Abstract—A new active soft switching circuit for Zero Voltage Switched Pulse Width Modulated (ZVS-PWM) full bridge converter is presented in this paper. The proposed circuit has two auxiliary circuit cells (Auxiliary circuit cell-1, Auxiliary circuit cell-2), one for each ground referred active switch. Auxiliary circuit cell consists of an active switch, a diode, a resonant inductor and a capacitor, and a coupled winding derived from main power transformer. Auxiliary circuit when gated properly creates zero voltage across the main switch during its turn-on. Winding coupled to the power transformer helps in resetting auxiliary inductor current to zero and hence turn-off of auxiliary switch is lossless. Steady state operation of proposed circuit with necessary analytical expressions is presented. Circuit simulation results of the proposed active soft switched ZVS-PWM full bridge converter are presented.

Index Terms—Zero voltage switching, active soft switching, ZVS PWM full bridge.

I. INTRODUCTION

The constant demand in Power Processing Systems (PPS) for applications like water pumps, air conditioner fed from Photo Voltaic (PV) systems (as shown in Fig. 1) is towards higher efficiency and power density with low EMI. PPS for example in applications like air conditioners has to convert 48 VDC input from PV to 230 VAC. This paper focuses on the front end DC-DC converter required to meet such load demands.

Full bridge DC-DC converters are conventional choice for medium and high power applications. Isolation transformer provides high voltage gains apart from providing isolation. Switching at high frequency provides better power densities but overall system efficiency reduces because of increased switching losses. Soft switched full bridge converters such as ZVS-PWM full bridge converters addresses this issue [1]-[5]. Salient features of the circuits proposed in these papers are wide range of ZVS, complexity in implementation; higher conduction losses during freewheeling intervals, some of the auxiliary switches are not soft switched. A new active soft switching circuit for non-isolated and isolated converters is proposed in [6]-[9]. The novelty of these circuits lies in achieving soft switching for both main, auxiliary switches and gating to auxiliary switches are ground referred.

Proposed active soft switched ZVS PWM full bridge converter has two identical auxiliary cells connected to conventional full bridge as shown in Fig. 2. S1 to S4 are main switches and D1 to D4 are output rectifier diodes of the converter. C1 to C4 are capacitors and D4r1 to D4r4 are anti parallel diodes across the main switches S1 to S4 respectively. Auxiliary cell-1 consists of an active switch S4a, a diode D4a, resonant inductor L4r, resonant capacitor C4a, a winding (L4T) coupled to the primary of power transformer. Auxiliary cell-1 when operated properly achieves ZVS to main switch S4. Gating sequence to main (S1 to S4) and auxiliary switches (S2r, S4r) are as shown in Fig. 3. Auxiliary switch S4r should be gated immediately when main switch S4 is turned off and before S2 is gated. Auxiliary switch S2r is also gated in the similar way as that of S2r. Turns ratio between primary and secondary of power transformer is n. Turns ratio between primary and coupled windings (L2T, L4T) is kT.

II. STEADY STATE ANALYSIS

Steady state analysis of the proposed active soft switched ZVS PWM full bridge converter is presented in this section. To reduce the complexity of analysis, following assumptions are made.

• All the devices are assumed ideal (no Rdson for switches, no forward voltage drop for diodes).
• Output filter inductor is large enough to treat it as a constant current source.
• Parasitics of transformer such as inter winding capacitance, leakage inductance are neglected.
Interval 1 ($I_1$) ($t_0 < t < t_1$): This is a power transfer interval and circuit conditions during this interval are as shown in Fig. 4. Devices $S_1$, $S_2$, $D_1$, and $D_2$ are in conduction during this interval.

This interval ends when gating to the main switch $S_2$ is turned off.

Interval 2 ($I_2$): ($t_1 < t < t_2$) Next switch to turn-on is $S_3$, by the end of this transition interval capacitor $C_3$ across $S_3$ has to discharge completely and body diode $D_{B3}$ should be in conduction. Gating $S_3$ while body diode $D_{B3}$ in conduction ensures ZVS for main switch $S_3$. Circuit conditions during this interval are as shown in Fig. 5.

This interval ends when $S_1$ is turned off.

Interval 3 ($I_3$) ($t_2 < t < t_3$): This is a freewheeling interval. Circuit conditions during this interval are as shown in the Fig. 6. All rectifier diodes in the secondary $D_1$-$D_4$ are in conduction sharing full load current equally.

This interval ends when resonant inductor current reaches reflected load current.

