IMPROVING THE UTILIZATION FACTOR OF ISLANDED RENEWABLE ENERGY SYSTEMS

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Abstract

Although all energy produced by grid-tied renewable energy systems can be delivered to the grid for consumption by a wide user base, energy delivered by an islanded renewable energy system is limited by the time varying consumption of those served. A set of metrics is proposed to better evaluate this impact on the economic value of the system. This impact can be very significant in developing countries.

Smart systems can reduce energy consumption during periods of high demand through load shedding, but this technology is expensive and unproven in the context of a developing country. Smart systems typically do not add loads during periods of low demand, partly due to the incremental cost of electrical energy from non-renewables. A prioritized dump load control scheme is proposed that strategically diverts excess energy in a 100% renewable energy system to a set of loads useful to the community, first to satisfy the needs of the most valuable use, then to the next most valuable use, etc. A low cost architecture including hardware and software is introduced as a means to implement this scheme, appropriate in the context of developing communities so their economies can more rapidly evolve.

Keywords: 100% Renewables; Hybrid renewable energy system; Islanding; Pico-Hydro; Prioritized Dump Load; Holistic Community Development

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1. Metrics Used to Evaluate Performance of Islanded Renewable Energy Systems

Renewable energy systems powered by 100% renewable resources do not run continuously at full capacity due to maintenance, variable weather conditions such as wind and solar irradiance, and variable availability of water to run hydro turbines. Utilization factor k_u is defined (Sivanagaraju and Sreenivasan, 2010) as the energy generated divided by the plant capacity (nameplate kW power rating) integrated over a period of time. It is used to evaluate the design and operational performance of an energy system, to derate its benefits, and to determine its unit cost through an economic life cycle cost analysis over the power plant's lifetime. According to Bhattacharyya (2013) the utilization factor of micro/mini hydro systems in India can be low due to the unavailability of sufficient water during the dry season versus what is available during the monsoons.

Renewable energy producers can usually deliver all their available power if connected to a large scale utility grid. Conversely, renewable energy producers in an islanded system can deliver no more than what can be consumed at that time, assuming we consider energy storage as a load while being charged. Either energy production must be reduced in times of low consumption, or excess energy must be dissipated in dump loads. Solar energy production is reduced by letting the operating voltage rise from its maximum power point toward V_{OC}. Wind and hydro energy production is typically reduced through braking, regulating the supply of water, or by diverting excess energy to dump resistors heating air or turbine exhaust water, with no use to the users. The latter, shown in Figure 1, is very common in Nepal for micro and pico-hydro systems.

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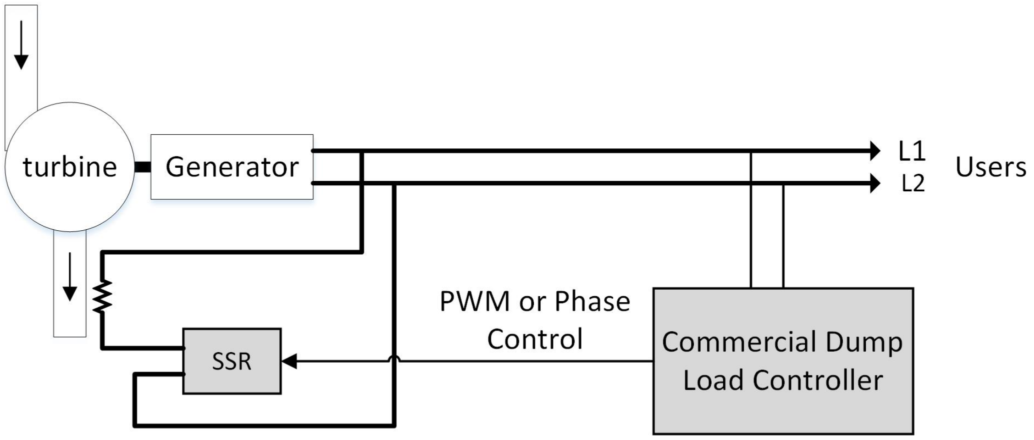

Fig. 1: Traditional Diversion in Pico or Micro Hydro Facilities in Developing Countries

Fig. 2: Traditional water heater "dumb" dump load in MHP (micro-hydro-power) plant in Nepal

Fig. 3: Resistive water heater elements are used to dissipate energy into the turbine's exhaust water.

