AN IMPROVED CONTROL ALGORITHM FOR AN ELECTRONIC LOAD GOVERNOR

Dr D. S. Henderson and W Pearson

Napier University, 219 Colinton Road, Edinburgh, EH14 1DJ, UK.

1. INTRODUCTION

Micro hydroelectric sets are defined as those with unit ratings of less than 100 kW. They are often situated in remote communities, particularly in developing countries. As they are often isolated from grid networks their technical characteristics are such that they require a governor to maintain the frequency at an acceptable level for the users. The specification for a rural electricity supply is a lot less rigorous, or rigid, as that for Western countries, Woodward[1]. The communities which install these sets usually have limited finance and limited skilled labour, if any, to operate and maintain the equipment. Unfortunately, as the kW rating of hydroelectric plant decreases then the cost per kW increases, Wallace[2]. Hence, for a community to afford a micro hydroelectric generating set, the capital cost of the plant must be as low as possible and the plant must be as simple to install, operate and maintain as is possible.

The philosophy that must be adopted is that 'medium-efficiency plant which can be afforded is of greater value than high-efficiency plant which can not be afforded'. As a result, communities can reap the benefits of an electricity supply of modest output rather than have no supply at all.

A key item of the plant is the governor. Traditionally, speed governors such as the mechanical-hydraulic type have been installed which adjust the speed of the set by controlling water flow - through the action of a water regulating device on the turbine. Such devices, e.g. spear valves or guide vanes are highly engineered turbine components and are designed for high-efficiency operation. The modern equivalent is the electro-hydraulic governor which uses electrical or electronic means to sense changes in speed but still controls the water flow. The cost of such a governor is often dearer than the cost of the generator at these ratings.

The accepted alternative to the speed governor is the Electronic Load Governor (ELG) which maintains the speed of the set by adjusting an electrical ballast load connected to the generator terminals, maintaining a balance between the total electrical load torque and the hydraulic input torque from the turbine, as shown in Figure 1. In this case, the water flow is kept constant and hence the water regulating device can be dispensed with. Typically the cost of the ELG is about one tenth that of the speed governor and so the economic advantage of the ELG is twofold, as a result of the lower capital cost of the governor and of the turbine.

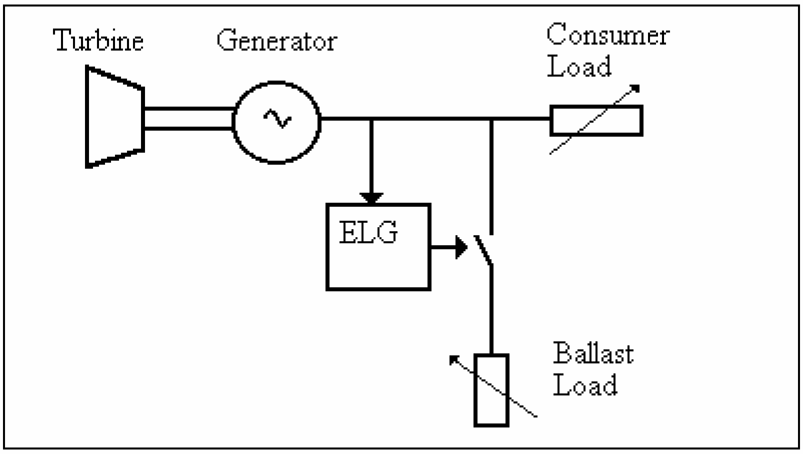

Figure 1. - Load Governing Principle.

2. TYPES OF ELG

The two most commonly employed techniques used for load governing are;

i) the phase delay action, Woodward[3], where the ballast load comprises a permanently connected single resistive load circuit of magnitude equal to (or slightly greater than) the full load rated output of the generator. As a result of the detection of a change in the consumer load, the firing angle of a power electronic switching device, such as a triac, is adjusted, thus altering the average voltage applied to, and hence the power dissipated by, the ballast load.

