Phase-Shift Modulation for Flying-Capacitor DC-DC Converters

Philipp Rehlaender, Frank Schafmeister, Joachim Böcker
Power Electronics and Electrical Drives, Paderborn University
Warburger Str. 100
Paderborn, Germany
Phone: +49 (0) 5251 60 2159
Fax: +49 (0) 5251 60 3443
Email: rehlaender@lea.upb.de
URL: http://lea.upb.de

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Keywords

≪High frequency power converter≫, ≪Switched-mode power supply≫, ≪DC-DC converter≫, ≪3-Level Inverter≫.

Abstract

Multi-level flying capacitor converters are an attractive solution for PFC and inverter stages due to their increased output frequency and the application of semiconductors of lower voltage. Due to the beneficial figure of merit of lower-voltage semiconductors switching losses and conduction losses can be reduced. Consequently, this paper analyzes the three-level flying capacitor (FC) module as a replacement for the conventional half bridge. It discusses flying-capacitor voltage control options when being employed for the conventional half-bridge LLC converter with a flying-capacitor inverter and proposes a simple-to-implement modulation to fully utilize the benefits of the three-level structure of the FC module. It explores potential applications to propose a flying capacitor phase shift converter and a three-phase three-level LLC resonant converter with a five-level line-to-line voltage.

1 Introduction

Multi-level flying capacitor (FC) converters are an attractive solution for higher-voltage applications because they can utilize semiconductors with a reduced blocking voltage. They are usually employed in power factor correction (PFC) stages or inverters to show outstanding performance [1–3]. By employing a multi-level voltage-source inverter to such systems, the individual switching frequency of the semiconductors can be kept low while the output frequency increases with the number of levels [4–6]. As an effect, the output filter can be designed for a much smaller inductance due to the increased effective frequency and number of voltage levels.

Additionally, the designer profits from the lower semiconductor blocking voltage since low-voltage power MOSFETs can be utilized that feature a better figure of merit (FOM) compared to high-voltage semiconductors [3, 7–9]. Due to the significantly better FOM of low-voltage devices, FC converters may also be used to DC-DC converters. While traditional DC-DC converters do not profit from the increased number of voltage levels, the use of low-voltage devices of an improved FOM can result in a better system performance.

Consequently, a FC cell (cf. Figure 1b) can be used to replace the traditional half-bridge leg (cf. Figure 1a). An exemplary application may be the LLC half bridge converter, which is visualized with an

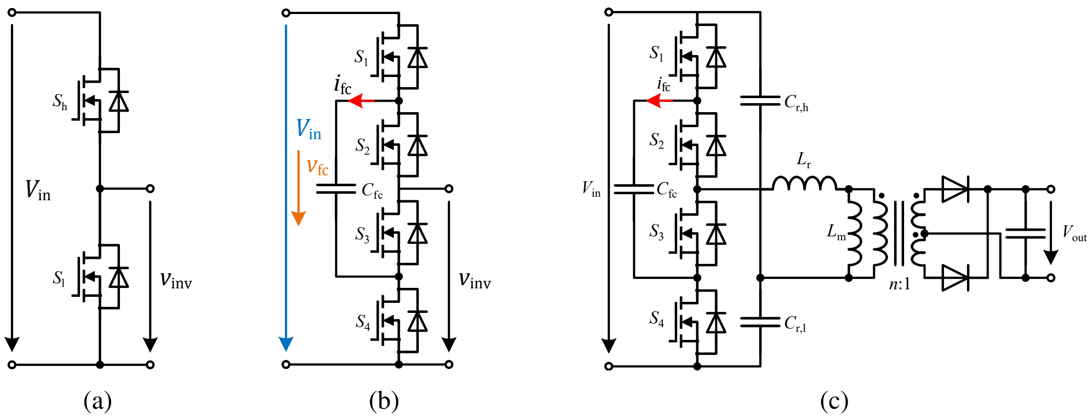


Fig. 1: (a)Traditional half-bridge module, (b) the flying capacitor module and (c) the flying capacitor inverter with a half-bridge LLC resonant converter with splitted resonant capacitor .

