Mini-project report

Analysis and Design of Electronic Load Controllers for Micro-hydro Systems in the Developing World

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Analysis and Design of Electronic Load Controllers for Micro-hydro Systems in the Developing World

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Abstract – **The main objective of this paper is to present a review of the literature and available technology, as well as general background research into Electronic Load Controllers (ELCs) for off-grid micro-hydro systems in the developing world. The financial and technical issues surrounding the control of typical micro-hydro system components under variable loading conditions shall be discussed.**

Keywords – **electronic load controller, micro-hydro, off-grid power, synchronous generators, asynchronous generators, induction generators.**

1 Introduction

It is estimated that, around two billion of the world's population have no access to modern forms of energy, such as electricity or fossil fuels [1]. The vast majority live in rural villages in the developing world, far from existing electrical grids and often scattered around the landscape, making distribution to individual houses difficult and costly [2]. Therefore, the majority of these communities depend on human power and biomass alone, and as a result, time that could be spent on income generating activities is used up on time consuming daily tasks, such as collecting firewood. Such monotonous activities keep these people in poverty. Although monthly costs for electricity may be affordable, grid connection fees in remote areas are often very high, especially when many poorer households are having to survive on as little as US$1 a day [1]. As a result, alternative solutions to rural electrification are required. Stand-alone power generation plants can provide the answer since they remove the need for long and inefficient transmission lines. Local ownership takes away the need to deal with city-based energy tariffs, allowing flexibility in the supply options to include poorer households in the community. In addition, profits are kept within the local community, thereby contributing to the development of these areas.

Where suitable resources are available, renewable energy systems such as micro-hydro, wind and solar are becoming a viable option for supplying sustainable power to rural areas of the developing world. However, to accomplish the objective of sustainably increasing electrification in these areas, the technology needs to be integrated into the local culture. Reliance on expensive imported parts and/or expertise is not a sustainable solution.

The key features of a successful technology for increasing rural electrification in the developing world are considered to be:

- *Simplicity of design* – local people should be able to understand the technology.
- *Ease of manufacture* – local people should be able to manufacture the system with the tools, materials and expertise available to them.
- *Robustness* – the technology needs to withstand extreme local conditions.
- *Ease of maintenance* – if it does break, local people should be able to fix it quickly and easily using locally available tools and materials.
- *Cost* – when relying on less than US$1 per day, cost is likely to be paramount.

2 Micro-hydro Power

Where a suitable water source is available, micro-hydro is one of the most cost-effective energy technologies to be considered for rural electrification in the developing world [3-5]. Micro-hydro power is the generally accepted term for hydroelectric systems of 100kW [6] or smaller. Unlike conventional large-scale hydro, it generally employs 'run-of-river' style techniques that store little or no water, but allow the exploitation of the river's hydroelectric potential without significant damming. It is one of the most environmentally benign energy technologies available and has been proven to be extremely robust, with systems lasting for over 50 years whilst requiring little maintenance [1].

3 Principles of Micro-hydro

Micro-hydro turbines convert pressurised water into mechanical shaft power, which can then be used to drive other machinery, such as an electrical generator. The power available is proportional to the product of pressure head and volume flow-rate of the water through the turbine.

$$P = \eta \rho g Q H$$

P **=** *Mechanical power produced at the turbine shaft (W)*
η **=** *Hydraulic efficiency of the turbine*
ρ **=** *Density of the water (kg/m^3)*
g **=** *Acceleration due to gravity ($9.81 m/s^2$)*
Q **=** *Volume flow-rate (m^3/s)*
H **=** *Effective pressure head (m)*