As with all power electronic switching of this nature, this technique introduces harmonics onto the electrical system. It is worthwhile to note that these harmonics are continuously present to some extent as long as the ballast load is energised.

The presence of these harmonics will cause overheating of electrical equipment connected to the system and of the generator, this is usually counteracted by derating of the generating plant, Barnes[4].

ii) the binary load action, Henderson[5], where the ballast load is made up from a switched combination of a binary arrangement of separate resistive loads. The load proportion carried by each step is in the ratio 1:2:4 and when switched in sequence, the ballast load exhibits a stepped characteristic, as shown in Figure 2. The summation of all of the ballast load steps is equal to (or slightly greater than) the rated output power of the generator.

In response to a change in the consumer load, a switching selection is made to connect the appropriate combination of load steps. This switching operation occurs during the transient period only, thereafter full system voltage is applied to the new fraction of the ballast load and hence harmonics are not produced at all by this method in the steady-state. In addition, it is usually the practice to adopt solid-state switching relays which include a zero-voltage switching circuit that reduces the harmonic distortion associated with the transient switching period.

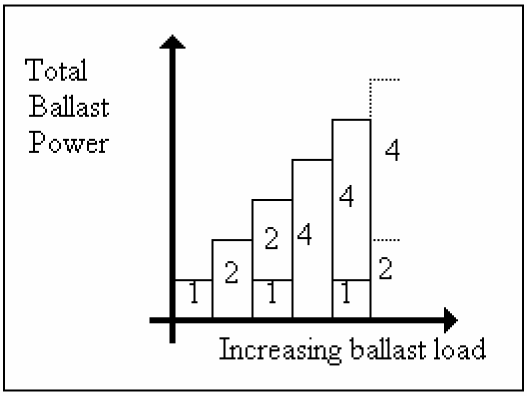

Figure 2. - Ballast Load Characteristic.

3. CONTROL SYSTEM COMPONENTS

The control system has the main components of:

- the governor (ELG) comprising a microcomputer printed circuit board (PCB) and an input/output (I/O) PCB incorporating a regulated power supply.
- the consumer load.
- ballast load, comprising discrete units of electrical load weighted in a binary sequence of 0.125, 0.25 and 0.5 per unit (p.u.) per phase.
- one current transformer (CT) per phase.

A general connection schematic, for a single phase system, of the main components is shown below in Figure 3.

