A Dual-Active-Bridge based Bi-Directional Micro-Inverter with Integrated Short-Term Li-Ion Ultra-Capacitor Storage and Active Power Smoothing for Modular PV Systems

Shahab Poshtkouhi\textsuperscript{1}, Miad Fard\textsuperscript{1}, Husam Hussein\textsuperscript{1}, Lucas Marcelino Dos Santos\textsuperscript{1}, Olivier Trescases\textsuperscript{1}, Mihai Varlan\textsuperscript{2} and Tudor Lipan\textsuperscript{2}

\textsuperscript{1}University of Toronto, 10 King’s College Road, Toronto, ON, M5S 3G4, Canada
\textsuperscript{2}Solantro Semiconductor, Ottawa, ON, K2E 7Y1, Canada

E-mail: shahab.poshtkouhi@utoronto.ca

Abstract—This work targets modular nanogrids for remote locations, where photovoltaic modules can be gradually introduced to grow the renewable energy capacity at minimal capital cost, while reducing diesel fuel consumption. Today’s grid-tied micro-inverters provide a modular solution for ac power generation in nanogrids but battery storage remains centralized, requiring an additional ac-dc converter. The main contribution of this work is a new micro-inverter platform and control scheme with bi-directional power flow between the nanogrid, the photovoltaic module and integrated short-term storage, using new high energy-density Lithium-Ion Capacitor technology. A real-time power smoothing algorithm is also proposed and the performance of the new 100 W micro-inverter is experimentally verified under various closed-loop dynamic conditions.

I. INTRODUCTION

There is a growing demand for stand-alone flexible ac nanogrids in areas ranging from underpopulated remote communities and research stations, to developing nations that lack a power infrastructure. Off-grid power systems are traditionally based on diesel generators; however the high cost of maintenance and fuel transport makes the integration of solar energy attractive [1]. For example, [2] presents a 70 kW off-grid photovoltaic (PV) system in Canada. Dynamic load shedding is a key strategy for energy management in off-grid systems having minimal storage [3]. This work targets small-scale remote nanogrids (up to tens of kW) where PV modules are used either as the primary energy source, or as a supplement to diesel generators. In these applications, there is a need for modular power electronics with minimal capital cost, while allowing gradual expansion of generation capacity. The intermittent nature of PV, and thus the need for storage, is a major challenge in these applications, even if power-quality and up-time requirements are reduced compared to conventional grids. Low-power micro-converters (MIC) [4], [5] and micro-inverters (MIV) [6]–[8] provide high-granularity distributed Maximum Power Point Tracking (MPPT) [9]–[11] at the module or sub-string level. This leads to increased robustness to clouds, dirt, and aging effects as well as irradiance and temperature gradients. Existing MIVs satisfy the need for low capital-cost and expandable ac generation, but not storage. A typical off-grid MIV based ac power system is shown in Fig. 1(a).

The Energy Storage System (ESS) is usually based on a large centralized bi-directional ac-dc converter, connected to a battery bank or a flywheel [12], [13]. The ESS generally includes a sophisticated Battery Management System (BMS), with cell-level monitoring and balancing circuits. The objective of this work is to (1) introduce a new bi-directional MIV architecture with integrated ESS, as shown in Fig. 1(b), and (2) demonstrate a PV power smoothing algorithm that takes advantage of the integrated storage to improve power quality and reduce stress on the generator. The new MIV hardware can incorporate either (1) short-term storage using new Lithium-Ion Capacitor (LIC) technology, for power smoothing and load transient mitigation, or (2) long-term storage using batteries (ac-battery). Aside from injecting real-power into the nanogrid, the MIV architecture can also provide reactive power on demand. The short-term storage can also be used to mitigate the relatively slow diesel generator start-up [14]. While the MIV cost is slightly increased due to the bi-directional capability, the improved system modularity has tremendous value in the target applications.

This paper is organized as follows. The chosen short-term storage technology, Lithium-Ion Ultra-Capacitors (LICs), is discussed in Section II. The proposed MIV architecture and control scheme are discussed in Section III. An averaging-based power smoothing algorithm is discussed in Section IV. Experimental results are reported in Section V, demonstrating both the dc-dc and dc-ac stages operating in closed loop. The tests are performed on a 100 W PV module, which is a suitable candidate for high modular nanogrids with low incremental cost.