The value of an islanded renewable energy system must be derated by any diversion or reduction in production required during times of low demand. Although this could be lumped into the utilization factor k_u, that would hide the impact of limited demand. Therefore, two new measures are introduced, the 'production factor' k_p, and the 'consumption factor' k_c.

The production factor k_p is defined as

$$k_p = \frac{E_p}{P_{capacity} * T} \qquad \text{(eq. 1)}$$

Where E_p is the islanded system's energy (MJ) that could have been produced at the pertaining meteorological and environmental conditions if consumption was unconstrained. $P_{capacity}$ is the nameplate power rating of the system. T is the time k_p is evaluated over.

The consumption factor k_c is defined as

$$k_c = \frac{E_d}{E_p} \qquad \text{(eq. 2)}$$

Where E_d is the energy actually delivered to useful loads.

$E_d = P_{capacity} * T * k_u$ for grid-tied systems (eq. 3)

$E_d = P_{capacity} * T * k_p * k_c$ for islanded systems (eq. 4)

k_p is the derating factor due to limits on power generation due primarily to variable and less than optimum weather and water supply, while k_c is the derating factor due to variable consumption in an islanded renewable energy system.

Sivanagaraju and Sreenivasan (2010) also define the load factor as the ratio of average demand to the maximum demand. Although somewhat related to consumption factor k_c, its denominator is the maximum energy demand, not the demand that could have been supported by the system under the environmental conditions over the evaluation period. Consumption factor k_c is a more appropriate metric to understand the impact of limited consumption.

RIDS-Nepal has been working in the Jumla district in Northwest Nepal since 1996, and has observed that during the day most people are working in the fields, so the value of k_c is so low during these periods that production is not warranted. Indeed, many of the hydroelectric systems in this region are shut down during the day to reduce wear and resulting repair and maintenance costs. Furthermore, RIDS-Nepal has observed that the turbine capacity of many of these systems is considerably more than the peak demand of the village it serves, so they are purposely run with constricted water flow to reduce maintenance and the amount of excess energy dumped into the river as heat. RIDS-Nepal has observed that in some cases the turbines are run at approximately 50% of their capacity while still satisfying the peak load. Furthermore, the village consumption varies over the 16 hours the system operates (4pm – 8am), from near its peak (~45% of capacity) consumption for ~4 hours around dinner (5pm - 9pm), to only ~10% of peak to provide minimal lighting throughout the rest of the day (4pm – 5pm) and night (9pm – 8am).

$$k_c \cong \frac{(0.45*4)+(0.045*12)}{24} \quad \text{(eq. 5)}$$

$$k_c \cong 0.10 \quad \text{(eq. 6)}$$

This surprisingly low consumption factor k_c significantly impacts the sustainability of these systems in several ways. First, the funding of operations and maintenance expenses are more difficult to justify due to the reduced benefits delivered by the system. Second, the reduced utilization during the day, and the resulting shutdown of the system during that period, stymies the economic development needed to ease the burden of the needed tariffs. Indeed, RIDS-Nepal has observed that many of the pico- and micro-hydro systems in this area are in service for only a few months to as much as 2 years maximum until significant maintenance expenses arise, at which time the system becomes inoperable or its performance significantly degrades.

The effect of consumption factor k_c is not limited to hydro and wind renewable energy systems. Once a solar system's batteries are fully charged, any excess production must be curtailed or dumped, reducing k_c. Although not as drastic as the example of hydro systems in the Jumla district described above, it can still be significant.

2. Improving the Consumption Factor in Developing Countries

The developed world is just now addressing the consumption factor k_c through smart metering which can shed optional loads or shift demand to times of low consumption. Although not directly increasing the consumption factor, load shedding allows a higher base load than normally could be supported without brownout, which does directly increase the consumption factor k_c. Unfortunately not all loads are considered to be optional by the consumers, so the impact of load shedding is limited.

Adding demand where there otherwise was little, which we'll call "Load Adding" as opposed to "Load Shedding", is not normally used, partly due to the incremental cost of electricity with non-renewable energy sources.

