An Electrolytic-Free Offline LED Driver with a Ceramic-Capacitor-Based Compact Stacked Switched Capacitor (SSC) Energy Buffer
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Abstract—This demonstration shows a ceramic capacitor based stacked switched capacitor (SSC) energy buffer that replaces the limited life electrolytic capacitors used for twice line frequency in an offline LED driver. Two LED drivers are displayed: one with electrolytic capacitors, and the other with the SSC energy buffer. It is demonstrated that both systems have similar performance even though the SSC energy buffer has less than half the passive volume of the electrolytic capacitors.

I. INTRODUCTION
Single-phase ac–dc converters with high power factor require energy storage to buffer the difference in instantaneous power between their ac and dc ports. Typically, electrolytic capacitors are used to buffer this twice-line-frequency energy owing to their relatively high energy density and low cost. However, the short lifetime and temperature constraints of electrolytic capacitors are a concern [1], especially in applications where long lifetime is required, e.g. LED drivers and solar micro-inverters [2]. Film and ceramic capacitors have much longer lifetime, but lower energy density. To compensate for their lower energy density, film and ceramic capacitors can be charged and discharged over a wider voltage range than is practical with electrolytic capacitors at relatively high frequencies, provided a mechanism is available to maintain the dc bus voltage within a required narrow range. A number of strategies to increase the energy utilization of capacitors have been proposed, including the use of an additional bidirectional dc–dc converter [3], [4], energy buffer incorporated into the power stage [5], [6], and switched capacitor energy buffers [7]–[12]. The Stacked Switched Capacitor (SSC) energy buffer architecture has the least complexity amongst the switched capacitor approaches and also partially overcomes the efficiency and flexibility limitations associated with the other techniques [9]–[12].

A number of different SSC energy buffer topologies have been introduced, including unipolar and bipolar versions. Each of these versions has enhanced variants, which improve the performance of these designs; in case of unipolar designs by adding an extra switch and in bipolar designs, by modification of the control scheme [11]. In addition, capacitance ratios can be optimized to further increase the effective energy density of the SSC energy buffer [12]. In this demonstration, two 8-W, 21-V output offline LED drivers will be displayed while powering identical LEDs; one LED driver will use its original electrolytic capacitors, while the other will use an SSC energy buffer. The SSC energy buffer has a 5% output voltage ripple and achieves a round-trip efficiency of above 98%. It will be demonstrated that the performance of both systems is similar, i.e., they both have same output voltage ripple and there is no light flicker even with the SSC buffer, although the SSC energy buffer has far less passive volume than the electrolytic capacitors it replaces.

II. OPERATING PRINCIPLE
An SSC energy buffer comprises two series-connected blocks (referred to as backbone and supporting blocks) of switches and capacitors, as shown in Fig. 1 [9]. It works on the principle that while the voltage across each block, and each individual capacitor, is allowed to vary across a wide range, the variations in voltages across the two blocks compensate for each other, resulting in a narrow range dc bus voltage. In the unipolar design, the supporting block capacitors can only connect in series with the backbone block capacitor. However, in the bipolar design the supporting block capacitors can switch between a series and an anti-series connection with the backbone block capacitor(s). This demonstration focuses on the enhanced unipolar SSC energy buffer. Figure 2 shows the topology of the demonstrated system. It has a flyback converter as the ac/dc converter and a 1-2 enhanced unipolar SSC energy buffer for twice line frequency buffering. This SSC energy buffer has one backbone capacitor (C1), two supporting capacitors (C21 and C22) and three supporting switches (S20, S21 and S22). In the conventional design, all capacitors have equal capacitance and different voltage ratings. However this demonstration presents an optimized 1-2 enhanced SSC energy buffer that maximizes the effective energy density by optimizing the

Figure 1: Stacked Switched Capacitor (SSC) energy buffer architecture.
Figure 2: Demonstrated system.
capacitance ratios. The capacitors are precharged to appropriate voltage levels through a specific precharge switching sequence before the buffer starts normal operation. These initial voltage levels help maintain a narrow range dc bus voltage during normal charge/discharge operation of the buffer. Figure 3 shows the dc bus and individual capacitor voltages during normal operation of a 1-2 enhanced unipolar SSC energy buffer with capacitors of equal capacitance. These waveforms assume that the SSC energy buffer is charged and discharged with constant current. During normal operation the switches turn on and off in sequence, as shown in Fig. 3. S20 is on (and all the other switches are off) when the energy buffer starts to discharge from its fully charged state. When the dc bus voltage reaches its minimum allowed value, S20 is turned off and S21 is turned on so that the voltage across C21 adds to the voltage across C11 and elevates the dc bus voltage back to its maximum allowed value. Now C11 and C21 are discharged in series until the minimum bus voltage threshold is again reached, and the next switch transition takes place. This process continues until all the capacitors have been utilized. After this the charging process must begin, which is simply the reverse of the discharging process.

