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A NEW RANGE OF 5kW MICROHYDRO GENERATING SETS

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ABSTRACT

Isolated rural dwellings in many countries rely on local generation of electricity, typically by means of diesel generating sets. Microhydro systems offer an alternative which has become more realistic with recent advances in control technology. This paper describes the design and development of a 5 kW microhydro generating set which utilises one of a range of proprietary centrifugal pumps operating reversed as a turbine. Tests on a range of pumps covering various combinations of head and flow rate have shown excellent performance as turbines with efficiencies similar to or exceeding those in the pump mode. The use of an electronic load governor allows the use of a run-of-the-river principle (i.e. no storage) and constant flow operation. The governor diverts surplus power through a dummy electrical load and avoids the need for a separate turbine speed governor and accurate turbine flow control. Malfunction protection and load management systems are also incorporated to allow maximum utilisation of available power.

The electronic load governor operates with a brushless self-excited synchronous generator to a produce stable electrical output of 5 kW at 230 V, 50 Hz AC. A flywheel is included between the turbine and generator to help maintain generator frequency within required limits during electrical load transients. The system has been tested with five turbine variants, for operating conditions covering heads ranging from 28 m to 155 m and flows ranging from 28 l/s to 9 l/s respectively.

1. INTRODUCTION

Microhydro electric power generating systems (usually considered to be < 100 kW) offer a means of supplying remote areas or village communities with electricity when supply through a national distribution system is not physically or economically feasible. An attractive feature of microhydro systems is that they are powered by a renewable energy resource and there are opportunities for their development in many countries, as reviewed by Heng (1992).

Some studies on microhydro in developing countries such as Papua New Guinea and India (e.g. Holland, 1989) have cited a number of drawbacks such as high capital cost, maintenance problems, disputes over ownership, lack of industrial load to raise utilisation to a reasonable level, and excessive dependence on scarce engineering skills. On the other hand, Robinson (1988), for example, has shown that microhydro can be a viable source of energy if properly designed.

This paper considers the design and development of 5 kW systems, suitable for small privately owned schemes on remote farms or domestic properties. These systems must be low in cost to be affordable by private users, and the design should be based on the following criteria:

(i) Avoidance of the need for professional engineering expertise to install, commission, or operate the system.
(ii) Maximum use of widely available proprietary components.
(iii) Use of recent electronic load governing technology to provide reliable and fast responding control without the need for mechanical speed governing systems.

A typical microhydro installation is shown schematically in Figure **1**. The microhydro generating scheme using modern control technology as described in this paper comprises:

1. Intake
2. Penstock pipeline
3. Turbine (centrifugal pump operated in reverse)
4. draft tube and return duct to river
5. Synchronous generator (brushless synchronous machine)
6. Coupling, flywheel (to aid load governing) and brake
7. Electronic load diverting governor
8. Electrical safety logic
9. Electrical distribution system.

For use in isolated locations, a synchronous generator is preferred (Boys et al., 1981), as excitation and voltage regulation are built-in, whereas an induction generator requires external excitation and voltage regulation. The speed, and therefore the frequency, are controlled by the electronic load governor (Woodward and Boys, 1984), which manages the total electrical demand presented to the synchronous generator, and automatically diverts unused available power to banks of dummy resistive loads. The flywheel smooths the frequency variation during the switching of the governor when responding to consumer load changes. The flywheel also acts as a brake disc for the fail-safe mechanical brake. A load management system gives an audible or visual warning to the consumer to shed load if an overload occurs. If an overload continues all power is diverted to the dummy resistive load. Studies of New Zealand urban residential electricity consumption have established that the maximum demand in residential housing is approximately 12 kW, and the average 24 hour demand is approximately 1.5 kW. To design a generating system to satisfy maximum demand is too expensive, and to design for the average load would not offer a very useful system. The design power of 5 kW was therefore chosen as a basis for developing a microhydro system for an isolated New Zealand farm house (Giddens,1986).

Following sections outline the selection and testing of pump units to use as turbines, the load governing system and the embodiment design of the 5 kW microhydro system package. Heng (1992) gives a more detailed description of this material.