FC inverter in Figure 1c. However, in operation, the flying capacitor voltage v_{FC} must be controlled to half of the input voltage ($v_{FC} = V_{in}/2$) to ensure that every MOSFET is only stressed with half of the input voltage and avoid a dynamic increase of this voltage. Therefore, this paper analyzes the phase-shift modulation as a method to control the flying capacitor voltage and proposes an easy-to-implement three-level modulation to fully exploit the three-level structure of the FC converter enabling a quasi phase-shift modulation voltage pattern.

2 Flying-Capacitor DC-DC converters

In traditional applications of the FC converter (PFC and inverter applications), all levels of the modulations were utilized since the fundamental frequency of the filter was much lower than the switching frequency. However, in DC-DC converters (phase-shifted full bridge, LLC resonant converter, etc.), this is not the case since the inductor current changes polarity after half a switching period. To replace the conventional half-bridge with a FC module, a control mechanism must be found to control the FC voltage and avoid a run-off. The flying capacitor stage can be switched in four different states:

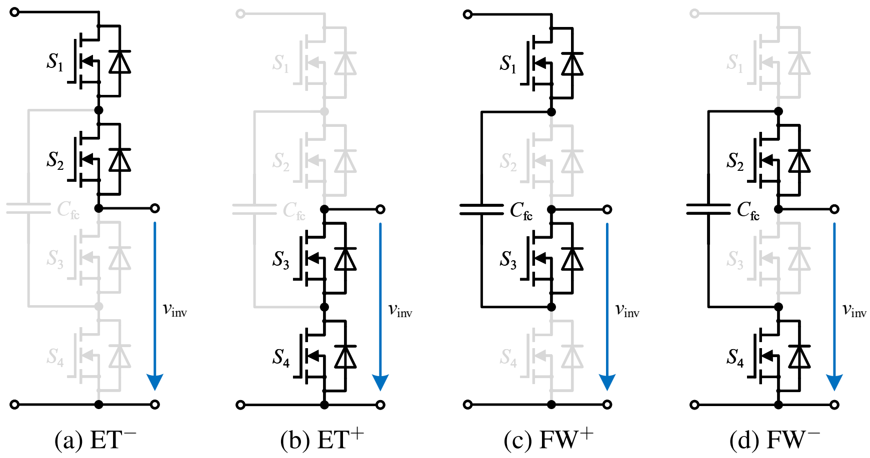
- $v_{inv} = V_{in}$ (ET$^+$, see Figure 2a),
- $v_{inv} = 0$ (ET$^-$, see Figure 2b),
- $v_{inv} = V_{in}/2$ (FW$^+$, see Figure 2c),
- $v_{inv} = V_{in}/2$ (FW$^-$, see Figure 2d).

In the following, the sequence of these states is analyzed to derive a balancing operation of the flying capacitor voltage and anaylze the modes of operation.