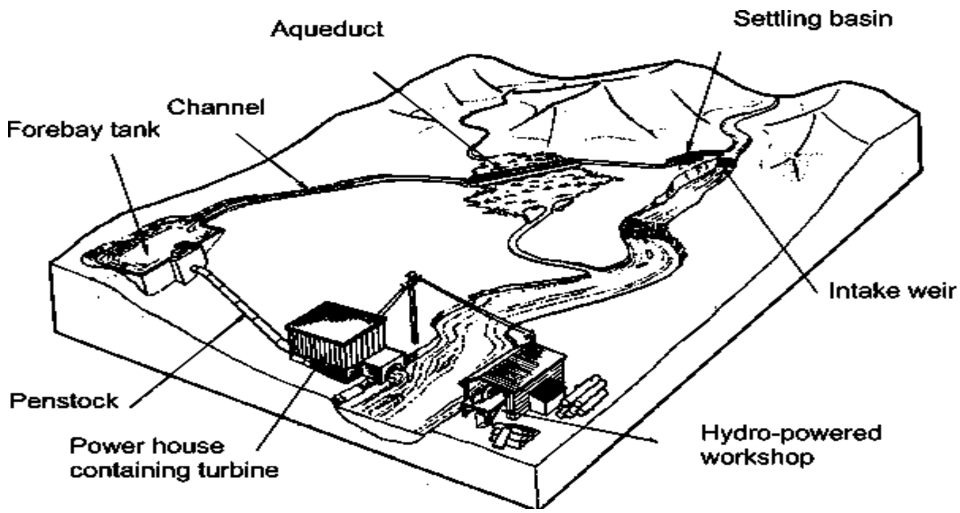

Figure 1: Components of a typical micro-hydro site layout [3]

Figure 1 illustrates a typical micro-hydro scheme. Water is taken from the river by diverting it through an intake at a small weir (a man-made barrier across the river which maintains a continuous flow through the intake). The water goes straight into a settling basin where it is slowed down sufficiently for suspended particles to settle out. A channel or canal then carries it to the forebay tank, which ensures that a constant head of water is maintained going into the penstock (a pressure pipe leading directly to the turbine). Finally, after extracting the energy from the flow, the water discharges from the turbine down a tailrace back into the river.

3.1 Micro-hydro System Components

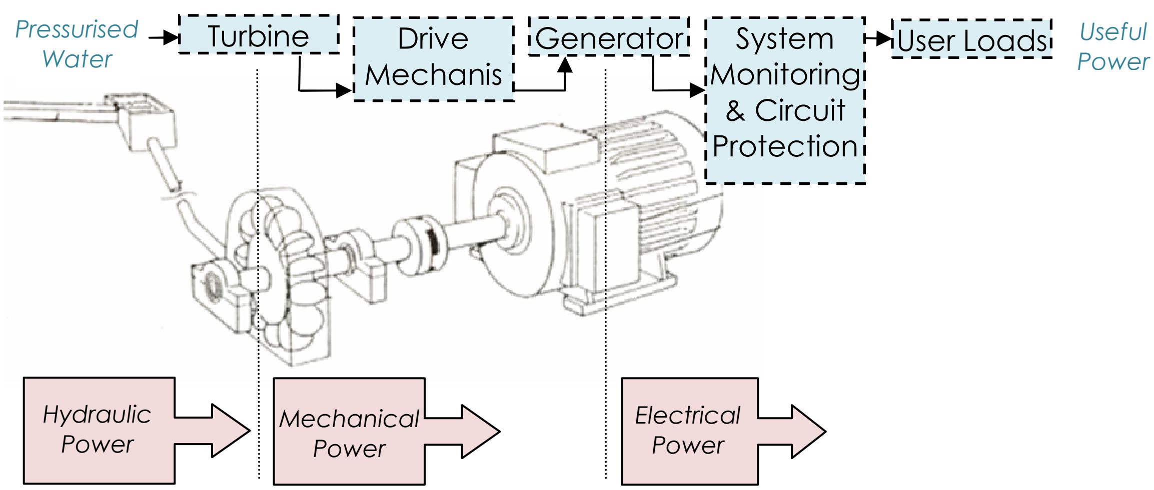

Figure 2: Block diagram of a typical micro-hydro system (Image adapted from [3])

Figure 2 shows how the component parts of a micro-hydro system convert power from one form to another as it flows through the system.

3.1.1 Turbines

A turbine converts the hydraulic power in pressurised water into mechanical power in the form of a rotating shaft. There are many varieties of turbine, each with its own benefits and drawbacks. However, the Pelton and cross-flow turbines are the most widely used for micro-hydro power in the developing world [3], as they are reaction turbines. Unlike impulse turbines, which are the standard for larger scale hydro-power, they don't require expensive pressurised casings or intricately machined blade profiles. The Pelton turbine is simply a wheel with buckets attached around the circumference so that a jet of water causes it to rotate when it is directed in line with the buckets. Pelton turbines are very efficient, but it is difficult to align them correctly. As a result, the cross-flow turbine is normally the most popular choice. It can be manufactured very easily by cutting pipe lengthways to make the blades and welding them between a pair of disks to make a drum shape. It operates over a wide range of head and flow rates and has good part-flow efficiency.