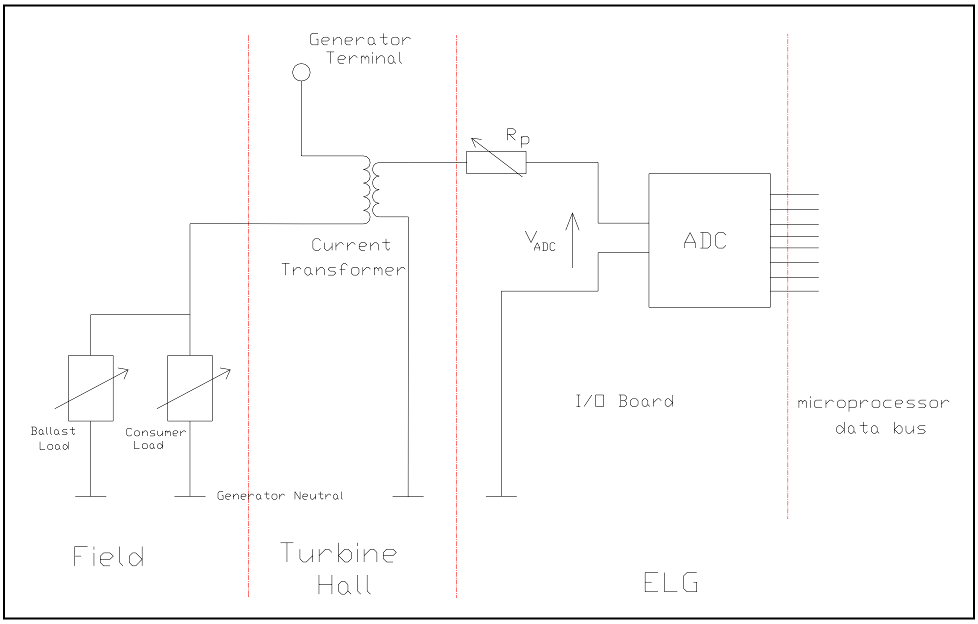

Figure 3 - Electrical Connection Schematic

The CT primary winding carries the generated output current of both the consumer and ballast loads. The current induced in the secondary coil of the CT is converted to a voltage across a variable resistor and passed to an analogue to digital converter (ADC) on the governor I/O PCB. The voltage to the ADC will generally be scaled 0 to 2 p.u. of load representing zero to full scale on the ADC. The voltage waveform from the secondary of a voltage transformer is passed to a Schmitt trigger for shaping.

4. SOFTWARE DEVELOPMENT

The software for the microcomputer was written and tested on a development system. The microcomputer uses a high-level language, FORTH, and the development system was run on a host PC. Communication between the PC and the microcomputer for program development purposes was via an RS232 serial link. In the target situation, the microcomputer stands alone, the host PC and the serial link are removed and the program is stored in EPROM.

4A. Description of the Original Control Strategy

A simplified flowchart of the main load governing program is shown in Figure 4. Once the necessary auto-start and initialisation procedures are executed, the program enters a continuous loop and reads the first variable, as set during commissioning.

This is the width of the frequency deadband, necessary due to the stepped nature of the ballast load.

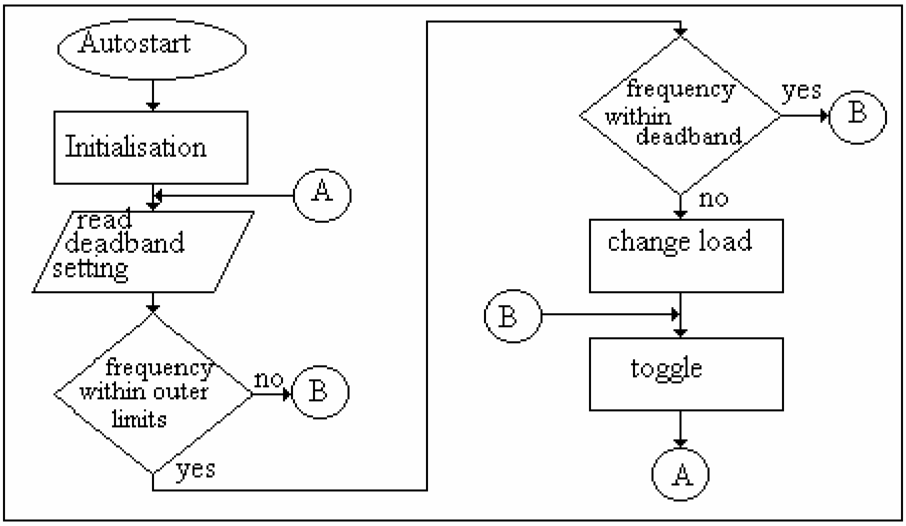

Figure 4. - Flowchart of the Main Load Governing Program.

The frequency measurement process is handled by an interrupt routine. On detection of a negative going change in polarity of the terminal voltage waveform, a counter is energised. On the repetition of this event (i.e. after one cycle of the ac. waveform), the counter is stopped and read, then the value stored in memory. This value equates to the *period* of the waveform over that cycle.

The main program compares the most recent reading of the period against values corresponding to the upper and lower limits of the deadband. If the frequency is within the deadband range then no action is taken. If the frequency is outwith the deadband then the ballast load is changed accordingly. An output line is then toggled on or off to enable monitoring of the operation of the ELG. The loop then repeats itself indefinitely until the power supply to the unit is removed.