Interval 4 ($I_4$) ($t_3 < t < t_4$): This interval starts when auxiliary switch $S_4a$ is gated immediately when $S_1$ is turned off. Resonant inductor current raises linearly during this interval until it reaches reflected load current in the primary. All the rectifier diodes ($D_1$-$D_4$) are in conduction during this interval. Equations governing this interval are as follows.

$$i'_{D4}(t) = \frac{V_{dc}}{L_{4r}}(t-t_3)$$

$$i'(t) = n(i_{D1}(t) - i_{D3}(t))$$

This interval ends when resonant inductor current reaches reflected load current.

Interval 5 ($I_5$) ($t_4 < t < t_5$): Resonant inductor ($L_{4r}$) resonates with resonant capacitor ($C_{4r}$) during this interval. Voltage across the main switch $S_4$ decreases from $V_{dc}$ to zero.
during resonance. Circuit conditions during this interval are as shown in Fig. 8. Equations governing this interval are as follows. By the end of this interval, body diode of main switch $S_4$ will be in conduction. Gating $S_4$ while $D_{B4}$ in conduction ensures ZVS during turn-on.

This interval ends when main switch $S_4$ is turned off. **Interval 8 (I_8):** Next switch to conduct is $S_1$, hence capacitor $C_1$ has to discharge completely and anti parallel diode $D_{B1}$ should conduct to ensure ZVS turn-on for $S_1$. Circuit conditions during this interval are shown in Fig. 11.

**Interval 9 (I_9):** This is a freewheeling interval. Main switch $S_1$ and anti parallel diode $D_{B1}$ are in conduction during this interval. All the rectifier diodes $D_1-D_4$ are in conduction since voltage applied across the primary of transformer is zero during this interval.

Circuit conditions during I_9 are as shown in Fig. 12. This interval ends when gating to active switch $S_3$ is removed.

**Interval 10 (I_10):** Auxiliary switch $S_{2a}$ is gated immediately when $S_3$ is turned off as shown in Fig. 3. The circuit condition during this interval is as shown in Fig. 13. Current through resonant inductor ($L_{2r}$) raises linearly. All the rectifier diodes $D_1-D_4$ continue to conduct during this interval.

This interval ends when resonant inductor current reaches reflected load current. **Interval 11 (I_11):** Resonant inductor $L_{22}$ and resonant capacitor $C_2$ resonates during this interval. Output rectifier diodes $D_3$ and $D_4$ gets reverse biased and $D_1$ and $D_2$ conducts full load current. By the end of this interval, capacitor $C_2$ across the main switch $S_2$ discharges completely and body diode $D_{B2}$ starts conducting. Gating $S_2$, while $D_{B2}$ in conduction ensures ZVS during turn-on. Circuit conditions during this interval are depicted in Fig. 14.
Interval 12 (I_{12}): The circuit condition during this interval is as shown in Fig. 15. The resonant capacitor voltage is clamped to $-V_{dc}/k_1$ since $D_{B2}$ is in conduction during this interval. This resets resonant inductor current linearly to zero. Turning off $S_{2a}$ when resonant inductor current is zero ensures ZCS during its turn-off.

Next interval is positive power transfer interval i.e., $I_1$. Equations governing interval 1 to interval 6 also holds good for interval 7 to interval 12.

Modes of operation along with interval description are shown in Table I. Theoretical waveforms for proposed converter is shown in Fig. 16 & Fig. 17. Auxiliary circuit intervals i.e., linear charging interval ($t_3 < t < t_4$), Resonant interval ($t_4 < t < t_5$) and resetting interval ($t_5 < t < t_6$) are indicated in Fig. 17. As mentioned earlier, voltage across the coupled winding helps in resetting the resonant inductor current to zero. Turning off the auxiliary switch after resetting the resonant inductor current reduces the switching losses in the auxiliary switches as shown.

