Developments in Controls to Govern Mini- and Micro-Hydropower Systems

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ABSTRACT

Control requirements, algorithms, cost constraints and potential for mini- and micro-hydropower are discussed, emphasizing the needs of isolated systems. Over 95% of all sites and 26% of the global technical hydropower are estimated to lie below 1 MW. Inexpensive reliable adaptive controllers with self diagnostics are needed to overcome the lack of trained personnel and to tap this resource. Developments of nonlinear models and digital control algorithms are described. Conventional and microprocessor based controls for small hydropower systems are surveyed. Electronic load controllers for micro-hydropower systems are discussed. These can significantly improve frequency control and reduce inertial requirements. Utilizing all secondary and off peak energy can greatly improve system economics. Recommendations are given for further research. Development of controllers for equipment below 1 MW is encouraged. A bibliography and an extensive list of manufacturers is provided.

INTRODUCTION

Many people in the world desire sources of energy to improve their standard of living. Others who already have petroleum fuelled generators are looking for alternative renewable energy resources. Most experts project that the world petroleum production will peak and then decline within the next few decades. Already expensive fuel will become increasingly more difficult to obtain. There is thus a strong interest in utilizing local hydropower resources.

Major portions of the global hydropower resources are still undeveloped (Armstrong, 1985). Most sites under 10 MW have been ignored as uneconomical compared with low cost fuel and traditional engineering costs. However, projections by the author suggest over 95% of all hydro sites lie between 10 kW and 1 MW (Hagen, 1985a). Furthermore 26% of all technically available hydropower lies in this region. This potential hydropower under 1 MW is greater than all existing hydro electric systems.

Mass production of standardized components coupled with local manufacture and labor can significantly reduce the costs of such small hydropower sites and make them economically competitive. China, as an example, had installed over 88,000 hydropower units in this power range by 1980 (Hangzhou Regional Centre for SHP, 1986)! Increases in energy prices, changes in tax laws, and utilization of the best large hydropower sites, have generated significant interest in smaller hydropower systems. Recent publications dealing with hydropower under 10 MW have been written by the United Nations (ECDC-TCDC, 1982), the US Department of Energy (McKinney, Warnick et. al. 1983), Fritz (1984), and the National Rural Electric Cooperative Association (Inversin, 1986). The First International Conference on Small Hydropower was held in Singapore in 1984, while the Second was held in Hangzhou, China in 1986.

Controls are critical to the viable economic operation of hydropower systems, especially in smaller sizes. Hydrosystem controllers must meet the objectives of economically providing quality power within equipment constraints (described below). An electric grid is effectively an "infinite" load, and provides the frequency and voltage control for small generating systems attached to it. However, isolated systems must control the frequency and voltage of the generator. Induction generators need a source of reactive power and thus traditionally cannot operate independent from the grid. Most mini- and micro-hydropower sites are remote from a grid and thus have all the difficulties of operating in a standalone mode and have severe cost constraints to be competitive.

Texts by Fritz (1984) and Warnick (1984) give a thorough presentation of all aspects of small to large hydropower systems (over 1 MW) including controls. Inversin (1986) similarly focuses on the needs of micro-hydropower systems. He gives an excellent presentation of the controls needed. He particularly details mechanical and non-traditional controls appropriate to remote sites in developing countries. The present review will concentrate on electric and electronic controls applicable to micro- and mini-hydropower systems (10 kW to 100 kW, and 100 kW to 1 MW). It generalizes and updates a previous more technical review paper (Hagen, 1985b).

NEED FOR CONTROLS

Turbine speed, generator frequency and voltage are critically important in hydropower systems. They must be controlled to prevent damage to the hydropower system or the load equipment, and to ensure proper operation of the loads. Automated controls are even more important for smaller hydropower systems where operators cannot be afforded. Rapid advances in electronics suggest the potential for adequate controls at economic prices. These requirements, equipment and potentials are described in this review. Special attention is given to smaller systems.

Speed/Frequency

If the power that a turbine "generates" (or converts) is not equal to the load on the system, the turbine (and generator) speed will change proportional to the power difference and inversely proportional to the system's inertia. The generator speed is proportional to the turbine speed (unless a variable speed drive or electronics are used). Loss of load in the system (load shedding or rejection) can result in the turbine (and generator) speeding up until its efficiency drops to zero.

This runaway speed can be 1.5 to 3.5 times the normal or design operating speed depending on the rotor type and setting. However, stresses in rotating equipment vary as the square of the speed. Thus stresses in the turbine and generator increase 2 to 12 times. The bearings also heat up rapidly. Thus loss of load and turbine runaway can destroy the generator, turbine and the shaft bearings. Certain types of generators are more sensitive than others to overspeed.

Power

The voltage also increases with generator speed. Higher voltage rapidly shortens the life of incandescent bulbs. High voltages can overheat or short out other electrical equipment. Reductions in frequency (speed) reduce electrical impedance in motors and transformers. These can then overheat and burn out. They also make incandescent lights difficult to start. Motors are reasonably tolerant to frequency fluctuations. However, clocks and other electrical and electronic equipment that depend on the electrical frequency will not operate properly with such fluctuations. Paper mills also require precise frequency control. Fritz (1984) and Inversin (1986) provide further discussion on such load and system requirements.