The original control strategy determined whether additional or reduced load on the generator was needed to restore the required frequency. If additional ballast load was required then the relative magnitudes of the current in each phase were compared to find the lowest, and one step of ballast load would be added to that phase. If reduced loading was required then the currents for each phase would be compared to find the highest and one step of ballast load would be removed from that phase. In this way successive program cycles would increment the ballast load until the measured frequency was within acceptable limits.

Due to the time dependent nature of the generating set response to load changes, the effects of this control action were dominated by the inertial response of the generating set until sufficient steps of ballast load had been applied/removed to counter the disturbance. The effects of this would be that the frequency of the voltage waveform would rise or fall coupled with a surge or dip in the magnitude of generated voltage, depending on the nature of the disturbing load change. A typical transient is shown in Figure 5 which also shows the maximum frequency point, f_{max}, and the time for the frequency to return within the deadband, the 'return time'.

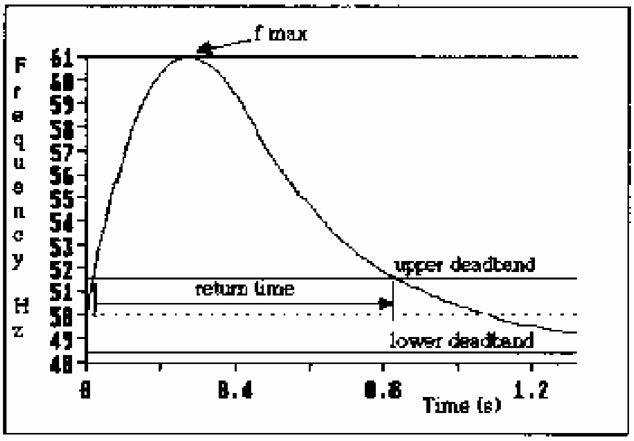

Figure 5 Typical frequency transient

4B. Application of Control Theory to Revise Strategy

Although it was recognised that the control system was non linear, principally due to the inertia of the generating set and characteristics of the generated current and voltage expressions, the starting point of developing the control software was taken to be a description of the controller action in terms of classic linear control theory. A block diagram representation of the generating set and ELG is shown in Figure 6.