2.1 Phase-Shift Operation in Flying-Capacitor DC-DC Converters

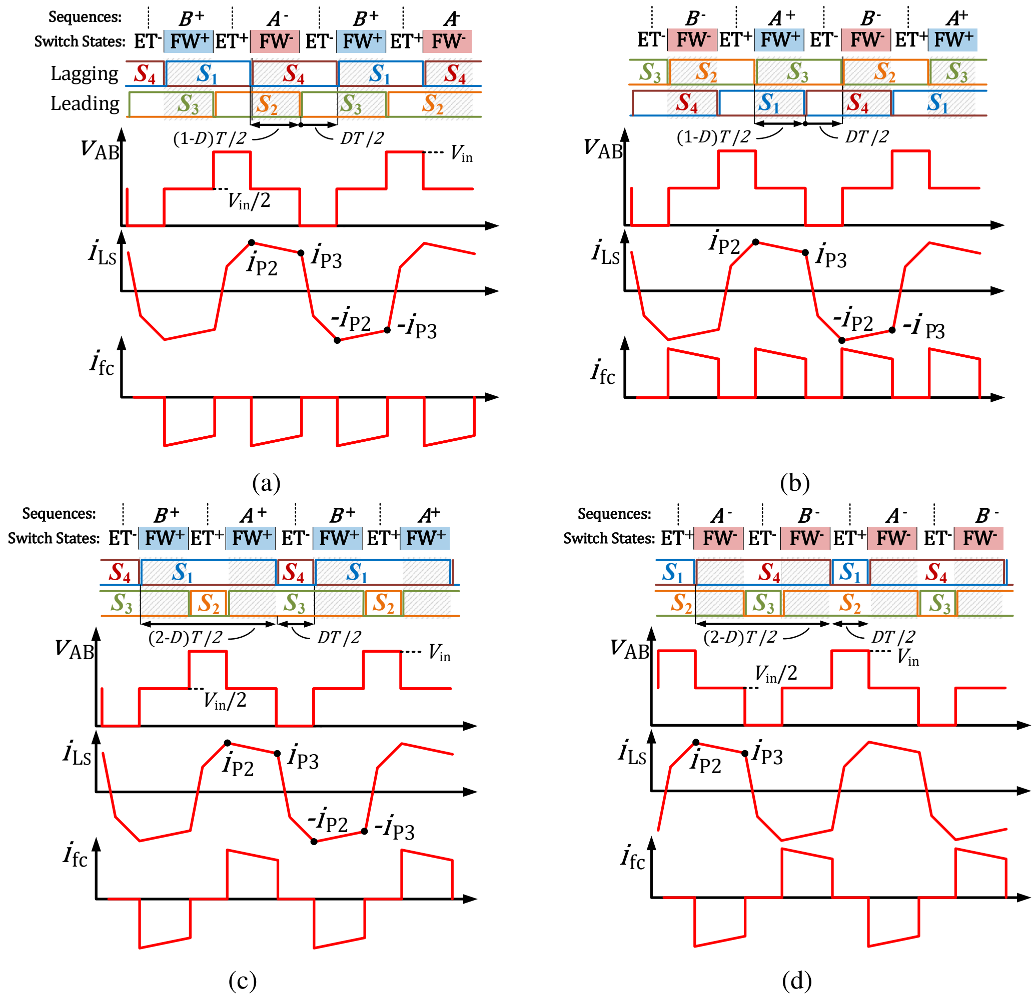
When utilizing a phase-shift modulation to the FC module, the switching signals of the semiconductors S_1-S_4 (cf. Figure 1b) are phase shifted to the input signals of S_2-S_3 as depicted in Figure 3a. Compared to the traditional phase-shift modulation of the full-bridge inverter, this modulation cannot be as easily adapted since for either phase-shift modulation (Figure 3a, 3b), the flying capacitor current is either negative (cf. Figure 3a) or positive (cf. Figure 3b) resulting in a run-off of the flying capacitor voltage v_{FC}. Additionally, in the phase-shift modulation, the MOSFETs are stressed with different turn-off currents [10–12] as visualized in Figure 3a, 3b (current values named after [13]) and conduction losses [12].

The same voltage pulses of the phase-shift modulation can also be achieved by the asymmetrical phase-shift modulation or duty-cycle modulation depicted in Figures 3c and 3d [11, 14, 15]. This modulation



(a) ET$^-$ (b) ET$^+$ (c) FW$^+$ (d) FW$^-$

Fig. 2: Switching states of the flying-capacitor module.



(a) (b) (c) (d)

Fig. 3: Phase-shift modulation (a,b) and asymmetrical phase-shift modulation (c,d).

results in positive and negative flying-capacitor currents enabling a full utilization of the three levels of the flying capacitor module in a quasi phase-shift-modulation voltage pattern. However, the modulation results in unbalanced losses since two switches are turned on for $(2-D)T/2$ where $D \in [0,1]$ whereas the other two switches are only turned on for $DT/2$ resulting in unbalanced conduction losses. Additionally, the switches are also turned off at different current levels resulting in unbalanced switching losses.