II. LI-ION ULTRA-CAPACITOR AS SHORT TERM STORAGE

Electrochemical Double-Layer Capacitors (EDLC), also known as ultra-capacitors (u-caps), have a symmetric input and output specific power in the range of 0.5-25 kW/kg [15],
which is at least ten times higher then typical Lithium-Ion (Li-Ion) batteries [16]. U-caps also offer higher cycle-life, lower Equivalent Series Resistance (ESR) and reduced susceptibility to high depth-of-discharge. A LIC is a hybrid device that combines the intercalation mechanism of traditional Li-Ion batteries with the cathode of EDLCs, as shown in Fig. 2(a) [17]. The cathode exhibits an activated carbon material, while the anode is generally pre-doped with Lithium ions, resulting in a lower anode voltage, and a higher cell voltage of 3.8-4 V versus 2.5-2.7 V for conventional EDLCs [17]. Unlike EDLCs, LICs have a minimum operating voltage, $V_{LIC, min}$, which limits their energy density. Overall, LICs have $2-4 \times$ higher energy density than EDLCs, as shown in Fig. 2(b). LICs are well suited to the distributed PV ESS, where relatively high energy for power smoothing on the time-scale of minutes, and high cycle-life are required. Unlike batteries, LICs are expected to match the required 20-25 year lifespan of PV systems.

### III. Dual-Active-Bridge Based Micro-Inverter with Integrated Storage

The detailed two-stage MIV architecture composed of dc-dc and dc-ac stages is shown in Fig. 3 and Fig. 4, respectively. Two dc-dc converters interface to the PV voltage, $V_{pv}$, as shown in Fig. 3(a). The synchronous boost connected to the LIC is operated in duty-cycle control to regulate $V_{pv}$ to the reference voltage, $V_{pv, ref}$, which is set by the MPPT block. The second converter is an isolated Dual-Active-Bridge (DAB) that interfaces with the high-voltage dc link, $V_{bus}$. The DAB topology was selected based on soft-switching operation and simple phase-shift power control [19]–[21]. Both dc-dc converters are bi-directional, such that the LIC can transfer energy to/from other elements in the nanogrid. The average power from $V_{pv}$ to $V_{bus}$, $P_{DAB}$, is

$$P_{DAB} = \frac{V_{pv} V_{bus}}{n \omega_s L_{DAB}} (1 - \frac{\phi}{\pi}), \quad (1)$$

where $n$ is the transformer turns ratio, $L_{DAB} = L_{ext} + L_{leak}$ is the DAB inductance, $\phi$ is the phase-shift between the two bridges, and $\omega_s = 2\pi f_s$, where $f_s$ is the switching frequency.

$P_{DAB}$ can be regulated through adjusting the phase shift, $\phi$, between the corresponding primary and secondary bridges (for example $\phi_2$ and $\phi_1$), which are driven at a duty cycle of $D_1 = 50\%$. As a result, $\phi$ is used to indirectly regulate the LIC current, $I_{LIC}$, to the reference, $I_{LIC, ref}$, for power smoothing, as described in Section IV, while MPPT is achieved by regulating $V_{pv}$ to MPP voltage. This is obtained through adjusting the duty cycle of the LIC synchronous boost converter, $D_2$. This control process is illustrated in Fig. 3(b) and Fig. 4(b).
respectively. These two inner loop compensators are designed based on the separation of time constants; hence the bandwidth of \( G_{c1}(s) \) is much lower than \( G_{c2}(s) \) to ensure stability.

The ac–dc inverter stage consists of a soft-switching synchronous buck converter, followed by a low-frequency unfolder, as shown in Fig. 4(a). The high-voltage buck converter regulates the dc link voltage, \( V_{bus} \), while shaping the PLL-synchronized grid current to achieve unity power factor, unless reactive support is requested. The inductor current, \( I_{Lbuck} \), is regulated in Boundary Conduction Mode (BCM) for soft-switching and high-efficiency [22]. The required on-time, \( T_{on} \), of the high-side (low-side) switch in positive (negative) real power flow operation is

\[
T_{on} = L_{buck} \frac{\Delta I}{V_{bus} - V_{grid,rect}},
\]

where \( L_{buck} \) is the buck converter inductance, \( V_{grid,rect} \) is the rectified grid voltage, and \( \Delta I \) is the current ripple of \( L_{buck} \). The simplified control diagram for the dc–ac stage with zero reactive power is shown in Fig. 4(b). Reference values for \( T_{on,ref} \) throughout the half line-cycle are pre-calculated and stored in a Look-Up Table (LUT), such that the average inductor current \( < I_{Lbuck} \geq T_{s} \) is sinusoidal. The PI controller scales \( T_{on} \) to adjust the power transfer, based on the \( V_{bus} \) regulation loop. The average power can be positive or negative depending on the PI controller \( G_{c3}(s) \) output. The power flow direction is set accordingly by driving \( c_{11} \) and \( c_{12} \) in the correct order by using the sign of PI controller output, \( K \).

