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State-of-the-Art in Mini-Hydro Electrical Design

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ABSTRACT

Recent advances in solid-state electronics and electrical equipment are finding applications in mini-hydroelectric powerplants. Numerous new products are on the market but there is very little documentation to allow designers to select appropriate design criteria and equipment for installations in the size range between 50 to 500 kW. The paper looks at the advances in micro-hydro technology (less than 50 kW) and small-hydro (greater than 500 kW) technology. The art of mini-hydro design is to be able to select the appropriate features from micro and small-scale technologies that minimize cost and still deliver reliable, high quality electrical power.

INTRODUCTION

More research and development is being conducted in the area of very small hydroelectric power systems than ever before. Countries with any significant amount of rainfall want to know how to develop their hydropower resources quickly, with the lowest cost. Developing countries especially are looking to small decentralized hydropower as an alternate to expensive extension of the national electric power grids or continued consumption of diesel fuel. Usually, the lower cost alternatives make use of local materials and equipment to the extent possible. Thus, numerous countries are conducting research on the application of local resources toward the development of small hydropower potential.

Usually these country programs involve the determination of the state-of-the-art in small hydro design and what type of program makes sense for their country or region, the development of a local design, and the implementation of a pilot project. This paper is written in the hope of helping researchers and program managers establish current design practices in mini-hydro powerplants.

The term mini- in this paper will refer to installations with capacity between 50 and 500 kW. Installations below 50 kW are referred to as micro-hydro, and those between 500 kW and 5,000 kW small hydro. Other assumptions are that the power output will be alternating current (AC) using a synchronous generator.

The typical features of a mini-hydro installation are shown in Fig. 1. These consists of the civil works (intake structure, power canal, forebay, and penstock), powerhouse, and the electrical distribution system.

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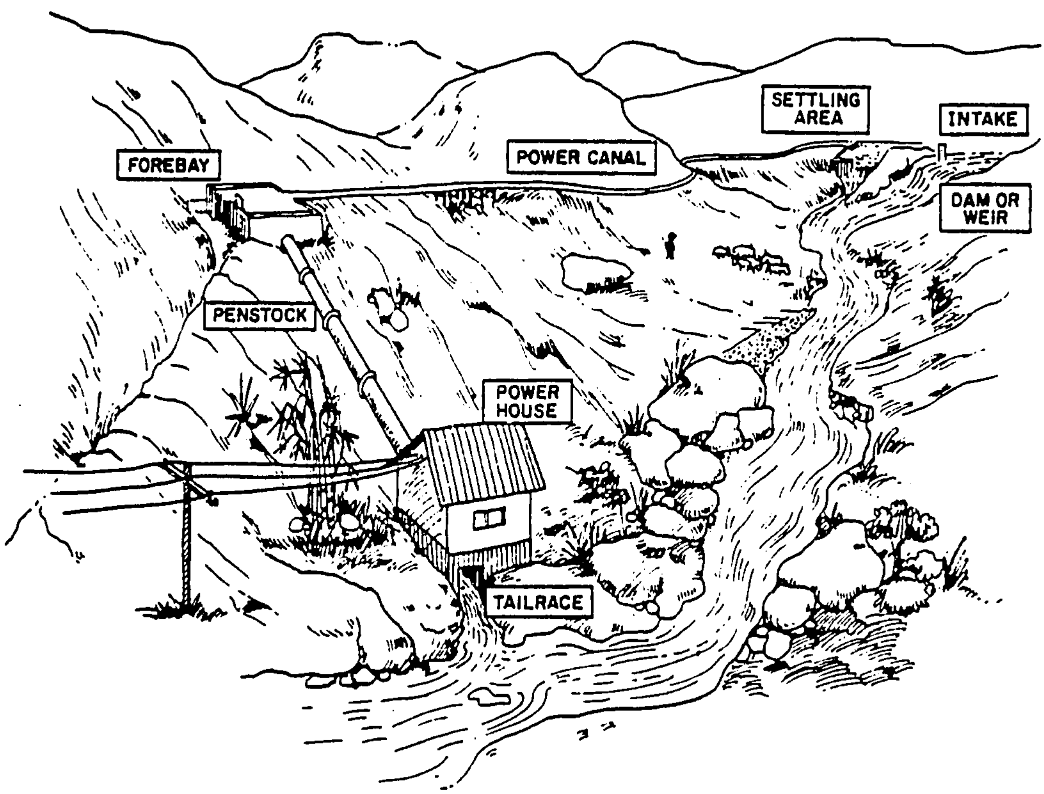

Fig. 1 Typical features of a mini-hydropower plant.