3.1.2 Drive Mechanisms

The purpose of the drive system is to take the rotational energy from the turbine and transfer it to the generator at the correct speed for power generation. A direct drive with the generator and turbine mounted on the same shaft (as shown in Figure 2) is the simplest option, but only available if the turbine rotates at the correct speed for the generator. Turbines usually rotate slower and therefore belts and pulleys, chains and sprockets or gears are often required to get the generator rotating at the required speed.

3.1.3 Generators

Generators convert kinetic energy from rotation of the turbine into electrical energy. There are two types of generators suitable for micro-hydro systems:

Synchronous Generators (Alternators)

Synchronous generators use permanent or electro-magnets to create the magnetic field required to generate a current in the output coil. Therefore, excitation of synchronous generators is not grid dependent, making them ideal for standalone power generation systems. In the case of off-grid use, a voltage regulator (usually built in) maintains a constant voltage irrespective of consumer load variations [7]. The frequency generated by synchronous generators is directly proportional to the shaft speed, meaning that synchronous generators are easier to regulate.

$$rpm = \frac{120f}{p}$$

rpm = shaft speed (rpm)
f = electrical frequency (Hz)
p = number of magnetic poles on the generator windings

Asynchronous (Induction) Generators

Asynchronous generators require external excitation to create the magnetic field required to induce the current in the windings that is necessary for them to start. This can be achieved by the use of a suitably sized capacitor(s) [7-8] and an external DC source. In spite of this, asynchronous generators are generally the cheapest option for micro-hydro schemes below 30-50kW [2, 8-9], as induction motors (which are widely and cheaply available throughout the developing world) can simply be operated in reverse as induction generators. Above 30-50kW, the excitation capacitors start to become expensive and synchronous generators become the more attractive option. For induction machines, the shaft speed and electrical frequency are non-linearly related:

$$rpm = \frac{120f}{p}(1-s)$$

rpm = shaft speed (rpm)
s = slip[1] (varies between 0-10% depending on loading and size of the machine)

[1]Slip is a function of the (DC) resistance in the rotor windings of the generator. The higher the resistance, the higher the slip.

3.1.4 User Loads

The user loads are the ordinary electrical appliances that the whole micro-hydro system has been designed to produce power for. In rural areas of the developing world, they will most commonly include lights and perhaps a television or a radio.

3.1.5 Circuit Protection

Circuit protection devices are required to protect wires, connections and electrical equipment from an over current, e.g. short circuit. Excess current leads to excess heat or leakage current that makes the circuit protection devices open the circuit. This in turn also protects the people operating electrical equipment from electrocution. Circuit protection devices include: fuses, fuse elements, fusible links, circuit breakers, electrical surge protection (ESP) etc.

3.1.6 System Monitoring Equipment

Throughout the operation of the ELC, its performance ideally needs to be monitored continuously, as in many cases, it would be almost impossible for the operator to know if the ELC is working as specified. Monitoring devices for both voltage and frequency should be used, showing continuous live data, as well as logging results at frequent time intervals to check the performance of the ELC and make sure the voltage or frequency is kept at acceptable levels

4 Micro-hydro Control Systems

All electrical equipment is designed to operate at a specific voltage and frequency and operating off of these designed values can cause serious damage and reduce the life of the equipment [3, 9]. For example, an electric motor will overheat if the frequency is too high, or may burn out on starting if the voltage is lower than specified. As previously mentioned, when electricity is generated, its frequency is determined by the shaft speed of the turbine/generator and the number of magnetic poles in the generator (as well as the resistance within the rotor windings, known as slip, in the case of asynchronous machines). Although most synchronous generators have some form of voltage regulation, the voltage output will still be affected by shaft speed variations. Therefore, effective shaft speed regulation and control of real time load variation on the system is important in electricity generating systems to ensure that the voltage and frequency of the electrical power provided to the user loads remain constant and the turbine and generator do not spin dangerously out of control [2-3, 10].