Fig. 4. (a) Architecture and (b) simplified control diagram for the dc–ac stage.

IV. POWER SMOOTHING ALGORITHM

The short-term storage can be used to filter the PV module’s output power, \( P_{pv} \), which can improve the nanogrid power quality by reducing the \( dP/dt \) factor [23], as well as the fuel economy in the diesel generator [24], [25]. In fact, taking full advantage of the distributed ESS at the system level requires load monitoring, intelligent load-shedding and coordinated MIV control, which is beyond the scope of this paper and considered as future work. The LIC energy capacity for each MIV is chosen based on providing/absorbing the rated PV power for approximately five minutes, which provides a sufficient buffer for startup and typical cloud variations.

The smoothing process is illustrated in Fig. 10(a). \( P_{pv} \) is sampled every 10 s and passed to a moving averaging window of approximately 5 minutes, based on the low-latency Hull digital filter [26], generating \( P_{pv,ave} \). At each sample point, the Least Square Estimation (LSE) method is used to generate the polynomial \( s(\theta) \) that best fits this curve, by finding the optimization vector variable \( \theta \):

\[
\hat{\theta} = \arg \min_{\theta} \sum_{n=1}^{m} (P_{pv,ave}(n) - s(n, \theta))^2,
\]

where \( m \) is the number of previous samples which are used for the prediction. In this case, an averaging window of 5 minutes is considered, and thus \( m = 30 \), assuming that the measurements are done every 10 s. To simplify the solution, it is generally assumed that the signal \( P_{pv,ave} \) can be modelled with a polynomial, in which case the estimate \( s(\theta) \) can be expressed as

\[
s(\theta) = H\theta,
\]
where $H$ is any matrix of size $m \times (p + 1)$, and $p$ is the order of polynomial which is used in the estimation. In this work, $p = 8$ is chosen. A higher order polynomial increases the prediction accuracy resulting in a smoother power curve, however the computation effort increases substantially with $p$.

A common expression for $H$ is as follows

$$H_{m,p+1} = \begin{pmatrix} 1 & 1 & \cdots & 1 \\ 1 & 2^1 & \cdots & 2^p \\ \vdots & \vdots & \ddots & \vdots \\ 1 & m^1 & \cdots & m^p \end{pmatrix}. \quad (5)$$

It can be shown that $\hat{\theta} = (H^T H)^{-1} H^T P_{pv,ave}$, and thus $s(\theta)$ can be constructed using (4). By evaluating $s(m+1, \theta)$, $P_{pv,ave}(m + 1)$ is forecasted. In order for $P_{pv}$ to follow the average power curve, the difference power, $P_{diff}$, must be supplied or absorbed by the LIC:

$$P_{LIC,ref}^*(m + 1) = \begin{cases} P_{LIC} - \eta_{LIC} P_{diff}, & P_{diff} \geq 0, \\ P_{LIC} - \eta_{LIC} P_{diff}, & P_{diff} < 0, \end{cases} \quad (6)$$

where $\eta_{LIC}$ is the LIC dc-dc converter efficiency, and $P_{LIC,ref}^*(m + 1)$ is the calculated LIC power reference at sample-time $m + 1$. $P_{diff}$ is defined by the following

$$P_{diff} = s(m + 1, \theta) - P_{pv,ave}(m + 1). \quad (7)$$

The smoothing process is illustrated in Fig. 5. The SOC management loop is implemented to gradually steer the LIC State-of-Charge (SOC) to $\approx 50\%$ by generating the offset LIC current command, $I_{LIC,ref}$. The SOC is estimated by the LIC voltage, by considering the well-known quadratic formula for stored energy of a capacitor, $E = \frac{1}{2}C_{LIC}V_{LIC}^2$. Maintaining the SOC near the mid-range is essential to maximize the potential swing. The LIC current command at sample time $m + 1$, is therefore

$$I_{LIC,ref}(m + 1) = \frac{P_{LIC,ref}^*(m + 1)}{V_{LIC}} + I_{LIC,ref}^*(m + 1). \quad (8)$$

### V. EXPERIMENTAL RESULTS

A 100 W MIV prototype was fabricated on a custom Printed Circuit Board (PCB). The prototype parameters are listed in Table I. A 100 W Building-Integrated PV (BIPV) module with the specifications listed in Table II was used for testing. The dc-dc and dc-ac stages are digitally controlled by an on-board FPGA and 16-bit micro-controller, respectively. The DAB transformer was designed as a custom planar magnetic element in order to reduce the weight and profile of the prototype.

