The Ashfield Mill Electronic Load Governor
- Operational Results

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Introduction

A digital Electronic Load Governor has been developed and undergone its initial testing. Two alternative control algorithms have been developed and tested on a 20 kW turbine-generator set at a full-scale micro-hydroelectric installation in Scotland. Initial results, whilst encouraging, suggest that there is scope for further improvement in the control algorithm deployed. This paper presents a summary of the salient details of the installation. It goes on to provide the operational history and performance of the set complete with energy production figures and a brief economic evaluation of the installation. The paper concludes with a discussion on the future outlook of the project.

1. Background

Hydroelectric development began at the Ashfield Mill site in 1925 however, due to industrial decline, the powerhouse was abandoned in the 1970's. Reinstatement of hydropower production began in 1991 with the installation of a refurbished open-flume Francis type turbine and generator. The rated output of this set is 100 kW and it is governed by a traditional mechanical-hydraulic type governor.

This was followed by a 20 kW generating set which coincidentally provided the first on-site application and testing of an innovative Electronic Load Governor (ELG). The ELG was the first known design based on digital/microprocessor electronic circuits incorporating a three-phase balancing feature. The generator controlled by the ELG operates in an electrically isolated situation and the electrical energy from the set is primarily used in the residence of the owner for heating purposes (the consumer load). The ballast load is used for space heating in the powerhouse and in nearby factory and greenhouse units. This generating set is the subject of a European Commission THERMIE contract to enable on-site demonstration. The EC Project reference number is HY/329/94/UK.

The THERMIE contract specified that the installation must undergo a 12 month Demonstration period. This was completed in June 1998 and the generating set has continued to provide reliable service ever since.

2. The Ashfield Mill Site

The site is located at Ashfield Mill, Ashfield, Dunblane, Scotland, UK. The installation, as shown in Figure 1, comprises the following major components; weir, intake, tunnel, tank, and powerhouse which are described briefly below and in more detail in a previous paper [Henderson & Maclean, 1997[1]]. The power house contains two turbine-generator sets, a 100 kW open-flume Francis turbine and the 20 kW set that was installed under the THERMIE project.

Figure 1 - The Ashfield Mill Site

2.1 Weir

The weir is 34 m long and creates a gross head of 6.4 m. A fish pass is incorporated at the North end of the weir.

2.2 Intake

Situated at the South end of the weir, the intake comprises two wooden gates individually controlled by a hydraulic ram operating system. Trash grids are located at the other end of the tunnel.

2.3 Tunnel and tank

The tunnel, of length 65 m, runs under the mill buildings from the intake to the tank which houses the open-flume Francis turbine. The intake bellmouth for the 20 kW turbine is located in the tank wall.

2.4 Powerhouse

Situated over the tailrace, the powerhouse contains the generator of the 100 kW set and the pipework, turbine-generator and control equipment (in a purpose built control room) for the 20 kW set.

2.5 Bellmouth and inlet pipework

A bellmouth unit was designed and manufactured using fibreglass on a steel-flanged framework. This is designed to reduce the inlet pipe entry head loss from 0.6 to 0.03 m and is connected to the inlet flange of the pipework leading to the 20 kW turbine.

2.6 20 kW Turbine-generator set

The hydraulic characteristics of the site are;
Gross head - 6.4 m
Net head - 6.0 m
Design flow - 600 l/s.

A Kaplan type turbine was initially considered for this application but was ultimately ruled out due to likely cavitation problems due to the relative setting of the turbine with respect to the headwater and tailwater levels. Consequently the final selection, as shown in Figure 2, is a 20 kW crossflow stainless steel turbine with a 4-cell runner (400 mm in diameter, 800 mm in length) and a running speed of 263 rev/min connected by a belt drive to a 31 kVA, 4-pole, 3-phase, 400 V, 50 Hz brushless synchronous generator with AVR and voltage trimmer. The generator operates on an isolated electrical network and provides energy for private consumption by the owner and developer.

Figure 2 - The 20 kW Turbine-Generator Set

2.7 Control room

A control room houses the control cubicles of the two sets along with facilities for laboratory test equipment.

2.8 20 kW Set Control cubicle

The control, measurement and protection equipment for the set is contained in a custom built control cubicle.