Penstock and Governor

The water flow through the turbine is usually adjusted to control the turbine speed. Flowing water in the penstock (intake pipe) has a large inertia. Attempts to rapidly change the flow by adjusting input valves or wicket gates can cause high pressures (pressure surges, water hammer or resonances) that can burst the penstock or damage other components. Surges can also occur in draft tubes (exit pipes). Rapid loss or additions of load can cause similar effects. The rate of change of water flow and rotor speed must therefore be carefully limited. Low turbine/generator inertia or relatively slow speed governors can result in unstable operation of the system and destructive speed excursions.

Inertial Requirements

These limits on how fast the flow can be changed, speed limitations on the turbine/generator, and instability problems traditionally impose minimum requirements on the turbine/generator inertia (i.e. flywheels may be needed). Hydropower systems with relatively low inertia compared to that of the water column cannot even operate isolated from an electrical grid. Usually values over 8 for the ratio of mechanical start-up time to water column acceleration time have usually been recommended. Hadley (1970) suggests a minimum of 2.5 for Pelton (impulse) turbines and 3.0 for Francis and Kaplan (reaction) turbines. Gordon and Whitman (1985) have installed systems with appropriate water hammer control that have ratios less than 0.5. They give methods for calculating the inertia in isolated systems that include frequency control requirements, governor response times and other equipment.

Water Level and Safety

Safety concerns in dams, flood control strategies and storing water for peak power requirements result in additional requirements to control the water level behind the dam. Operations must be conducted in a certain order and rate during system startup and shutdown. Protecting power company personnel and generating equipment impose other constraints. Finally, provisions must often be made to monitor the systems operation and automatically report to remote offices. (These are often called Supervisory Control and Data Acquisition or SCADA systems.) Gaynor (1983, 1985) reviews controls for mini- and micro-hydro systems and compares both synchronous and induction generators.

Activating nonpriority loads at night to use off peak power can significantly improve economics by making optimum use of the power available. By very rapidly switching loads, the load on the generator can be maintained equal to the turbine's power and thus control its speed. "Load controllers" are now becoming a means of effectively governing very small hydro systems.

DEVELOPMENTS IN CONTROL ALGORITHMS

Commercial controllers typically use conventional PI or PID (Proportional, Integral, Derivative) control algorithms e.g. Carson (1983). Derivative control has only been added more recently in hydro systems to improve the response rate. However, this often comes at the expense of a sharp deterioration in water hammer (Ransford 1983). Good discussions of speed control are given by Warnick (1984) and the US Dept. of the Interior (1975) training manual.

Linear Models

Control algorithms are usually based on a linearized analysis of the system dynamics about the operating point. In governing a hydropower system, the primary attention may be on the dynamic equations of a turbine/generator. However, the dynamics of the water column are critically important, and the response of the governor itself must also be considered. The system is usually perturbed by changes in system load. Details of these three sets of linearized equations are given by Jaeger (1970), Ford (1978), and Chaudhry (1979). Frick (1980) extended these analyses to include the effects of variable head in low-head hydro sites where there is little water storage.

The discrete nature of digital measurements and the finite time required to calculate the desired response further modify the classical equations when microcomputers are used. These digital control algorithms are presented by Kopacek and Zauner (1982). They also survey the publications on using microcomputers to control hydropower stations as do Fasol (1984, and before with Kopacek).

Nonlinear Effects and Algorithms

A turbine's efficiency and dynamics is actually a highly non-linear function of water head (effective pressure) and flow. This is most noticeable when the turbine is started or stopped or when large load changes occur. These situations are also when there is the greatest danger of damaging the penstock or turbine. A detailed development of these nonlinear equations was made by Chaudhry (1980) for Francis turbines. Muller (1982) developed an accurate nonlinear model of turbines with controlled guide vanes. Kopacek (1983) used this nonlinear model in comparison with conventional linear models in evaluating the response of the digital control algorithms they developed.

Highly nonlinear control algorithms are also being developed to improve the controller performance compared to conventional PID controls. For instance, Jaeger and Wozniak (1985) propose a maximum-slew-rate controller that adjusts a turbine's guide vanes at the maximum rate at which they can be moved within the penstock pressure constraints. This "bang-bang" (on/off) controller reduces the time to respond to a disturbance by 60% compared to a PI controller with comparable overshoot. Fine adjustment with conventional PI control within a "dead band" near the set point will limit the problems of over reaction to small disturbances or to noise. The introduction of microprocessors has thus permitted much greater accuracy in modelling the dynamics and effectively responding to changing conditions than was ever possible with traditional linear analog controls. Further discussion on use of microprocessors to control hydro systems can be found in other papers as listed in the bibliography.

Load Control

Most controllers adjust the water flow to control turbine speed. It is also possible to control optional loads to match the load to the power available. Becker (1977) studied load modulation to centrally control the speed/frequency of a small hydro system. At the other extreme, Schweppe et al. (1980) proposed distributing multiple load controllers throughout a large system. A three phase electronic load controller for a micro-hydropower system was developed and described in detail by Pittet (1982). Woodward, Boys and Elder have written numerous papers describing their proportional electronic load controller using discrete electronics (cf Woodward, 1983).

FLOW CONTROLLERS

Mechanical flyball speed sensors and actuators were first used to control hydropower systems. Hydraulic actuators were then introduced to provide more precise and rapid control. Such mechanical-hydraulic governors are used to control speed on most of turbines in China Jin, 1982). An alternative hydraulic proportional controller using water from the fore-bay rather than oil has been developed in Nepal (cf SKAT). The mechanical sensors are being replaced by electric or electronic sensors and coupled with electric relays to improve the controls (Elliott, 1983). Rapid advances in electronics are now bringing electronic and microcomputer based controls to the hydropower systems.