There are two types of control methods suitable for micro-hydro systems:

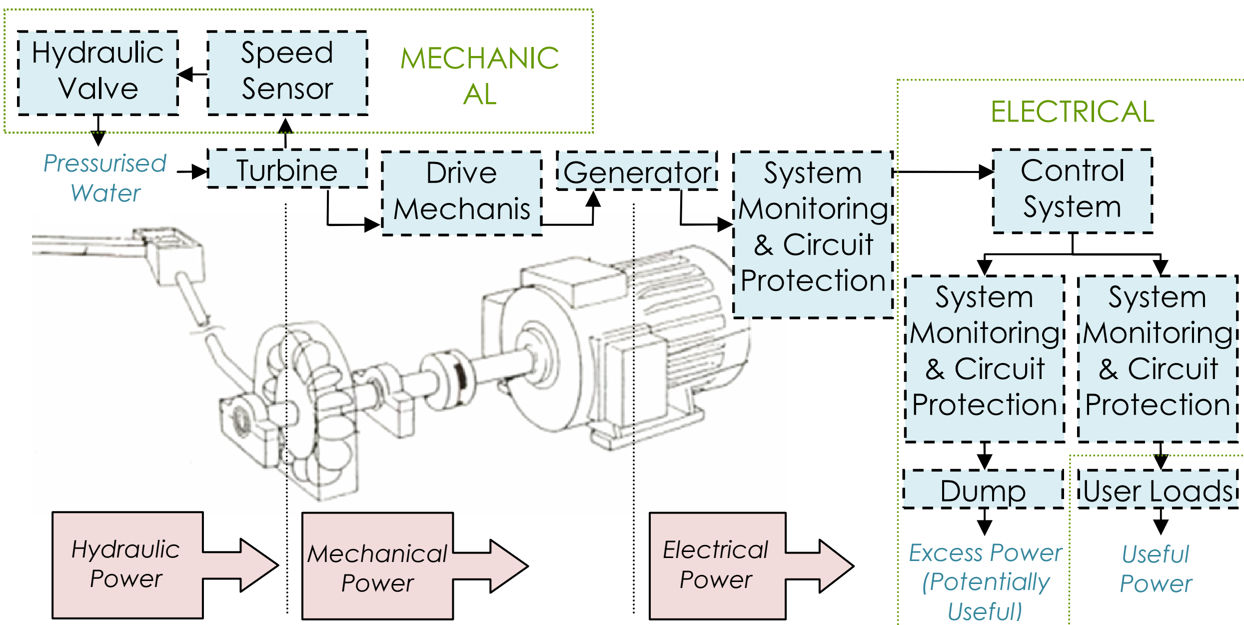

Figure 3: Diagram of a micro-hydro system showing both mechanical & electronic control (Adapted from [3])

4.1 Mechanical Control

A mechanical governor is essentially a valve on the turbine inlet that can be closed to restrict the flow (and therefore the power) going into the turbine to match the current electrical loading. Speed sensors on the turbine can be used to do this automatically [6], but such devices are expensive and as a result, many micro-hydro schemes in the developing world employ a permanent operator stationed in the power house to do this job by hand. Mechanical control is undesirable because it controls water flow directly and as a result, has a slow reaction to load variations [11-12], leading to difficulties when using sensitive loads that cannot withstand even short power fluctuations. They also contain many moving parts, which will inevitably require maintenance.

4.2 Electrical Control

Control of the voltage and frequency in a micro-hydro system can be achieved far more easily by using an Electronic Load Controller (ELC) [12] (see Figure 3). Electrical control is desired because it responds rapidly to user load fluctuations, can be built from cheap and widely available basic electrical components and it requires virtually no maintenance. On average the cost of an ELC is about 10% [6] that of a mechanical governor.

5 Electronic Load Controller (ELC)

When equipped with an ELC, the turbine always runs at full power and shaft speed/frequency control is achieved by adjusting the electrical power output rather than the hydraulic power input. An ELC is an electronic governor that functions as a frequency and/or voltage regulator on a generator by diverting surplus electrical energy to a resistive dump load [9, 11].

5.1 Dump Loads

In a micro-hydro system with electronic control, dump loads (also known as ballast loads) are activated by an ELC to dissipate power that is not required by the user loads. Dump loads are electrical resistive loads sized to equal or be slightly greater than the total power output of the generator they are connected to. Usually ambient air or water heaters are used to get rid of the surplus power, however devices such as food dryers or kettles can make use of it if set up to do so.

