The Advantages and Operation of Flying-Capacitor Boosters

Viktor Antoni, Development Engineer - Electronic Design, Vincotech, Hungary

1 Introduction

High-efficiency solar inverters are getting more and more in demand in the recent years. However, cost efficient solutions are also desirable. To achieve this, not only the inverter but also the booster stage have to be low cost and high efficient. Two- and three- level boosters are commonly used in solar inverters. The three-level solutions are able to decrease the voltage stress on the semiconductors and the output voltage ripple, and therefore the inductor size can be decreased. Due to three-level operation, switched voltage level is half of the DC-link voltage. Thus, one can use semiconductors with lower blocking voltage, which are faster and cheaper. For three-level operation an adequate DC-link capacitor (capacitive voltage divider) has to be utilized, which can then split the two-level DC voltage into three voltage levels. In this case the PWM signal needs to be corrected to ensure the symmetry of the neutral point of the divider. Usually two inductors are used in the input in three-level boosters. This article describes the Flying Capacitor Booster solution, which increases the efficiency while being still cost efficient without enormous three-level DC-link capacitors and with only one choke on the input.

2 The Flying-Capacitor Booster

In this topology the additional voltage levels are synthetized by a capacitor, so-called flying-capacitor.

In a three-level case the voltage of the flying-capacitor is the half of the output voltage. The capacitor can offset the output voltage with $\frac{V_{dc}}{2}$ in positive and negative direction. The three-level flying-capacitor booster can be seen on Figure 1.
In the flying-capacitor booster due to the phase shift in the control of transistors, the input frequency is \( p \) times the switching frequency (\( p \) is the number of stages described later).

### 3 The Commutation Loops and Operation Modes of the Flying-Capacitor Booster

In a flying-capacitor booster the commutation loops include capacitors. A capacitor from the commutation point of view can be considered as zero impedance. Its main role in the commutation loop is to offset the two outer semiconductors from each other. With this offset the three-level flying-capacitor booster can be considered as two standalone boosters, in which the outer one’s commutation loop includes the DC-link capacitor, the outer diode, the flying-capacitor and the outer switch. The inner commutation loop includes the flying-capacitor, the inner diode and the inner switch. The two commutation loops can be seen on Figure 2.
In general the number of voltage levels are theoretically endless, but in practice three, four and five levels are used. The additional levels in $n$ level solution can be realized by adding extra outer commutation loops to the three-level converter. Every added booster’s commutation loop will be similar to the blue loop on Figure 2. The number of voltage levels can be calculated as the following:

$$n_{\text{level}} = p + 1$$

where $p$ is number of the commutation loops (boosters). The voltage of the capacitor can be calculated:

$$V_{\text{FC,}i} = V_{\text{DC}} \cdot \left(1 - \frac{i - 1}{p}\right)$$

where $i$ is number of the given commutation cells. The first loop refers always the most outer loop.

This article describes the operation and behavior of the three-level flying-capacitor booster. All other solutions can be realized based on this article.

In the operation of the three-level flying-capacitor booster, four different modes can be derived. During normal operation the voltage of the flying-capacitor is the half of the output voltage and the inductor current is perpetual. In the first mode both two switches are off, the current goes through the two diodes, and they are working in bypass mode. In this mode the
voltage of the flying-capacitor is not changing, the current of the choke is decreasing, and the output voltage is increasing. In the second mode, the lower switch (T27) is turned on. The current is charging the flying-capacitor resulting in its voltage to increase. In the third mode the inner switch is turned on (the outer switch is turned off), the current goes through the flying-capacitor, while its voltage is decreasing, and the output voltage will increase. In the last mode, both two switches are turned on. The voltage of the flying-capacitor will be stationary, while the current of the choke will be increasing. In the second and the third mode the inductor current change is dependent on the duty cycle (D). The operations and their effects can be seen on Figure 3 and Table 1.