COST

There is considerable interest in the cost of small, mini- and micro-hydropower systems. Curves, formulas, and case studies have been presented to support both best case and worst case costs. Curves such as #1 in Fig. 2 show that small hydro installations have reasonable costs (under $2,500/kW), but as the units get smaller, the costs rise inversely.[5] These curves tend to be derived from designs and implementation schemes that treat mini- and micro-hydro as scaled-down versions of small hydro projects.

On the other hand, curves #3 and #4 in Fig. 2 come from case studies of actual micro-hydro installations which utilized "low technology" features such as locally made turbines, unlined power canals, rock pile intake structures, etc.[2, 3] But just as mini-hydro is not scaled-down small hydro, neither can it be considered as scaled-up micro-hydro. Appropriate cost curves for mini-hydro such as curve #2 in Fig. 2 lay between the micro- and small hydro cost curves, and indeed, utilize features from both of these technologies. The art of mini-hydro design is to be able to select the appropriate features from micro- and small-scale technologies that minimize cost and still deliver reliable, high quality electrical power.

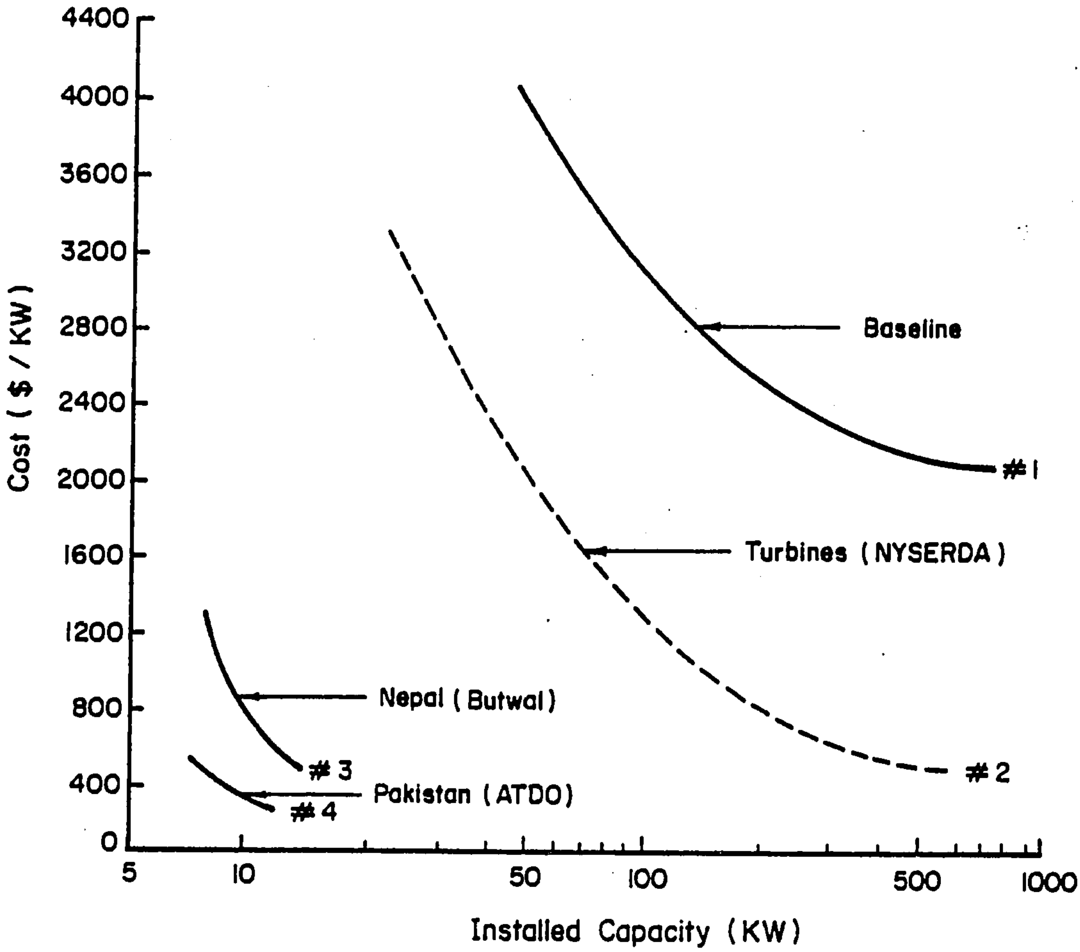

Fig. 2 Capital cost of small-, mini-, and micro-hydro.