III. PROTOTYPE DESIGN

A prototype ceramic-capacitor-based 1-2 enhanced unipolar SSC energy buffer for an offline LED driver is designed, built and will be demonstrated. An LM3444 120-Vac 8-W LED driver evaluation board is used as the platform for the prototype. It has a flyback converter and uses two 330-μF/35-V electrolytic capacitors for twice-line-frequency buffering. These capacitors are replaced by the SSC energy buffer in the prototype. Figure 4 shows the schematic of the prototype including the flyback converter. With the electrolytic capacitors, the nominal output voltage of the LED driver is 21 V with 2 V peak-to-peak voltage ripple (Rm = 5%) when the output power is 8 W. Table I lists the required capacitance values and voltage ratings for the capacitors C11, C21 and C22 of the SSC energy buffer using optimized capacitance ratios (assuming linear capacitances) and the actually selected values. Note that the voltage dependent capacitance of Type II ceramic capacitors requires the capacitance to be oversized. The maximum drain-to-source voltage across S21, S22 and S20 are 3.9 V, 2.1 V and 3.9 V, respectively. S21 needs to block bidirectional voltage, thus is implemented with two back-to-back connected MOSFETs (S21a and S21b). All switches need to carry bidirectional current. In the prototype, all switches are implemented using 30-V/5-A MOSFETs. The four switches are driven by two TC4427 two-channel gate drivers. Since the voltage V5 in Fig. 4 never exceeds 4 V, floating gate drivers are not needed for S22 and S21a.

The flyback converter is controlled by a LM3444 controller, and the SSC energy buffer is controlled by a MSP430 microcontroller. The microcontroller senses the dc bus voltage through a resistive voltage divider and produces the four required gate signals. Figure 5 shows a photograph of the SSC energy buffer next to the electrolytic capacitor it replaces. The total volume of the two electrolytic capacitors is 2010 mm³, while the total volume of the ceramic capacitors in the SSC energy buffer is 650 mm³. Even with all the other circuit elements included, the displaced volume of the SSC energy buffer is no greater than the volume of the electrolytic capacitors; and this volume could be further reduced through the integration of the control circuitry.

![Waveforms of 1-2 enhanced unipolar SSC energy buffer under normal operation.](image)

![Switch, gate-drive and control implementation of the prototype SSC energy buffer as part of an offline LED driver.](image)

![Photograph comparing the size of the SSC energy buffer to that of the electrolytic capacitors it replaces.](image)

<table>
<thead>
<tr>
<th>Capacitor</th>
<th>Required Linear Capacitance (μF)</th>
<th>Selected Ceramic Capacitance (μF)</th>
<th>Required Voltage Rating (V)</th>
<th>Selected Voltage Rating (V)</th>
<th>Volume (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C11</td>
<td>186</td>
<td>560</td>
<td>23</td>
<td>35</td>
<td>516</td>
</tr>
<tr>
<td>C21</td>
<td>952</td>
<td>1452</td>
<td>2.1</td>
<td>4</td>
<td>68</td>
</tr>
<tr>
<td>C22</td>
<td>558</td>
<td>1269</td>
<td>3.9</td>
<td>6.3</td>
<td>65</td>
</tr>
</tbody>
</table>
IV. EXPERIMENTAL RESULTS

Figure 6 shows the output voltage waveforms of the LED driver with the electrolytic capacitor and the LED driver with the prototyped ceramic-capacitor-based SSC energy buffer. As can be seen the output dc bus voltage ($V_{bus}$) is maintained within the required ±5% ripple range (±1V) in both cases. For the SSC energy buffer based LED driver, the supporting block voltage ($V_s$) is also shown in Fig. 6(b). Its variations tend to cancel the variations in the voltage across the backbone capacitor $C_{11}$, resulting in the small ripple on the dc bus. The round-trip efficiency of the prototype SSC energy buffer was measured to be 98.2%. A high efficiency is achieved as the switches in the SSC energy buffer switch at low multiples of the line frequency, resulting in low switching losses.

V. CONCLUSIONS

This demonstration shows a stacked switched capacitor (SSC) energy buffer that replaces the limited life electrolytic capacitors used for twice line frequency energy buffering in an LED driver. The SSC energy buffer maintains the same output voltage ripple as the electrolytic capacitors, but has less than half the passive volume compared to the electrolytic capacitors.

REFERENCES