Figure 3: Operation modes of a flying-capacitor booster
<table>
<thead>
<tr>
<th>Mode</th>
<th>Transistors</th>
<th>Inductor current</th>
<th>FC voltage</th>
<th>DC-link voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T25</td>
<td>T27</td>
<td>D&lt;0.5</td>
<td>D&gt;0.5</td>
</tr>
<tr>
<td>Mode 1</td>
<td>OFF</td>
<td>OFF</td>
<td>decreasing</td>
<td>-</td>
</tr>
<tr>
<td>Mode 2</td>
<td>OFF</td>
<td>ON</td>
<td>increasing</td>
<td>decreasing</td>
</tr>
<tr>
<td>Mode 3</td>
<td>ON</td>
<td>OFF</td>
<td>increasing</td>
<td>decreasing</td>
</tr>
<tr>
<td>Mode 4</td>
<td>ON</td>
<td>ON</td>
<td>-</td>
<td>increasing</td>
</tr>
</tbody>
</table>

Table 1: Output and FC voltage states

The transfer function \( y \) of the flying-capacitor booster is the following:

\[
y = \frac{V_{OUT}}{V_{IN}} = \frac{1}{1 - D}
\]

where \( D \) is the duty cycle.

The used modes are dependent on the duty cycle. If \( D < 0.5 \), then \( y < 2 \). In this case Mode 4 is not used and the operation will be the following:

... \( \rightarrow \) Mode 1 \( \rightarrow \) Mode 2 \( \rightarrow \) Mode 1 \( \rightarrow \) Mode 3 \( \rightarrow \) ...

If \( D > 0.5 \), then \( y > 2 \), and the operation will be:

... \( \rightarrow \) Mode 4 \( \rightarrow \) Mode 2 \( \rightarrow \) Mode 4 \( \rightarrow \) Mode 3 \( \rightarrow \) ...

In case of \( D = 0.5 \), \( y = 2 \), the operation:

... \( \rightarrow \) Mode 2 \( \rightarrow \) Mode 3 \( \rightarrow \) Mode 2 \( \rightarrow \) Mode 3 \( \rightarrow \) ...

The most commonly used operation is, when \( D \) is less than 0.5.

4 The Operation of the Flying-Capacitor Booster

In the flying-capacitor booster topology the two transistors have to be controlled by 180° phase shifting (Figure 4).

![Figure 4: The reference and modulation signals for the PWM](image-url)
This results that in case of $D = 0.5$, the operation modes will change between Mode 2 and Mode 3. The typical curves of the flying-capacitor booster can be seen on Figure 5 in case of $D = 0.2$. 
5 The Advantages of the Flying-Capacitor Booster

The flying-capacitor booster topology compared to the booster topology has the following advantages:

- As the operation is three-leveled, the voltage stress on the semiconductor is decreased. This results in lower EMI, lower current and voltage ripple.

The flying-capacitor booster topology compared to the symmetrical booster topology has the following advantages:

- It has two-level input and output connection, while the third voltage level is synthetized by the flying-capacitor. This way the large three-level capacitors can be eliminated on the input and the output.
- Only one input choke is needed.

In both cases the input frequency is double of the switching frequency. This results in a lower input ripple current or the inductance can be decreased. Because of the double frequency, slower semiconductors can be used, which deceases the costs while the switching losses are also lower. This means for optimal behavior SiC MOSFETs are not needed, but Si IGBTs can be used.
For more detailed comparison of the topologies and component selection, please see Vincotech’s benchmark “Boost your 1500 V string inverter”.

6 The Flying-Capacitor

6.1 Sizing of the Flying-Capacitor

The voltage supplied by a flying-capacitor has a key role in this topology. To keep the voltage ripple on the capacitor low, a suitable capacitor size is needed. To determine the needed capacitance, the switching frequency and the maximum allowed voltage ripple need to be considered. The size of the capacitance can be calculated as:

\[ C_{FC} = \frac{I_{peak}}{\Delta U_{FC} \cdot 2f_{SW}} \]

where \( \Delta U_{FC} \) is the maximum allowed voltage ripple, \( I_{peak} \) is the maximum current, and \( f_{SW} \) is the switching frequency of the transistors.