2.9 ELG

The Electronic Load Governor (ELG) is mounted on a 19" rack unit on sliding rails in the front of the control cubicle as shown in Figure 3. The control of the 20 kW set is intentionally very straightforward. Simple manual controls are available for speed and voltage. After run-up, the set reverts to automatic control by the ELG and the Automatic Voltage Regulator (AVR). These can be over-ridden by manual control at any time. Shutdown occurs automatically in the event of a fault. The control, protection and monitoring of the set is described in more detail in a previous paper [Henderson & Maclean, 1998[2]].

3. The Electronic Load Governor (ELG)

A prototype ELG was designed and assembled and underwent successful testing on turbines on a specially designed test rig in the hydraulics laboratory of Napier University. Three-phase and single-phase versions of the ELG were designed and tested for 50 Hz systems. The load governing technique adopted is that of binary load switching. As the principle design is for a three-phase system, the ballast load in each phase is sectioned into a 1:2:4 format and a current balancing feature is implemented. This requires knowledge of the current in each of the generator lines, achieved through the use of current transformers (CT's).

Figure 3 - The ELG in the Control Cubicle

As described in reference 1, two different control strategies have been developed, and both have now been tested on site under normal operating conditions. It is a feature of both strategies that on the occurrence of frequency excursions from a pre-set deadband (determined by the droop characteristic of the turbine), the programme determines whether additional or reduced load on the generator is needed to restore the frequency.

With the original strategy, when additional ballast load is required then the relative magnitudes of the current in each phase are compared to find which phase has the lowest value, and one step of ballast load is added to that phase. When reduced loading is required then the currents in the three phases are compared to find the highest, and one step of ballast load is removed from that phase. In this way successive program cycles increment the ballast load until the measured frequency returns within the deadband.

As an alternative, by measuring the line current using the CT's, and if the operational full load rating of the set is known (refer Section 4 below), then the ballast load current required to satisfy this full load condition can be calculated [Henderson & Pearson, 1997[3]]. This proportional control calculates the required corrective load and the difference between that and the ballast load already applied is added or removed in one switching sequence, on each phase sequentially.

4. Installation And Commission The ELG

The installation of the ELG involved simply fitting the unit onto rails mounted in the control cubicle (Figure 3). Connections were made to the 3 phase system - via a voltage transformer (VT) for power supply and voltage waveform sensing, and via CT's for current sensing. Connections were also made to the 9 solid-state switches which control the ballast load sections.

The commissioning procedure began with calibration of the current sensing circuits. These are responsible for establishing knowledge of the three line currents by creating a digital value in proportion to the operational full load current in each line of the power system.

Selection of the frequency deadband and an in-built delay in the ELG response time were effected through micro-switch settings. The deadband was set as a function of the turbine droop [Henderson, 1992[4]]. The delay was initially set to zero but was increased during commissioning tests to improve stability. The ELG Unit was thus simply installed and commissioned and was available for operation.

5. Operating History

The installation first started production of electrical energy in November 1996 supplying a domestic consumer load of approximately 10.5 kW on a daytime only basis. Before the ELG was commissioned at the end of June 1997, the set operated under manual speed control and was thus able to produce energy. During this period the set ran for 1331 hours and produced 17559 kWh of energy.

Since the commissioning of the ELG, the installation has been in regular operation supplying a consumer load comprising the heating and laundry requirements of the owner's house. A record of its operation since then is given in Table I.

Table I - Monthly Operating History

Month	Hours run	Cumulative hours run	Energy (kWh)	Cumulative energy (kWh)
July 1997	25	25	500	500
August	25	50	587	1087
September	77	127	700	1787
October	215	342	2163	3950
November	376	718	3993	7943
December	406	1124	4455	12398
January 1998	410	1534	4514	16912
February	369	1903	4052	20964
March	384	2287	4159	25123
April	398	2685	4341	29464
May	255	2940	2708	32172
June	159	3099	1689	33861
July	143	3242	1407	35268
August	150	3392	1450	36718
September	145	3537	1418	38136
October	325	3862	3478	41614
November	391	4253	4098	45712
December	393	4646	4274	49986
January 1999	387	5033	5254	55240
February	368	5401	5502	60742
March	387	5788	4490	65232
April	330	6118	3484	68716
May	202	6320	2120	70836
June	150	6470	1620	72456

Graphs showing the hours run per month and the cumulative energy produced (in kWh) per month are shown in Figures 4 and 5. The seasonal effect of less demand/water in the summer months is clear. Thus, approximately, the total number of hours run from November 1996 to the end of June 1999 is 7800 and the total amount of energy produced is 90000 kWh.

