Intelligent AC Distribution Panel for Real-Time Load Analysis and Control in Small-Scale Power Grids with Distributed Generation

David K.W. Li, Shahab Poshtkouhi, and Olivier Trescases
University of Toronto
10 King's College Road, Toronto, ON, M5S 3G4, Canada
E-mail: davidking.li@mail.utoronto.ca

***Abstract*— In this paper, a smart and resilient residential power network is pursued at small scale by augmenting household power distribution panels. A prototype ten-channel Intelligent Distribution Panel (IDP) capable of managing up to 38 kW is demonstrated. Each channel includes a relay and supports high-frequency current monitoring for smart metering. The AC current's fundamental and harmonic content up to 7^{th} harmonic are monitored and the status of each channel (*on*/*off*) can be effectively controlled using the proposed solution. In order to carry out energy management tasks such as load shedding, and providing user interaction, a low-power single-board computer is used. Tasks such as frequency locking, and real-time power monitoring are implemented using a Multiple Second Order General Integrator - Frequency Locked Loop (MSOGI-FLL) algorithm. The frequency and the calculated real and reactive power are within 1% of the readings from a commercial product for the majority of operating conditions.**

I. Introduction

A reliable and robust electrical power delivery network is critical for sustainable development [1]. It is challenging to extend the electrical grid infrastructure to rural, remote areas, due to high shipping and installation costs, resulting in an estimated 1.2 billion people living without reliable access to electricity [2]. To overcome the challenges of grid development, an organic nano-grid solution for power levels below 50 kW is introduced in this paper, as shown in Fig. 1. A major part of this solution is carried out by adding low-cost power electronics and processing units to existing power distribution panels, thereby creating an intelligent distribution panel (IDP) that serves to manage and regulate solar generation, storage, and loads. IDPs that are connected together form an autonomous, interconnected network where energy deprived IDPs seek access to energy sources through neighboring IDPs. This solution will provide rural communities with an affordable and reliable electrical grid.

While the primary objective is to address problems associated with rural electrification, the outcome of this work also benefits urban installations. The IDP's ability to shed loads during peak billing periods enhances grid stability and reduces average consumers' electricity cost. The IDPs can be further developed to form resilient power islands during grid failures, which is of particular importance to communities where the power grid is exposed to high risks such as natural disasters. The focus of this paper is on the implementation and verification of the IDP as one of the main building blocks to fulfill the nano-grid vision.

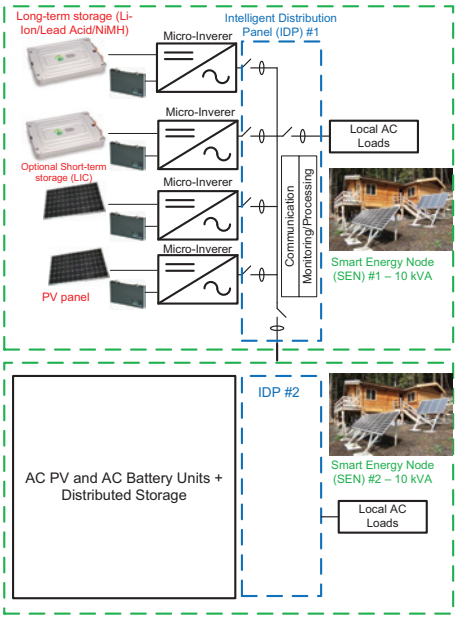


Fig. 1. Proposed nano-grid architecture.

II. IDP Architecture

The IDP is based on a typical residential AC power distribution panel augmented with the following components:

- An uninterruptible power supply (UPS),
- modular smart breakers and metering hardware,
- communication bus, and
- a motherboard hosting the central controller unit.

The IDP architecture and main components are illustrated in Fig. 2.

A. Smart Breakers

The smart breakers are responsible for monitoring and controlling the status of each AC channel. A smart breaker can be broken into two core components, a data acquisition (DAQ) board and a power board, which are assembled together, as shown in Fig. 3.

