator terminal through the triac. On changing the firing angles of the gate signal fed to the triac, the power consumed by respective ballast load can be controlled. Due to the limitations of the excitation system, the terminal voltage of generator is set to be 100 V. So, the reference generator current is set to be 3.3 A. Due to absence of over frequency protection devices and safety, the rotor is rotated at a lower reference speed of 1,050 rpm instead of 1,500 rpm. So, the reference frequency is set to be 35 Hz. The details of dc motor and synchronous motor used
are given in the Appendix.

Figs. 9a-9c show the current waveforms of generator, consumer and ballast load, respectively.

The experimental results at different load condition are shown in Table 4.

For the testing of Advance ELC, the variable consumer load was connected in R-phase only and the ballast load was connected to the respective phase. But Advance ELC can work under the condition of variable load in all phase. The results from Table 4 show that the frequency of the generated voltage is nearly constant and equal to 35 Hz. Moreover, the generator terminal current of each phase is also nearly equal to the rated terminal current, i.e., 3.3 A. The results prove that the Advance ELC balances both the frequency of the generated voltage and the generator terminal current. Moreover, the overloading of the generator is also reduced. The Advance ELC developed can work well for other generators with different rated frequency and rated current, too.

5. Conclusion

The simulation and experimental results show that the developed ELC works very well. The frequency of the system is nearly constant. The current of all the phases of the generator are also nearly balanced and equal to the rated terminal current. This shows that the proposed scheme has eliminated the problem of overloading of the generator in micro hydro power plant. Moreover, there are some transients in the speed, current and power of the system at the instance of switching of load which are under the acceptable range.

Acknowledgment

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Table 4 Generator, consumer and ballast current along with frequency at different time intervals.

<table>
<thead>
<tr>
<th>R-Phase</th>
<th>Y-Phase</th>
<th>B-Phase</th>
<th>Freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_G$</td>
<td>$I_B$</td>
<td>$I_L$</td>
<td>$I_G$</td>
</tr>
<tr>
<td>3.67</td>
<td>2.78</td>
<td>0.88</td>
<td>3.02</td>
</tr>
<tr>
<td>3.71</td>
<td>2.81</td>
<td>0.92</td>
<td>3.20</td>
</tr>
<tr>
<td>3.21</td>
<td>2.85</td>
<td>1.29</td>
<td>3.13</td>
</tr>
<tr>
<td>3.64</td>
<td>0.29</td>
<td>1.33</td>
<td>3.28</td>
</tr>
<tr>
<td>3.20</td>
<td>1.59</td>
<td>1.62</td>
<td>3.37</td>
</tr>
<tr>
<td>3.38</td>
<td>0.86</td>
<td>2.48</td>
<td>3.23</td>
</tr>
<tr>
<td>3.41</td>
<td>0.24</td>
<td>3.10</td>
<td>3.19</td>
</tr>
</tbody>
</table>

$I_G$ = generator current; $I_B$ = ballast current; $I_L$ = load current; Freq. = frequency.
References


Appendix

Ratings and parameters of synchronous generator used in the simulation are as follows:

1.2 KVA, 400V, 50 Hz, 1500 rpm

\[ X_d = 1.734 \text{ p.u.}, \quad X'_d = 0.177 \text{ p.u.}, \quad X''_d = 0.111 \text{ p.u.} \]

\[ X_q = 0.861 \text{ p.u.}, \quad X'_q = 0.199 \text{ p.u.} \]

\[ T_d' = 0.018 \text{ s}, \quad T'_d'' = 0.0045 \text{ s}, \quad T''_d'' = 0.0045 \text{ s} \]

\[ R_s = 0.02 \text{ p.u.}, \quad H = 1 \text{ s} \]

The specification of the DC shunt motor are:

*Output power:* 2 KW

*Speed:* 1,500 RPM

Armature voltage: 220 V

Armature Current: 12 A

Field voltage: 220 V

Field Current: 0.8 A

The specification of the generator are:

*Output power:* 1.2 KVA

*Speed:* 1500 RPM

Star connection: 220 V/3.5 A

Delta connection: 127 V/6.1 A

Field voltage: 220 V

Field current: 1.4 A

Power factor: 0.8