#### A. MIV Operation

The measured efficiency of the DAB, LIC and dc-ac stages are shown in Fig. 6. These efficiency curves are nearly symmetrical and thus the data is shown for the positive power flow. The converter stages achieve a peak efficiency of 95.1%, 97.2%, and 96.3%, for DAB, LIC and dc-ac stages, respectively. A new switching technique is currently under development to improve the light-load efficiency of the DAB converter. The steady-state DAB waveforms at the rated power of 100 W are shown in Fig. 7. The dynamic response of the PV voltage control loop for a step change in $V_{pv,ref}$ and $I_{LIC,ref}$ are shown in Fig. 8(a) and (b), respectively. In both

![Fig. 5. Power smoothing and LIC SOC control.](image)

![Fig. 6. Measured efficiency of the DAB, LIC and dc-ac stages.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
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<td>Dc-dc Stage Switching Frequency, $f_s$ (DAB and LIC Converter)</td>
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<tr>
<td>Input Capacitance, $C_{in}$</td>
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<td>Bus Voltage, $V_{bus}$</td>
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<td>μH</td>
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<td>Dc-ac stage Inductance, $L_{buck}$</td>
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<td>μH</td>
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<td>Transformer Turns Ratio, $n$</td>
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### TABLE I MIV PROTOTYPE SPECIFICATIONS
cases, $I_{LIC}$ and $V_{pv}$ are well regulated to their respective reference values. The inverter dynamic response for an input power step is shown in Fig. 9.

### B. Smoothing Algorithm Performance Evaluation

<table>
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<th>Parameter</th>
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<td>Nominal MPPT PV Voltage, $V_{mpp}$</td>
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<td>Nominal MPPT PV Current, $I_{mpp}$</td>
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<td>Total Minimum LIC Voltage, $V_{LIC, min}$</td>
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<td>Total Maximum LIC Voltage, $V_{LIC, max}$</td>
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<td>Wh</td>
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<td># of Series-Connected LIC Modules</td>
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</table>

The measured power curve of the BIPV module is shown in Fig. 10(a). The test was run on November 16, 2013, for a rooftop installation at the University of Toronto. A relatively cloudy day was chosen to illustrate the power smoothing process. The activation of the PV module’s internal sub-string bypass diodes at the start of the day is clearly visible, leading to fast variations in power at sunrise. The power smoothing algorithm depicted in Fig. 5 was separately implemented on a PC running NI LabVIEW, allowing a flexible choice of filtering parameters, while all other controls are implemented locally in the micro-controller and FPGA. Two 4.4 Wh LICs are connected in series, resulting in a voltage range of $4.4 \text{ V} \leq V_{LIC} \leq 7.6 \text{ V}$. The specifications for the PV and LICs used in this experiment are listed in Table II. The net generated power, $s(\theta)$, is approximately $7 \times$ smoother than $P_{pv}$, as shown in Fig. 10(b). The LIC voltage swing throughout the cloudy day is shown in Fig. 10(c), which demonstrates the proper sizing of the storage module for the considered averaging period. The slow SOC regulation loop correctly steers the LIC voltage towards 6.2 V throughout the day. The level of smoothing can be optimized by tuning the filter parameters to utilize a wider range of the LIC’s capacity. There is clearly a trade-off between the amount of power smoothing and the energy yield of MIV, based on the LIC converter efficiency.

### VI. CONCLUSIONS

A new bi-directional MIV architecture and simple control scheme were developed for modular low-cost nanogrid applications. The MIV architecture introduces a new integrated short-term storage solution using LIC technology as opposed to a conventional central storage solution. Furthermore, a lag-free averaging scheme is introduced which decreases the real power variations by up to $7 \times$ on a typical cloudy day in Toronto by utilizing the short-term storage. This can potentially benefit the stability of the nanogrid and saves on fuel
costs as well as improving generator life-time and reducing maintenance costs. Stable MIV operation was achieved by incorporating a dual loop approach in the dc-dc stage. The DAB indirectly regulates the LIC’s current, while MPPT is implemented by the LIC dc-dc converter. The four-quadrant dc-ac stage operates in BCM current control which ensures a high efficiency of up to 96.3%, and can be programmed to provide reactive power. Further work is required to improve the light-load efficiency of the DAB. The trade-off between the degree of power smoothing and the nanogrid efficiency also needs to be further explored at the system level.

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