### Table I: Modes of Operation of Proposed Active Soft Switched ZVT PWM Full Bridge DC-DC Converter

<table>
<thead>
<tr>
<th>Interval</th>
<th>Description</th>
<th>Devices in conduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_1$</td>
<td>Positive Power Transfer</td>
<td>$S_1$, $S_2$, $D_1$, $D_2$</td>
</tr>
<tr>
<td>$I_2$</td>
<td>Transition from positive power to freewheeling</td>
<td>$S_1$, $C_2$, $C_3$, $D_1$, $D_2$</td>
</tr>
<tr>
<td>$I_3$</td>
<td>Freewheeling</td>
<td>$S_1$, $D_{B3}$, $D_3$, $D_2$, $D_3$, $D_4$</td>
</tr>
<tr>
<td>$I_4$</td>
<td>Auxiliary cell-1 interval 1</td>
<td>$S_{A1}$, $S_3$, $D_1$, $D_2$, $D_3$, $D_4$</td>
</tr>
<tr>
<td>$I_5$</td>
<td>Auxiliary cell-1 interval 2</td>
<td>$S_{A3}$, $S_3$, $D_3$, $D_4$</td>
</tr>
<tr>
<td>$I_6$</td>
<td>Auxiliary cell-1 interval 3</td>
<td>$S_{A4}$, $S_3$, $D_{B4}$, $D_3$, $D_4$</td>
</tr>
<tr>
<td>$I_7$</td>
<td>Negative Power Transfer</td>
<td>$S_4$, $S_3$, $D_3$, $D_4$</td>
</tr>
<tr>
<td>$I_8$</td>
<td>Transition from negative power to freewheeling</td>
<td>$S_4$, $C_1$, $C_4$, $D_2$, $D_4$</td>
</tr>
<tr>
<td>$I_9$</td>
<td>Freewheeling</td>
<td>$S_4$, $D_{B1}$, $D_1$, $D_2$, $D_3$, $D_4$</td>
</tr>
<tr>
<td>$I_{10}$</td>
<td>Auxiliary cell-2 interval 1</td>
<td>$S_1$, $S_{B2}$, $D_1$, $D_2$, $D_3$, $D_4$</td>
</tr>
<tr>
<td>$I_{11}$</td>
<td>Auxiliary cell-2 interval 2</td>
<td>$S_1$, $S_{B2}$, $D_1$, $D_2$</td>
</tr>
<tr>
<td>$I_{12}$</td>
<td>Auxiliary cell-2 interval 3</td>
<td>$S_1$, $S_{B2}$, $D_{B2}$, $D_1$, $D_2$</td>
</tr>
</tbody>
</table>

III. RESULTS AND DISCUSSIONS

Circuit simulations results of proposed active soft switched ZVS-PWM full bridge DC-DC converter is presented in this section. Gating to the main switches are
shown in Fig. 18. It can be seen from the figure that gating to the ground referred switches $S_2$, $S_4$ are PWM controlled. Main switches $S_1$, $S_3$ are gated complementary with proper dead time between switches of same legs i.e., between $S_1$ and $S_2$ or $S_3$ and $S_4$. Gating to auxiliary switch $S_{4a}$ of auxiliary cell-1 and main switches $S_1$, $S_4$ are shown in Fig. 19. It can be seen from this figure that auxiliary switch $S_{4a}$ is gated immediately after $S_1$ is turned off and before $S_4$ is turned on.

Gating to auxiliary switch $S_{4a}$, current through auxiliary inductor $I_{4a}$, gating to main switch $S_4$ and drain to source voltage of main switch $S_4$ are shown in Fig. 20. Similarly gating to auxiliary switch $S_{2a}$, current through auxiliary inductor $I_{2a}$, gating to main switch $S_2$ and drain to source voltage of main switch $S_2$ is shown in Fig. 21. Voltage of main switch $S_2$ is shown in Fig. 21. The following inferences are drawn from these figures.

- Drain to source voltage of main switches $S_2$ and $S_4$ is zero during their turn-on because of auxiliary cell-1 and auxiliary cell-2. Hence main switches are turn-on with ZVS.
- Auxiliary switch current which is same as auxiliary inductor current is made zero before its turn-off. This ensures ZCS turn-off for auxiliary switches.
- Auxiliary switches conduct for smaller duration of time (apx 7-10%) of total switching period. Hence conduction losses due to additional circuit will be less.

Fig. 18. (from top) Gating to main switches $S_1$-$S_4$.

Fig. 19. (from top) Gating to main switches $S_1$, Gating to auxiliary switch $S_{4a}$, Gating to main switch $S_4$.

Fig. 20. (from top) Gating to auxiliary switches $S_{4a}$, Resonant inductor current $I_{4a}$, Gating to main switch $S_4$, Drain to source voltage of $S_4$.

Fig. 21. (from top) Gating to auxiliary switches $S_{2a}$, Resonant inductor current $I_{2a}$, Gating to main switch $S_2$, Drain to source voltage of $S_2$.

Gating and drain to source voltage of main switches $S_1$ and $S_3$ are shown in Fig. 22 and Fig. 23 respectively. It can be seen from these figures that drain to source voltage has come down to zero before gating to main switches are given. It can be concluded that additional auxiliary cells did not disturbed the ZVS mechanism for main switches $S_1$ and $S_3$.

IV. CONCLUSION

A new active soft switched ZVS-PWM full bridge DC-DC converter is proposed in this paper. The proposed auxiliary circuit achieves zero voltage during turn-on for main switches without affecting the zero voltage turn-on conditions for other switches. Proposed auxiliary circuit operates for small duration of time (10% of $T_s$) and hence additional conduction losses would be less. Current through the auxiliary switch is made zero during turn-off which reduces the turn-off losses in the auxiliary switches.
REFERENCES


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