Analysis of Partial Power Processing Distributed MPPT for a PV Powered Electric Aircraft

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Abstract—Habitations in remote areas around the world lack basic infrastructure to achieve an efficient supply chain. Over 90% of roads are unpaved and fuel infrastructure is scarce. The Solarship, a hybrid between a bush plane and airship, was conceived to address this problem. It is a buoyant low-altitude aircraft with an electric power train and wing mounted photovoltaic array. Fully electric operation requires efficient lightweight power electronics to achieve a minimum range of 200 km carrying a 200 kg payload. A detailed system model is developed to explore the impact of wingspan, flight speed and drag coefficient on the flight range. A Partial Power Processing (PPP) converter based on the bidirectional Cuk topology is demonstrated for this application. Due to the PPP concept, the converter is rated for only 26% of 2.7 kW generated PV power. The rating is optimized based on the battery and photovoltaic array voltage ranges. The experimental prototype uses Silicon Carbide MOSFETS and achieves a system efficiency of up to 99.3% with an effective specific power of 5.23 kW/kg.

I. INTRODUCTION

Canada, Africa, Australasia, Brazil, and Northern Eurasia represent the world’s largest commodity regions and have combined remote areas of over 50 million square km, with over 90% unpaved roads and very limited fuel infrastructure. The world’s largest commodity economies have gaps in their ability to move cargo. To move goods from California to Toronto by truck costs less than 10 cents per ton/km, while moving goods from Bujumbura to the eastern Congo costs more than $10 per ton/km. Solarship is a buoyantly-assisted airplane made possible through a confluence of modern developments, as shown in Fig. 1. Advanced aerodynamics, synthetic textile laminates, smart power electronics, lightweight batteries, and high-efficiency photovoltaics are the enabling technologies for a practical solar aircraft.

The Solarship aims to address the economic and logistical barriers that prevent adequate supply delivery to remote regions around the globe by (1) reducing the cost of transport, (2) enabling movement in-and-out of areas where other transport methods are ineffective due to lack of fuel and runways, and (3) ensuring cold chain storage and distribution. The Solarship is a hybrid between a bush plane and an airship. The added buoyancy from the Helium filled wing increases the payload, while the heavier-than-air design eliminates the need for expensive anchors.

Fig. 1. (a) 11 Meter prototype during test flight. (b) Solarship for future design.

One of the greatest advantages compared to standard aircraft is the ability to land in a small area the size of a soccer field. The simplified Solarship electrical architecture is shown in Fig. 2. The architecture, which is similar to ground based Electric Vehicles (EVs) [1], consists of a central battery pack, two electric motors driven by inverters, and a set of dc-dc converters for performing Distributed Maximum Power Point Tracking (DMPPT) on the wing-mounted PV array.

Fig. 2. Solarship electrical system overview.
Optimizing the Solarship design is a multidisciplinary challenge, due to the strong influence of the wingspan on the lift capability, the available area for PV power harvesting and the required electrical systems. The minimum short-term requirement of the aircraft design is to achieve a 200 km electric range with a 200 kg payload for a 2014 field-trial in Canada.

A DMPPT Partial Power Processing (PPP) converter approach is considered for this weight-sensitive aerospace application. The objective of PPP is to reduce the power rating of the dc-dc converter, and thus reduce the mass of heatsinks and magnetic components. The objectives of this paper are to 1) report the results of system-level optimization of the Solarship for future designs, based on the stated range and payload objectives, 2) investigate the impact of PV voltage drift on the DMPPT PPP converter, and 3) demonstrate a lightweight PPP converter. The power rating of the PPP based dc-dc converter is highly sensitive to the system level design, which is not treated in the literature thus far.

