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Efficient Microgrid Management System for Electricity Distribution in Emerging Regions

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***Abstract*—In this paper we describe the motivations and design process for our open-source, low-power, and high-accuracy AC power meters suitable for several different off-grid metering applications. The described metering and switching hardware is more power efficient than off-the-shelf systems with equivalent capability while being able to measure much smaller loads accurately. The metering system we've developed is suitable for monitoring up to a collection of 20 circuits each drawing power as low as 1W up to 500W as is often found in a rural microgrid setting. Created with modularity in mind, the software and hardware design can easily be modified to be used as part of a home-solar power system, an AC micro-grid, or as a meter for each load in a room. The designs and source code will be made publicly available in August of 2012.**

***Index Terms*—Microgrids, Power Infrastructure, Off-grid Power**

I. Introduction

An estimated 20% of the world's population lacks access to modern sources of energy [1]. Much of this unelectrified population is rural and out of the reach of the centralized grid. To provide power in these regions, off-grid distributed power sources are required. Basic needs such as lighting and cell phone charging can be met with single home solar systems but as needs grow, larger generation sources are necessary. When the electrical energy demands of a community grow beyond the power that can be supplied by solar lanterns and solar home systems, the next step is the creation of a microgrid to aggregate a community's usage into a system that can provide a more economical and centralized source of electricity. They also have the added benefit of providing services to a wider range of community level infrastructure [2]

Financing a microgrid however is not feasible for a community to do without outside investment. For such an investment to be attractive to a business owner, there needs to be an expectation that the initial investment can be recovered. In many of the existing rural microgrid installations, the return of investment has not been shown to be reliable. This is due to both the cost of of the installation, generation, and administration of the grid systems and customers and the high level of system losses and inefficiencies in the way that the grids have been implemented [3]. In this paper we describe a microgrid management solution we have developed that can make this possible. The microgrid solution integrates energy metering, switching, communication, and central computation. Since commercial solutions allowing for these features are not available at a price point suitable for the developing world, we designed and developed a system to allow for more cost-effective management of consumer electricity.

The four basic features of metering, switching, communication, and central computation allow for sophisticated management to be provided at reasonable cost. Accurate metering of electricity consumption allows a utility to charge for electricity delivered rather than a flat rate. It has been demonstrated that significant cost savings can result from the implementation of accurate metering of electricity generation using renewable energy sources—metering of electricity usage was shown to encourage conservation [4]. The incorporation of a relay for each circuit allows for the automatic disconnection of customers in case of overuse or lack of payment. Communications allows these systems to be remotely monitored, potentially lowering maintenance and alerting a utility quickly to problems. Lastly, with a central microprocessor, algorithms for load management or demand response can be incorporated into the grid management system.

II. Background

Microgrids are localized grouping of generation storage and loads. A microgrid can have a single point of connection to a centralized grid and can either be operated in grid-connected mode or it can be islanded. There have been many projects that try to implement microgrids in rural developing regions. Microgrids (Figure 1) are seen as an effective way to integrate distributed non-grid controlled generation and also provide for a higher local quality of service [5], [6]. They are especially relevant for rural electrification because of the lack of a predictable central grid connection.

There are existing commercial solutions that can provide metering and disconnection. However, these commercial (Kill-a-Watt, Watts-up) and open-source (ACme) appliance load power meters, are not specifically geared at the application of metering households in rural developing regions, where usage levels are below the accurate range of these meters [7]. Measuring variations in usage requires $< 1\,\mathrm{W}$ resolution to detect vampire loads which could create expensive drain on a system. Furthermore, the existing solutions are designed with a very different goal in mind—aggregating appliance power use and communicating over mesh wireless networks. Therefore, the cost and power use of these meters is too high to be applicable for rural microgrids. The existing meters often do not provide integrated relays or the ability to aggregate

