Improved Electronic Load Controller for Three Phase Isolated Micro-Hydro Generator

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Abstract—Electronic Load Controller (ELC) is a power electronic device used in place of conventional speed governor in small isolated micro hydro-power plant for load frequency control. ELC functions by dumping excess energy into dummy loads when consumers switch off their loads, thereby maintaining the total load on the generator constant. Existing types of ELC uses three sets of dummy loads and three sets of power electronic switch for controlling power of each phase. This paper presents a method for controlling power consumed from each phase by using a single dummy load and a single power electronic switch. This results in significant reduction in component count and the adjoining costs. The paper shows how the proposed scheme of ELC can maintain the system frequency constant and balance the terminal current in all three phases even when the consumers' loads are unbalanced.

Keywords—Micro Hydropower Plant; Electronic Load Controller; Dummy Load.

I. INTRODUCTION

Micro Hydropower Plants (MHP) are growing source of electrical energy in the rural areas of developing countries where the population is small and sparsely distributed and the extension of national grid is not financially feasible because of high-cost investment required for transmission line. The MHP designers and planners have made their efforts to reduce the construction cost of MHP by using ELC instead of conventional oil pressure mechanical governor [1-2]. When there is change in system load, the frequency tends to change. In order to keep the frequency constant, the conventional speed governing system regulates the input water supply to the hydraulic turbine. But in ELC, corresponding to reduction in system load, additional dummy loads are introduced to the system without making any changes to prime mover [1]. This makes the total load, dummy load plus the consumer loads, in the system constant resulting in constant speed operation. This avoids the use of any flow regulating device and makes the scheme simple.

Previous forms of ELCs use at least three sets of dummy loads and three sets of power electronic switch to dump power from each phase to the dummy loads [2]. Fig. 1 shows the schematic of a popular form of ELC, AC Voltage Controller based ELC, implemented with the synchronous generator. In this type of ELC, a dummy ballast load is connected in parallel with the consumer's load through a pair of anti-parallel connected thyristors. The power consumption by the dummy load is controlled by varying the firing angle 'α' of the thyristor- pair. This form of ELC has major disadvantages like harmonics introduced due to chopping of current through ballast load, consumption of reactive power by ballast load and, lack of current sensing mechanism and independent gate signal generation which results in phase current imbalance and thus generator over-sizing is required [1] .

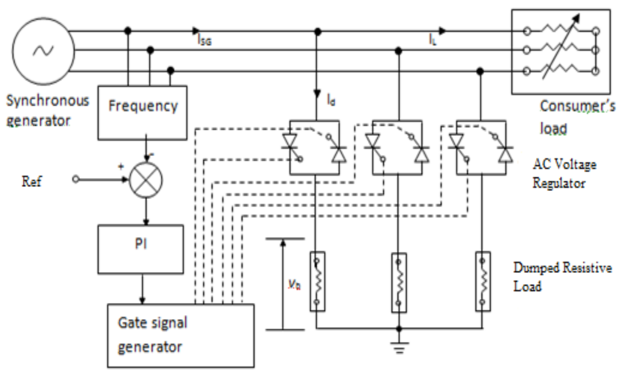


Fig 1 Detail circuit diagram of ac voltage controller based ELC

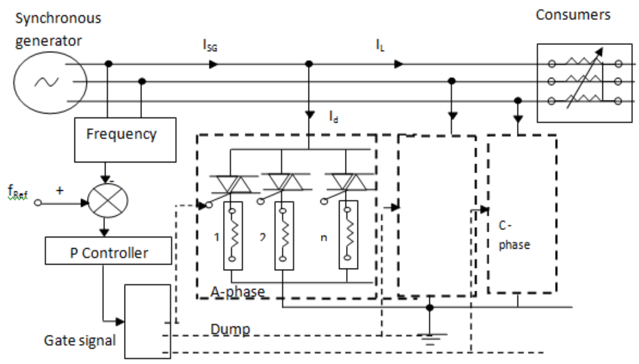


Fig. 2 Detail circuit diagram of discrete resistance type ELC.

Fig. 2 shows another type of widely used ELC, Discrete Resistance type ELC. This type of ELC turns on or off the discrete resistance bank rather than chopping the voltage across the dump load to increase or decrease the power consumed by the dump load. The major drawbacks of this ELC are the requirement of discrete sizes of dummy loads, large number of dummy loads and the high cost associated with them.