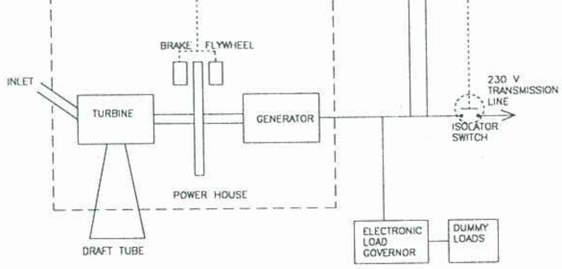


Figure 1 A packaged microhydro generating set

2. TURBINE TESTING AND SELECTION

2.1 Centrifugal Pumps as Turbines

To keep cost down, the microhydro system was designed around a series of ISO centrifugal pumps, which can operate effectively as turbines (Buse, 1981; Shafer, 1982). In principle, any centrifugal pump can operate as a turbine. However, Engenda and Rautenberg (1988) stress that the use of pumps as turbines should be considered only where:

(i) where initial cost is more important than efficiency and breadth of operating range;
(ii) where flow is more or less constant;
(iii) where tested turbine data for the pump to be used are available.

Characteristics of pumps are freely available from pump manufacturers, but their characteristics as turbines usually have to be determined by testing under the conditions of planned usage.

When the pump is operated as a turbine, both the direction of flow and the direction of rotation of the impeller are reversed for the impeller to become the turbine runner. Consideration of impeller/runner leakage flows and machine efficiency in relation to head change and flow rate through the machine, indicates that for a given energy transfer between rotor and working fluid the turbining head and flow rate are greater than in operation as a pump. It follows that for pump and turbine operation at the same speed, and both at the best efficiency point (BEP), the turbining head and discharge are greater than the pumping head and discharge respectively.

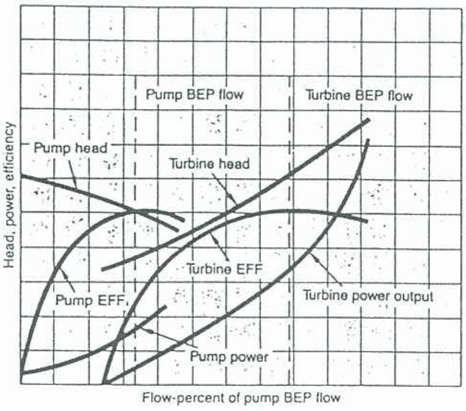
Figure **2** shows typical characteristics of a centrifugal pump operated at the same speed first as a pump then as a turbine, with curves normalized by the value of head, flow rate, efficiency and power at the pump BEP. Note that the location of the turbine BEP is at a higher head and flow rate than the pump BEP. The ratio of turbine to pump head and discharge vary with specific speed but are reported in the range 1.1 to 2.2 (Spangler, 1988). The turbining maximum efficiency tends to be about he same as in pumping, but the turbining maximum efficiency curve is flatter offering a wider range of operation without such an adverse effect on efficiency.

Available formulae for determining turbining performance from given pump performance data were used by Heng (1992) to give an indication of turbining performance. However a microhydro turbine supplier will need to supply full performance characteristics and therefore full tests of candidate centrifugal pumps as turbines are generally necessary.

2.2 Pump Selection for Turbine Operation

A range of proprietary ISO 2858:1975 centrifugal pumps manufactured in Australia were chosen for this exercise, using the following guidelines:

(i) 6 kW shaft power output (4.8 kW electrical output at 0.8 power factor).
(ii) Head and discharge ratio of turbine to pump of 1.5 to 2.0.
(iii)Turbine efficiency equal to 98% of pump efficiency.
(iv) Similarity rules without any scale effects.



Pump and turbine RPM = constant

Figure 2 Normalised performance characteristics for pump operating in normal pump and in turbining mode

The five pump sizes selected were: 50x32-200, 65x40-200, 65x50-160, 80x65-160, and 80x65-125. The pumps were tested first as pumps then as turbines. A conical draft tube with an outlet flow straightener was fitted on the "turbine" outlet, and total head was measured just downstream of the flow straightener. the draft tube doubled as a converging entry transition for pumping mode tests. The trials were carried out in the Civil Engineering Fluid Mechanics Laboratory of the University of Canterbury. The measurement systems employed allowed experimental uncertainty to be limited to +/- 1.0% on discharge, +/- 0.5 m on head, and +/- 100 W on shaft power.