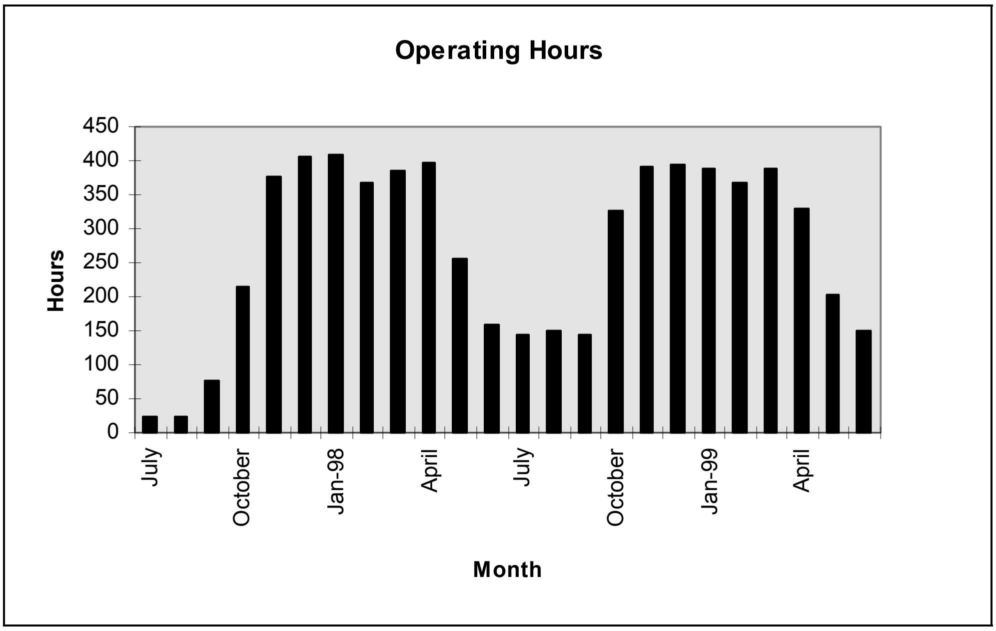

Figure 4 - Operating Hours

The total electricity produced during the 12 month Demonstration period was 33861 kWh and at the avoidance cost of £07.13 per kWh, the effective annual revenue generated by the owner is £2414.30. The results of the associated economic analysis are not particularly favourable. This is due entirely to the relatively low electrical energy output achieved during the Monitoring Phase. An output of 33861 kWh represents a load factor of only 18.4% compared with 94% predicted.

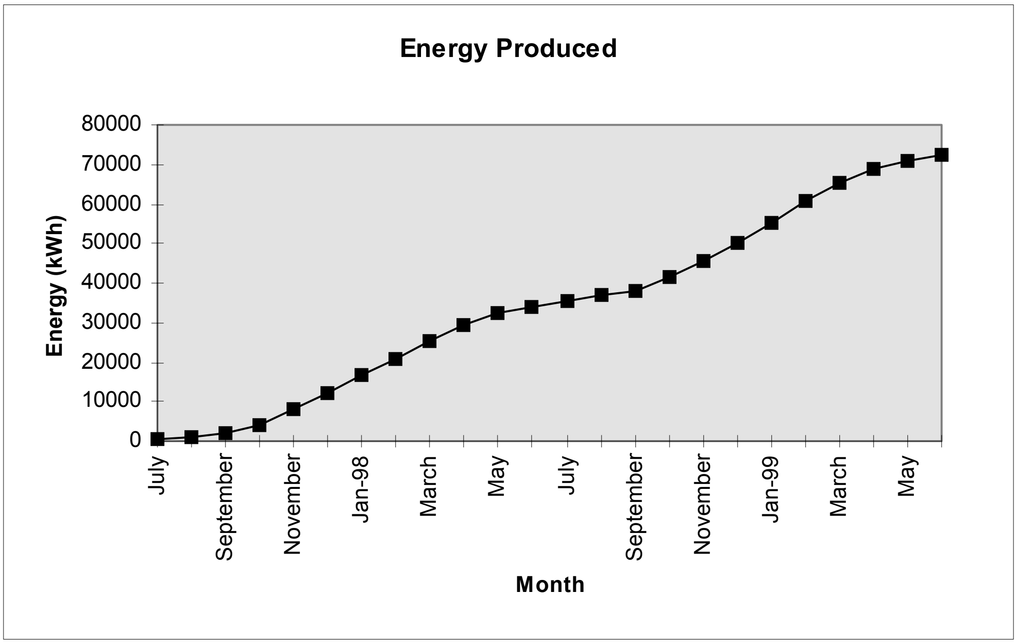

Figure 5 - Energy produced

The relatively low output has come about due to a number of factors, namely;

- lower than average summer water flow levels,
- the load which the owner connected to the system was lower than the rated output of the set, and,
- restricted output during this period whilst modifications were made to the ballast load and to the inertia of the set.