II. PARTIAL POWER PROCESSING

The PPP concept is outlined in Fig. 3 for a single PV string, where $V_{PV}$ and $I_{PV}$ are the PV string voltage and current, respectively, $V_{BATT}$ is the battery bus voltage, $\eta_P$ is the converter efficiency, $I_P$ is the current at the battery port, and $\Delta V$ is the voltage at the secondary port of the PPP converter. Converters based on PPP have been previously proposed in [2] for PV systems in battery backup systems, and in [3] as a PV array regulator for spacecraft applications. An experimental PPP prototype with both buck and boost capabilities is presented in [4] for a fuel-cell application. While the PPP concept has been successfully demonstrated in the literature, the impact of voltage drift on $\Delta V$, and the system-level design considerations for PV applications have not been treated. The processed power of the dc-dc converter, $P_P$, is proportional to the difference between the battery and PV voltages,

$$P_P = \Delta V \cdot I_{PV},$$

which implies that for sufficiently low $\Delta V$, the processed power can be minimized compared to the full PV power.

A. Modes of Operation and System Efficiency

In order to minimize the power rating of the dc-dc converter in Fig. 3, the converter needs to operate both in buck and boost modes, since the battery voltage may be greater or less than the PV voltage. Buck mode operation is shown in Fig. 4. The arrow above the converter indicates the direction of power transfer. In this mode, $V_{PV}$ is given by,

$$V_{PV} = V_{BATT} - \Delta V,$$

where $V_{PV}$ is less than $V_{BATT}$.

Boost mode operation is shown in Fig. 5. In this case,

$$V_{PV} = V_{BATT} + \Delta V,$$

where $V_{PV}$ is greater than $V_{BATT}$. In boost mode, the direction of power transfer in the dc-dc converter is reversed. Note that in both modes, power is transferred

![Fig. 3. Partial power processing dc-dc converter connected between a PV string and a battery.](image)

![Fig. 4. Buck mode in the PPP converter, $V_{BATT} > V_{PV}$.](image)

![Fig. 5. Boost mode in the PPP converter, $V_{BATT} < V_{PV}$.](image)
efficiency, \( \eta_p \), in both modes \([2]\). For buck mode,

\[
\eta_{sys} = \frac{P_{BATT}}{P_{PV}} = \frac{V_{BATT}(I_{PV} - I_P)}{V_{PV}I_{PV}} \cdot \frac{1 - \frac{\Delta V}{V_{BATT}}}{1 - \frac{\Delta V}{V_{BATT}}}.
\]

(4)

For boost mode,

\[
\eta_{sys} = \frac{P_{BATT}}{P_{PV}} = \frac{V_{BATT}(I_{PV} + I_P)}{V_{PV}I_{PV}} \cdot \frac{1 + \eta_p \frac{\Delta V}{V_{BATT}}}{1 + \frac{\Delta V}{V_{BATT}}}.
\]

(5)

From (4) and (5), it is clear that for a small ratio of \( \Delta V/V_{BATT} \), when the PV and battery voltages are nearly identical, the system efficiency is not sensitive to the converter efficiency, \( \eta_p \), as shown in Fig. 6.

![Graph showing system efficiency using a PPP scheme in (a) buck mode and (b) boost mode.](image)

**B. Converter Topology**

The operation described in Section II-A is realized by a four quadrant isolated converter. Four quadrant operation is necessary since current must flow in both directions, and the converter must be capable of bipolar voltage output.

It is possible to realize the above requirements by starting with an isolated bidirectional converter, modified to achieve bipolar operation. The Dual Active Bridge (DAB) proposed in \([5]\) is suitable, however it has eight switches, while soft-switching is lost both at light-load and when operating over a wide voltage range \([5]\). The bidirectional LLC resonant converter \([6]\) is capable of achieving soft-switching under light-load conditions, however it also contains eight switches and achieving buck mode under a wide operating range is a challenge due to variable frequency operation. The isolated Čuk converter shown in Fig. 7 is capable of bidirectional operation, contains only two low-side switches, and operates at fixed frequency. At the same time it has three magnetic components and may require external snubbers. The Čuk converter is chosen in this work due to its reduced number of high-frequency switches and simpler magnetics design compared to the full-bridge design in \([4]\). The magnetic component size is reduced by operating at a high switching frequency, enabled by Silicon Carbide (SiC) MOSFETs. Continuous current in both inductors reduces the size of the input and output capacitors. Duty cycle control is used to achieve MPPT, while the conversion ratio, \( M = \Delta V/V_{BATT} \), is ideally independent of the load condition in Continuous Conduction Mode (CCM),

\[
M = \frac{n_2}{n_1} \frac{D}{1 - D}.
\]