2.3 Results of Pump and Turbine Tests

It was desired to have the turbine delivering 6 kW shaft power at the BEP. This was accomplished with three of the five pumps in the standard configuration, but the impeller diameters of the 65x40-200 and the 80x65-160 had to be reduced to 185 mm and 142 mm respectively to avoid excessive power output at the BEP. A summary of the operating conditions and turbine-to-pump performance ratios at 3,000 r/min, 6 kW and BEP are shown in Tables 1 and 2 respectively. Note in Table 1 the increase in specific speeds, N_{st} and N_{sp}, and efficiency as the pump shape varies from radial flow for the high head 50x32-200 to mixed flow for the low head 80x65x125. Performance curves for the five turbines are shown in Figure **3**. These should not be treated as guaranteed performances for any ISO pumps of these dimensions.

Table 1: Optimum Operating Conditions at 6 kW Shaft Power in Turbining Mode

Machines	Head (m)	Discharge (l/s)	Efficiency (%)
50x32-200	155	9	44
65x40-200(185)	85	13	56
65x50-160	64	14	70
80x65-160(142)	43	21	72
80x65-125	28	28	78

Table 2: Turbine to Pump Performance Ratios at BEP

Machines	N_{st}	N_{sp}	Head	Disch	Effy	Pwr
50x32-200	0.025	1.7	2.20	1.66	0.91	0.76
65x40-200(185)	0.050	2.5	1.76	1.28	0.98	0.88
65x50-160	0.075	3.7	1.57	1.23	1.03	0.96
80x65-160(142)	0.125	5.2	1.44	1.23	1.03	1.04
80x65-125	0.200	7.9	1.35	1.38	1.03	1.06

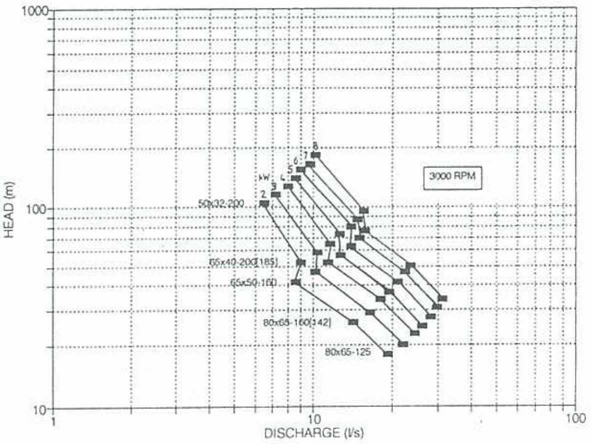


Figure 3 Turbine selection chart for ISO centrifugal pumps

3. SELECTION OF GENERATOR AND LOAD GOVERNING SYSTEM

3.1 Generator Selection

Whilst advances are now being made in the use of induction generators in stand-alone power generating systems, synchronous generators are still the common type of electric machine used in microhydro applications. For this project a Markon Type B21D 6 kVA, 230 V. single phase, 50 Hz at 3,000 r/min, 2 pole self-excited brushless generator with automatic voltage regulation and drip-proof enclosure was specified.

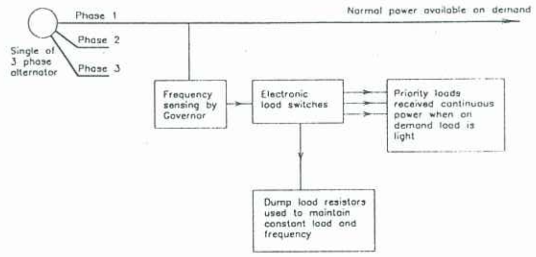
3.2 Selection and Operation of Load Governor

The electronic load governor used is the single most important item enabling cost reductions in the microhydro system. It replaces earlier costly designs for mechanical speed governors and allows constant flow through the turbine, eliminating any problems of hydraulic instability. The electronic load governor used in this project, developed originally by Woodward and Boys (1984) of the University of Auckland, was manufactured by Delphi Industries Ltd, Auckland.

