A Dual Active Bridge DC-DC Converter with Optimal DC-Link Voltage Scaling and Flyback Mode for Enhanced Low-Power Operation in Hybrid PV/Storage Systems

Shahab Poshtkouhi and Olivier Trescases
University of Toronto, 10 King’s College Road, Toronto, ON, M5S 3G4, Canada
E-mail: shahab.poshtkouhi@utoronto.ca

Abstract—Today’s PV micro-inverters (MIVs) provide a modular solution for generation, however the energy storage architectures remain centralized, requiring an additional bi-directional ac-dc converter, with complex cell balancing circuits. Distributing storage capacity within the smart PV panels allows power fluctuations to be locally buffered, while minimizing the need for additional power electronics and balancing circuits. The dual-active-bridge (DAB) topology, which is adopted in this paper, provides bi-directional power flow; however it generally suffers from poor efficiency at low power. It is shown that with a minor modification, the DAB can be operated as a two-transistor flyback converter for improved efficiency. In addition, the dc-link voltage can be dynamically adjusted for the best performance in DAB mode. The proposed control scheme is demonstrated on a 100 W prototype, with up to 8% increase in efficiency at low power.

Index Terms—Photovoltaic (PV) micro-inverters, efficiency, isolated dc-dc stage.

I. INTRODUCTION

The continuous decline of photovoltaic (PV) module prices, compounded with attractive feed-in tariffs in a variety of jurisdictions, is leading to the rapid deployment of PV installations throughout the world [1]. The intermittent nature of PV and other renewable energy resources, and thus the need for energy storage and/or load shedding, is a major challenge in small-scale PV based grids. This is despite the fact that power-quality and other grid strict requirements such as frequency variations are reduced compared to conventional grids. Low-power dc-dc micro-converters (MIC) [2], [3] and ac-dc micro-inverters (MIV) [4], [5] provide high-granularity Maximum Power Point Tracking (MPPT) [6], [7] 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 [7]. A conventional MIV based ac power system is shown in Fig. 1. The Energy Storage System (ESS), which is definitely required for islanded operation on the scale of one or more houses for example, is usually based on a high-power centralized bi-directional ac-de converter, which is interfaced to a battery bank or a flywheel [8], [9]. Existing MIV architectures satisfy the need for low capital-cost and expandable ac generation, while there is compelling argument to extend this technology to include small-scale distributed storage. A novel topology with distributed storage is proposed in [10] for grid stabilization, while saving fuel, and improving the generator lifetime. MIV Integrated storage helps to buffer the frequent irradiance fluctuations, while also providing local back-up power and reactive power support [11], [12]. A low-power single-stage multi-port converter for PV and battery is proposed in [13], while a 3-kW interconnection of a battery pack and a PV module through an isolated dc-dc converter is discussed in [14]. The general architecture of a two-stage MIV with an integrated ESS is shown in Fig. 2. While two-stage MIVs have a slightly lower efficiency than single-stage MIVs, the high-voltage dc link capacitance, $C_{bus}$, can be used for ac power decoupling in single-phase systems [15], [16].

Interfacing the low-voltage dc storage, either batteries or ultra-capacitors, directly to the PV bus is preferable for high efficiency [14]. Lithium-ion ultra-capacitors [17], which offer 2-4× higher specific energy than conventional Electric Double Layer Capacitors and can withstand more than 200000 charge/discharge cycles, are an attractive future candidate for short-term MIV integrated storage. The focus of this work is on the front-end dc-dc stage.

The objective of this paper is to 1) discuss a bi-directional isolated dc-dc stage for the PV-bus connection, which is al-

![Fig. 1. Conventional micro-inverter based PV system with central ESS.](image-url)
II. PROPOSED DAB ARCHITECTURE AND PRINCIPLE OF OPERATION

The proposed dc-dc architecture is shown in Fig. 3(a). This converter is a modified Dual-Active-Bridge (DAB) that interfaces \( V_{PV} \) with the dc link, \( V_{bus} \).

A. DAB Mode

The DAB topology was selected based on (1) galvanic isolation, (2) soft-switching operation and (3) simple phase-shift power control [19], [20]. In addition, the DAB topology is bi-directional, therefore the storage can be used to transfer energy to/from other elements in the grid. The average power from \( V_{PV} \) to \( V_{bus} \), \( P \), is

\[
P = \frac{V_{PV}V_{bus}}{n\omega_s L_{DAB}} \phi (1 - \frac{\phi}{\pi}),
\]

where \( n \) is the transformer’s turns ratio, \( L_{DAB} \) is the DAB inductance, which is the sum of transformer’s leakage inductance, \( L_{leak} \), and an optional external inductance, \( L_{ext}. \phi \) is the phase-shift between the two bridges, and \( \omega_s = 2\pi f_s \), where \( f_s \) is the switching frequency.