(6)

![Isolated bidirectional Čuk converter.](image)

In order to achieve a bipolar output, an additional bridge is used at the secondary side, similar to the unfolder in single-stage PV microinverters \([7]\), as shown in Fig. 8. The unfolder can actively invert \( \Delta V \) in boost mode. The unfolder is realized by a bridge of four bidirectional blocking switches as shown in Fig. 9. Only two sets of switches are enabled in each mode: \((S_1, S_4)\) in buck mode, \((S_2, S_3)\) in boost mode. Given that \( \Delta V \) changes sign very slowly based on irradiance and battery voltage fluctuations, the low-frequency unfolder only contributes to conduction losses. It is therefore recommended to use low \( R_{on} \) and low \( V_f \) devices. Moreover, the bridge provides an additional safety disconnect feature for the PV array, which is why it is connected on the secondary side. The complete PPP topology is shown in Fig. 10.

The design procedure for the Čuk converter is well covered in the literature \([8]\) and not repeated here. If \( \Delta V \) is smaller than \( V_{BATT} \), the input current, voltage stress, and inductor voltage swings decrease in the converter. This allows the reduction or elimination of any required snubbers in the converter, use of smaller inductors, and higher FOM switches.
of cell temperature [10]. Two worst-case conditions for $P_P$ are defined assuming MPPT operation,

$$P_{P,1} = (V_{BATT,\text{max}} - V_{MPP,\text{min}}) I_{PV}$$  \hspace{1cm} (7)$$

$$P_{P,2} = (V_{MPP,\text{max}} - V_{BATT,\text{min}}) I_{PV},$$  \hspace{1cm} (8)

where $V_{BATT,\text{max}}$ and $V_{BATT,\text{min}}$ are the maximum and minimum battery voltage, respectively, $V_{MPP,\text{max}}$ is the maximum PV MPP voltage at the maximum irradiance and minimum temperature, $G_{\text{max}}$ and $T_{\text{min}}$, respectively, $V_{MPP,\text{min}}$ is the minimum PV MPP voltage at $G_{\text{max}}$ and $T_{\text{max}}$. $P_r$ is then given by

$$P_r = \max\{P_{P,1}, P_{P,2}\},$$  \hspace{1cm} (9)

and depends heavily on the PV environmental characteristics.

### III. Solarship System Model

A detailed parametrized system model was produced to predict the Solarship behavior for varying wingspan and flight speed, under time-varying irradiance and temperature conditions. This model accurately captures the performance of the electrical and mechanical subsystems, including losses.

#### A. Electrical Model

The electrical model consists of the PV array and battery, with the load power modeled according to the flight conditions. The PV array modeling is based on [11]. The power of the array is dictated by the available surface area on the solar ship wing. A time varying irradiance profile is fed into the model during the transient simulation. For a typical day, the profile is symmetrical around solar noon, assuming an optimal departure time. The profile is obtained using the method in [12], where the hourly irradiance is estimated from historical monthly averaged clear day data for the mean day of the particular month. Historical data was used, since this is an empirical value and captures environmental conditions in the geographical location of interest, which is Thunder Bay, Canada. The cell temperature, $T_e$, is modeled according to [13]:

$$T_e - T_a = R_{th} G,$$  \hspace{1cm} (10)

where $T_a$ is the ambient temperature, $R_{th}$ is a thermal coefficient and $G$ is the irradiance. The battery is modeled according to [9]. For each design iteration, battery specifications are determined based on the Specific Energy (SE) in kWh/kg, the allowable battery mass from the mechanical design, and the nominal battery voltage.