The latter restriction has now been removed and so it is reasonable to assume that in future the owner will be able to operate the set at a much higher power output, and so achieve substantially better economic performance.

6. Operation Of The ELG

The ELG Unit itself has performed well, in particular from the point of view of the hardware. It has always been able to operate when required and the software has operated as designed. The ELG Unit is part of a system of components which must all work together in harmony. Key elements of this are the rating of the ballast load sections, the inertia of the rotating components and the hydraulic stability of the water column moving through the turbine, draft tube and pipework system. To different extents, all of these elements affected the initial performance of the ELG, however modifications and improvements were undertaken in a bid to achieve satisfactory operation of the complete system.

6.1 Modifications after commissioning

6.1.1 Mass moment of inertia

During the ELG testing the speed of response time of the set to a step change in consumer load was considered to be too short, i.e. the response was too fast. This produced an overshoot response which was considered to be a contributory factor in the inconsistency of the governing action. Application of the relationship between the energy stored in the rotating elements of the set and the apparent power rating of the generator showed a less than adequate inertia constant, H, of 0.346 s instead of a preferred value in excess of 2 s.

It was decided to design and produce an experimental mild steel flywheel, 500 mm in diameter and 18.4 mm thick, keyed on the generator shaft and bolted to the generator pulley. The inertia constant was thus increased to 1.028 s. The set ran more smoothly with an increased time response and the ELG operation improved but the change in frequency per kW of consumer load change was too high at 7 Hz/kW. This indicated that the nominal turbine speed was too low. Subsequent tests using increased generator pulley diameters showed that the optimum pulley diameter is 140 mm which increased the turbine nominal speed from 234 rev/min to 263 rev/min, improved the frequency response to 3.5 Hz/kW and further improved the ELG performance.

It was anticipated that a further increase in the inertia constant to $H = 3.5$ s would give valuable data on the turbine performance and again improve the ELG performance. Results of tests of a flywheel of dimensions 747 mm diameter and 17.25 mm thick ($H = 3.56$ s) confirmed that the performance of the system was indeed superior. The set ran smoothly with no indication of speed fluctuation and the time response was considerably increased.

6.1.2 Ballast Load Sections

A critical aspect of the operation of the ELG is the accuracy of the sections of ballast load which are switched by the ELG Unit in response to changes in the consumer load. It was thus important to ensure that the ballast load sections were as close to their specification as possible. Further, it was realised that in the summer months, that as the river flow was relatively low, it was necessary to adopt a "summer" rating for the ballast load which more closely matched the maximum output available from the generator.

6.1.3 Draft tube outlet

Excavation of the river bed area immediately below the draft tube exit was done in order to ease the flow of water away from the draft tube itself.

6.1.4 Software Options

The two different versions of the software algorithm, as described above, were tested once the remainder of the system was considered to be adequately tuned. The original control strategy proved to be very reliable, operating in a stable manner and without any particular problems.

Recognising the potential advantages of adopting the proportional control algorithm, the program was changed through the simple replacement of an EPROM. The improvement in the response of this algorithm was immediately obvious, with significantly reduced transient periods when frequency excursions occur. Operational problems with this algorithm did however become evident. These were initially thought to be as a result of either the introduction of a current deadband (possibly fighting the frequency deadband) or a "non-zero" solution when calculating the amount of load-change required.

Further testing and observation both at site and in the laboratory (where the turbine-generator set is simulated by a motor-generator set) have shown that although these two aspects would have an effect on the behaviour of the system, a more fundamental issue was behind the problems that occurred. Presently the program looks at the current balance in each phase on an individual basis, and calculates the correct amount of ballast load required for each phase. Given that the resolution of the corrective action in each phase is 1/7th p.u. each phase is thus controlled to that degree of accuracy.

The frequency/load characteristic of the set determines the width of the necessary frequency deadband as a function of the minimum increment of ballast load. On a per phase basis, the minimum increment is 1/7th p.u., suggesting that an increment of 1/21st p.u. (when compared with the total load) would be considered as the minimum increment for calculation of the deadband. However, given that each phase is considered on an individual basis, the combined effects of two or more phases having instantaneous current values just inside the edge of their resolution can lead to the frequency settling at a value outside that deadband, refer Figure 6.