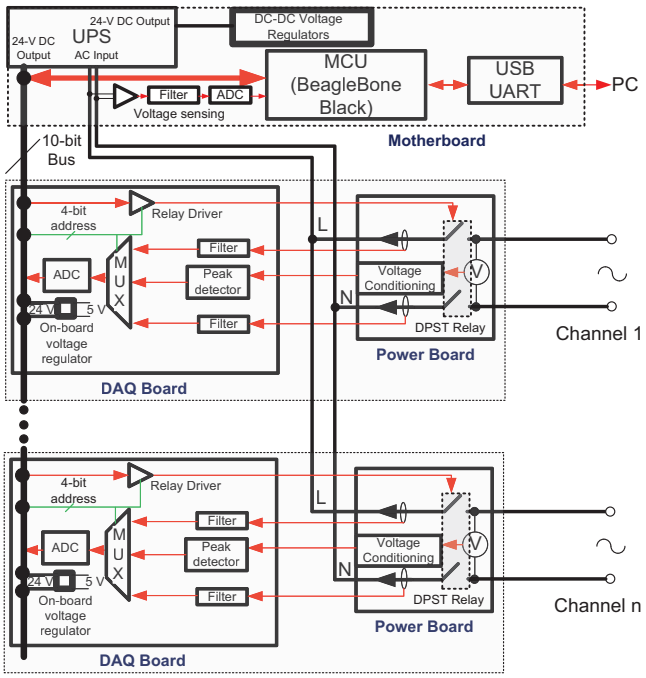


Fig. 2. IDP Architecture.

The power board monitors and controls the AC current flow in each channel. It is equipped with a voltage detector circuit to sense the presence of AC voltage, as well as two hall sensors which measure the current flowing through the breaker. The power board also houses a Double Pole Single Throw (DPST) relay that opens/closes the channel based on a command from the central controller.

The main role of DAQ board is to process and translate the analog information from the power board into digital signals and drive the relay on power board. All analog signals are fed to an anti-aliasing second-order Sallen-Key filter [3]. The filter's output is sampled by a 12-bit analog-to-digital converter (ADC) at 12.5 kSample/sec. The digital data is transmitted to the central controller through the 5-V Serial Peripheral Interface (SPI) line on the communication bus. The same SPI line is also used by the central controller to send commands to the 24-V relay driver on the DAQ board. When activated, the relay disconnects the AC line at the zero-crossings of the electrical current.

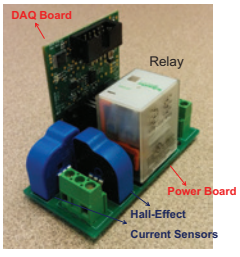


Fig. 3. Assembled Power and DAQ boards.

B. Motherboard and Central Control

The motherboard, as shown in Fig. 4, houses the central processor unit and provides connections to all peripherals including the smart breakers and the 240-VAC to 24-V UPS. The UPS does not keep the AC system alive and is only meant to power the internal circuitry of IDP. This unit is equipped with a battery sized to maintain the IDP operation for 12 hours without grid power in the event of a power outage.

The motherboard is also responsible for sensing the AC voltage at Point of Common Coupling (PCC). The voltage sensing network is similar to the current sensing circuitry on the smart breakers. A high-precision voltage divider generates an analog signal that is passed through an anti-aliasing Sallen-Key filter before it is fed to a 12-bit ADC. The sampled voltage is then transmitted via an optocoupler to the CPU.

The information collected on individual channels are routed to central computation unit on the IDP, the Beaglebone Black (BBB). The BBB utilizes a Cortex A8 CPU clocked at 1 GHz, suitable for real-time complex power measurement and supervisory control algorithms. Additionally, wireless adapters can be attached through available peripheral USB ports.

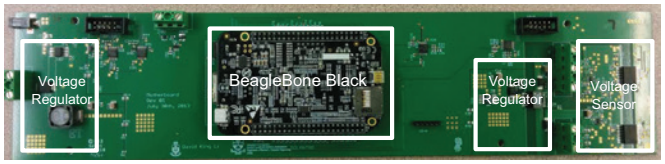


Fig. 4. The IDP motherboard PCB (top view).

III. Functions and Processing

A. MSOGI-Based Frequency Locking and Harmonics Detection

Harmonics generated by non-linear loads are a frequent cause of power quality problems [4]. Excess harmonic contents induce excessive losses and can lead to failures of electrical equipment and appliances. They must be closely monitored and mitigated in power infrastructure. In areas where a stiff grid is not available, monitoring harmonics is particularly difficult since the fundamental frequency is subject to higher volatility due to lack of mechanical inertia introduced by high-power generators. The varying grid frequency and harmonics content render the computationally extensive Fast Fourier Transform (FFT) based algorithms inaccurate [5], [6].

In order to achieve efficient low-latency power and frequency measurements, a Multiple Second Order General Integrator - Frequency Locked Loop (MSOGI-FLL) [5], [6] is implemented in the IDP to monitor the state of fundamental, harmonic, and frequency of the AC voltage and individual channel currents. The simplified schematic of a Second Order General Integrator (SOGI) with FLL is shown in Fig. 5. The MSOGI-FLL utilizes multiple second order bandpass filters, formed using integrators, in combination with a frequency

locked loop to rapidly lock on the fundamental component and its harmonics.