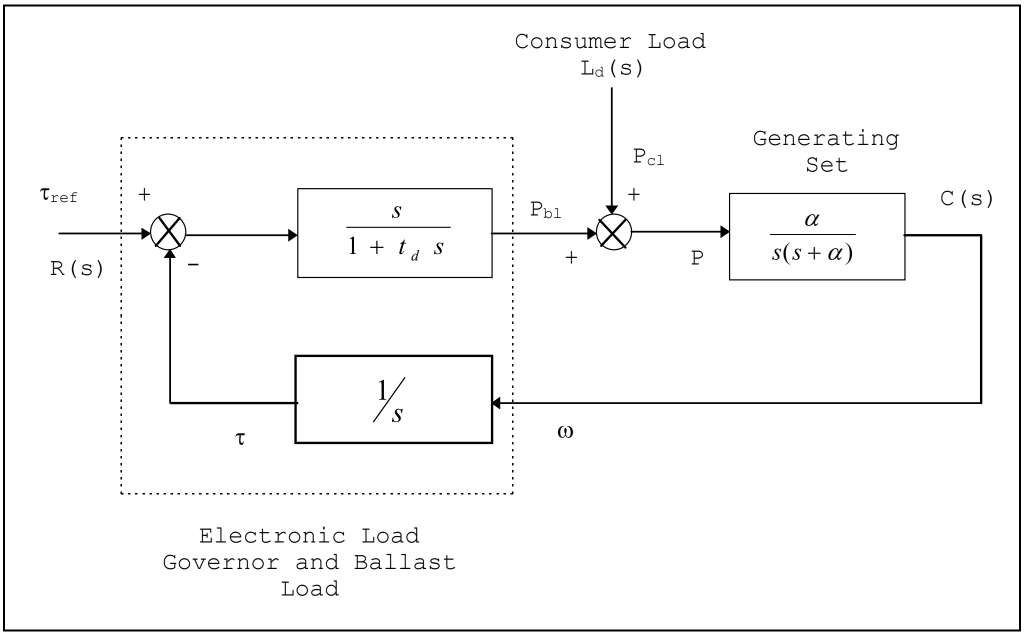

Figure 6 - Control Block Diagram

The reference signal, R(s), is the desired period of the waveform, 20 ms for 50 Hz. The forward path of the ELG is effectively a differentiator translating changes in periodic time to changes in power described by the droop curve characteristic. The changes in power are, in practice changes in ballast load, and these are applied to the system at the summing junction with the consumer load disturbance. This summing junction is actually the torque balance for the rotating equipment. The power demanded is input to the rotating set characteristic and results in the controlled periodic time of the generated output from the set, C(s). The output is, in turn, fed back to the controller where the software integrates the frequency over one cycle to arrive at a generated periodic time.

The droop of the set is a characteristic of the turbine used in the set. Typically droop is specified in Hz/p.u. A given disturbance to the load on a turbine will result in a change in speed of the machine through the fundamental torque balance of the set. The dynamics of the speed change are determined by the inertia of the set. The function of the ELG is to hold the speed of the set constant.

The input range to the controller is a measured periodic time which could vary as a function of the droop of the system. Controller output could be anywhere between application or removal of all steps of ballast load. In this respect, a proportional band could be recognised in terms of ballast load per unit-frequency deviation (p.u./Hz), itself the complementary to units of droop (Hz/p.u.).

Since the ballast load is of finite resolution, actuating error between the desired frequency or setpoint periodic time, which could not be absolutely corrected and some offset would always be present, giving rise to a frequency deadband. As the accuracy of the corrective action would be directly proportional to the resolution of the ballast load, integral action is taken to be zero.

Responses of a generating set, to various load disturbances, are shown in Figure 7.

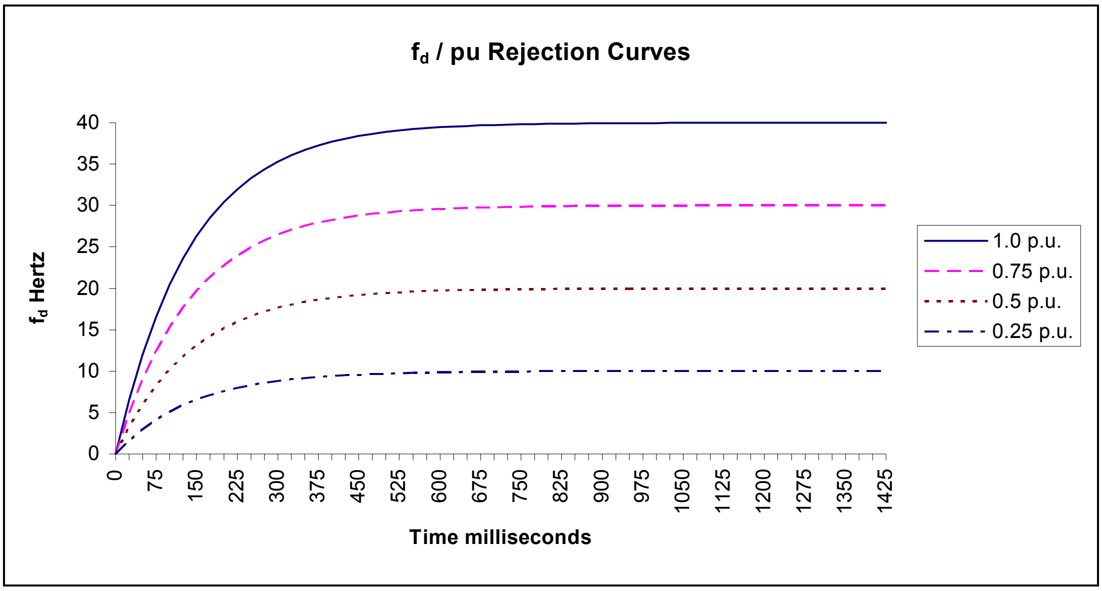

Figure 7 - Generating Set Response to Load Rejections

It was recognised that by over application or removal of ballast load the system would respond more quickly, the limit being full ballast load switching. In this respect it would be possible to apply derivative action to the system. If a disturbance of 0.5 p.u. was applied to a set then application of a 1 p.u. would result in an almost nine-fold improvement in response time over the application of a countering 0.5 p.u. adjustment. This would represent a gain of 2 in the correcting action. At some point the excess load would be required to be switched out, (dynamic switching), to prevent a correction induced disturbance.