In the conventional phase-shift modulation the switching intervals are repeated every period of the transformer current. If the switches S_2 and S_4 are operated as the leading leg, the intervals are repeated in the order

$$\begin{aligned}&\mathbf{ET}^{+}(S_1,S_2) \rightarrow \mathbf{FW}^{-}(S_2,S_4) \rightarrow \\ &\mathbf{ET}^{-}(S_3,S_4) \rightarrow \mathbf{FW}^{+}(S_1,S_3).\end{aligned} \tag{1}$$

If the switches S_1 and S_3 are operated as the leading leg, the intervals are repeated in the reverse order:

$$\begin{aligned}&\mathbf{ET}^{+}(S_1,S_2) \rightarrow \mathbf{FW}^{+}(S_1,S_3) \rightarrow \\ &\mathbf{ET}^{-}(S_3,S_4) \rightarrow \mathbf{FW}^{-}(S_2,S_4).\end{aligned} \tag{2}$$

Considering the preceding states four different sequences can be derived: the transition through a freewheeling interval from ET^{+} to ET^{-} labeled type A sequence and the transition through a freewheeling interval from ET^{-} to ET^{+}, which are labeled type B sequence [12]. Both transitions can utilize either the positive or negative freewheeling state, which is emphasized through the superscript.

For the A type or B-type transition, the flying capacitor can be either charged or discharged (assuming steady state). The A^{+} transition hereby results in a charging current whereas the A^{-} transition results in a discharging current:

$$\boldsymbol{A}^{+}(i_{\mathrm{fc}} > 0)): \;\; \mathbf{ET}^{+}(S_1,S_2) \rightarrow \mathbf{FW}^{+}(S_1,S_3) \rightarrow \mathbf{ET}^{-}(S_3,S_4), \tag{3}$$

and

$$\boldsymbol{A}^{-}(i_{\mathrm{fc}} < 0): \;\; \mathbf{ET}^{+}(S_1,S_2) \rightarrow \mathbf{FW}^{-}(S_2,S_4) \rightarrow \mathbf{ET}^{-}(S_3,S_4). \tag{4}$$

The two possible transitions from ET^{-} to ET^{+} (labeled type-B sequence) can also result in a discharging current (B^{+}) or a charging current (B^{-}):

$$\boldsymbol{B}^{+}(i_{\mathrm{fc}} < 0): \;\; \mathbf{ET}^{-}(S_3,S_4) \rightarrow \mathbf{FW}^{+}(S_1,S_3) \rightarrow \mathbf{ET}^{+}(S_1,S_2) \tag{5}$$

and

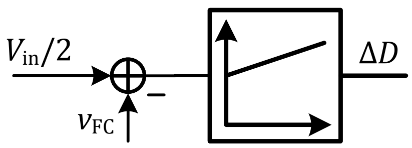
$$\boldsymbol{B}^{-}(i_{\mathrm{fc}} > 0): \;\; \mathbf{ET}^{-}(S_3,S_4) \rightarrow \mathbf{FW}^{-}(S_2,S_4) \rightarrow \mathbf{ET}^{+}(S_1,S_2). \tag{6}$$

This analysis emphasizes that the description of above. The conventional phase-shift modulation either results in a continuous discharging current (Figure 3a) or continuous charging current (Figure 3b).

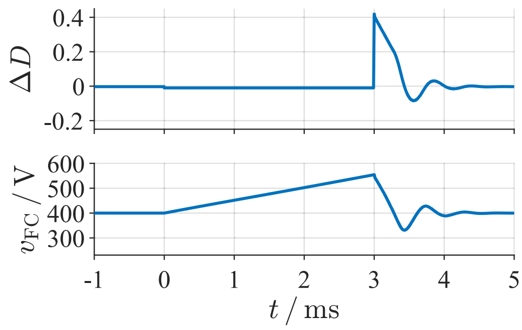
2.2 Flying-Capacitor Voltage Control for LLC Resonant Converters

While a full utilization of the traditional phase-shift (Figure 3a, 3b) modulation is not possible for the FC DC-DC converter, the introduction of a phase shift to the gate signals between S_1-S_4 and S_2-S_3 can be utilized to control the FC voltage in an LLC resonant converter that is traditionally operated with 50 % duty cycle and no phase shift. While ideally the FC current is zero for when there is no phase-shift, even a small delay in the operation may lead to a run-off of the FC voltage and can, therefore, result in a destruction of the switches. By operating S_2-S_3 as the lagging leg (cf. Figure 3a, 3b) if $v_{\mathrm{FC}} < V_{\mathrm{in}}/2$ and S_1-S_4 as the leading leg if $v_{\mathrm{FC}} > V_{\mathrm{in}}/2$ (in each with only a minor phase shift) the flying capacitor voltage can be controlled.