Some representative systems which provide conventional intake water flow control are as follows: Digitek, Inc. manufactures a microcomputer based system for small hydro systems (1 MW to 10 MW), as do L&S Electric, Inc.; Phoenix Control Systems, Inc.; and Tetragenics. The H-O-H company has equipment that includes water level controls. Similar equipment is provided by ASEA Generation; A/S Norsk Elektrisk; Brown Bovari; and Disag Dieselmoteren AG (cf. Berseng; Butz; or Elfstadius 1983). J.M. Voith provide equipment to upgrade controls and provide automatic operation (Beyrich and Veil, 1985).

In these systems, the major functions of pushbutton/contact inputs, analog inputs, central processor unit, digital output, communications, and memory are usually on separate boards. These are plugged into a common bus card rack and connected to a power supply. The operator interacts through a terminal and printer. These can be expanded to multiple subsystems connected together.

Basler Electric provides a wide variety of standard control and protective equipment. Their recent exciters reverse the excitation voltage upon load rejection. This prevents catastrophic overvoltage when the system overspeeds (Schaefer, 1985). General purpose microprocessor-based protective relays that accommodate multiple sensors have been designed to replace a separate piece of equipment for each factor. Such units are being provided by ASEA of Sweden, and the General Electric, Westinghouse, Allen Bradley and Multilin companies. In 1980, Beckwith defined a generalized microcomputer based controller to connect a hydro system to a local electricity grid. Beckwith, Inc. now manufactures this "PRIDE" protective relay system which automatically trips on frequency and voltage excursions. It will also automatically reconnect a small hydro system to the grid. Woodward Governor Co. also has microprocessor based control systems.

ELECTRONIC LOAD CONTROLLERS

Controlling turbine speed by matching the system load to the turbine's power is a recent innovation in mini- and micro-hydropower systems. This is a major departure from traditional methods of controlling the water flow. By controlling useful-loads, this strategy can improve the fraction of available power that is economically used (system load factor). Holland (1982) says that load control can thus provide a crucial means to improve the economic viability of a system. He describes how these load controllers are being built by small manufacturers in many countries.

The system load is usually controlled incrementally or continuously. Incremental (or "discrete" or "digital") load control is the most common method. With incremental control, individual loads are switched on or off. Continuous control can be provided by adjusting the portion of a cycle that current passes through the load. This is called "Phase Control" after the electrical phase of the voltage at which the power semiconductors or "thyristors" that control the current are switched on. Phase control switching can generate substantial electromagnetic noise (EMI) and is typically used for small loads. Incremental load control relays are usually switched at the voltage zero crossover point.

The Intermediate Technology Development Group (ITDG) developed an electronic load controller using analog electronic equipment. These are now being tested in China, Nepal and Malaysia, and are being further developed by the Cooperative Research Group (RN-SHP Secretariat, 1986). Leroy-Somer (France/Canada) makes an "Electronic Load Governor" which uses analog circuits to switch twelve equal resistive ballast loads on or off. This is being marketed together with Atelier Bouvier's micro-hydro Pelton turbine (Petit, 1981). Single or three phase load control of 1 kVA to 180 kVA systems are available from Energy Independence Research Corp. Load controllers for micro-hydro plants up to 50 kW are available from Thomson and Howe Energy Systems, Inc. (Pereira, 1985). Phoenix Power Systems developed an electronic load controller incorporating an electronic tachometer and the Woodward 2301 controller (Bogert, 1985). Eight loads of 6.25 kW are controlled in one 50 kW micro-hydro system, for instance. They use phase control to provide continuous load control in combination with the discrete loads.

An example of a discrete rather than analog controller is provided by Delphi Industries Ltd. This load controller was developed at the University of Auckland, New Zealand by Woodward, Boys and Elder (e.g. 1984). It counts the number of cycles out of 512 per cycle that the cycle is fast or slow. It accordingly switches in or out a binary series of three or four loads (e.g. 1:2:4:8), thus providing fixed proportional control. Such control is sensitive to noise and signal shape fluctuations, so the input is filtered to smooth the response. This filtering slows the controller response. Therefore a flywheel may be needed to provide the minimum turbine/generator inertia that is required to maintain stability. Their 12 kW single phase controller was priced at approximately $700 or $50/kW. The cost of an additional flywheel must be added to this reasonable price when comparing controllers.

Hybrid System with Integrated Loads

A microcomputer based control and instrumentation system for mini-hybrid hydro-energy systems has been developed by Boston University (Dubow, 1982), in cooperation with Roorkee University, India (Roorkee, 1982). This three year demonstration program was funded by USAID. Load control using thermal, mechanical and electrochemical loads was integrated with flow control of the hydropower system. Three phase multitasking control algorithms were coded in the Pascal and Assembly languages. An STD bus system was used with 8 MHz Intel 8086 controller, analog to digital (A/D), input and output (I/0) and controller boards. System response was of the order of one cycle (20 ms). Thapar and Perreault (1985) further detail the distributed control system, while O.D. Thapar et al. (1985) describe the installation and related aspects.

COSTS

Most major hydroelectric equipment manufacturers provide controls for small to large hydro systems (over 1 MW). Rapid increases in capabilities and reductions in costs of programmable controllers and microcomputers now make such controls economically feasible for small hydro systems though they had been considered too expensive (Frick and Alexander, 1979). Programmable controllers for small modular hydro systems (1 MW to 10 MW) were estimated as costing \$15,000 to \$35,000 depending on the number of units controlled (Pereira, 1984). A \$40,000 control system for a 1 MW plant (\$40/kW) may be only 2% of the total system cost of about \$2,000,000. However this can be more than the entire cost of a 10 kW system. A 2% budget for a 10 kW system at \$4,000/kW installed limits costs to \$800 or \$80/kW. This shows the severe cost constraints for controls for mini- and micro-hydro equipment. Innovative approaches and mass production are needed to adequately meet the needs of such very small systems.