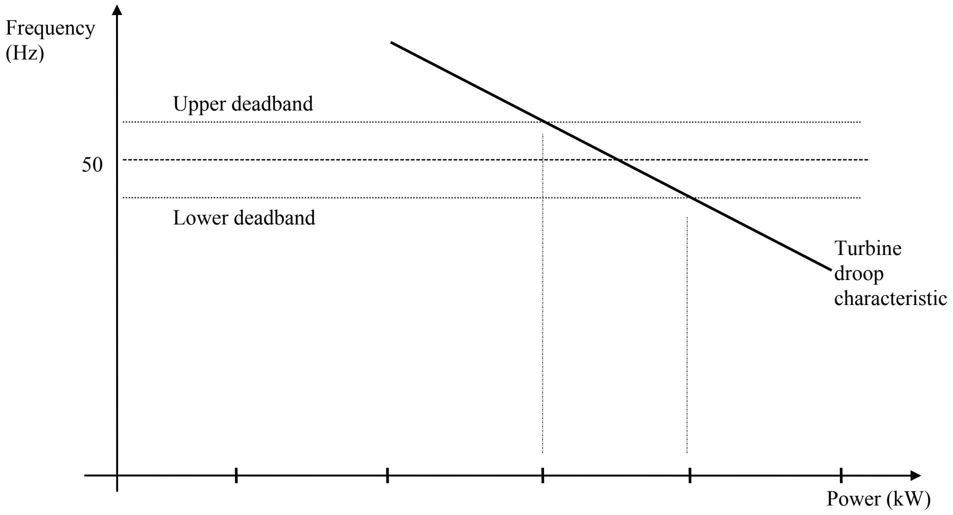

Figure 6 - Deadband and Droop Interaction

A solution to this could be to set a wider deadband, however this would defeat the object of the ELG which is to control the speed of the set to provide an output waveform with a frequency as close to nominal value as possible. Thus the preferred solution is to detect this condition and then force the Unit to adjust load by one step in one phase only. This effectively provides a degree of finer control as and when required. A revised algorithm to achieve this has been developed and is being tested at the time of writing this paper.

7. Outlook/Conclusions

The ELG Unit has been shown to operate in a satisfactory manner when compared to its design. The on-site demonstration has highlighted the need for the design and installation of the associated ballast load sections to be as close to specification as possible, otherwise the ability of the ELG to perform as designed is impaired. The opportunity has also been taken to test two different control algorithms, and tests determined that the use of a proportional control strategy gave a better performance that the original strategy used. Improvements in the operation of this algorithm are in hand. Recent research [Henderson & Pearson, 1998[5]] has indicated that further improvements could be gained by adopting a derivative control.

The capital cost of the ELG Unit is small in comparison to the total cost of the installation, and so reductions in the cost of the Unit through series production, whilst having a significant effect on the cost of the Unit itself (savings of between 20 and 30% might be expected), would have only a marginal effect on the total cost of other similar installations.

The replication potential of the ELG Unit should be high. Electronic Load Governing is now the standard method used for controlling the speed of micro hydroelectric generating sets (i.e. those with outputs less than 100 kW), and so there is a significant market for such a unit. There are a number of other designs of Electronic Load Governor on the market, and this one differs in the technology used in its design. As a result it is relatively inexpensive and is very simple to install and operate. The need for the ballast load sections to be accurately specified and installed is an area that will have to be emphasised in future replications.

It is the intention in the long term that commercialisation of the ELG Unit will be achieved through the licensing of the design to a suitable company. No such company has been identified at present, although to a large extent, this is serially dependant on the outcome of the successful demonstration of the Unit.

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Biographical details of the author

Dr D S Henderson graduated with an Honours degree in Electrical Engineering from the University of Edinburgh in 1975. After a year on the Scottish Engineering Training Scheme he then joined NEI Peebles Ltd as a Project Engineer. In this position, and also as a Senior Project Engineer with the same company, he spent a significant proportion of his time on small hydroelectric projects, e.g. the Kielder project in the UK. Since 1986 he has been with Napier University as lecturer in Power Engineering. During this latter period he has completed a part-time Ph.D. research study which was on the subject of a Three-phase Electronic Load Governor for Micro Hydro Generation. He also works as a part-time consultant in the small hydro sector.