4C. Description of Revised Software Algorithm

Using the idea of the proportional band it was possible to estimate the magnitude of corrective load required by expressing the deviation of the measured frequency from the required frequency as a proportion of the droop deviation. The equation would be of the form:

$$Z_{inc} = Z_{ballast.} \times \frac{f_{measured} - f_0}{f_{droop}}$$

Where Z_{inc} is the increment of ballast load required to effect adjustment, $Z_{ballast}$ is the maximum ballast load, $f_{measured}$, f_o and f_{droop} are the measured, required and droop band frequencies in Hertz. This expression would result in a calculated fraction of the droop and so the required fraction of the ballast load to be applied or removed. Assumptions regarding linearity between load and speed and that the maximum ballast load is scaled to 1 p.u. power rating are implicit in this approach. The advantage of this strategy over the original strategy was that corrective action would be applied in one computing cycle rather than over several cycles. A similar algorithm to the initial control software could hopefully be utilised for distributing the corrective load between the three phases thus keeping the set optimally loaded. In practice the balancing algorithm became unwieldy and would have presented a potentially unacceptable computational overhead to the microprocessor.

It was noted during the balancing software design phase that if the generator was optimally loaded then the power absorbed by each phase load would be 1/3 p.u. of the generator set rating i.e., for a three phase machine:

$$P_{red} = P_{yellow} = P_{red} = {}^{1}\!/_{3}\ set\ rating$$

For any phase the power absorbed in that phase, P_{phase} , would be the power utilised in the consumer phase and the power dissipated in any ballast load present. Thus, neglecting power factor:

$$P_{phase} = V_{phase}\, I_{consumer} + V_{phase}\, I_{ballast} \quad W$$

This can be represented in a p.u. system of operation as:

$$\frac{P_{phase}}{P_{phase\ rated}} = \frac{V_{phase}\, I_{consumer} + V_{phase}\, I_{ballast}}{V_{phase}\, I_{phase\ rated}} = \frac{1}{3} \quad p.u.$$

For a constant supply voltage V_{phase} ,variation in the phase power would comprise of changes in line current, $I_{consumer}$, due to changes in consumer load and variations in phase ballast current, $I_{ballast}$. By measuring the line current from the current transformers and if the design rating of the set is known then the ballast load current required to satisfy the optimal load equation can be calculated. Since the power dissipated in a load is proportional to the current through the load, the p.u. equation can be written in the form:

$$\frac{I_{consumer}}{I_{phase\,rated}} + \frac{Z_{phase}}{Z_{phase\max}} = {}^{1}\!/_{3} \ \ rated\ \ p.u.$$

$Z_{phase\ max}$ is the maximum available phase ballast load equivalent to 1 p.u. phase load; Z_{phase} is the ballast load present in the phase; $I_{consumer}$ is the phase consumer current and $I_{phase\ rated}$ is the rated phase current. This equation was used as the final control algorithm applied sequentially to each phase when a frequency excursion was detected. The required corrective load was calculated and the difference between that and the ballast load already applied was added or removed from each phase.

5. PERFORMANCE IMPROVEMENT

5A. Predicted Improvement

A simple numerical model using a spreadsheet was developed from the original algebraic model written in BASIC. The predicted response for a 0.5 p.u. load rejection disturbance using numerical control expression is shown in Figure 8.