BENEFITS OF LOAD CONTROL

There are a number of benefits in using load control in place of or in addition to flow control. These are highlighted as follows:

Response, Precision and Stability

Pressure surges and fluctuations limit the rate the water flow can be changed. Conventional PID controllers take 5 to 10 seconds to the maximum frequency deviation, and typically allow the frequency to vary 1.5% for a 5% load change. Load control is only limited by the rate the loads can be switched and the speed that changes can be sensed. They can potentially respond in milliseconds and the maximum speed deviation can be much smaller given appropriate loads. The accuracy and stability of crystal oscillator based circuits is far superior to analog circuits. Load control could potentially enable stable control of any isolated hydro system.

Load Management

In many parts of the world, oversubscribed systems result in frequent (often daily) power outages due to required load shedding. Load management could reduce this by switching lower priority loads off at peak periods and on at off peak periods. Storage cookers and water heaters can be used in this manner. Load management or control also enables run-of-river hydropower systems to use much more of their hydro-resource that would otherwise be diverted and unused.

The global peak in worldwide petroleum production expected in the next couple of decades will bring growing scarcity coupled with rising demand and increased prices for energy and chemicals. With appropriate storage facilities, heating, refrigeration and chemical synthesis can improve the benefit/cost ratios significantly over conventional hydro-electric systems with only flow control. Load controllers will enable economic utilization of many potential mini/micro-hydro sites that are currently ignored.

Reduced Civil Works, Equipment and Inertia

Adding derivative control to improve the response of flow controllers has been proposed to reduce or eliminate surge tanks, discharge regulators, and reduce pipelines, or flywheels. With much more rapid response, direct load control should provide even greater benefits. Carson (1983) notes that an additional $700,000 was spent to improve by a factor of two the frequency reponse of a small isolated hydro-electric system to a load fluctuation of 5% of full load (=$1000/kW of load fluctuation). We estimate that a load controller with resistive loads could give more than 10 times better response at less than 25% of these costs. The rapid load controller response could enable a hydropower system to operate isolated from a grid without additional flywheels.

Thus in larger systems it may be most beneficial to provide for both flow and load control. Load control can minimize the control required for the flow to system startup and shutdown. In very small systems, active flow control could be eliminated. Valves could be opened and closed manually provided there are mechanical limits on how rapidly this could be done.

RELIABILITY AND REMOTE OPERATION

Failure of the control system can severely damage hydropower equipment or the attached loads. Skilled technicians and parts are difficult to find in remote locations or developing countries. The reliability of the controller and it's ease of repair and adjustment is thus critically important.

Mechanical and Hydraulic Controls

Mechanical controls have often been installed at remote sites due to their simplicity and ruggedness. Bearings are their most frequent source of failure. Regular lubrication and inspection is necessary. Leaky or failed oil seals will cause hydraulic controls to fail. Oil cleanliness is also vitally important. Clogged orifices are a major source of trouble. Electrical relay contacts can corrode and cause erratic performance or fail altogether. These must be periodically inspected and cleaned or replaced. Inversin (1986) discusses many aspects of designing for remote operations. He describes many of the innovative and passive concepts that have been implemented in the developing countries.

Electronic Controls

Analog control circuits use common inexpensive technology. However they contain a large number of components that can fail. Analog circuits often require adjustments at the factory and often in the field by moderately skilled technicians, but the equipment to adjust them is fairly common. Discrete electronics typically do not require (or provide) any adjustments. Recent advances in large scale circuit integration can substantially reduce the number of components and thus potentially improve the circuit reliability.

Conventional microcomputers also have many components and boards. The contacts where separate boards are plugged into the bus are a frequent source of computer failure or erratic performance. Placing the complete controller on a single board eliminates this problem. Otherwise, gas tight pin connectors (e.g. DIN euroconnectors) give much better performance than flat card edge connectors. Complete microcontrollers are now available on a single chip, eliminating many chips and improving reliability.

Controller Protection

Dewan (1984) and Beckwith (1985) give excellent discussions on the various relays etc. conventionally used to protect generating equipment in small hydro systems. Very rapid high voltage transients are a major cause of failure of electronic equipment. Lightning or switching large electrical loads can cause transients thousands of volts with rise times of a few nanoseconds which may only last a few microseconds. Electronic filters do not protect equipment from these transients, but semiconductor transient surge protectors are available that will. Metal oxide varistor (MOV) surge arrestors are now commercially available to protect power lines, transformers and other electrical equipment (Freeman 1985). They are replacing conventional silicon carbide gapped arresters. Caution must be used with the inexpensive small MOVs commonly used in electronics. They can well pass relatively high voltages over 600V or 800V, and may fail after a few "hits". If used, diagnostic lights should be provided to verify their continued operation. Optoisolators can also be used to effectively isolate signal lines and protect circuits from high common mode voltage differences, etc.

Noise, Smoothing and Hysteresis

Electrical noise on the power line, electromagnetic interference (EMI) and vibration/imbalance in the rotors can create noise in the signal lines, control processor or sensors. These will affect the controller's stability, precision and response rate. Power generating stations are particularly strong sources of EMI. Carson (1983) describes controllers that were seriously affected by EMI and how they had to shield signal lines and the controller against it. Fiber optic cables will completely eliminate EMI in signal lines.