This paper deals with design and analysis of a new type of ELC that has a single dummy load and single power electronic switch to control the power consumed from each of the phases making generator terminal current in all three phases balanced.

II. PROPOSED SCHEME

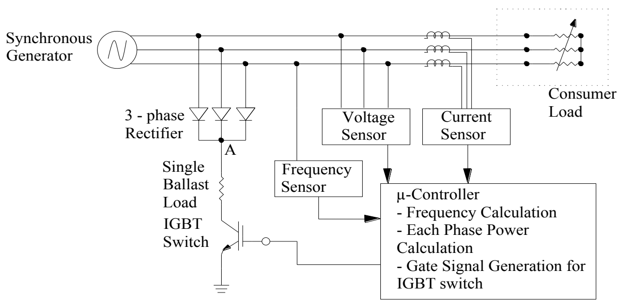


Fig. 3 Proposed Scheme of ELC

Fig. 3 shows the proposed scheme of ELC. A set of diodes forms the half-wave rectifier circuit. The dummy load is connected at the DC bus marked 'A'. An IGBT switch completes the circuit by connecting the other end of the dummy load to the generator neutral which is grounded. The main feature of the proposed scheme of ELC is the ability to draw different currents through different phases of the ac side of the rectifier terminals which allows it to compensate for the unbalanced consumer currents. The three phase half wave rectified waveform of point A is shown in Fig. 4(a). Current drawn from different phases by the dummy load can be controlled by employing different duty cycle for each 120^0 conduction period corresponding to each phase as shown in Fig. 4(b). For example, if the duty cycle of PWM gate signal for the IGBT is varied only for the region marked 'R' in the Fig. 4(b), it will change the current being consumed by the dummy load from the R phase only.

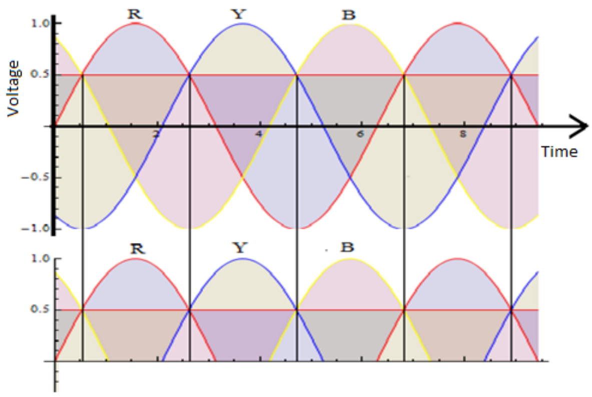


Fig. 4 (a): Three phase half wave rectified waveform

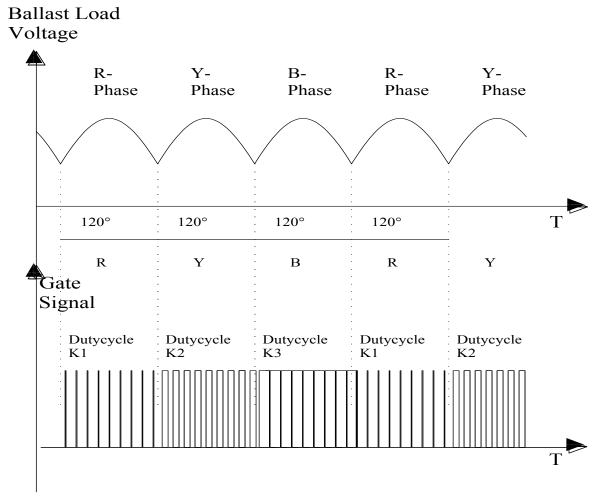


Fig. 4 (b): Rectified Voltage waveform across dummy load (top) and gate signal with different duty cycle corresponding to each phase (bottom).

It is understood that for controlling the power consumed from R-phase, the duty cycle should be varied only for the duration marked 'R'. However, there has to be some means for the controller to detect that the duration marked 'R' has been reached. In order to detect this, the generator terminal voltages of all three phases are sensed (through PTs). The sensed terminal voltages are then compared to each other and the truth table I is used to correctly determine which region has been reached at a particular instant of time.