5.2 Responding to User Load Variation

When the user load decreases, the power consumed reduces, but the power generated is kept constant. As a result, the turbine/generator shaft speed increases and therefore so does the electrical frequency/voltage. This change is detected by the ELC (by comparing the period of the sine waveform to a reference value), which then diverts the surplus power to a dump load. Figure 4 shows how the constant power generated is balanced with the varying user load by the addition of a dump load.

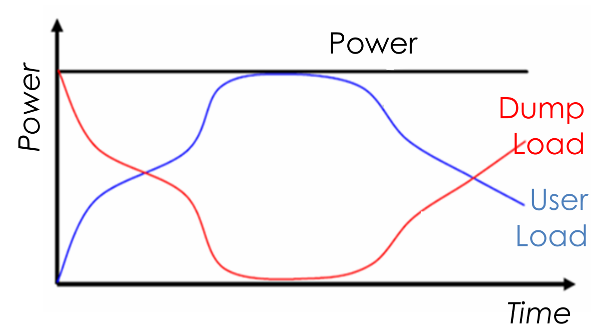

Figure 4: Power Generated = User Load + Dump Load (Adapted from [13])

5.3 Automatic Control Modes

In the case of an ELC, either frequency or voltage is the variable that needs to be controlled. The difference between the measured value, *MV*, (i.e. actual frequency/voltage generated) and the desired value, *DV*, (i.e. the reference frequency/voltage) gives the error, *e*:

$$MV - DV = e$$

The error is used by the controller to decide how much power to send to the dump loads.

There are four main automatic control modes suitable for MH ELC designs.

Proportional (P) – Here, gain[2] is proportional to the current error, and multiplying the error with the gain brings the MV (shown below in red) closer to the DV.

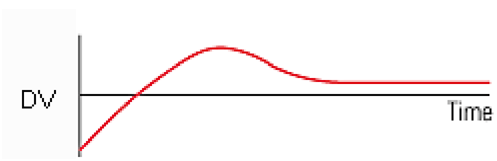

Figure 5: Proportional control (Adapted from [14])

Proportional control is simple and easy to set up, making it the cheapest control mode. It is also stable, unless a large gain is selected, causing the controller to over compensate for the error, and thus causing system instability. Nevertheless, proportional control is undesirable for use in MH ELCs because it is affected by external disturbances presented to the system, thus the MV never returns to the DV, i.e. there will always be some offset.

Proportional plus Integral (PI) – The integral term has the unique ability to return the process to the DV. This is because the integral gain is proportional to the magnitude and the duration of the error, therefore by adding and integrating all the instantaneous errors over time, this gives the accumulated offset that should have been corrected previously. This is then multiplied by the integral gain and added to the controller output. The integral gain determines the magnitude of the integral term's contribution to the controller. Integral term is not usually used on its own because of its slow response to load variations and in most cases, it is unstable.

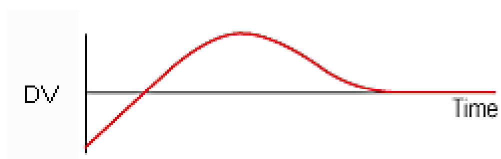

Figure 6: Proportional plus Integral (PI) control (Adapted from [14])

The PI controller is the preferred method of control for ELCs designed for developing countries, because it is inexpensive (compared to PID) and it returns the process to the DV.

Proportional plus Derivative (PD) - When the output changes quickly, the derivative term helps reduce overshoot and reduces settling time. This mode of control, just like proportional control, is affected by external disturbances, which results in an offset in the system output. For this reason it is not desired for MH ELC use.

[2] Gain is a measure of the ability of a circuit to increase the power or amplitude of a signal from the input to the output (the mean ratio of the output to input signals).

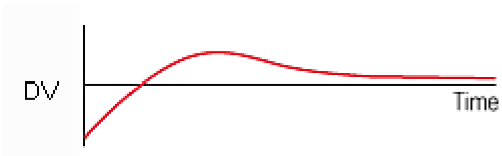

Figure 7: Proportional plus Derivative Control (Adapted from [14])

Proportional plus Integral plus Derivative (PID) – This mode of control employs three separate parameters: proportional (P), integral (I) and derivative (D). The P term determines the reaction to the current error, the (I) term determines the reaction based on the sum of recent errors and the (D) term determines the reaction based on the rate at which the error has been changing. The combination of these three control terms is used to adjust the process and achieve the DV.