POWERPLANT

There are four major component areas in the mini-hydro powerplant (see Fig. 3). First is the turbine which converts waterflow into rotary motion. Second, is the generator which changes the rotating motion to electric energy in the form of an AC voltage at the machine terminals. Third is the exciter system which supplies direct current (DC) power to the rotating field of the synchronous generator. This system includes the voltage regulator and exciter. The fourth component is the power control and protection equipment. Advances in each of these component areas have had a positive impact on mini-hydro design in the past few years.

The advances in the state-of-the-art in mini-hydro design have primarily been in the electrical components of the powerplant; the generator, exciter system, control and protection. Recent trends in turbine design are towards using pumps as turbines, and the local manufacture of cross-flow turbines. Standard centrifical pumps have been used as turbines for a couple of decades in scattered cases, but the idea seems to have been rediscovered. The US Department of Energy funds several studies to identify which pumps could be converted, and what modifications could

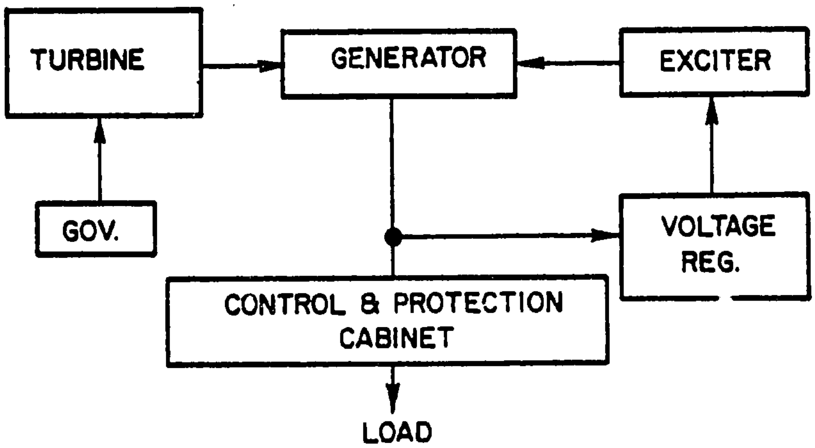

Fig. 3 Components of a generator system.

be made to increase the efficiency of the unit. Along with the government funded research came manufacturers who are now offering standardized turbine-generator packages using their pumps in reverse.

Several manufacturers now advertise their "standardized unit" as a new cost savings feature for mini-hydro installations. This is primarily a new marketing approach, not a new advance in turbine technology.

GENERATORS

Advances in small generator design have been primarily in the use of lighter weight materials, and better insulating materials.

Manufacturers have been utilizing lighter weight materials to save on construction, shipping and handling costs. High strength aluminum is used in applications where cast iron had previously been used. The lighter weight metal also dissipates heat better. This, combined with more efficient cooling fans, has allowed the manufacturer to reduce dead air space, and the size and weight of the generator (for a given capacity).

Improvements in epoxy insulating materials is allowing the newer generators to operate at a lower temperature, and hence with better efficiency than older generators. The new coatings last longer, dissipate heat more easily, are non-corrosive, and do not soften at higher temperatures. All of these features give the generator a longer life. Newer generators have increased the surface area per unit volume by adding fins and dimples to the generator frame. This helps the generator dissipate heat and operate at lower temperatures, thereby improving longevity.

Bearing improvements have reduced the maintenance requirements of today's generators and added to their reliability and life.

EXCITER SYSTEM

Voltage Regulators

Voltage regulators regulate by sensing AC generator output voltage and then controlling the

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amount of DC current supplied to the exciter field. The exciter provides the excitation for the main generator field. The voltage regulator maintains the output voltage of a generator as nearly constant as possible during all operating conditions.