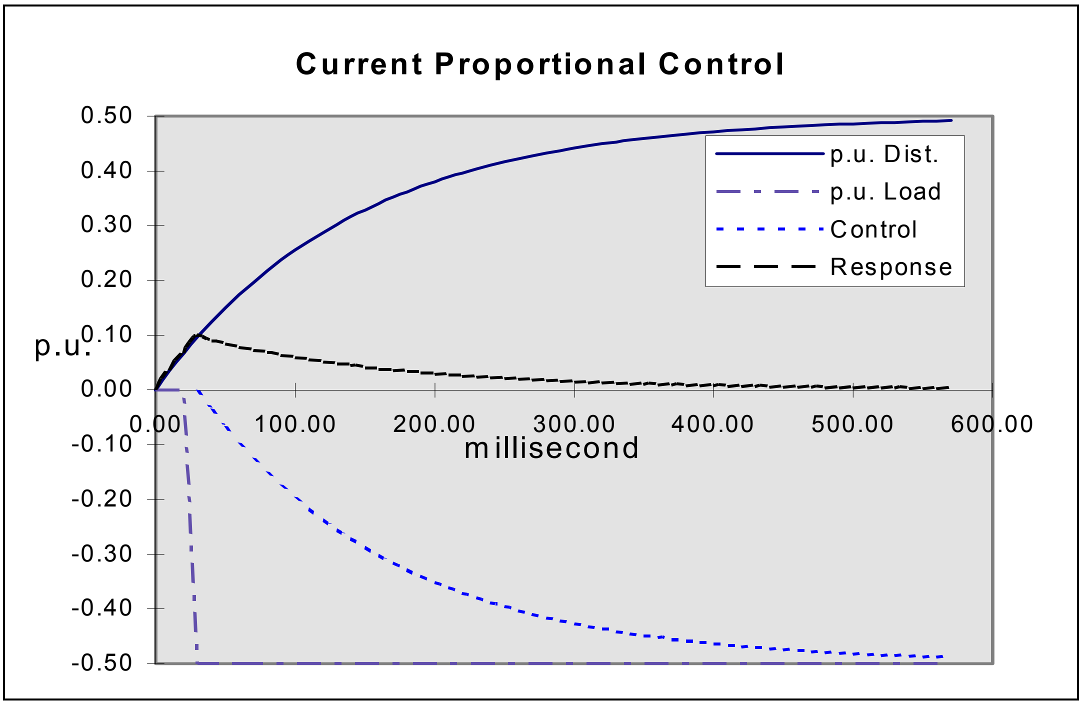

Figure 8 - Current Proportional Control

5B. Actual Improvement

The original program did not have any knowledge of the actual load condition on the generator and dealt with the change of load by simply adding or removing only one step of ballast load from one phase during each program loop. Therefore in the event that the ballast load was required to change from, say, zero application to full application, then the minimum number of step changes required was 21 (7 steps in each of the three phases).

Hence the reaction time of the governor was not optimised in any way. With a typical program loop time of 22 ms, this gave rise to a minimum reaction time of 462 ms in the case of a full load rejection. As a result, the maximum frequency, f_{max}, was reaching relatively high values during a transient period caused by such an event.

Using a Pelton turbine as the prime mover, a full load rejection test was performed with the original algorithm controlling the ELG. The resulting frequency vs. time plot for this test is given in Figure 9, the “old” data series. The frequency can be seen to rise above 59 Hz at its peak and the time to return within the deadband, the 'return-time', is in the order of 800 ms.

As described above, an improved control algorithm was written and then tested in order to provide a comparison with the original program. The results of these tests, on the same turbine, are also given in Figure 9, the “new” data series. The new algorithm shows f_{max} reduced by 11% and the 'return-time' reduced by 40% when compared with the old one.