#### B. Mechanical Model

The wingspan and mechanical structure of the Solarship dictate the available PV area and battery mass. The solar panels are placed on the wing of the Solarship. The surface area available for solar panels, $A_{solar}$, changes as a square function of the wingspan, $W$,

$$A_{solar} \propto W^2.$$  \hspace{1cm} (11)
The lift, $L$, and battery mass, $M_{\text{Batt}}$, of the Solarship are related by
\[ M_{\text{Batt}} \propto L \propto W^3 \propto V_f^2. \quad (12) \]
The cubic function is a result of the increase in Helium volume available in the Solarship and the square function is a result of the drag that must be overcome by the electric motor. The load power, $P_{\text{Load}}$, is determined by the drag force, $F_D$, which is a function of the aircraft speed, $V_f$, drag coefficient, $C_d$, air density, $\rho$, and surface area of the Solarship, $A_s$:
\[ P_{\text{Load}} \propto F_D = \frac{1}{2} \rho C_d V_f^2 A_s. \quad (13) \]

IV. Simulation Results

The electrical and mechanical equations are incorporated within a MATLAB Simulink model. The short-term objective is to achieve a minimum flight range and payload of 200 km and 200 kg, respectively. The aircraft travels at a constant speed until one of two conditions is met: the target flight range is achieved, or the battery reaches its minimum voltage, in which case the simulation is halted.

A. System Design Analysis

A simulation study was carried out to analyze the relationship between $C_d$, $W$, $V_f$, and flight range achieved. The simulation was iterated for several values of $W$ and $V_f$ at a fixed $C_d$ and a transient simulation was performed for each point. The resulting range is plotted for every coordinate of $(W, V_f)$.

The results of this iteration are shown in Fig. 11 for drag coefficients $C_{d,1}, C_{d,2}$, where $C_{d,1} < C_{d,2}$. The mission objective of 200 km is achieved with increases in $W$ and $V_f$. This is because wing area and lift capability are increased, subsequently allowing more solar power and carrying capacity for batteries. The impact of the drag coefficient can also be seen from Fig. 11, where the minimum target range can be achieved for smaller $W$ at $C_{d,1}$.

B. PPP Converter Rating for Solarship Application

The power rating of the converter, $P_r$, is dependent on $\Delta V$. The goal is to determine the limits of $V_{\text{MPP}}$ at the expected temperature and irradiance conditions. The results of the limits for $V_{\text{MPP}}$ are listed in Table I. The battery voltage limits are $V_{\text{BATT},\text{max}} = 400$ V and $V_{\text{BATT},\text{min}} = 288$ V. Using (7) to (9), the power rating of the PPP converter is therefore determined:
\[ P_r = \max \{ P_{r,1}, P_{r,2} \} = 687.4 \text{ W}. \quad (16) \]

Knowing $P_r$, the percentage of power processed compared to a full power processing converter is:
\[ \frac{P_r}{P_{\text{MPP,max}}} = 0.26, \quad (17) \]

where (17) indicates that the PPP converter power is rated to 26% of the full input power from the PV string.

<table>
<thead>
<tr>
<th>$T_a$ (°C)</th>
<th>$R_{th}$ (K)</th>
<th>$V_{\text{MPP}}$ (V)</th>
<th>$I_{\text{MPP}}$ (A)</th>
<th>$P_{\text{MPP}}$ (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0</td>
<td>370</td>
<td>7.16</td>
<td>2.64</td>
</tr>
<tr>
<td>35</td>
<td>0.03</td>
<td>301</td>
<td>6.94</td>
<td>2.09</td>
</tr>
</tbody>
</table>