Filtering the input signal will smooth the signal. However this reduces the controller response rate and decreases stability. Additional inertia may then be required to maintain stability. "Dead Band" or hysteresis can also be used to compensate for noise and to limit the rate of relay switching due to the controller "hunting" for the set point.

Electronic Relays

The rapid advances in power semiconductors now enable manufacturers to make electronic relays capable of switching 10 kW with a single relay (40 amps at 220 V). These have logic level switches that can be connected directly to the microprocessor. Quality relays include optoisolation protection and high reliability. When properly sized and cooled, such relays will last indefinitely.

Adaptive Control and Self Diagnostics

The expense and lack of trained technicians is a major hindrance to implementing mini- and micro-hydro systems especially in the developing countries. This problem can be bypassed by providing adaptive control and self diagnostics. With microcomputer based controllers, software can be written which will automatically adjust the controls for optimal operation and compensate for changes in the flow, loads and generating equipment. Self diagnostics software can enable novices to diagnose and repair equipment failures by board swapping.

One microprocessor based adaptive governor to handle isolated hydro-electric systems is described by Findley et al. (1980). Ye and Maurin (1982) further discuss using multiple adaptive variables to control the speed of a hydro-electric system. Malik et al. (1983) dynamically vary the PID control weighting parameters. ASEA Generation use adaptive control to optimize the efficiency of the hydro system and accommodate variations in the turbine performance with time (Elfstadius, 1983). They also provide diagnostic routines.

These developments suggest the potential that microprocessor based controls for mini- and micro-hydropower systems can be simpler, more reliable, and less expensive than mechanical or hydraulic controls. They could automatically adapt to the actual hydrosystem and loads. Self diagnostic indicators could be provided so that operators need only know how to "exchange the board if the red light is on". Spare boards could be maintained by a local distributor, and failed boards returned to the manufacturer for repair.

RECOMMENDATIONS FOR FURTHER RESEARCH AND DEVELOPMENT

These recent advances in control algorithms and equipment hold great potential for mini- and micro-hydro controllers. The adaptive control algorithms with self diagnostic capabilities need to be developed and implemented on a single board microcontroller that can be inexpensively mass produced. Appropriate protection and diagnostic indicators are needed to ensure reliable operation and simple rapid repair if failure does occur. Some major research concerns are as follows:

Load Cycling Limitations, Reliability and Efficiency

The durability of real loads and relays when used with a load controller is a significant factor that needs further study. Frequency and stability requirements mandate minimum switching rates. Noise in the input signal and oscillations in the water flow, loads or control algorithms could cause much more frequent switching. This could result in a very large number of relay closures and load cyclings. Such switching could cause failure of certain relays or thermal loads.

Rapid cycling of refrigeration units or heat pumps substantially reduces their performance. Heat pumps are being designed to operate at varying speeds to improve their performance, rather than switching them on and off. The high capacitance of electrolysis cells also limits the maximum rate at which they can be switched. The desire for rapid switching for precise control thus needs to be balanced against efficiency and durability limitations of switching loads. It may be advantageous to combine some proportional load control with the switching of discrete loads.

Time and Energy Limitations in Load Control

Thermal loads frequently have temperature and thus time or energy limitations. Water heaters have minimum and maximum temperatures. Refrigerators have maximum temperatures and thus minimum duty cycle settings. Electrochemical synthesis often requires certain pressures and temperatures for efficient operation. The relationship between the limitations of these factors with the need to control the turbine/generator and optimize the use of the hydro-resource available needs to be examined. This may require both flow and load control.

Rotor Fatigue and Water Hammer

Load rejection in conventional hydro systems can cause problems of shaft oscillations, vibration and water hammer (Rudd, 1980). Load switching will thus cause torque impacts on the generator, turbine and shafts, and reactive forces on the water column. The frequency content of load switching should therefore be compared with the system's mechanical resonances to see if potentially destructive mechanical excitation could occur. The load control algorithms may need to be modified accordingly.

Standalone Induction Generators

Induction generators are less expensive than synchronous generators, but traditionally cannot be used in a standalone installation. Woodward et al. (1983) have proposed using switched capacitors to provide the reactive power needed to run isolated induction generators. Microprocessor based capacitor switching is now commercially available to improve the power factor at user sites. Consideration should be given to the potential of adapting this technology to enable induction generators to operate in a standalone mode. This would also regulate the power factor and complement the load switching for frequency control.

CONCLUSIONS

There have been extensive developments in control algorithms and rapid increases in the capabilities of microprocessors and power electronics. These indicate a significant potential to increase controller capabilities, improve reliability and reduce costs. The capabilities of controllers in large hydropower systems could be economically provided for smaller equipment. Proper protection, self diagnostics and adaptive control algorithms can permit practical operation of microprocessor based controls in remote installations. This would eliminate the need for highly skilled technicians to operate, adjust or repair the controller. Load controllers with income producing loads will improve system dynamics and economics of any hydro system. They make mini- or micro-hydro systems increasingly competitive with conventional diesel engines. We recommend that microprocessor based load controllers be aggressively developed to utilize the very large number of hydropower sites and significant hydro-potential available under 1 MW.

DISCLAIMER: Products and manufacturers listed are for the readers' information and do not indicate endorsement by the author or by the Renewable Energy Resources Information Center. We request that readers notify us of any corrections or omissions in the following bibliography and directory.