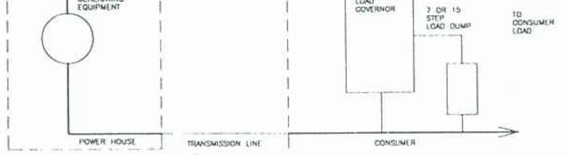
The governor operates by varying a control ballast resistive load in response to variations in the generated frequency. If the consumer load is increased, a decrease in turbine speed will result with a consequent drop in electrical frequency, causing the governor to reduce the ballast load accordingly. The governor uses zero voltage switching where the moment of switching corresponds to voltage zero, this minimises harmonic distortion and radio frequency interference. The switching between different loads is stepped.

The governor measures frequency by timing the period of the voltage waveform and utilises a 4 bit pulse counter to give a binary output which switches 4 triacs controlling 4 dump loads sized in the ratio 1:2:4:8. The governor is thereby able to provide any ballast load in equal steps between 1 and 15 times the smallest load, by appropriate combinations of the four loads. In operation, an input frequency of 49.3 Hz or less corresponds to a count of zero and all triacs will be switched off. At exactly 50 Hz, a load of 7/15 units will be switched on . If the frequency is above 50.7 Hz, all triacs will be switched on.

Because the governor is sensitive to frequency, which is the same throughout the supply system, governors may be installed at any point in the system circuit. An arrangement for a single phase system is shown in Figure 4. Dumped load may be put to good use for additional water or space heating. Multiple governor units may be used in a single phase system where it is desired to control dump loads and low priority loads at two or more locations.



Operation of the electronic load governor



A typical single phase application

Figure 4 Load governor arrangement

3.3 Governor Stability and Flywheel Requirement

The electronic load governor relies on obtaining an accurate measurement of the frequency from the period of the voltage waveform. However the transient reactance of the synchronous machine causes a phase shift in the output voltage whenever a change in external load occurs, such that an imperfect measurement of the period of the waveform results. This may lead to the governor overcorrecting and applying and removing load alternately at each switching, such that there is an instability at the switching frequency of 25 Hz. This is avoided by use of a low pass filter, which itself may introduce a delay causing a low frequency (approximately 2 Hz) instability.

This potential instability is handled in practice by using a flywheel of suitable inertia, an essential feature of systems using a governor such as the Delphi. A series of tests were carried out in which a range of flywheels were mounted between the turbine output shaft and the Markon generator. A 2 kW load was instantaneously switched on at the consumption point, tending to cause a sudden drop in generator speed. Effects on generator frequency were observed using an oscilloscope. It was desired to find the a flywheel inertia which would result in a critically damped response to the transient, and with the oscillation within the governor bandwidth (49.3 to 50.7 Hz). It was found that a flywheel inertia of 0.11 kgm^2 as recommended by the governor manufacturer led to generator frequency oscillations overshooting and undershooting the governing bandwidth. An inertia of 0.44 kgm^2, four times that recommended, was necessary to give the desired stability.

4. SYSTEM IMPLEMENTATION

4.1 Overview of System Design

The mechanical layout of the system for field installation is shown in Figure 5. The parametric design is identical for all 5 variants and only detail dimensions for pipework vary to accommodate the alternative turbine sizes. The penstock includes a shut-off gate valve. A similar valve is located in the flushing pipe which bypasses the turbine. The 470 mm diameter 12 mm thick flywheel is mounted on a half coupling at the turbine output. A stub shaft drives from this half coupling through a Fenaflex type F50 rubber coupling to the generator shaft. A Twiflex MSF mechanical calliper emergency disc brake is mounted to act on the flywheel. If a malfunction occurs which triggers a plant shutdown, power to a latching solenoid is disabled causing springs to actuate the brake linkage. The flywheel and brake assembly are enclosed in a 6 mm thick steel plate shroud. The electrical protection system is mounted in a cabinet adjacent to the generator.

4.2 Electrical Safety and Protection System

The 5 kW microhydro system is designed to be installed by a user with minimum engineering knowledge, and Heng (1992) has prepared an installation, operation and maintenance manual which minimises any required engineering input for the user's site. Main considerations that will need engineering for a given site will be the layout and installation of the intake, penstock and discharge pipe. Here only an overview of the safety and protection system is given. The microhydro system operating on a run-of-the-river principle, will generate a constant base load of 4.8 kW at 0.8 power factor. During maximum demand periods this can easily be exceeded. A reduction in water supply to the turbine through low river flow or blockage of the flow at the penstock intake can likewise result in an overload and require protection of the generating equipment.