The MSOGI-FLL code is developed and simulated in MATLAB to verify its precision in tracking the fundamental, harmonics and line frequency, f. The trajectory of MSOGI-FLL tracking to an arbitrary function, $u(t)$, is illustrated in Fig. 6. $u(t)$ is defined as

$$u(t) = 10 \cdot cos(2\pi ft) + 5 \cdot cos(2\pi(3f)t) + 2 \cdot cos(2\pi(7f)t), \quad (1)$$

where f = 55 Hz, which is much lower than the lower bound frequency limit for many electrical appliances and equipments, proving the effectiveness of FLL to lock to an extreme range of grid frequency.

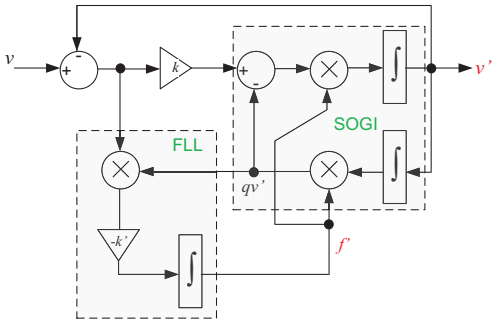


Fig. 5. MSOGI-FLL architecture [5].

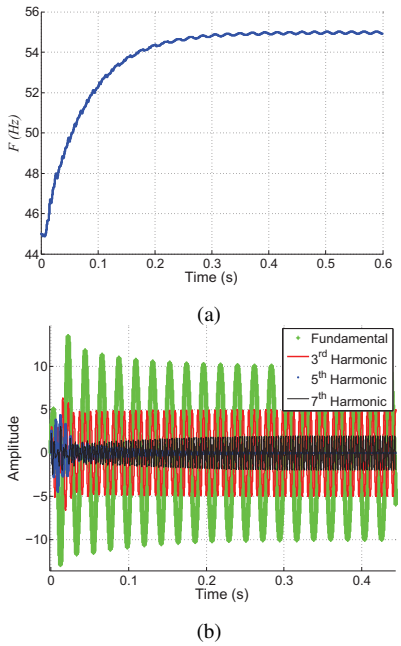


Fig. 6. Simulation results for MSOGI-FLL demonstrating the start-up and successful locking of (a) frequency, and (b) fundamental and harmonics.

B. System Level Control

Supervisory and tertiary control can be implemented at the system level. On start-up, the nano-grid's voltage is checked to ensure it is in a stable state for loads to connect. With the grid stabilized and all the loads connected, the IDP sequentially diagnoses the quality of power flowing through each smart breaker on a regular basis. The power measurements and diagnostic results are transmitted to a user-designated device (local computer, smart phone, etc.). Should any of the channels draw power exceeding the settings pre-defined by the user, the IDP automatically disconnects the relevant relay and alerts the user of the situation. Users can also program the IDP to disconnect low priority loads during periods of peak billing to save up on their electricity bills in case a grid-tied system is in use.

When faults or power shortage occur, each IDP can help restore the grid by shedding loads based on their power ratings and user-designated priority. In addition, it is possible to connect two IDPs through one of the channels and allow power to flow from one IDP to another at individual users' discretion. This feature is very useful in case of a local power outage.

Islanding happens when an electrical line remains live when the grid connection is disrupted [7]. An IDP equipped with a wireless adapter can update line status to utility workers, hence ensuring safety and protecting utility workers during islanding incidents.

IV. Experimental Results

The assembled IDP is shown in Fig. 7. The pitch of each channel is designed for compatibility with existing AC panels.

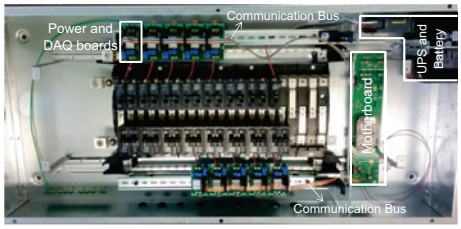


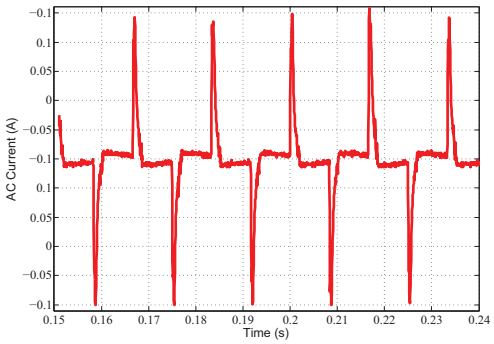
Fig. 7. Assembled ten-channel IDP.