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DIRECTORY OF MANUFACTURERS

This listing of equipment manufacturers is compiled from Hydro Review (Winter 1984) and Water Power and Dam Construction (February 1984) for the First International Conf on Small Hydro Power. They do not necessarily have equipment for very small systems. (These publications have updated their lists in 1986). Alternate Sources of Energy (ASE) also lists manufacturers. The handbooks, sourcebooks, texts and reviews listed above provide further lists of manufacturers. These companies broadly provide controls (C), governors (G), or SCADA (Supervisory Control and Data Acquisition) systems (S) as designated by the letters after the address.

A.C.E.C. Div EGC, P.O. Box 4, B-6000 Charleroi, Belgium: Phone 32-71-442327/442421, Telex 32/51227 ACEC B; C,G.

American Hydro Power Co., 4026 Chestnut St., Philadelphia, PA, 19104 USA: Phone 215-386-2293; C.

American Ligurian Company, Inc., 15 Ralsey Road So., P.O. Box 1005, Stanford, CT 06902 USA; Phone 203-324-7351, Telex 99-6417; G.

Machinenfabrik Andritz AG, Statteggerstr. 18, P.O. Box 24, A-8045 Graz-Andritz, Austria: Phone 0316-602-0, Telex 03-1313, 03/– 1722; G.

ARLAT, Inc., 1 Vulcan St., Toronto, Ontario M9W-1L3 Canada: Phone 416-245-4167; G.

Armfield Engineering Ltd., Crow Arch Lane, Ringwood, UK Hants BH24 1PE: Phone 04254 2405, Telex 418295 ARLICO G;G.

Associated Electric Co, Inc., 54 Second Ave, Chicopee, MA, 01020 USA: Phone 413-781-1053; C,G.

Axel Johnson Engineering Corp., 666 Howard St., P.O. Box 7067, San Francisco, CA 94120 USA: Phone 415-777-3800, Telex 330422 AJC CAL SFO; C,G.

Balaju Yantra Shala P. Ltd, P.O. Box 209, Kathmandu, Nepal: Phone 133379, 14809; G.

F. Bamford & Co., Ltd, Ajax Works, Whitehill, Stockport, Cheshire, UK: Phone 061-480 6507, Telex 668518; G.

P.T. Barata Indonesia, J1 Kapten P, Tendean No. 12-14A, Jakarta, Indonesia: Phone 795 708, Telex 473 16; G.

Barber Hydraulic Turbines, P.O. Box 340, Barber Pt, Barber Dr, Port Colborne, Ontario, L3K 5W1 Canada: Phone 416-834-9303, Telex 061-5471; C,G.

Basler Electric, P.O. Box 269, Highland, IL, 62249 USA: Phone 618-654-2341; C.

BBC Brown Boveri, Inc., 1460 Livingston Ave., North Brunswick, NJ, 08902 USA: Phone 201-932-6273; C.

Beckwith Electric Co., Inc., 11811 62nd St. N., Largo, FL, 33543 USA: Phone 813-535-3408; C.

Bell Engineering Works, Ltd, Member of Escher Wyss Hydraulic Group, 6010 Kriens, Lucerne, Switzerland: Phone 041 495111, Telex 78167 BELL CH; G.

Bouvier Hydropower, Inc., 12 Bayard Lane, Suffern, NY 10901 USA: Phone 914-357-2840; C.

Boving & Co. Ltd., Villiers House, 41-47 Strand, London WC2N 5LB, UK: Phone 01-829 2401, Telex 28444; G.

Canyon Industries, Inc., 5346 Mosquito Lake Rd, Deming, WA 98244, USA: Phone 206-592-5552; G.

Carl G. Brimmekamp & Co., Inc., 102 Hamilton Ave., Stamford, CT 06902 USA: Phone 203-325-4101; G.

C-E/Neyrpic, Inc., (Combustion Engineering) 969 High Ridge Road, Box 3834, Stamford, CT 06905 USA: Phone 203-322-3887; G.

Cornell Pump Co., 2323 S.E. Harvester Dr., Portland OR 97222, USA: Phone 503-653-0330, Telex 910-453-8377; G.

Dependable Turbines Ltd., 7-3005 Murray St., Port Moody, B.C. V3H 1X3 Canada: Phone 604-461-3121, Telex 04-54262; C,G.

Disag Dieselmoteren AG, 7320 Sargans, Switzerland.

Digitek, Inc., P.O. Box 468, Kenmore, WA 98028 USA: Phone 206 – 485-6571; C,G,S "Hydro-Scada Microcomputer Based Control and Monitoring Systems".

Diversified Electrical Products, P.O. Box 390, 1430 F Church St., Bohemia, NY, 11716 USA: Phone 516-567-5710; C.

Dominion Engineering Works, Ltd., 795 1st Ave., Lachine, Quebec H8S 2S8, Canada: Phone 514-634-3411, Telex 05-821673; C,G.

Energy Independence Research Corp., P.O. Box 1776, Lummi Island, WA 98262-1776 USA: G "Dynamic Power Balance Circuitry". Attn. John MacGregor.

Energy Research & Applications, Inc., 1820 Fourteenth St., Santa Monica, CA 90404, USA: Phone 213-452-4905; G.

EQEX Corp., Menlo Park, CA, USA; C.

Essex Development Associates, Inc., 6 Essex St. Lawrence, MA USA: Phone 617-687-2312, Telex 95-1459; G.

Evans Engineering & Power Co., Priory La, St. Thomas, Lauceston, Cornwall, UK: Phone 0566-3982, Telex 45639 COMPUT G; G

Federal Pacific Electric, Raleigh, NC, USA; C.