Many micro-grids in the developing world are powered by 100% renewables since hydrocarbon-based fuels are so expensive, especially considering transportation costs. 100% renewable energy sources have an exceedingly low incremental cost of electricity delivered, assuming system capacity isn't exceeded. Incremental energy utilization is also very valuable in developing nations, for example to help solve basic needs such as:

- Powering pumps to supply clean water or irrigation
- Heating water for hygiene and cooking
- Maintaining the temperature of the slurry in a high-altitude biogas digester to the needed mesophilic (~25°C - ~40°C) or even thermophilic conditions (~40°C - ~60°C) for optimum performance
- Refrigerating fruit for long term storage
- Heating air and powering grow lights in greenhouses to provide year-long nutrition.

This list is not exhaustive, and each village will have to determine the most valuable uses of this excess energy based on their particular needs. Due to low incremental cost and the high value of energy utilization, load adding not only can, but should, be used in islanded pic/micro-grids in developing countries.

3. Prioritized Useful Dump Load Control

Given the number of potential uses for inexpensive, excess energy in the developing world, some mechanism is needed to ensure that the energy is routed to the most valuable load. Due to the dynamic nature of the consumer load profile, the mechanism has to be automatic, with no required decision making by distributed customers to turn useful loads on and off. Because production and consumption are already being balanced in many islanded systems, usually by heating water in dump loads useless to the users, the prioritization of a set of useful dump loads is pursued in this paper.

3.1 Simple Useful Dump Load Control

Figure 4 shows the schematic of a low cost and context-appropriate scheme using ubiquitous water heater thermostats to route excess power to the highest priority useful load needing power as determined by the temperature setting of the thermostat mounted to the water bath associated with that load. For example, thermostat TH1, solid state relay SSR1, and water heater element WHE1 are the components needed to support the highest priority useful dump load. For example, WHE1 and TH1 might be mounted to a hot water tank in a community bathing facility. Similarly TH2, SSR2, and WHE2 are needed to support the next highest priority useful dump load, and SSR3 and WHE3 would be needed to support the lowest priority load which must be able to absorb all available power.

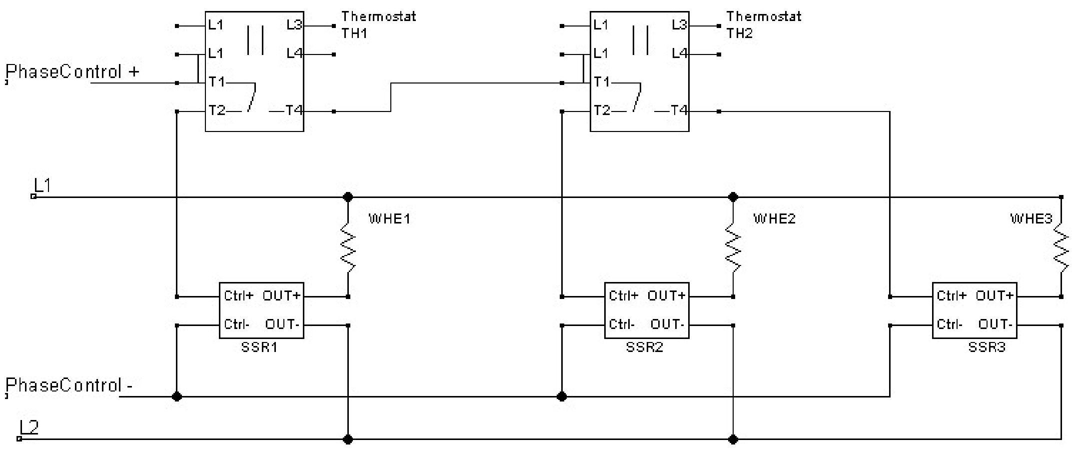

Fig. 4: Example Hardware Architecture of Simple Dump Load Control

This scheme can utilize a high percentage of all the available power generated by a 100% renewable energy system during periods of low consumption in the village served. This helps justify operation of the system 24 hours a day, increases the value of the facility, provides consistent energy to drive economic development, and helps the local population justify the funds needed to maintain the system. This scheme routes excess energy to a set of useful dump loads, starting with the highest defined priority load needing power, and shifting power to the next highest priority load once the first useful dump load is met, e.g. the water is hot enough, etc. Conceptually there is no limit to the number of useful dump loads that can be included to obtain values of k_c approaching unity, a 10x improvement over the k_c seen by RIDS-Nepal in Northwestern Nepal.