The basic functions of a voltage regulator are:

1. to measure the sensing of the generator output voltage;
2. to provide a reference voltage to compare with the sensing voltage;
3. to amplify the error difference between the sensed voltage and the reference voltage; and
4. power control: when the sensing voltage does not agree with the referenced voltage, corrective action must be started so that the power stage delivers the necessary excitation to regain the desired voltage.

Older electromechanical regulators operated by controlling the amount of field current that flowed from the output of the exciter to the exciter field (a small DC generator).

Newer solid-state voltage regulators operate by taking AC power from the output of the generator (see Fig. 4). This allows a high level field forcing voltage to be quickly applied to the exciter field, with the end result that the generator system voltage recovers much faster than with the old electromechanical voltage regulators. Another advantage over electromechanical devices is that solid-stage voltage regulators have no moving parts to wear out.

Solid-stage regulator provide better regulation, usually within 1%, faster response, greater stability, stronger construction (rugged) and improved reliability.

Exciters

Exciters supply excitation power to the main generator field. They are used because the generator field usually requires more power than a voltage regulator can provide. There are two basic types of exciters – rotary and static. The two types of rotary exciters are DC brush type and brushless.

Older DC brush-type rotary exciters use commutators (mechanical rectifiers) to covert

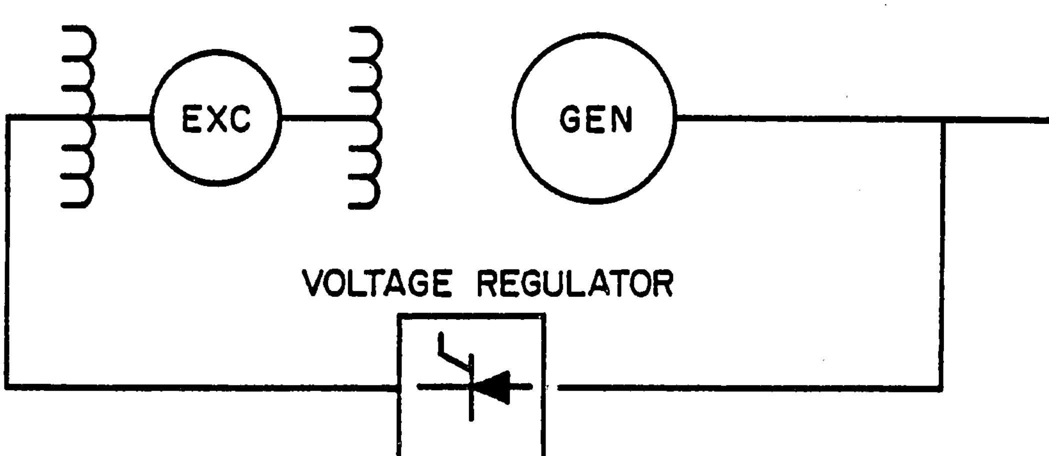

Fig. 4 Static voltage regulator

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their output to DC. Brush-type exciters may be directly coupled to the generator (e.g., driven on the same shaft), or they may be belt-driven. Some disadvantages of a brush-type exciter are that it has commutators which require occasional maintenance, and, when belt-driven, the belts need to be replaced periodically.

On newer brushless rotary exciters, the field poles are the stator, or stationary element. The rotor has the AC winding and rotating silicon diode rectifiers. These rectifiers convert the AC to DC. The DC leads are run along the shaft to the main generator field which is the rotor of the generator. Brushless exciters must be directly coupled to the generator shaft. This type of machine does not require slip rings, commutators, or brushes. Brushless generators are virtually maintenance free, and the most popular type of exciter/generator manufactured today.

Static exciters, like solid-state voltage regulators, rectify the generator output and feed the power to the generator field (see Fig. 5).