As outlined by Bryce and Giddens (1985), the approach to the design of system malfunction protection equipment depends on:

(i) The designer's responsibility to the customer.
(ii) Requirements of any statutes and regulations.
(iii) The skill that will be available for recognising and responding to a malfunction.
(iv) System design life.
(v) Facilities for maintenance and repair.
(vi) Cost.

There are four levels of protection which cover the fault states that may occur. These are characterised by the degree of isolation from the consumer: 1. Consumer circuit protection; 2. Consumer mains protection; 3. Transmission line; 4. Generator.

The supply is from an automatic, unattended source in which the voltage, frequency and current can vary outside their normal supply limits due to a malfunction in any part of the complete system. In principle protection is provided by sensing voltage, current and frequency separately and making an appropriate protective response. The brake solenoid will unlatch and activate the disc brake, on detection of over- or under-voltage, over- or under-frequency (speed), or over-current. The scheme is illustrated in Figure **6**.

Over/Under-Voltage: For the generator, extreme voltages can be caused only by serious overspeeding or failure of the voltage regulator. In either case plant shutdown is appropriate and initiated by an under/over-voltage relay which requires voltage to be maintained within the range 180 to 260 V. This relay will also initiate a shutdown on overspeeding due to loss of generator excitation.

Over/Under-Frequency: Despite the presence of the load governor, over frequency (overspeed) may still occur due to load rejection, loss of excitation, or failure of automatic voltage regulation, ballast loads or the load governor itself. Under frequency may be caused by an overload by the consumer. If this occurs an alarm is sounded after 20 seconds, then a shutdown triggered if the consumer does not reduce load. A frequency relay with lower and upper limits of 45 and 55 Hz is used to trigger a system shutdown on under- and over-speed respectively.

Over-current: An overcurrent relay will disable the system in the event of excessive generator current caused by an equipment fault.

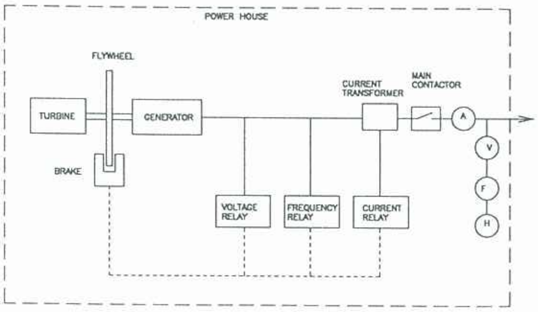


Figure 6 Malfunction protection system

5. CONCLUSION

This paper has briefly described the design and performance of a stand-alone 5 kW microhydro system using a range of ISO centrifugal pumps operating as turbines to offer a versatile coverage of possible head and flow rate conditions at the user's site. The next phase of the project will be to evaluate some of these 5kW systems in the field, and to compare performance with other sets developed at the University of Canterbury,including a low head/high flow rate axial flow turbine set.

6. ACKNOWLEDGEMENT:

The authors gratefully acknowledge the considerable guidance and background knowledge provided by Mr E.P. Giddens, who for many years led microhydro research at the University of Canterbury.