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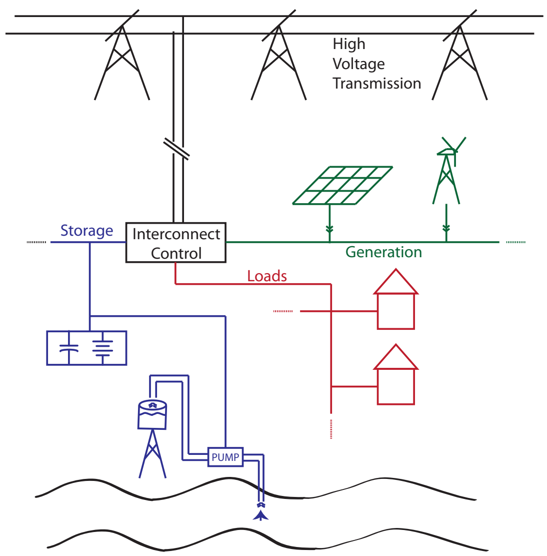

Figure 1. Microgrid conceptual diagram

grid usage and communicate to a remote database over GPRS communications, a feature that is necessary for load and supply management and enforcing cost recovery for electricity provided remotely.

III. Hardware Design

The hardware design constraints of our architecture were based on the projected usage and desired functionality of a rural microgrid power management system. The core behavior desired of grid management hardware is the following:

1) accurately measure electricity usage of each household connected to the local generation source.
2) allow for centralized control of each household on the grid to enforce payment scheme and prevent theft.
3) aggregate the usage from each of the households in a central micro-controller that can interface to a variety of payment management gateways.

There are two types of hardware modules in our system:

1) metering daughterboards (Figure 2)
2) grid-controller motherboards (Figure 3)

The metering daughterboards (Figure 2) are designed to be able to measure and switch up to $10\,\text{Amps}$ of current at $240\,\text{VAC}$. They communicate their usage data to the motherboard over SPI communication lines. The latching relays on the daughterboards are controlled by the micro-controller on the motherboard through another set of digital communication lines. All communications between the motherboards and daughterboards is through optically-isolated channels. This design decision was driven by the need to have very robust communications and ensures that any electro-magnetic interference (EMI) from the power lines will not affect the motherboard.

The grid-controller motherboards (Figure 3) are designed to control and collect data from the daughterboards and aggregate

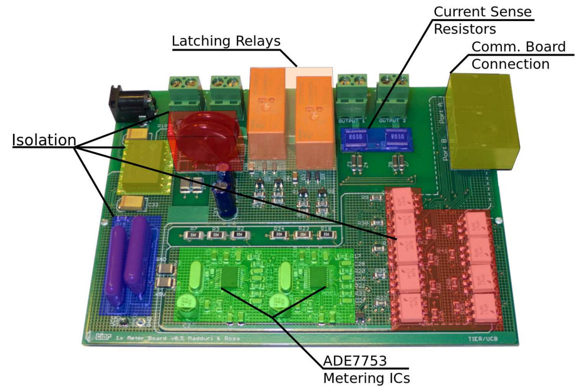

Figure 2. Metering daughterboard with annotations.

the usage on a local micro-controller. The motherboards also have integrated storage and communications, both over a cellular and an serial-to-usb interface.

The entire system was designed to be powered by a 5 VDC bus. The motivation here was to ensure that a small backup source could provide power to the grid management system independently of the state of the grid generation.

A. Metering Daughterboards

The design of the metering daughterboards (Figure 2) was driving by the guiding principle of providing a low-cost, accurate, and robust solution to measuring small amounts of electricity power usage. The metering itself is performed by an Analog Devices ADE7753 metering IC. The ADE7753 has a many built-in ADCs and DSP to perform various power measurements—active, reactive, and apparent energy usage—accurately over a wide range of environmental conditions. The motivation to lower manufacturing and component costs led us to an integrated design that has two sets of metering and switching sub-circuits on a single board. Each metering sub-circuit was designed with the following specifications in mind:

1) Must measure and switch electricity at 240 VAC with currents as high as 10 Amps. Each component is sized to meet the voltage and current specs. The relays on the board are rated up to currents of 16 Amps at 240 VAC. Electrolytic capacitors are typically the components that are the first to fail, we ensure that they are over-sized in order to extend lifetime of the systems. Special care is given to trace widths and other board layout parameters to ensure thermal stability with high currents.
2) Metering accuracy must be $\pm 0.1\,\text{Watts}$ at low usage levels ($\sim 1\,\text{Watt}$) and limited to $\pm 1\%$ at $500\,\text{Watts}$. To ensure high degree of accuracy of the metered loads, high-tolerance current-sense-resistors are used. The differential traces from the current sense resistors are routed pairwise to ensure close coupling of any common-mode disturbance.
3) Must maintain total power drawn by each metering circuit under 250 mWatts—this includes all power drawn by current sense resistors, relays, metering IC, and support and communications circuitry. We use latching