The switching waveforms of the DAB converter are shown in Fig. 4(a). The slopes of the DAB inductance current, \( I_{L_DAB} \), in switching states I and II are respectively calculated as

\[
s_1 = \frac{V_{PV} + V_{bus}}{nL_{DAB}} \tag{2}
\]

\[
s_2 = \frac{-V_{PV} + V_{bus}}{nL_{DAB}} \tag{3}
\]

In two-stage MIV architectures, \( V_{bus} \) is generally regulated to a fixed voltage by the inverter stage. The reference voltage, \( V_{bus}^* \), is usually chosen to optimize efficiency at the nominal operating point [7]. It can be shown that the DAB converter achieves turn-on Zero-Voltage-Switching (ZVS) and maximum efficiency when \( V_{bus} = nV_{PV} \), as the reactive circulating current is minimized [19].

![Fig. 2. Two-stage MIV architecture with integrated storage [10].](image)

![Fig. 3. a) Proposed modified DAB dc-dc architecture for improved low power efficiency. b) Switch configuration in Flyback mode.](image)
The DAB inductance circulates charge in every switching period in this mode. The charging slope of $I_{LDAB}$ is the same as $s_3$ and the discharging slope is

$$s_5 = -\frac{V_{PV}}{L_{DAB}} - \frac{V_{bus}}{n L_m}.$$

Finally, the output diode’s current, $I_D$, delivers charge to the bus with the following slopes in switching states II and III

$$s_6 = \frac{s_4 + s_5}{n},$$

$$s_7 = \frac{s_4}{n}. \tag{8}$$

The 2T-flyback topology exhibits several advantages over DAB mode for low power conditions, including less switching and gate-drive losses (two switching devices versus nine in the DAB mode). Unlike the more conventional single transistor flyback topology, the body diodes of $M_2$ and $M_3$ clamp the drain voltage on the switching devices $M_1$ and $M_4$, which reduces Electromagnetic Interference (EMI) and limits the blocking voltage rating on the primary switches to $V_{PV}$. The Flyback mode is operated with fixed on-time, $T_{on}$, in Pulse Frequency Modulation (PFM) mode [23], where $T_{on}$ is given by

$$T_{on} = D_1 T_s, \tag{9}$$

where $D_1$ is the duty cycle in Flyback mode, and $T_s$ is the switching period.

The corresponding waveforms of the converter are shown in Fig. 4(b). There are two inherent limitations to the 2T-flyback topology: 1) $D_1$ must be less than 50% in order to avoid transformer saturation, and 2) $V_{bus}$ must be less than $n V_{PV}$, to ensure that the body diode of $M_5$ transfers power to $V_{bus}$ when the primary-side switches are off. As a result, $V_{bus}$ needs to be reduced in Flyback mode. The presence of $L_{DAB}$ results in additional losses, since it circulates current in a switching period. The energy captured in $L_{DAB}$ is transferred back to the input capacitance, $C_{in}$, in the 2T-flyback topology, as opposed to a conventional flyback scheme, which does not provide a return path for the charge in the leakage inductance. In addition, $L_{DAB}$ results in the soft turn-on of the output diode.

The Flyback mode exhibits uni-directional power transfer. The converter can operate with reverse power flow by adding another switch on the primary side. This additional switch is not included in the experimental prototype, as the efficiency in DAB mode is sensitive to conduction losses at the low-voltage, high-current primary-side. While possible, reverse power capability is not strictly needed in low-power Flyback mode; the DAB can be prevented from operating in this condition by adopting burst-mode control instead, albeit at slightly lower efficiency than Flyback mode.