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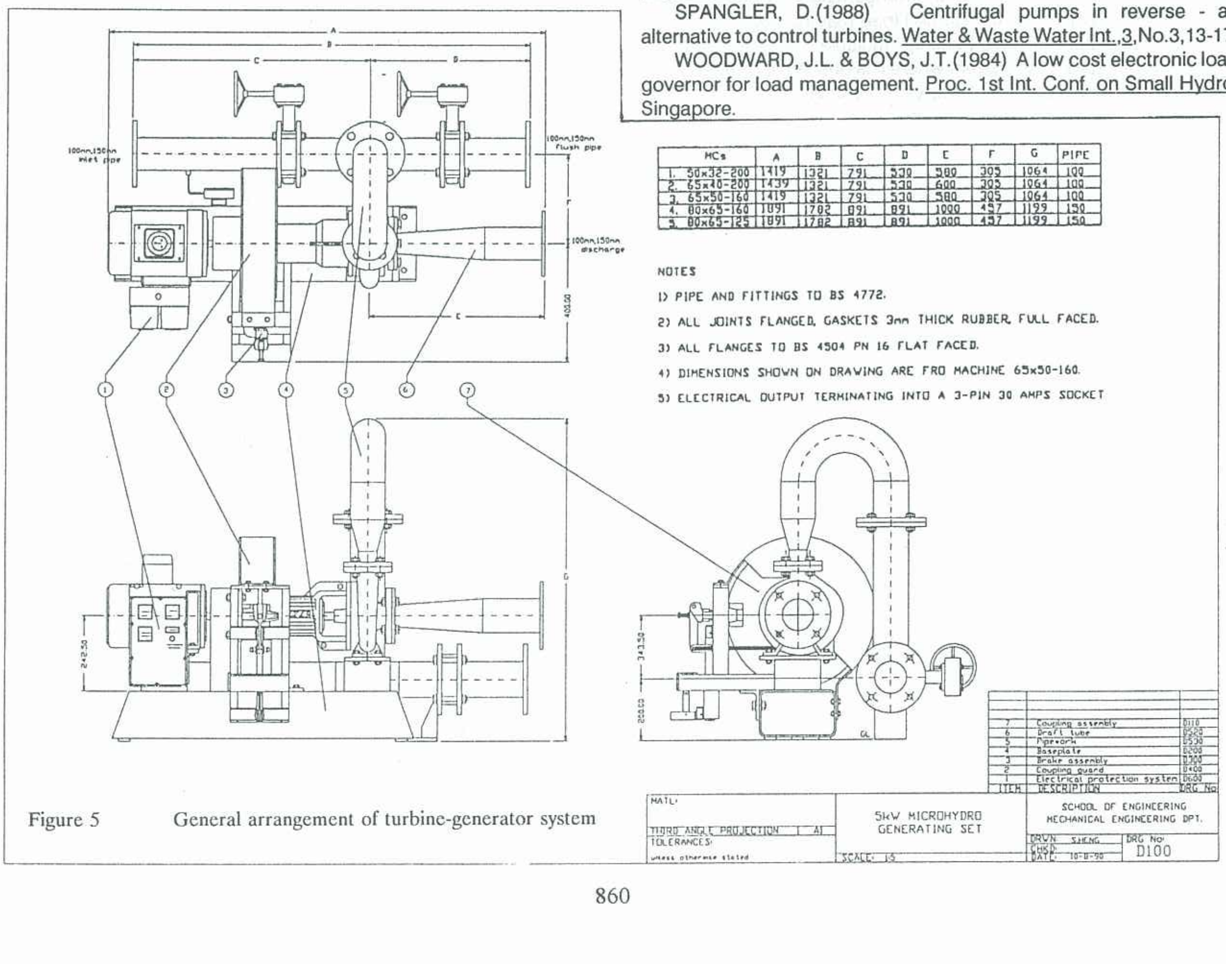

HCs	A	B	C	D	E	F	G	PIPE
1. 50×32-200	1419	1321	791	530	580	305	1064	100
2. 65×40-200	1439	1321	791	530	600	305	1064	100
3. 65×50-160	1419	1321	791	530	580	305	1064	100
4. 80×65-160	1091	1702	891	891	1000	457	1199	150
5. 80×65-125	1091	1702	891	891	1000	457	1199	150

NOTES

1) PIPE AND FITTINGS TO BS 4772.

2) ALL JOINTS FLANGED, GASKETS 3mm THICK RUBBER FULL FACED.

3) ALL FLANGES TO BS 4504 PN 16 FLAT FACED.

4) DIMENSIONS SHOWN ON DRAWING ARE FRO MACHINE 65x50-160.

5) ELECTRICAL OUTPUT TERMINATING INTO A 3-PIN 30 AMPS SOCKET

ITEM	DESCRIPTION	DRG No
7	Coupling assembly	D110
6	Draft tube	D520
5	Pipework	D530
4	Baseplate	D200
3	Brake assembly	D300
2	Coupling guard	D400
1	Electrical protection system	D600

Figure 5 General arrangement of turbine-generator system