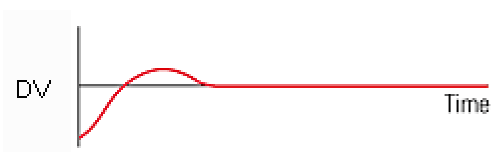

Figure 8: Proportional plus Integral plus Derivative Control (Adapted from [14])

PID control mode is considered to give the best performance for most systems, because it has the fastest reaction times to load variations, presents no offset to the system and it has the fastest settling time. However, due to the complexity and cost implications of the PID control mode, it is rarely used for MH ELCs in developing countries.

5.4 Load Regulation Strategies

There are two main techniques [6] employed for regulating how much power is sent to the dump loads:

5.4.1 Phase Angle Regulation

As Figure 9 shows, at a specific moment (phase angle) during each half period, a trigger signal is sent to a TRIAC[3], which opens the circuit connecting the dump load/s. The pathway remains open and power flows to the dump load/s until the current flowing through it drops to zero at the end of the AC half period (zero crossing). Calculating the correct phase angle at which the dump loads should be activated is vital, as this governs exactly how much power is sent to the dump load.

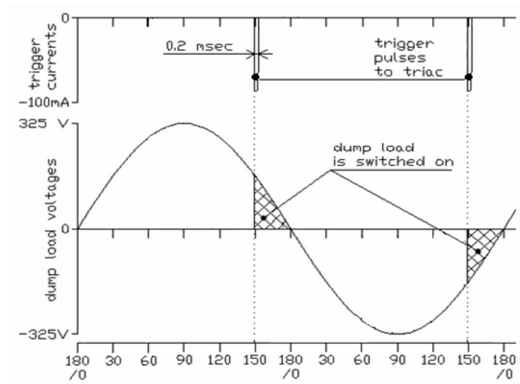

Figure 9: Half cycle triggering of the dump load using phase angle regulation (Adapted from [15])

Any combination of dump loads may be used, opening up the option of using food dryers or battery chargers. However, when a large dump load is switched on part way through the AC half period, serious harmonics are created within the generator current (this is worst when voltage is at its highest, i.e. at a phase angle of 90^0),

[3] Bidirectional electronic switch that when triggered will conduct until the current drops below a certain threshold level, e.g. every AC half cycle zero crossing.

thus the generator has to be oversized by approximately 25% to cope [6, 11, 15].

5.4.2 Binary Load Regulation

This involves using a series of dump loads, in which each subsequent dump load has twice the capacity of the previous one (see Figure 10).

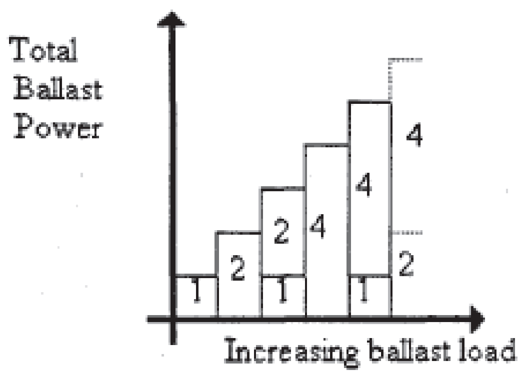

Figure 10: The summation of the ballast load steps in response to change in consumer load [6].

With *n* dump loads, a total of 2^n can be activated, with each separate combination representing a different total dump load power. Power is dissipated in small steps by switching on and off different combinations of the dump loads. Thus each dump load is switched either completely on or completely off, avoiding serious harmonics. However, this method requires a large number of dump loads with specific capacities and as a result, it is unlikely that any of the surplus power can be utilized, e.g. by food dryers etc. [6, 11, 15].