TABLE I. TRUTH TABLE FOR DETERMINING THE PHASE TO BE SWITCHED

	Condition Required			
Region Reached	$V_R > V_Y$	$V_Y > V_B$	$V_B > V_R$	Meaning
R	1	X	0	V_R is largest
Y	0	1	X	V_Y is largest
B	X	0	1	V_B is largest

A. Determination of Dummy Load Resistance

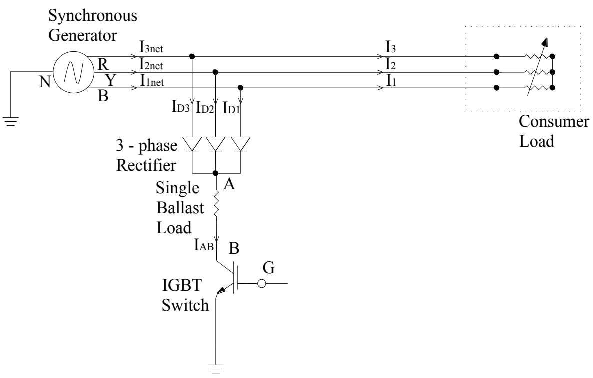


Fig. 5: Configuration of Consumer Load and Dummy Ballast Load

The calculation of the dummy load resistance is based on the requirement that, when all consumer loads are turned off, then the dummy load should be able to consume the full 3-phase power of the generator. In this condition the IGBT switch is kept fully ON (i.e. duty cycle of 100%) at all instant of time and the voltage waveform at point A will be as shown in Fig. 6

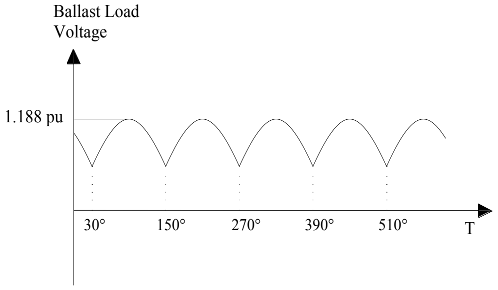


Fig. 6: Three phase half wave rectified voltage waveform

The rms value of voltage at point 'A' can thus be determined as follows:

$$V_A = \sqrt{\frac{\int_{\frac{\pi}{6}}^{5\frac{\pi}{6}} (\sqrt{2}*\mathrm{Sin}[\theta])^2\, d\theta}{5\frac{\pi}{6}-\frac{\pi}{6}}} = \frac{1}{2}\sqrt{\frac{3\sqrt{3}+4\pi}{\pi}} = 1.18891 \text{ pu}$$

Now, assuming the full-load power on each phase to be 1pu, the total 3 phase full load generator power is 3 pu. Thus the power dissipated by the dummy load resistance when all consumer loads are turned off should equal to 3pu. From this condition, we can determine the dummy load resistance as follows:

$$\frac{{V_A}^2}{R} = 3 \text{ pu.}$$

So, we get, $R = \frac{3\sqrt{3}+4\pi}{12\pi} = 0.47116$ pu

Thus, Optimal Dummy Load Resistance (R) = 0.47116 pu

B. *Determination of Current Balancing Logic*

It is necessary to adjust the duty cycle of the IGBT for each 120^0 conduction period so that different amount of powers can be consumed from each phase. In order to achieve this we need to calculate different duty cycle for each of the phases. The duty cycle for each of the phase should be made such that the generator terminal currents in each phase should be balanced, and this will result in reduction of generator overloading. In the Fig. [5], the generator terminal currents are marked as I_{1net}, I_{2net} and I_{3net}. It is evident that I_{1net} is composed of the consumer current I_1 and the diode current I_{d1}. The waveform of each of the three current is shown in fig 2(b). For a duty cycle of k_1 in region R, the expression for rms value of I_{1net} can be written as,