6.2 The Balancing of the Capacitor Voltage

For the appropriate operation the flying-capacitor, voltage has to be half of the output voltage. To achieve this, it must be regulated at all time. This can be done by changing the operation modes. As it can be seen in Table 1, Mode 1 and Mode 4 have no effect for the flying-capacitor, so for regulation Mode 2 and Mode 3 have to be used. The regulation state diagram can be seen on Figure 6.

![Figure 6: The flying-capacitor regulation](image-url)
The needed modes are depending on the duty cycle. In case of \( \leq 0.5 \), the operation will be the following:

\[ \ldots \rightarrow \text{Mode 1} \rightarrow \text{Mode 2} \rightarrow \text{Mode 1} \rightarrow \text{Mode 3} \rightarrow \ldots \]

If the flying-capacitor voltage exceeds the set point, the operation can be modified to decrease the voltage:

\[ \ldots \rightarrow \text{Mode 1} \rightarrow \text{Mode 3} \rightarrow \text{Mode 1} \rightarrow \text{Mode 3} \rightarrow \ldots \]

If the flying-capacitor voltage is less than the set point:

\[ \ldots \rightarrow \text{Mode 1} \rightarrow \text{Mode 2} \rightarrow \text{Mode 1} \rightarrow \text{Mode 2} \rightarrow \ldots \]

In case of \( \geq 0.5 \), the needed modification will be the same, only Mode 4 will be used instead of Mode 1:

\[ \ldots \rightarrow \text{Mode 4} \rightarrow \text{Mode 3} \rightarrow \text{Mode 4} \rightarrow \text{Mode 3} \rightarrow \ldots \text{ to decrease the voltage} \]

\[ \ldots \rightarrow \text{Mode 4} \rightarrow \text{Mode 2} \rightarrow \text{Mode 4} \rightarrow \text{Mode 2} \rightarrow \ldots \text{ to increase the voltage} \]

### 6.3 The Pre-Charge of the Flying Capacitor

This section describes the details of the method proposed by Mitsubishi Electric Corporation [1] to protect the flying capacitor booster, when there are no control signals (e.g.: during startup). In case when all the control signals of the transistors are low, the flying-capacitor voltage cannot be regulated. In that operation an extra effort is needed to keep the flying-capacitor voltage on the safe side. Failing to eliminate the overvoltage on the semiconductors may cause a fatal error in the system. There are two operation modes, when all the transistors are OFF: 1) When the input is applied and the output is equal with the input (e.g.: startup), and 2) when the input is zero and the output is not. This happens, for example, when one string is not connected to the circuit and other boosters are working. In both two cases the voltage of the flying-capacitor is zero, and the voltage sharing of the two transistors is not defined. To keep the voltage level of the semiconductors below the breakdown voltage, additional balancing has to be used.

During startup the current flows through the two diodes and charge the output capacitance. In this case the output voltage is equal to the input voltage, while the flying-capacitor voltage is zero. This is dangerous for the lower switch. To eliminate this problem, another current path has to be added, in which the current can charge also the flying-capacitor. For this a diode can be used, a cathode of which has to be connected to a capacitive voltage divider, where the lower point of the flying-capacitor is clamped at the half of the DC-link voltage. This can be seen on Figure 7
As the voltage of the capacitor can be calculated from the following expression: \( \frac{Q}{C} \), and the charge will be the same for \( C_{out1} \) and \( C_{out2} + C_{FC} \), the flying-capacitor voltage will be the following:

\[
V_{FC} = V_{OUT} \frac{C_{out1}}{C_{out1} + C_{out2} + C_{FC}}
\]

where \( V_{OUT} \) is equal with \( V_{in} \) (if the forward voltage of the diodes are not considered).