6 Analysis of Existing ELC Designs

ELCs perform quicker, last longer and cost less than their mechanical counterparts. However, they are not without limitations. Electronic systems are rarely well understood at a local level in the developing world. As a result, ELCs generally have to be imported and external expertise sought if any faults occur. Although ELCs are cheaper and better performing than mechanical governors, ELCs are still normally the most expensive part of a micro-hydro system. There is a need for a robust ELC that can be produced from simple electronic components by (relatively) local electricians in the developing world. A number of designs are already available:

6.1 The Hummingbird ELC

The Hummingbird ELC [15] is designed for a single phase synchronous generator, but by changing/adding a few components, it's also possible to use an asynchronous generator. It's suitable for generators rated at up to 7kW, when using 2 dump loads, or 10kW with 3 dump loads. Capacity could be increased to 21kW with 6 dump loads or even 30 kW with 9 dump loads in a 3 phase variant using thyristors in place of TRIACs, however, the triggering circuit would then be relatively more complex.

6.1.1 Method

The Hummingbird ELC uses PI Control, and phase angle regulation with TRIACs controlling the power to the dump loads. Phase angles for the dump loads are regulated such that when one dump load has a phase angle of 90^0, the other/s are either completely on or completely off. This reduces the level of distortion of the generator current and therefore the amount by which the generator needs to be oversized to compensate for this (~5% rather than 25%).

6.1.2 Cost

The Hummingbird is relatively inexpensive, given that components such as op-amps, resistors, TRIACs, thyristors etc., are cheap, and readily available in most developing countries. According to Jan Portegijs, designer of the Hummingbird, the ELC would cost around US$ 425 when built in a professional electronics workshop (US$ 125 for the components and US$ 300 labour costs). This price would reduce significantly if the ELC could be built by a local technician in the developing world, as labour costs would be much lower.

6.1.3 Observations

Although the Hummingbird ELC closely matches most of the requirements for suitability of use in the developing world, it uses a huge number of components (possibly to address the cost issue, i.e. a number of cheap components in place of a single expensive one). This makes the circuit [15] relatively complicated and as a result, hard to manufacture, install, test and repair by the locals in the developing world.

6.2 Homo Luden's (HL) ELC

This ELC [11] is a digital development of the Hummingbird, and is designed for up to 25 kW, single-phase synchronous off-grid generators, working at 220-240V, 50Hz and using up to eight dump loads. The HL ELC could also be used on 120V systems by using an appropriate step down transformer, limiting it to half the power. It can also be configured for any other reasonable frequency, simply by changing the parameters within the software. A similar design is marketed by Indonesian based *Reconersys* as a *Digital Load Controller (DLC)* [13].

6.2.1 Method

The HL ELC also uses frequency as an input signal, and just like the Hummingbird, it uses PI control and phase angle regulation with TRIACs. However, the main component of this ELC is the PIC microcontroller, programmed to undertake most of the tasks within the circuit and thus reducing the number of components required.

6.2.2 Cost

PICs are readily available, quite powerful, versatile and relatively inexpensive. The PIC used in this ELC has a retail value of under US$18 (PIC16F628) [16], which is relatively cheap when compared to the number of components it substitutes. Changing any of the parameters in the PIC can be done easily and cheaply through software, reducing the cost of future upgrades on the system.

6.2.3 Observations

The complete circuit of the HL ELC would be relatively easier to understand for local people compared to the Hummingbird's complex circuit. Programming the PIC would require the purchase of the relevant software and programming equipment i.e. a computer. Local people would need to be specially trained, to enable them to manufacture, install, test and repair this particular ELC.

7 Future Work

The next stage of this project will be to design and build a prototype for an ELC for use in the developing world. It will build on techniques used in both the Hummingbird ELC and HL ELC, as well as learning from their problems and introducing some new ideas.

7.1 Proposed ELC design specification

The proposed ELC must:

- Maintain constant frequency/voltage from the load side of the system by constantly measuring the frequency/voltage, instantly recognising load variations, and then automatically activating the dump loads as required to match the difference between input power from the generator and the output power to the user loads.

- Be robust and inexpensive.

The proposed ELC should:

- Be modular, for easy maintenance.
- Use minimal components with no moving parts to reduce the amount of maintenance.
- Be relatively easy to install, avoiding the need for specialist personnel and equipment.
- Operate with either synchronous or asynchronous generators, at 50 or 60Hz and with single or three phase systems.
- Use load prioritisation[4] during periods of high demand to avoid overloading the generator.
- Have a self diagnostic function for dump load circuit faults to facilitate maintenance.
- Have system monitoring capabilities that allow real time viewing of the output voltage/frequency.

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