A. Residential Load Modeling

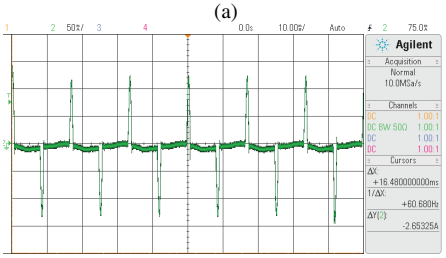
Some typical household load profiles, such as ovens, air conditioning units, and wall chargers, have been captured and logged using isolated voltage probes and a high bandwidth current probe and processed in MATLAB for their power factor, crest factor, real and reactive power. These loads can be emulated using an electronic load (e-load). Due to the limited ability of the e-load because of the built-in passive rectifier, the residential load profile is instead approximated by varying the crest and power factors as available degrees of freedom. The AC current of a commercial charger and the reconstructed waveform from the e-load are shown in Fig. 8 (a), (b), respectively.

B. IDP Measurements

The measurement results of IDP versus the e-load reading at four different load profiles and varying frequency are detailed in Table I. The results match well within 1% at high power



(a)



(b)

Fig. 8. (a) The AC current measurement, and (b) the reconstructed waveform for a typical 60 W laptop charger in idle state (not charging).

levels ($\geq$ 100 W/VAR/VA), while at low power, significant mismatches can occur. These errors can be potentially reduced by further calibration.

The relay turn-*on* and turn-*off* events are shown in Fig. 9 (a), (b). The relay disconnect happens at AC current's zero crossing point, and it is envisioned that the turn-*on* can also benefit from soft switching by proper timing control.

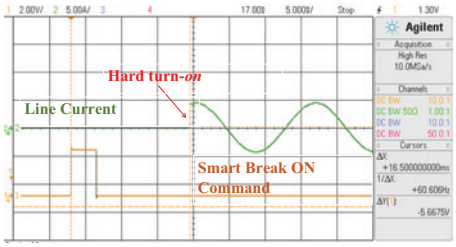
TABLE I

COMPARISON OF IDP MSOGI-FLL OUTPUTS AND READINGS FROM E-LOAD FOR FOUR TEST CASES

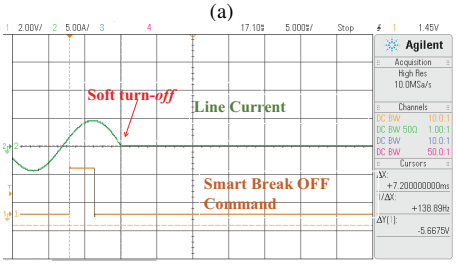
Test 1	P (W)	Q (VAR)	S (VA)	f (Hz)
E-load Reading	694.10	620.00	930.52	59.99
IDP Measurement	687.31	624.54	928.69	60.08
Error Percentage	-0.98 %	0.76 %	-0.20 %	0.15 %
Test 2	P (W)	Q (VAR)	S (VA)	f (Hz)
E-Load Reading	12.6	4.23	13.27	59.99
IDP Measurement	12.79	3.06	13.16	60.09
Error Percentage	-1.5 %	1.50 %	-0.82 %	0.16 %
Test 3	P (W)	Q (VAR)	S (VA)	f (Hz)
E-Load Reading	91.05	657.57	664.19	59.99
IDP Measurement	72.41	653.48	657.48	60.07
Error Percentage	-20.47 %	-0.62 %	-1.01 %	0.13 %
Test 4	P (W)	Q (VAR)	S (VA)	f (Hz)
E-Load Reading	811.71	830.74	1161.66	55.01
IDP Measurement	804.24	833.32	1158.11	55.47
Error Percentage	-0.92 %	0.31 %	-0.30 %	0.85 %

V. CONCLUSIONS

An intelligent power distribution panel that can monitor and control power flow within an average household is presented in this paper. The IDP can enhance grid stability, and reduce the cost of electricity for an average household, as well as alerting utility workers of energized electrical lines during faults. Experimental results demonstrate that the IDP can accurately track the power quality and consumption of a household under various loads and grid conditions.



(a)



(b)

Fig. 9. The smart breaker command and AC line current when (a) connecting, and (b) disconnecting the channel.

VI. ACKNOWLEDGEMENTS

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