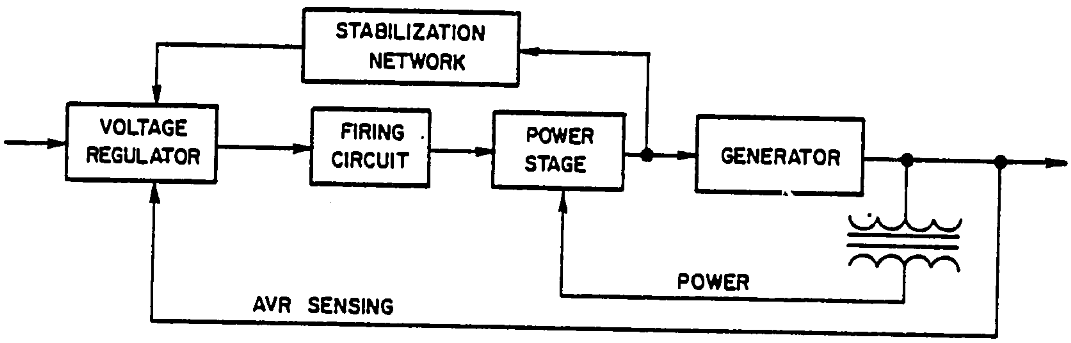

Fig. 5 Shunt static excitation system

Many small isolated electric generators are required to sustain the substantial current overloads associated with starting large motors. Typically, such overloads can be several times the normal running current. Brushless exciter-equipped generators and their associated voltage regulators are unable to meet these requirements because the generator output provides the input power for the voltage regulator. As the generator output decreases, the ability of the voltage regulator to provide exciter field power also decreases, and the result can be a total loss of excitation.

The excitation support system compensates for this inherent limitation by providing a constant voltage regulator power source even with the generator terminals short-circuited. This support system will allow newer generators to start up to .75 HP of motor load per kW of generator capacity.

CONTROL AND PROTECTION

Protection

Historically, fuses or electro-mechanical relays have been used for the protection of power system components such as generators, motors, and transformers. These relays have been used for disconnection by detecting a variety of electrical faults, including: (1) over-current; (2) over-voltage; (3) over and under-frequency. For larger units, current imbalance, generator ground, phase

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differential balance, and excitation failure, are also monitored. In the case of three-phase systems, each phase is generally monitored separately. Since these AC relay devices are often designed for larger generation installations, their reliability is extremely good. However, their cost, which can be several hundred dollars per fault per phase, precludes extensive use for mini-hydro installations.

The use of newer solid-state relays can provide improvements in several areas. The vibration and shock capabilities of these relays have virtually no restraints other than product cost. Accuracy to almost any level required can be provided with solid-state techniques. Unfortunately, their increased cost is rarely justified in mini-hydro application. Nonetheless, the cost of solid-state devices has been continually going down, and if this trend continues more widespread use could take place.

Control

One of the most important steps which can be taken to effect cost reductions is to eliminate the speed governor. With a micro-hydro unit this can be done if the turbine is operated at constant flow and the total load on the generator is maintained constant. The cost benefits arise in a number of ways: the speed governor is a very expensive item, and may account for as much as 25% of the total cost of a micro set, turbine design can be simplified since continuous automatic variation of flow is no longer required.

Maintaining the total load on the generator constant may be achieved by automatically varying the load taken by a ballast load unit as the consumer load changes. An electronic load governor senses voltage or frequency and maintains it substantially constant by controlled switching of thyristors in the ballast load circuit.[6] This technique is more appropriate in the smallest sizes, but is applicable up to 50 kW sets, single- or three-phase. Such governor units are available from a number of sources but there is little operating experience available.

The author is aware of one load controller on the market from Canada, two from the U.S., one from Indonesia, England, New Zealand, and research directed toward production of controllers in Ecuador, India, and Nepal. More advanced units offer features such as programmable speed drops allowing parallel operation of generators.

Since load controllers are practical only up to about 50 kW, they are inappropriate for the full range of mini-hydro installations. However, the concept of constant load integrated with a crude mechanical water control is being introduced for units greater than 50 kW. The idea is that the electronic load controller will respond to all sudden changes of load by varying the surplus power into the ballast resistors. For larger changes, and slower daily changes in the load, the mechanical water control equipment responds. The advantage of this system over the standard mechanical governor is that the system can have fine frequency control with a very cheap water control device. The mechanical control can be pulsed rather than controlled proportionally, and a simple, less expensive, valve actuator can be utilized.

Other control advances have taken place in small-hydro technology. Extensive research and development activity has taken place in the last ten years on digital control of power systems. Recent work has defined monitoring and control requirements for various types of generation including small hydro. Certain functional requirements for the operation of small hydro plants are shown in Fig. 6. These functional requirements relate to the internal operation of a facility, such as turbine control, sequencing control (e.g. start-up), and generator control as well as the external interface of the hydroplant to a utility grid. Possible functions for the external interface include remote operation and data acquisition.