$$I_{1NET} = \sqrt{\frac{\int_0^{\frac{\pi}{6}} (I1\sqrt{2}\mathrm{Sin}[\theta])^2\, d\theta + \int_{\frac{\pi}{6}}^{5\frac{\pi}{6}} ((I1\sqrt{2}+\frac{\sqrt{2}}{R}\sqrt{k1})\mathrm{Sin}[\theta])^2\, d\theta + \int_{5\frac{\pi}{6}}^{\frac{\pi}{2}} (I1\sqrt{2}\sqrt{k1}\mathrm{Sin}[\theta])^2\, d\theta}{2}} \quad (1)$$

which is a function of I_1 and k_1.
Thus, $I_{1net} = f_1(I_1,k_1)$.
Similarly, it can be shown that $I_{2net} = f_2(I_2,k_2)$ and $I_{3net} = f_3(I_3,k_3)$.
In order to achieve current balancing,
$I_{1net} = I_{2net}$
i.e. $f_1(I_1,k_1) = f_2(I_2,k_2)$ (2)
and,
$I_{1net} = I_{3net}$
i.e. $f_1(I_1,k_1) = f_3(I_3,K_3)$ (3)

I_1, I_2 and I_3 can be measured and thus are known variables. Eq. (2) and Eq. (3) are two of the equations required to solve three variables k_1, k_2 and k_3 in terms of I_1, I_2 and I_3. The third equation comes from the criterion that, the value of k_1, k_2 and k_3 should be such that in addition to achieving generator terminal current balance, the power consumed by the dummy load should also make the total load on the system constant so that frequency is kept constant.

If the power consumed by the dummy load be called P_{dummy}, then the third criterion requires that:

$P_{consumer} + P_{dummy} = 3$ pu or $P_{dummy} = 3 - P_{consumer}$. (4)

However, P_{dummy} is the control variable for the PI controller used for closed loop control of the frequency, so $P_{dummy} = O_{PI}$ (where O_{PI} is output from the PI controller). Since, P_{dummy} is solely determined by the duty-cycle used for various regions (i.e. k_1, k_2, k_3)

$P_{dummy} = f_d(k_1,k_2,k_3)$

So the third criterion becomes, $f(k_1, k_2, k_3) = O_{PI}$ (5)

Thus, by using Eq. (2), Eq. (3) and Eq. (5) it must be possible to determine k_1, k_2 and k_3 in terms of I_1, I_2, I_3 and O_{PI} all of which can be either measured or calculated in the run-time. The problem associated is that the functions f_1, f_2 and f_3 makes it impossible to obtain a general solution and we have to use numerical solution to obtain k_1, k_2 and k_3. This means the equations cannot be pre-solved and used in the microcontroller, but for each control loop, numerical solution method has to be applied to obtain the value of k_1, k_2 and k_3 for that loop. This makes the processing time for a loop prohibitively large for 8-bit microcontroller so we had to pursue for different method.

From the interdependence seen in Eq. (2), (3) and (5) between k_1, k_2 and k_3 it is evident that the duty cycle k_1 of R-phase not only depends on the consumer current of R-phase (i.e. I_1) but also depends on the consumer current of other phases (I_2 and I_3). So, we make an educated guess by making k_1 directly proportional to product of (1- I_1), the current rejected by consumer 1, and weighted sum of (1-I_2) and (1-I_3) such that the weight taken is in between the value of 0-1. The whole result is then scaled by O_{PI}, in order to make the overall power balance and control the frequency in a closed loop.

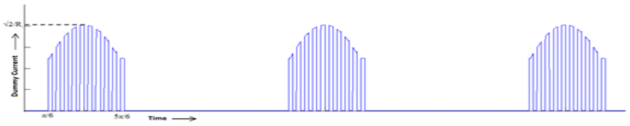
Then we can determine the duty cycle of the various phases by the following equations:

$$k_1 = (1-I_1 + (1-I_2)*weight + (1-I_3)*weight)*O_{PI} \quad (6)$$

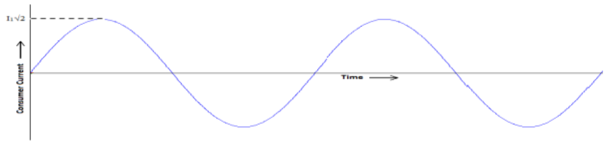
$$k_2 = (1-I_2 + (1-I_1)*weight + (1-I_3)*weight)*O_{PI} \quad (7)$$

$$k_3 = (1-I_3 + (1-I_1)*weight + (1-I_2)*weight)*O_{PI} \quad (8)$$

In the above equation, the value of weight was determined by using a experimentation software tool developed in Wolfram Mathematica^{TM} software and with some hit and trial experimentation, the best value of the weight for which we get fair amount of current balancing was found to be 0.1 if any of I_1, I_2 and I_3 is less than 0.5 and 0.333 if otherwise.