C. Dual Mode Control

The conceptual control diagram of the converter is shown in Fig. 5. $c_{1-8}$ denote the gating voltages for switches $M_{1-8}$. The DAB mode is adopted if $P$ is higher than a threshold value, $P_{\text{thresh}}$, or if $P$ is negative, in which case the storage is charged directly from the bus. In DAB mode, $\phi$ is controlled to regulate the power flow to/from the dc-ac stage, while the storage element’s State-of-Charge (SOC) and MPPT operation can be controlled by the dedicated interface converter.
In Flyback mode, \( T_s \) is adjusted by the controller, \( G_{e2}(s) \), in order to regulate \( P \) to \( P^* \). Assuming that the magnetizing inductance of the transformer, \( L_m \), is much larger than \( L_{DAB} \), the power flow is given by

\[
P = \frac{(V_{PV} D_s)^2 T_s}{2L_m}.
\]  

(10)

Thus, the conduction losses in this mode are approximated by

\[
\text{Flbk,cond} = \frac{1}{2} \left( 2R_{on, pri} + R_{L,DAB} \right) I_{FLBK, pri}^2 + 2.5R_{on, sec} I_{FLBK, sec}^2,
\]

where \( R_{on, pri} \) and \( R_{on, sec} \) are the primary and secondary side switches’ on-resistances respectively, and \( R_{L,DAB} \) is the lumped winding resistance of the transformer and inductor. The factor of \( 2.5 \times \) on the secondary side comes from the fact that, there are two back-to-back switches, \( M_f \), and \( M_r \) on one leg in the secondary side to support the flyback operation.

Neglecting the clamping diodes’ conduction interval, the RMS current for the two switches, \( I_{M1}, M_4 \), and in the output diode, \( D \), in the 2T-flyback converter can be obtained as [25]

\[
I_{M1, M4} = \frac{n V_{PV} \sqrt{D_1}}{V_{bus} (1 - D_1)},
\]

(16)

\[
I_D = \frac{D_2 T_s V_{bus} \sqrt{D_2}}{n^2 L_m}.
\]

(17)

where \( D_2 \) is approximated by the following

\[
D_2 = \frac{n V_{PV} D_s}{V_{bus}}.
\]

(18)

The total conduction loss in Flyback mode is

\[
P_{FLBK, cond} = \left( 2R_{on, pri} + R_{L,DAB} \right) I_{FLBK, pri}^2 + \frac{1}{2} V_F I_D + R_{on, sec} I_D^2,
\]

where \( V_F \) is the output diode’s forward voltage.

B. Switching Losses

The switches in DAB mode can be turned on realizing Zero Voltage Switching (ZVS) [24]. However the turn-off losses are not eliminated. The total switching losses in this mode can be approximated by

\[
P_{DAB, sw} = \frac{1}{2} f_s t_{off} (V_{PV}(i_{pri}(0) + i_{pri}(\phi)) + V_{bus}(i_{sec}(0) + i_{sec}(\phi)),
\]

(20)

where \( t_{off} \) is the turn-off time of the MOSFETs. Switches \( M_1 \) and \( M_2 \) exhibit hard switching at turn-off in Flyback mode. Thus, the corresponding switching loss in Flyback mode can be approximated as

\[
P_{FLBK, sw} = \frac{V_F^2 D_1 t_{off}}{2(L_{DAB} + L_m)}.
\]

(21)

The switch drive losses are not considered here; However, there are nine switches actively driven in DAB mode compared to only two switches actively switching in Flyback mode. Furthermore, \( f_s \) is much lower in Flyback mode then in DAB mode, which further reduces the switch drive losses.

C. Core Losses

Core losses are present in the high-frequency transformer in both DAB and Flyback modes and can be approximated using the Steinmetz equation [26]

\[
P_{core} = k f_s^\alpha B_{peak}^\beta,
\]

(22)

where \( B_{peak} \) is the peak flux density, and \( k, \alpha, \) and \( \beta \) are the Steinmetz parameters, which depend on the core, and are
usually found by curve fitting. Core losses constitute a low percentage of the total losses in DAB mode [24] due to high-frequency ac-ac operation. However, core losses are dominant in Flyback mode. This is due to high peaks in core voltage, and lower frequency operation, which increases $B_{\text{peak}}$ in the transformer.

This analysis neglects the skin effect in all conductors, which can be significant, especially in DAB mode due to high frequency operation.

D. Loss Comparison in Two Modes

The calculated loss breakdown for $P = 10$ W and $P = 40$ W is shown in Fig. 6. The conduction losses in all active and passive elements are lumped together. The switching losses also include the drive losses. In Flyback mode, the switching losses are reduced by at least 10×, mostly by eliminating the turn-off losses on the high voltage side, at a cost of marginally increase in conduction losses. The transformer and inductor core loss is slightly higher in Flyback mode, due to higher $B_{\text{peak}}$. The core losses in Flyback mode increase rapidly with the power due to higher $B_{\text{peak}}$ and $f_s$. This is not the case for the DAB converter, in which the core losses remain almost constant over the power range.