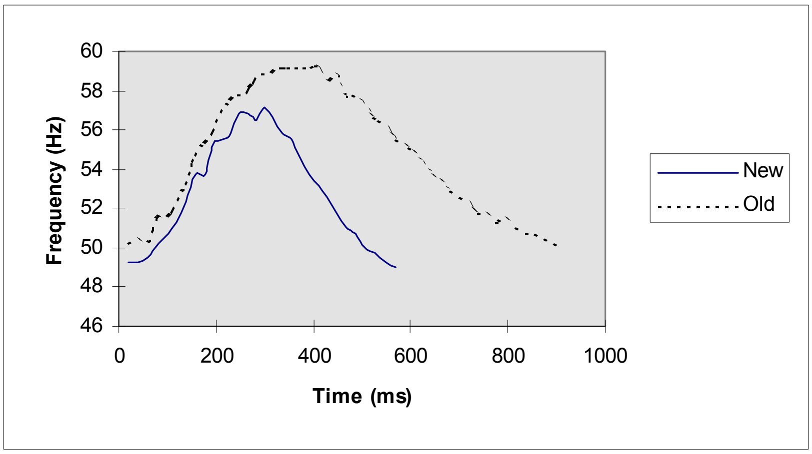

Figure 9 Comparison of the original and new algorithm results

.6. SITE APPLICATION

The first on-site application of the ELG, using the improved control algorithm, is at a site being developed in Scotland. The site is located at Ashfield Mill, two miles North of Dunblane on the Allan Water. The existing weir is located at an old cloth dyeing mill site and creates a net head of approximately 6m. Hydro development, providing mechanical power, began at this site in 1925, however the original powerhouse was abandoned in the 1970's. The present site owner and developer is installing two turbine-generator sets to capture the energy available in the water.

The first generating set is now operational and comprises a re-furbished Gilkes turbine and Crompton Parkinson generator. The rated output of this set is 100 kW and it is governed by a traditional mechanical-hydraulic type governor.

It is the second generating set which is governed by the ELG. This is a crossflow type turbine driving, via a belt drive, a 31kVA, 400V, 3-phase synchronous generator. The generator operates in an electrically isolated situation and the electrical energy from the set is primarily used in the residence of the owner for heating and lighting purposes (the consumer load). The ballast load is used for space heating in the powerhouse and in nearby factory units.

This generating set is the subject of a European Commission THERMIE grant to enable on-site demonstration. The CEC Project reference number is HY/329/94/UK. It is expected that this unit will be commissioned in the Autumn of 1996.

7. CONCLUSIONS

The initial research and development of an Electronic Load Governor suitable for application in isolated situations was successful. Testing of the original control algorithm has shown up the fact that the methodical application of the binary configuration of the ballast load steps was not ideal. An advanced control algorithm has been developed, specifically designed to address this limitation.

Its implementation results in a small but noticeable improvement (reduction) in the magnitude of the frequency rise on full load rejection and a significant improvement (reduction) in the duration of the transient period itself.

The revised software as described is basically a numerical control technique and effectively uses self tune parameters of proportional gain and derivative time. Whilst the revised algorithm exhibits improved control response in terms of magnitude of frequency excursion and voltage fluctuations the response could be further improved through the use of gain i.e. over or under application of load relative to the correcting load required.

8. ACKNOWLEDGEMENTS

The authors wish to thank Napier University for their support in this project.

9. REFERENCES

1. Woodward, J.L. and Boys, J.T., 1980, *Water Power & Dam Construction*, Vol. 32, No 7, p37-39.

2. Wallace, A.R., Henderson, D.S. and Whittington, H.W., 1989, "Capital Cost Modelling of Small Scale Hydro Schemes*", Proceedings 24th Universities Power Engineering Conference*, Belfast, UK.

3. Woodward, J.L., 1986, "Appropriate Speed and Frequency Control of Micro Hydro Plants", *Proceedings of Workshop on Micro Hydro Installations*, Papua New Guinea.

4. Barnes R. 1989. IEE *Power Engineering Journal*, Vol. 3, No 1, 11-15.

5. Henderson, D.S. and Macpherson, D.E., 1990, "Development of a Three-Phase Electronic Load Governor for Micro Hydro Generation", *Proceedings 25th Universities Power Engineering Conference*, Aberdeen, UK.