Flygt Canada, 300 Labrosse, Pointe Claire, Quebec H9R 4V5 Canada: Phone 514-695-0100; C

Flygt Corp., 129 Glover Ave., Norwalk, CT 06856 USA: Phone 203-846-2051; C.

Flygt AB, P.O. Box 1309, S-17125 Solna, Sweden: Phone 08-980060, Telex 195 58, 190 18; G.

Foth & Van Dyke, 2737 S. Ridge Rd., P.O. Box 19102, Green Bay, WI 54307-9012 USA: Phone 414-497-2500; C,G.

Fuji Electric Corporation of America, 727 W. 7th St. Suite 235, Los Angeles CA 90017 USA: Phone 213-622-4490; C, G.

Fuji Electric Co., Ltd, New Yurakucho Bldg., 12-1, Yurakucho 1 – chome, Chiyoda-ku, Tokyo 100, Japan; G.

Galt Energy Systems, Ltd., Suite 502, Cambridge Place, Box 1354, Cambridge, Ontario N1R 3BO Canada: Phone 519-623-1390; C,G.

GEC Energy Systems, Ltd, Cambridge Road, Whetstone, Leicester LE8 3LH, UK: Phone 0533-863434, Telex 34611; G.

General Electric Technical Services Co. Inc, Building 513W or 4-305, One River Rd, Schenectady, NY 12345 USA: Phone 518-358-0152/5575, Telex 145342; C,G.

Generation Unlimited, P.O. Box 1816, Newport Beach, CA 92663 USA: Phone 714-642-4817; C.

Gilbert Gilkes & Gordon Ltd., Kendal, Cumbria LA9 7BZ, UK: Phone 0539-2008, Telex 65125; G.

Gilkes, Inc., P.O. Box 628, Seabrook, TX 77586 USA: Phone 713-474-7622; G.

GSA International Corp., (International Hydropower Div), P.O. Box 536, Croton Falls, NY 10519 USA: Phone 914-277-8000, Telex 226000 ETLXUR; C.

H-O-H Power, 10904 Brunswick Rd, Grass Valley, CA, 95945 USA: Phone 914-277-8000; C.

Halliwell Nowe Engineering, Inc., P.O. Box 2783, York, PA 17405 USA: Phone 717-848-8822; S.

Hayward Tyler, P.O. Box 492, Burlington, VT 05401 USA: Phone 802-863-2351, Telex 95-4646; G.

Henwood Associates, Inc., 1818 11th St., Suite 4, Sacramento, CA USA: Phone 916-447-3497; C.

HITE, Turbinas Y Maquinas Hidraulicas S.A., Juan Prado No. 4, Neguri, Vizcaya, Spain: Phone 4-4602654; C,G.

Hydrolec North America, Inc., 925 Leroy Somer Blvd., P.O. Box 40, Granby, Quebec J2G 8E2 Canada: Phone 514-378-0151; C,G.

Hydroart SpA, via Stendahl 34, 20144 Milan, Italy: Phone 02-479104, Telex 332281 HY ARTI; G.

Hydro Systems (Tas) Pty Ltd, 445 Macquarie St., Hobart Tasmania, Australia: Phone 02-348499, Telex AA 58260 EFAUS; G.

Hydro-Watt Systems, 146 Siglun Road, Coos Bay, OR 97420 USA: Phone 503-247-3559; G.

Ideal Electric Co., 330 East First St., Mansfield, OH 44903 USA: Phone 419-522-3611; C.

International Power Machinery Co., 834 Terminal Tower, Cleveland OH 44113 USA: Phone 216-621-9514; C,G.

Kamewa AB, Box 1010, 68100-Kristinehamn, Sweden: Phone 0550-84000, Telex 66050 KMWKSN S; G.

Keystone Valve USA, 9700 W. Gulf Bank Dr., Houston, TX 77040 USA: Phone 713-466-1176; C.

Kvaerner Brug A/S, Hydro Power Sector, PO Box 3610, Gb, Oslo 1, Norway: Phone 47-2-685550, Telex: 71650 kbn; G.

L&S Electric Inc., P.O. Box B, Mesker St., Schofield, WI 54476, USA: Phone 715-359-3155; C.

Larsen & Toubro Ltd., 3B Shakespeare Sarani, P.O. Box 619, Calcutta 700 071 India: Phone 442301, Telex 2762; G.

Leroy-Somer (SEA) Pte. Ltd., 197A Goldhill Center, Singapore 1024: Phone 255 73 33, Telex LSSEA RS 52637; G.

Litostroj, Djakoviceva 36, 61000 Ljubljana, Yugoslavia: Phone 061-556-021, Telex 31 100 YU TZL; G.

Marubeni America Corp. (Kubota, Ltd.), 3201 First Interstate Center, 999 Third Ave., Seattle, WA 98104 USA: Phone 206-344-5582; G.

McKay Water Power, Inc., P.O. Box 221, West Lebanon, NH 03784 USA: Phone 603-298-5122, Telex 95-3111; C,G.

MacKeller Engineering Ltd., Strathspey Industrial Site, Grantown-on-Spey, Morayshire, Scotland: Phone 0479 2577; G.

Mecanica Pesada S/A, Av. Rio Branco, 123-180 e 190 and, CEP 20048, Rio de Janeiro, Brazil: Phone 21-292-3113, Telex 21-21191 M. PRES BR; G.

Mini Hydro Co., 1800 S. Robertson Blvd., Suite 800, Los Angeles, CA 90035 USA: Phone 213-839-2563; C,G.