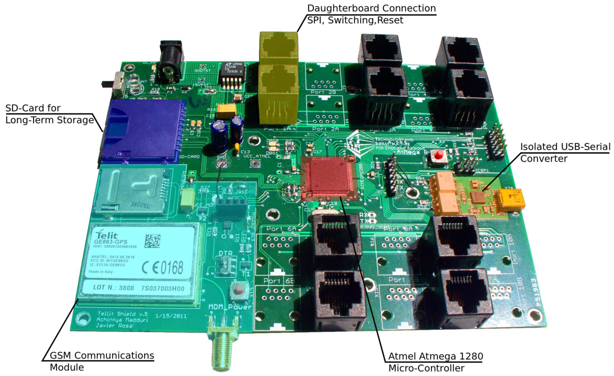

Figure 3. Grid-controller motherboard with annotations.

relays to ensure that the power draw from the relays is minimized regardless of switch state. The current-sense-resistors can be resized according to the required spec. In this case we ensure that they are minimally sized to have the required accuracy without dissipating any more power than required.

4) Must be robust and reject all disturbances from power lines from interfering with the operation of the grid-controller motherboard—disturbances include electro-magnetic interference (EMI) from appliances connected to the grid, and line surges due to faults and lightning strikes. We ensure full isolation between individual daughterboards and the motherboard by having opto-isolators on all communication lines. We also ensure that all the daughterboards are galvanically isolated by have a DC-DC isolating power converter on each board.
5) Per sub-circuit costs must be under $20 for medium quantity production—this includes both component and manufacturing costs. As was mentioned above, a big cost-reduction choice was to integrate 2 metering and switching sub-circuits on a single board. Component selection and minimizing board size were also important parts of the cost-reduction calculus.

B. Grid-controller Motherboards

The grid-controller motherboards (Figure 3) are responsible for controlling the relays on each of the connected daughterboards and for aggregating usage metrics from each of the metering ICs. An Atmel ATmega 1280 micro-controller is the central processor that integrates all the functionality of the grid-management hardware. An on-board SD card slot allows for the ability to store metrics over long time periods. The micro-controller also integrates both a Telit GE863 GSM modem as well as a FTDI usb-to-serial communications IC. This allows for communications with a remote database over a cellular network as well as a local computer over an optically isolated serial communications line.

IV. Software design

This grid-management system was intended to be adapted for use in a variety of configurations and developed in a collaborative open-source licensed (GPLV3) fashion with freely available tools. As such the software was designed to be modular and easily support changing the number of meters being controlled, the switching mechanism, and even the processor being used to control the entire system. Most of the submodules are programmed in C with a few using some features of C++. Calls made using low level assembly instructions are abstracted in the hardware abstraction layer (HAL). At the lowest level, the Wiring **(wiring.org.co)** HAL with a small number of additional features is used because of its familiarity to a growing base of micro-controller developers and because of its portability across the Atmel ATmega line which can simplify the process of a redesign. For example, if the number of meters being managed is downscaled, switching to a smaller and less expensive micro-controller would require a few pin-remappings and modified compilation arguments. In between the HAL and application layer we have the meter management, switching, circuit level communications, and an aggregate "Circuit" management module which all compartmentalize the various functions of the meter. The application layer is divided into two primary modes of interaction: "Interactive" mode and "Meter" mode. Finally, the code is documented using the Doxygen documentation system. All hardware and source code will be made available online in August.

The "Interactive" mode is designed for debugging, configuration, and quick exploration of meter state through a debug serial port independent of the metering serial port used to communicate with a data-logging and account management computer. "Meter" mode is intended to be managed by another computer and intentionally supports a limited feature set reducing the complexity of code responsible for reliable metering operation. Reported measurements include, voltage, current, apparent power, active power, as well as faults such as voltage sags and current spikes. These readings are all available through either a push or poll mechanism displayed in human readable and easy to parse CSV format. Reporting rates can vary from every second to every six minutes. Longer intervals can be used with an alternate configuration of the metering circuitry.

High-tolerance metering components have been selected to reduce the variability in design, but the highest accuracy is achieved by calibrating the conversion factors and offsets for each metering sub-circuit. A built-in in calibration routine is available which makes use of readily available equipment such as power resistors, a 2:1 transformer, and inexpensive multi-meters.