If the capacitance of \( C_{out1} \) and \( C_{out2} \) is equal and the capacitance of \( C_{FC} \) is significantly smaller than the capacitance of \( C_{out1} \) and \( C_{out2} \), the voltage of the flying-capacitor is half of the output.

\[
C = C_{out1} = C_{out2}, \quad C_{FC} \ll C, \quad V_{FC} \approx \frac{V_{in}}{2}
\]

When the string is not used and other boosters are working, the input voltage is zero, while the output voltage is not. In this case another diode has to be added to charge the flying-capacitor.
As it can be seen on Figure 8, the current path is the following:

\[ C_{out2} \rightarrow Dh \rightarrow C_{FC} \rightarrow D45 \rightarrow L \rightarrow C_{in} \]

In this case the sum of the flying-capacitor voltage and the input voltage can be calculated as the following:

\[ V_{fci} = V_{OUT} \frac{C_{out2}}{C_{out1} + C_{out2} + C_{FC} \times C_{in}} \]

As in the last expression, if \( C_{out1} \) and \( C_{out2} \) is equal and \( C_{FC} \times C_{in} \) is negligible compared to \( C_{out1} \) and \( C_{out1} \), the voltage is half of the output voltage.

\[ C = C_{out1} = C_{out2}, \quad C_{FC} \times C_{in} \ll C, \quad V_{fci} \approx \frac{V_{OUT}}{2} \]

This voltage is divided on the two capacitors. If the capacitance of the \( C_{FC} \) is much smaller than the \( C_{in} \) capacitor, then the voltage of the \( C_{in} \) capacitor is as low as it can be considered zero, and the voltage of the flying-capacitor is near to the half of the output voltage.

This method can be improved by closing the T27 switch. In this case the voltage is not divided by \( C_{in} \) and \( C_{FC} \) capacitors and the current path will be the following:

\[ C_{out2} \rightarrow Dh \rightarrow C_{FC} \rightarrow T27 \]

And the flying-capacitor voltage:

\[ V_{FC} = V_{OUT} \frac{C_{out2}}{C_{out1} + C_{out2} + C_{FC}} \]
6.3.1 Design considerations

During normal operation T27 creates an overvoltage spike at turn-off. If Df turns on to clamp this spike, T27 switch will be loaded with the reverse recovery of Df. To avoid Df clamping this overvoltage spike, an additional Zener diode (Dz) can be added in series with Df. The Zener voltage of the Zener diode should be higher than the spike of turn-off. This can be seen on Figure 9.

If the voltage of flying-capacitor is extremely higher than $\frac{V_{out}}{2}$, an additional current ripple will appear on the inductor. This ripple causes increased losses and noise. This ripple can be also moderated with this Zener diode.

If the voltage of $C_{FC}$ is less than the voltage of $C_{out2}$, an equalization current will flow between $C_{FC}$ and $C_{out2}$ resulting in an unbalance between $C_{out1}$ and $C_{out2}$. This unbalance can be decreased with a current limiting resistor (Rf), which can be seen on Figure 10.
7 Conclusion

The flying-capacitor booster is a high-efficient, low cost solution for solar inverter applications. The main advantages are the frequency multiplication, the lower semiconductor voltage, the lower voltage and current ripple, the lower switching losses, and the low EMI emission. The flying-capacitor size is significantly smaller than the required DC-link capacitor used in traditional booster topologies with the same power rating. The challenge is to regulate the voltage of the flying-capacitor especially when all the transistors are in OFF state (i.e.: before the converter is turned on). The balancing can be achieved by state regulation. Also the pre-charge challenge can be solved easily by additional diodes based on Mitsubishi Electric Corporation’s patent. With these diodes the flying-capacitor booster is a cost efficient alternative for the other booster solutions with higher efficiency.

Figure 10: The current limiting resistor
8 References