V. Experimental Results

A prototype was built to demonstrate the PPP converter, as shown in Fig. 12. The prototype specifications are listed in Table II. The converter weighs 516 g and contains no electrolytic capacitors for high reliability. The Čuk converter is controlled using an on-board microcontroller. Silicon Carbide MOSFETS rated for 1.2 kV are used for $Q_1$ and $Q_2$, eliminating the need for external snubbers.
### TABLE II. PPP CONVERTER PROTOTYPE SPECIFICATIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Battery Voltage, ( V_{BATT,\text{max}} )</td>
<td>400</td>
<td>V</td>
</tr>
<tr>
<td>Minimum Battery Voltage, ( V_{BATT,\text{min}} )</td>
<td>288</td>
<td>V</td>
</tr>
<tr>
<td>Maximum PPP output voltage ( \Delta V_{\text{max}} )</td>
<td>120</td>
<td>V</td>
</tr>
<tr>
<td>Minimum PPP output voltage ( \Delta V_{\text{min}} )</td>
<td>20</td>
<td>V</td>
</tr>
<tr>
<td>Switching Frequency, ( f_s )</td>
<td>200</td>
<td>kHz</td>
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<td>Turns ratio, ( n_1/n_2 )</td>
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<tr>
<td>Primary-side Inductance, ( L_{pri} )</td>
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<td>( \mu )H</td>
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<tr>
<td>Secondary-side Inductance, ( L_{sec} )</td>
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<td>( \mu )H</td>
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<tr>
<td>Primary-referred Magnetizing Inductance, ( L_m )</td>
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<td>mH</td>
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<tr>
<td>Leakage Inductance, ( L_L )</td>
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<td>( \mu )H</td>
</tr>
<tr>
<td>Input Capacitance, ( C_{IN} )</td>
<td>4.4</td>
<td>( \mu )F</td>
</tr>
<tr>
<td>Output Capacitance, ( C_{OUT} )</td>
<td>6.6</td>
<td>( \mu )F</td>
</tr>
<tr>
<td>Primary-side Capacitance, ( C_{pri} )</td>
<td>4.4</td>
<td>( \mu )F</td>
</tr>
<tr>
<td>Secondary-side Capacitance, ( C_{sec} )</td>
<td>6.6</td>
<td>( \mu )F</td>
</tr>
</tbody>
</table>

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The converter operates in the forward and reverse direction for buck and boost modes, respectively. The measured system efficiency for buck and boost modes is shown in Fig. 13 and Fig. 14, respectively. The efficiency drops for increasing \( \Delta V \) due to the higher processed power. The light-load efficiency could be further improved by operating the Cuk converter in burst-mode below \( P_{PV} = 400 \) W. The system efficiency is 98.8% in buck mode for a maximum power of \( P_{PV} = 2.7 \) kW and minimum \( \Delta V = 30 \) V. This corresponds to a processed power of \( P_P = 250 \) W. The efficiency in the reverse direction for \( \Delta V = 82 \) V is 97.6% at \( P_{PV} = 2.7 \) kW. This corresponds to a processed power of \( P_P = 602 \) W.

The steady-state waveforms of the converter are shown in Fig. 15, where the output voltage, \( \Delta V \), the secondary side capacitor current, \( i_{C,sec} \), and the primary switching node, \( V_{DS,pri} \), are shown at input power \( P_{PV} = 2.7 \) kW and a typical value of \( \Delta V = 30 \) V. The overshoot on the primary side MOSFET drain is within its 1.2 kV rating, and snubbers are not required.

A thermal image of the converter is shown in Fig. 16 for \( \Delta V = 30 \) V, \( P_{PV} = 2.7 \) kW, and output current \( I_{L,sec} = 7.33 \) A. The image shows that the warmest components are the diodes in the unfolder bridge, while the transformer core temperature is below 60 °C.
VI. CONCLUSION

The partial power processing converter concept can achieve a high power density for a string-level PV converter in this mass sensitive aerospace application. The system-level model for the Solarship is useful to optimize the battery and PV systems, while minimizing the processed power for the DMPPT dc-dc converters. The experimental prototype demonstrates that the isolated bidirectional Cuk converter with an added output bridge is a promising candidate for this PPP application. The string-level power converter achieves an effective specific power of 5.23 kW/kg and maintains an efficiency above 95% for a broad range of conditions. Further work is required to optimize the dynamic transition between buck and boost modes.

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