[a]



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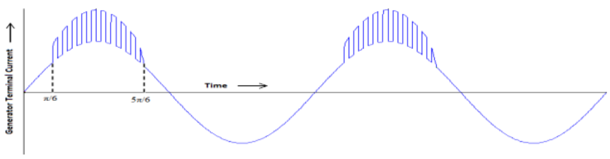

[c]

Fig. 7[a]: Dummy load current at a particular duty-cycle

Fig. 7[b]: Consumer load current at a particular time period

Fig. 7[c]: Generator terminal current at a particular time period

III. Modelling Of Proposed Scheme

The developed MATLAB simulation model for study of this type of Electronic Load Controller is shown in Fig. 8.

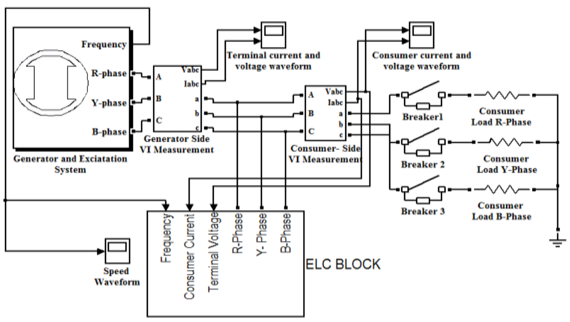

Fig. 8: MATLAB model of Developed Scheme

The model consists of a generator and excitation system block which includes a standard 3 phase synchronous generator and IEEE standard excitation system, three sets of consumer loads and an ELC. The ELC block includes the IGBT and the Dummy Load.

A. *Electronic Load Controller Model*

Fig. 9 shows the details of the ELC block. This block consists of the main controller block, IGBT and dummy load. The ELC works on closed loop system to maintain constant speed operation of generator. The input fed to ELC block are the terminal voltages of generator, consumer's load currents and the terminal voltage frequency. The ELC block compares the frequency sensed with the rated frequency and based on the deviation from the rated frequency determines the power to be consumed by dummy load through a closed PI loop. The current in the consumer side are sensed appropriately to find out the duty cycle to be maintained for each of the phases.

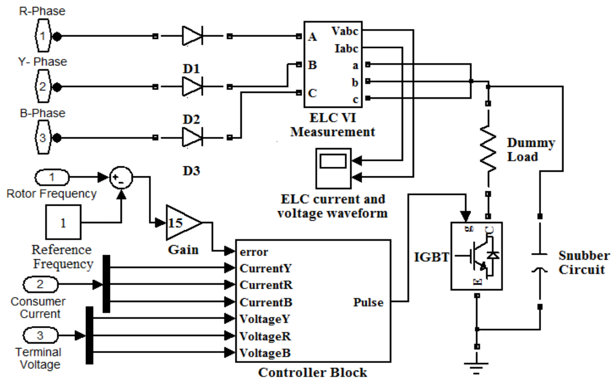

Fig.9: Developed Simulation Model of Electronic Load Controller

The sensed terminal voltages are used to determine which phase is to be switched on at a particular instant of time as already discussed in the previous section. For the controller section of the ELC, Embedded MATLAB function block which is analogous to the micro-controller is used. The consumer current signals, frequency error signals and the output of the comparator are all fed to the embedded MATLAB function block. Inside the function block, calculation discussed in previous section is carried out to find out the duty cycle k_1, k_2 and k_3 that needs to be applied to the IGBT gate. Once the calculation is done, we can use either of k_1, k_2 or k_3 as current duty cycle based on which region has been reached in current instant of time, using truth table I, to control the power consumed from each of the three phases.

IV. Simulation Results and Discussion

The developed MATLAB simulation model was tested on the following load conditions:

a. For the starting 2 sec all the consumer loads are on and at full load conditions.
b. At 2 sec, one of the consumer loads was completely switched off.
c. At 4 sec, another consumer load was turned off.
d. And, at 6 sec all of the consumer loads are turned off.
e. And at 8 sec all the consumer loads are switched back on.