The control concept to stabilize v_{FC} to $V_{\mathrm{in}}/2$ is depicted in Figure 4a. For $\Delta D < 0.5$, the switches S_1-S_4 are leading with the switches S_2-S_3 lagging; for $\Delta D > 0.5$, the switches S_2-S_3 are leading while S_1-S_4 are lagging. Simulation results are depicted for an 2.4 kW LLC resonant converter in Figure 4b for $C_{\mathrm{fc}} = 2\,\mu\mathrm{F}$ with $V_{\mathrm{in}} = 800\,\mathrm{V}$ and $V_{\mathrm{out}} = 48\,\mathrm{V}$, $I_{\mathrm{out}} = 50\,\mathrm{A}$. The resonant parameters are $L_{\mathrm{r}} = 30\,\mu\mathrm{H}$, $L_{\mathrm{m}} = 300\,\mu\mathrm{H}$, $C_{\mathrm{r}} = 90\,\mathrm{nF}$ and $n = 7$. For $0 < t < 3\mathrm{ms}$, the control was turned off. After $t = 3\,\mathrm{ms}$, the control was turned back on resulting in a stabilization of the flying capacitor voltage. For $\Delta D < 0$, the switches S_1-S_4 are leading; for $\Delta D > 0$ they are lagging. The results show that the flying capacitor voltage can be well controlled to half of the input voltage V_{in}.



(a)



(b)

Fig. 4: (a) Control concept to adjust the flying capacitor voltage v_{FC}. For $\Delta D < 0$, the switches S_1-S_4 are leading, for $\Delta D > 0$, they are lagging; (b) simulation results proving the concept.

3 A Loss-Balancing Phase-Shift Modulation for Flying-Capacitor DC-DC Converters

The preceding section showed that the conventional phase-shift modulation is unsuitable for the application on a flying-capacitor DC-DC converter as it results in a continuous charge or discharge of v_{fc}. While the asymmetrical phase-shift modulation of Figures 3c and 3d may be an option to utilize quasi phase-shift modulation voltage shapes, it is a non-ideal solution as it results in unbalanced semiconductor losses. To utilize the full potential of the phase-shift modulation in LLC resonant converters, this chapter presents a multi-level modulation to achieve quasi-phase-shift modulation voltage shapes. Benefits of phase-shift modulation in LLC resonant converters are the potential of employing it for start-up purposes [16, 17], a low-gain loss reduction [18–21], an extension of the operation in wide voltage-transfer ratio applications [22–25] or in balancing when utilizing interleaving of multi-rail LLC converters [26–28]. To utilize the benefits of the phase-shift operation, several concepts have been presented in literature [29, 30] where both concepts employed additional switches or additional capacitors and diodes. However, this section shows that a modulation exists to achieve these voltage shapes without the need of additional components.

The alternating-asymmetrical modulation (a2PSM) is depicted in Figure 5. It uses the same pulse pattern that was used for a conventional full-bridge inverter in [10–12]. To the author's knowledge, no such modulation has yet been utilized to a multi-level inverter. The modulation consists of turn-on intervals of the length $(2-D)T/2$, $T/2$, $DT/2$ and $T/2$ where the pulses are phase-shifted from S_1-S_4 to S_2-S_3 by T. The modulation can be easily implemented on a DSP/microcontroller (e.g. in TI C2000 controllers using the action-qualifier control registers, AQCTL) by using an up-down counter. By employing two PWM units, the same synchronized up-down counter can be utilized where the compare values for one PWM unit (yellow lines) are $(2-D)N_{\text{reg}}/4$ and $N_{\text{reg}} - DN_{\text{reg}}/4$ while for the other PWM unit (dark red lines), they are $DN_{\text{reg}}/4$ and $(2+D)N_{\text{reg}}/4$. During up-count, the flying-capacitor current is negative while for down count, it is positive considering steady state. Exemplary simulation results are depicted in Figure 6. Figure 6a shows ideal simulation results with no delays in the PWM signals. A simulation with an exemplary 80 ns phase shift between the signals of S_1/S_4 and S_2/S_3 is depicted in Figure 6b. This modulation results in a non-ideal flying capacitor voltage v_{fc}. In average the voltage is $\bar{v}_{\text{fc}} = 452\,\text{V}$, 52 V higher than the ideal voltage of $\bar{v}_{\text{fc}} = \frac{V_{\text{in}}}{2} = 400\,\text{V}$. However, contrary to the conventional phase-shift modulation depicted in Figure 4b, this does not lead to a continuously increasing/decreasing flying capacitor voltage but results in a steady state offset in the voltage.