Moteurs Leroy-Somer, Boulevard Marcellin Leroy, 16015-Angouleme Cedex, France: Phone 45-624111, Telex, 790044 F; G

New England Energy Development Systems, 71 N. Pleasant St., Amherst, MA 01002 USA: Phone 413-256-8466; C.

New Found Power Co. Inc., Box 576, Hope Valley, Rhode Island, USA: Phone 401-539-2336; G.

Neyrpic, (Service Minicentrales Normalisees) 75 Rue General Mangin, BP 75, 38041 Grenoble, Cedex, France: Phone 76-964830, Telex 320 750; G.

Nohab Turbinteknik AB, P.O. Box 925, S-46129 Trollhattan, Sweden; G.

Obermeyer Hydraulic Turbines Ltd., 10 Front St, Collinsville, CT 06022 USA: Phone 203-693-0295; C,G.

Ohio Transformer Corp., P.O. Box 191, Louisville, OH 44641 USA: Phone 216-875-3333; C.

Oriental Engineering & Supply Co., 251 High St., Palo Alto, CA 95301 USA: Phone 415-325-0925; C,G.

Ossberger-Turbinen-fabrik GmbH & Co., P.O. Box 425, D-8832 Weissenburg, Bayrn, West Germany: Phone 09141 4091, Telex 624672; G.

Pacific Diesel Co., 340 W. Nickerson, Seattle WA 98119 USA: Phone 206-283-1011; C,G.

PACS Industries, Inc., 61 Steamboat Rd., P.O. Box 397, Great Neck, NY 11022 USA: Phone 516-829-9060; C.

Page Hydro Power Systems, Inc., 228 Melrose Court, Iowa City, IA 52240 USA: Phone 319-354-9506, Telex 439001; C,G.

PEMCO Corp., P.O. Box 511 Bluefield, VA 24605 USA: Phone 703-326-2611; C.

Phoenix Control Systems, Inc., 1515 NW Ballard Way, Seattle, WA 98107 USA: Phone 206-784-1383; C,G.

Portmore Products, Portmore Rd., Lower Ballinderry, Lisburn, County Antrim, Northern Ireland: Phone 0846-651528; G.

Powertech Engineering Ltd., 100 Anzac Ave. P.O. Box 1417, Auckland, New Zealand: Phone 795-371; C.

P.S. Eckhoff Machinery, Inc. Stuyvesant Falls, NY USA; C.

Riva Calzoni S.P.A., Malano Works, Via Stendhal, 34-20144 Milano, Italy: Phone 02-47915, Telex 332292 RIVAT I; G.

Satin American Corp., 40 Oliver Terrace, Shelton, CT 06484 USA: Phone 203-929-6363; C.

Scientific Columbus, Inc., 1900 Arlingate Lane, Columbus, OH 43221 USA: Phone 614-274-7160; C.

Small Hydro East, Star Route 240, Bethel, ME 04217 USA: Phone 207-824-3244; G.

Small Hydroelectric Systems & Equipment Co, Inc. 5141 Wickersham, Acme, WA 98220 USA: Phone 206-595-2312/2225; C,G.

Sorumsand Verksted A/S, N-1920 Sorumsand, Norway: Phone 472-76-6200, Telex 76539 SANDN N; G.

Sorenson Governor Service, Div. Pneumatic & Hydraulic Dist. Inc., Marlboro Industrial Pk, Locke Dr, Marlboro, MA 01752 USA: Phone 617-481-3260; G.

Sulzer-Escher Wyss Ltd, Postfach, Hardstr, 319, CH-8023 Zurich, Switzerland: Phone 01 246 2211, Telex 822 900 11 SECH; G.

Synergetics International, Inc., P.O. Box E, 565 Odell Place, Boulder CO 80306 USA: Phone 303-530-2020; C.

Tetragenics, 55 East Granite, Box 1338, Butte, MT 59701 USA: Phone 406-782-8606; C.

Thomson & Howe Energy Systems, Inc., Site 17, Box 2, S.S.1, Kimberley, British Columbia, Canada V1A 2Y3.

Turbine Generator Corp., P.O. Box 744, Troy, NY 12181 USA: Phone 518-272-3431; C.

Vevey Engineering Works, Ltd., CH-1800 Vevey, Switzerland: Phone 021-510051, Telex 451 104; G.

Voest-Alpine International Corp., 120 Ferry Ave., Collingswood, NJ 08108 USA: Phone 609-962-9200; C,G.

J.M. Voith GmbH, Postfach 1940, St. Poeltener Str. 43, D-7920, Heidenheim, West Germany; G.

Voith Hydro, Inc., 228 Route 17 North, Upper Saddle River, NJ 07458 USA: Phone 201-934-1080; G.

Westinghouse Canada, Inc., P.O. Box 510, Hamilton, Ontario L8N 3K2 Canada: Phone 416-528-8811; C.

Westinghouse Electric Corp., Engineering & Instrumentation Services Div., 875 Greentree Rd., Parkway Center, Bldg. 8, Pittsburgh, PA 15220 USA: Phone 412-937-7140; C,G.

Woodward Governor Company, 5001 N. Second St. P.O. Box 7001, Rockford, IL 61125-7001 USA: Phone 815-877-7441; C,G.

Worthington Division – McGraw Edison Co., 5310 Taneytown Pike, Taneytown, MD 21787-0091 USA: Phone 301-756-2602; C,G.

ZPS, Titovi Zavodi Litostroj, YU 61001 Ljubljana, Djakoviceva 36, Yugoslavia; Phone 061-556-021, Telex 31 100 YU TZL; G.