The results obtained from the MATLAB Simulation at the above mentioned load conditions are shown below:

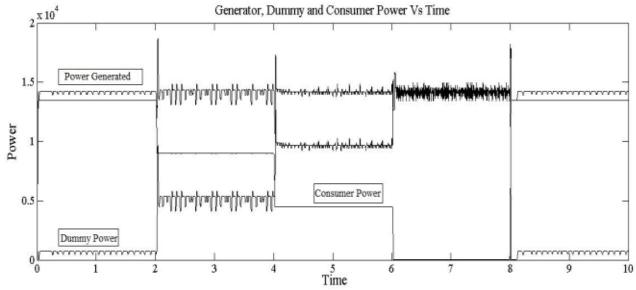

Fig. 10: Plot showing total power balanced at various load conditions

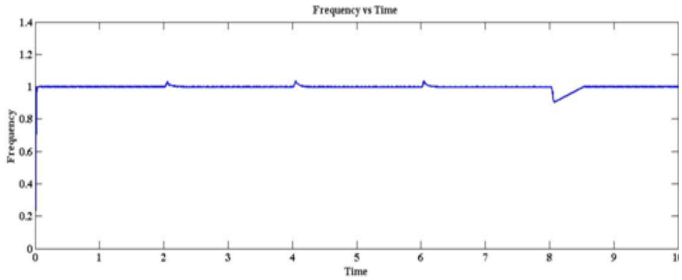

Fig. 11: Plot showing frequency stabilization at various load conditions

Fig. 10 shows the plot of power generated by generator, power consumed by dummy load and power consumed by consumer's load at various load conditions. Fig. 11 shows the plot of frequency of terminal voltage with respect to time and at various load conditions. The consumer's current, dummy current per phase and generator terminal current at various load conditions are tabulated in Table II.

From the simulation results of this scheme in MATLAB, it has been seen that this scheme works very well for isolated micro-hydro generators where isochronous mode of operation of generator can be used. The proportional integral controller employed was successful to maintain constant speed operation of generator. It was seen that by appropriately switching the IGBT the power to be consumed by the dummy load can be controlled such that the power generated by generator remains constant and the frequency also remains constant.

It was also seen from the simulation results that the terminal current drawn from the generator is fairly balanced under all load conditions. Thus the scheme can maintain the terminal current balance using a single dummy load and single IGBT switch.

There were some overshoot and undershoot in the frequency plot obtained from the simulation at the instant of switching of consumer loads. The deviation from the rated speed was for a short period of time and it quickly became stable back to the rated speed. It was seen that the sum of power consumed by the dummy load and the consumer load remained constant and equal to the total power generated by the generator.

In the proposed scheme, the ballast load is at DC side and it is turned ON and OFF at high chopping frequency. Hence, lower order harmonics are eliminated and higher order harmonics are introduced instead which are filtered by inductance of the machine itself. Hence the terminal current harmonics in the proposed scheme is less with compare to that in case of AC Voltage Controller Based ELC.

TABLE II. TABLE SHOWING VALUES OF TERMINAL CURRENT, DUMMY CURRENT AND CONSUMER CURRENT AT VARIOUS LOAD CONDITIONS

Current (RMS Value)	Condition I (0-2) & (8-10) seconds			Condition II (2-4) seconds			Condition III (4-6) seconds			Condition IV (6-8) seconds		
	R	Y	B	R	Y	B	R	Y	B	R	Y	B
Consumer Current	19.47	19.47	19.47	19.47	19.47	0	19.47	0	0	0	0	0
Dummy Current	1.10	1.10	1.10	6.176	6.53	24.11	8.9	29.14	23.92	29.95	29.95	29.95
Terminal Current	19.9	19.9	19.9	22.58	22.9	24.11	25.74	29.14	23.92	29.95	29.95	29.95

V. CONCLUSION

All previous forms of ELC used at least three dummy loads and three power electronic switches. This method manages to control the frequency by using a single dummy load and single IGBT switch. As the component count is reduced, the overall reliability of the system is improved. The developed form of ELC can be a good replacement for other existing form of ELC.

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