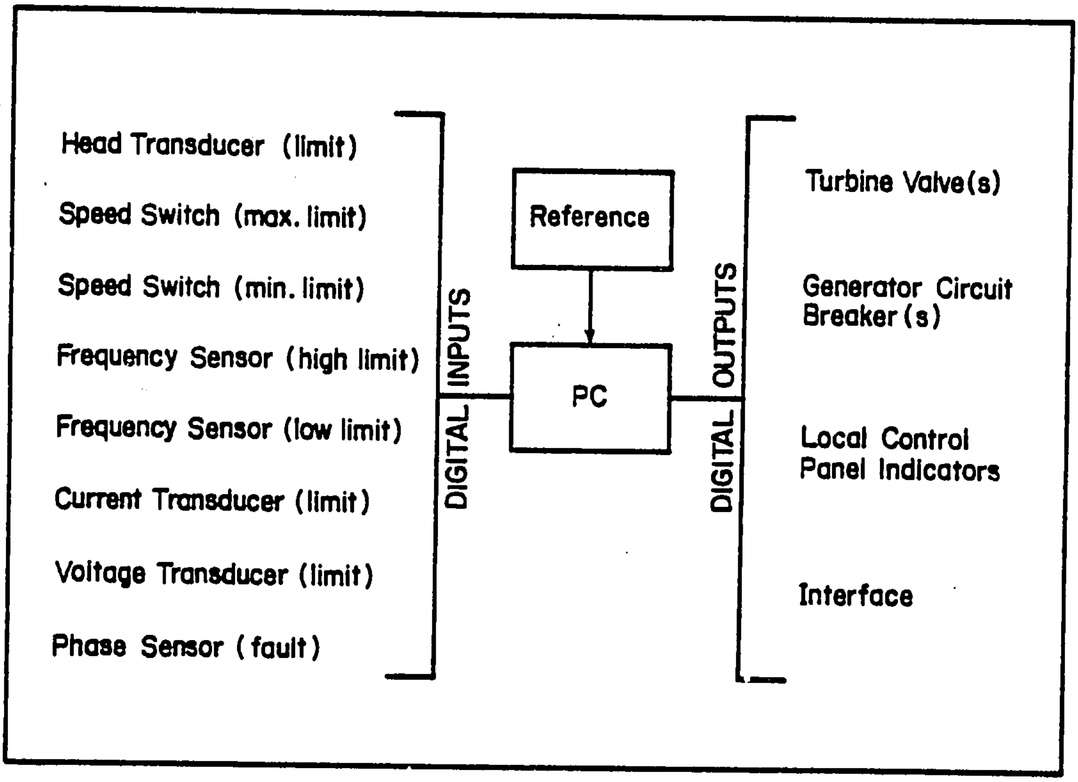

Fig. 6 Control functions using programmable controllers.

The data input processing and output are easily handled by today's programmable controllers (PC). P.C. are mini-computers that are programmed to perform specific control functions. P.C.'s on the market can perform speed control, protection, start-up and shut-down functions, and for interconnected hydro units, automatic dispatching and communication.

CONCLUSION

This paper has shown a number of developments in mini-hydro powerplant design that have come to use in the last few years. Many more improvements are being tested and will be available in the near future. Several institutions are conducting this research, but there is very little exchange of information between them. Hence, much of the work is being duplicated at several locations. Although separate independent research can support conclusions reached, there is not enough funding available today to justify such duplication of efforts.

REFERENCES

1. Basler Electric (1981), *Application of Static Exciter/Regulators in Electric Generating Systems.*

2. INVERSIN, ALLEN (1981), *A Case Study: Micro-Hydropower Schemes in Pakistan*, NRECA.

3. INVERSIN, ALLEN (1982), *A Case Study: Butwal's Experience with Micro-Hydropower Schemes in Nepal*, NRECA.

4. JURGUN, RONALD K. (1982), Industry's Workhorse gets Smarter, *IEEE Spectrum*, Vol. 19, No. 2, February 1982, pp. 35.

5. New York State Energy Research and Development Authority (1981), *Modular Small Hydro Configuration*, May 1981.

6. WOODWARD, J.L. (1980), *Village Microhydro – Can it be Appropriate*, First International Conference on Technology for Development, Canbera, Australia, Nov. 1980.

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