V. Testing Results

The grid management system is targeted to monitor a collection of small loads in typically adverse outdoor settings. Tests were conducted to evaluate the robustness of the system under extreme environmental conditions of high temperature and humidity. Switching endurance as well as the accuracy and precision of the system when measuring small and large loads was extensively tested. Additionally, the system power consumption was measured.

Given that very small loads are being metered, the power requirements of the board must be minimized. Even withouth aggressive power management of the metering ICs each

Test	Parameters
Temperature	-20C to 70C
Humidity	100% for 24 hours
Lightning	5kV,500A,5us
Static Discharge	8kV
High-Potential(dry)	4kV
High-Potential(after Humidity test)	1kV

Table I
ENVIRONMENTAL TESTS PERFORMED AT POWER STANDARDS LAB. OUR HARDWARE WITHSTOOD ALL THE TESTS ABOVE.

W	0	1	2	8	75	500
N	108	108	108	108	108	108
MeanWmeas	.0073	1.1	2.1	8.4	74.7	510.0
Mean%Err	N/A	5.6	4.7	4.5	.35	2.0
Std. Dev.	.026	.05	.02	.06	.1	1.85

Table II
ACCURACY OF METERS AT VARIOUS LOADS.

daughterboard draws 0.5 Watts (.25 Watts per circuit) and the motherboard with an active modem draws 0.5 Watts. Power reductions can be made by lowering the metering frequency and placing inactive components into low-power states.

As the system is intended to last several years, the robustness of latching relays is critical. Our benchtop tests ran the relays to 200,000 cycles until failure. The relays are resistant to vibration and can remain latched with up to 3 Gs of acceleration.

Various environmental tests were performed courtesy of Power Standards Lab in Alamada, CA. Test results and parameters are available in Table I.

Accuracy and precision of the meters was measured using various resistive loads across the range of expected use. Most importantly loads of ~1W are detectable and distinguishable from no loads being attached (Table II).

VI. CONCLUSION AND DISCUSSION

The grid-management system that we have described in this papers fills a very particular niche in providing the ability to enable accurate metering for very low loads along with the ability to switch individual loads from a centralized controller. The metering daughterboards have been tested and shown to be robust to adverse environmental conditions and high-voltages. We have also optimized the system by minimizing both power drawn and cost of each individual meter. One aspect that we wish to stress is that our design is very adaptable because of its modularity. Being an open-source architecture allows for future users to extend the application of our platform to their specific needs. We have engaged other groups who see it as an essential part of home-solar systems and power-quality monitoring devices. We are presently engaged in developing an integrated single-meter & cellular communications module. Finally, we are in active collaboration with a commercial entity that will deploy our grid-management system as part of a rural micro-grid project in Kenya. We hope to present the information collected from this deployment in a future study and provide field-test performance data.

VII. ACKNOWLEDGEMENTS

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REFERENCES

[1] "ENERGY FOR ALL: Financing access for the poor," *IEA World Energy Outlook 2011*, Sep. 2011.

[2] C. Kirubi, A. Jacobson, D. M. Kammen, and A. Mills, "Community-Based Electric Micro-Grids Can Contribute to Rural Development: Evidence from Kenya," *World Development*, vol. 37, no. 7, pp. 1208–1221, Jul. 2009.

[3] A. C. Brent and D. E. Rogers, "Renewable rural electrification: Sustainability assessment of mini-hybrid off-grid technological systems in the African context," *Renewable Energy*, vol. 35, no. 1, pp. 257–265, Jan. 2010.

[4] C. E. Casillas and D. M. Kammen, "The delivery of low-cost, low-carbon rural energy services," *Energy Policy*, vol. 39, no. 8, pp. 4520–4528, Aug. 2011.

[5] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "Microgrids," *IEEE power & energy magazine*, pp. 78–94, 2007.

[6] R. Lasseter, "MicroGrids," *Power Engineering Society Winter Meeting, 2002. IEEE*, vol. 1, pp. 305–308 vol. 1, 2002.

[7] D. Soto, E. Adkins, M. Basinger, and R. Menon, "A prepaid architecture for solar electricity delivery in rural areas," in *Proceedings of the Fifth* . . . , 2012.