This scheme's primary advantage is its simplicity and use of ubiquitously available hardware. However, water heater thermostats are not particularly accurate, have significant fixed hysteresis, and have limited range making them inappropriate for regulating the temperature in some applications, e.g. the lower limit of most hot water thermostats is too high for heating a greenhouse. Furthermore, the priority and temperature thresholds cannot practically be adjusted throughout the day and seasons. All these disadvantages can be addressed with a programmable dump load controller.

3.2 Programmable Useful Dump Load Control

The temperature accuracy, hysteresis, and range issues can be addressed by using electronic temperature sensors on the water bath associated with each useful dump load. Temperature sensors utilizing a DS18B20 integrated circuit are inexpensive, ubiquitous, reliable, and accurate. They are easily connected to a wide range of microcontrollers using the 1-wire serial interface standard. Figure 5 shows a hardware architecture implementing such a system.

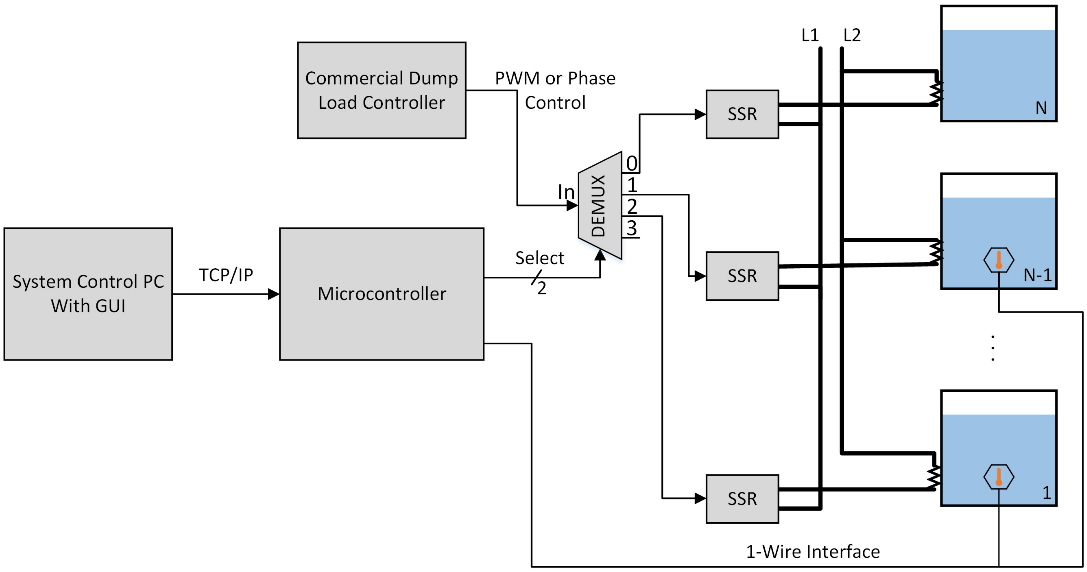

Fig. 5: Example Hardware Architecture of Programmable Dump Load Control

Figure 6 shows an example of the software architecture in the programmable controller. Grey objects are included to show how the firmware entities map to hardware.

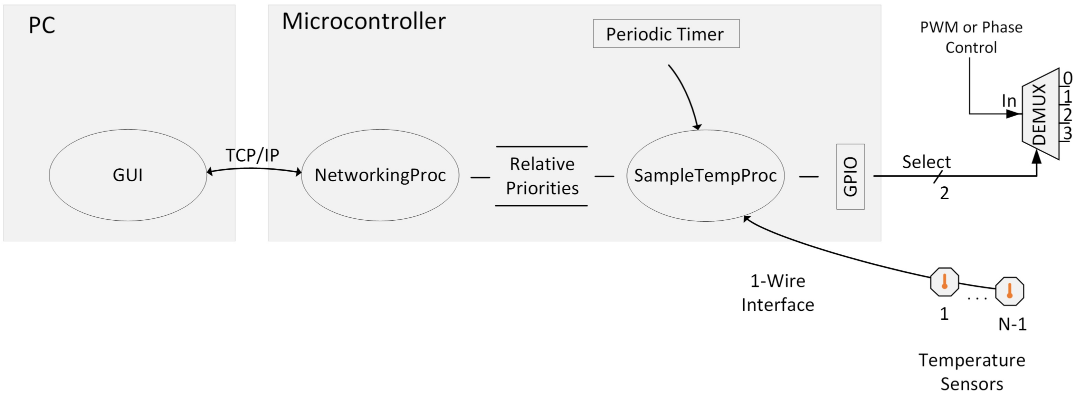

Fig. 6: Microcontroller Firmware Architecture

The PWM or phase control signal from the commercial dump load controller is used to modulate the amount of power consumed by the useful dump loads. Useful dump loads on either DC or AC lines can be supported with the selection and configuration of the appropriate commercial dump load controller and SSRs.