![Graphs showing power losses for different modes](image)

IV. EXPERIMENTAL RESULTS

A prototype of the system shown in Fig. 3(a) was fabricated on a custom Printed Circuit Board, with DAB power rating of 100 W. The specifications of the prototype are listed in Table I. The converters are digitally controlled using an on-

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power, $P_{\text{nom}}$</td>
<td>100</td>
<td>W</td>
</tr>
<tr>
<td>Dc-dc Stage Switching Frequency, $f_s$</td>
<td>195</td>
<td>kHz</td>
</tr>
<tr>
<td>DAB Mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flyback Mode</td>
<td>20-50</td>
<td>kHz</td>
</tr>
<tr>
<td>Fixed On-Time, $T_{\text{on}}$</td>
<td>8</td>
<td>$\mu$s</td>
</tr>
<tr>
<td>Input Capacitance, $C_{\text{in}}$</td>
<td>300</td>
<td>$\mu$F</td>
</tr>
<tr>
<td>Bus Capacitance, $C_{\text{bus}}$</td>
<td>100</td>
<td>$\mu$F</td>
</tr>
<tr>
<td>DAB Inductance, $L_{\text{DAB}}$</td>
<td>4.2</td>
<td>$\mu$H</td>
</tr>
<tr>
<td>Magnetizing Inductance, $L_m$</td>
<td>32</td>
<td>$\mu$H</td>
</tr>
<tr>
<td>Bus Voltage Range, $V_{\text{bus}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DAB mode</td>
<td>200-270</td>
<td>V</td>
</tr>
<tr>
<td>Flyback mode</td>
<td>170</td>
<td>V</td>
</tr>
<tr>
<td>Transformer Turns Ratio, $n$</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

![Steady-state waveforms of the converter](image)

Table I

MIV PROTOTYPE SPECIFICATIONS

Fig. 7. Steady-state waveforms of the converter in (a) DAB mode at $V_{PV} = 22$ V ($I_{LDAB}$:5 A/div), and (b) Flyback mode at $V_{PV} = 25$ V ($I_{LDAB}$:5 A/div).
A custom planar transformer was designed to reduce the weight and profile of the prototype. The steady-state waveforms in DAB and Flyback modes at $P = 70$ W, and $P = 15$ W, are shown in Fig. 7(a) and (b), respectively. $V_{bus}$ is adjusted to $nV_{PV}$ in DAB mode to achieve optimal efficiency, as it is illustrated by the flat portions in $I_{LDAB}$. The closed-loop dynamic response of Flyback mode for a step change in $P^*$, while the dedicated integrated storage converter is off, is shown in Fig. 8. $f_s$ is increased in Flyback mode by the controller to accommodate the higher input power.

![Figure 8](image_url)

**Fig. 8.** Step response of Flyback mode with the integrated storage interface off: $P$: 9.1 W → 19.5 W ($I_{in}$: 0.2 A/div, $I_{LDAB}$: 10 A/div).

The measured efficiency of the converter, $\eta$, in both modes is shown in Fig. 9. A peak efficiency of 94% is achieved in DAB mode, while Flyback mode has a superior efficiency up to $P = 40$ W. The power is limited in Flyback mode due to the maximum duty ratio of 50%. However, the design is such that the two efficiency curves intercept at a point close to the maximum transferrable power in Flyback mode. The converter operates at the edge of Discontinuous Conduction Mode (DCM) at the intercept point, such that the operation is switched to DAB mode at higher power.

![Figure 9](image_url)

**Fig. 9.** Measured efficiency, $\eta$, of the converter.

V. CONCLUSIONS

A novel DAB switching scheme was introduced for the dc-dc stage of module integrated power converters for PV applications. The modified flyback switching scheme exhibits 8% higher efficiency than DAB mode at 10 W, which comes at the cost of an additional switch. While Flyback mode exhibits more core losses and slightly more conduction losses compared to DAB mode, the switching losses are significantly reduced by eliminating most of the switching actions, and reducing the frequency.

ACKNOWLEDGEMENT

This work was supported by Solantro Semiconductor, the Ontario Centres of Excellence, the Natural Sciences and Engineering Research Council of Canada, the Canadian Foundation for Innovation and the Ontario Research Fund. The authors also thank Ray Orr, Ben Bacque, Mihai Varlan, and Chris Gerolami for discussions related to nanogrids and microinverters.

REFERENCES