A System Control PC, located at a convenient place in the village such as the pay-as-you-go vending office, provides a GUI used to specify the relative priority and temperature thresholds of the various useful dump loads using a time, date, and/or season schedule. This schedule can be easily modified by local operators based on village requirements. The current prioritization and threshold information is communicated over a TCP/IP communication channel to the NetworkingProc process on the microcontroller. The use of TCP/IP allows this microcontroller to reside close to the useful dump loads, while the PC and GUI can be at a location more convenient to the villagers.

All useful dump loads incorporate a temperature sensor except the lowest priority one which must be able to continuously absorb all potential excess power. For example resistive elements could be included in greenhouses to heat the air or soil by several degrees. There are a large number of rugged, waterproof, and low cost temperature sensors available utilizing the DS18B20 temperature sensor IC. Their accuracy is typically 0.5 to 1 °C which should be quite acceptable and much more accurate than thermostats used in hot water heaters. Although the 1-wire serial interface is slow, the temperature of the water bath or air associated with each load changes slowly, so the sensors can be sampled at a relatively slow periodic rate by the SampleTempProc process. This process determines the highest priority dump load needing additional power, and updates a set of GPIO pins to drive the 'Select' value to the demultiplexer (DEMUX) as shown in figure 5. The demultiplexer routes the PWM or phase control signal to the appropriate SSR.

1-wire interface drivers are available for many microcontrollers. Hysteresis can be controlled programmatically based on village input via the GUI.

Figure 5 only shows dump loads utilizing tanks of water and water heater resistors, suitable for a wide range of useful loads including hot water for bathing and cooking, and to stabilize a biogas digester at its optimum temperature. However, other loads can also be used since the DS18B20 thermometers are accurate over a wide range and can measure other substances including soil or air. For example, a solid state refrigeration unit could be used to maintain the temperatures of apples in cold storage.

Fig. 7: Warm/hot water as "useful" dump load for improved personal hygiene, very welcomed in cold areas.

Fig. 8: Heating water for increased anaerobic process in the production of biogas and heating a high-altitude greenhouse.

4. Summary

The current utilization factor for many pico and micro hydro systems in Northwest Nepal is a surprisingly low value of around 10% based on observations by an NGO working in the area, RIDS-Nepal. This low utilization significantly impacts the benefits of the systems making it difficult for the villagers served to grow economically and to maintain and operate them.

Two different 'smart' dump load control schemes are described that can utilize the energy that would otherwise be wasted. One scheme using hot water heater thermostats is extremely simple, inexpensive, and context-appropriate. However, it hard-wires a fixed prioritization among the loads and suffers from fixed hysteresis and relatively poor temperature accuracy. The other scheme uses a small microcontroller, DS18B20 based temperature sensors, a PC-based GUI, and SSRs. It removes the limitations of the water heater thermostat implementation. Although more complex than the simple scheme, it is still context-appropriate.

RIDS-Nepal is planning to implement the microcontroller-based solution in a pico-hydro facility in the village of Moharigaun in the Jumla district of Nepal. Useful dump loads will be used:

- To heat bathing water for showers and personal hygiene to eradicate the most common skin sicknesses
- To maintain the temperature of a high-altitude biogas digester for an increased anaerobic process under mesophilic (~25°C - ~40°C) or even thermophilic conditions (~40°C - ~60°C)
- To heat water to reduce the amount of wood needed to cook rice and tea
- To heat and power grow lights in a greenhouse to improve year-round nutrition.

Extensive monitoring will be employed to quantitatively measure the impact of the prioritized dump load control scheme.

Fig. 9: The village of Moharigaun in the remote North-East of the Jumla district of Nepal will use a variety of useful dump loads

5. References

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