A control of the flying-capacitor voltage can be achieved by modifying the compare values for the up- and down count respectively by increasing or decreasing the freewheeling intervals during the respective counter slope. The upper two compare values are, thus, modified to $(2+D-\Delta D)N_{\text{reg}}/4$ and $N_{\text{reg}} - (D-\Delta D)N_{\text{reg}}/4$ whereas the lower two compare values are modified to $(2-D+\Delta D)N_{\text{reg}}/4$ and $(D-$

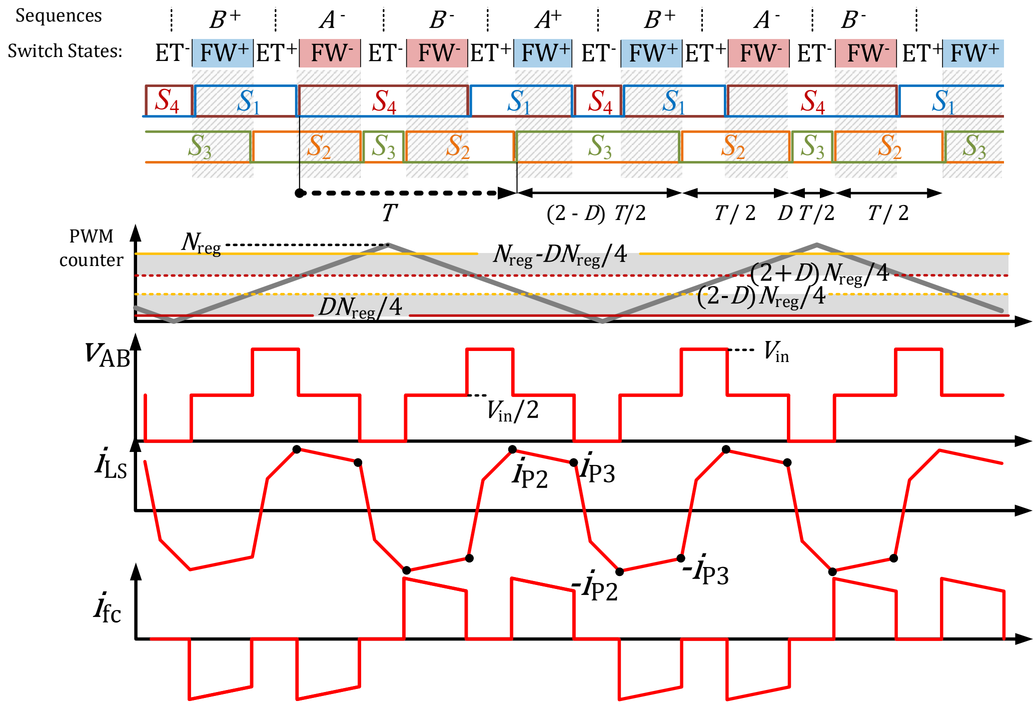
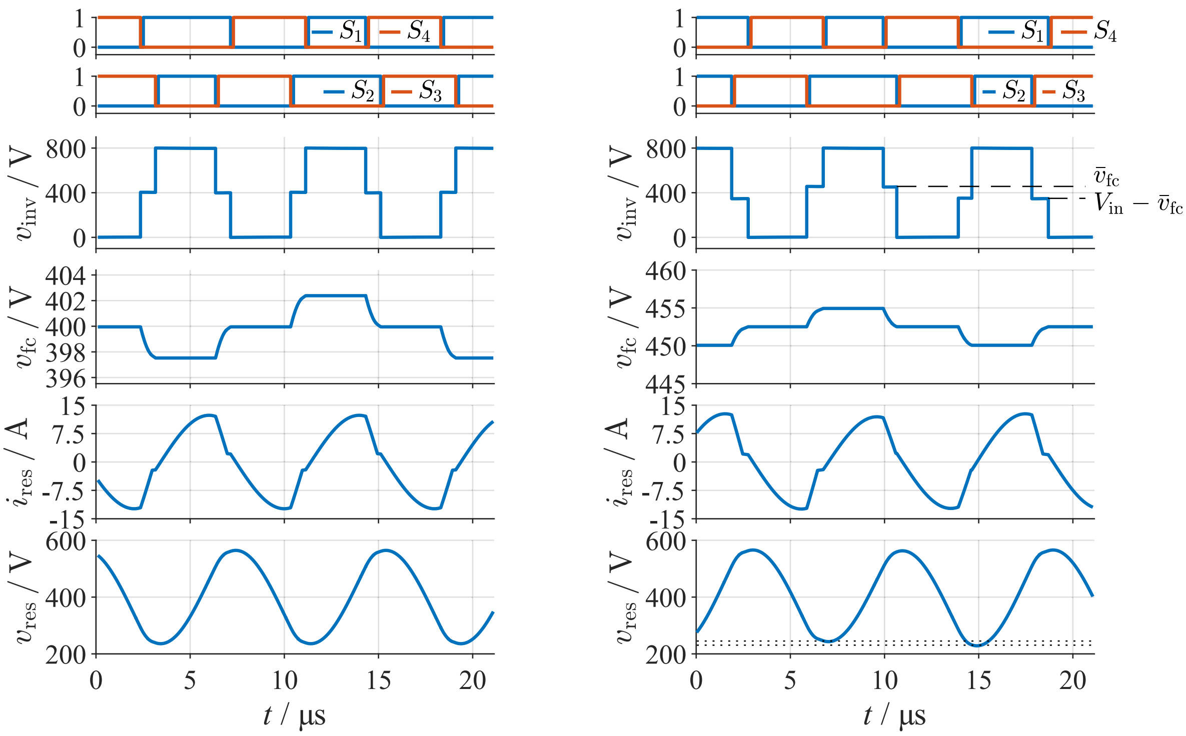
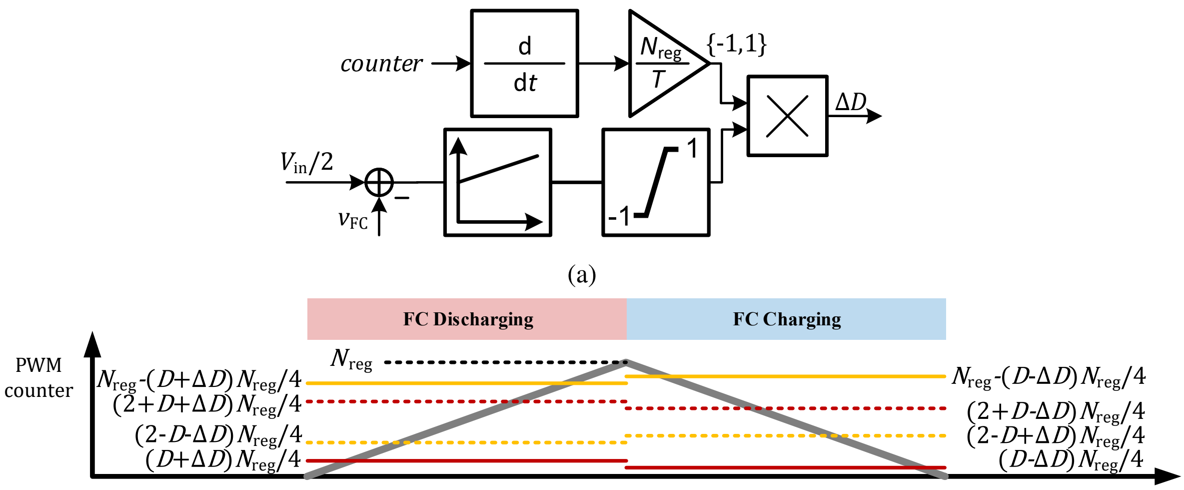


Fig. 5: Three-level alternating asymmetrical phase-shift modulation with balanced flying-capacitor currents.



(a) (b)

Fig. 6: 3-Level LLC converter simulation results. (a) balanced operation, (b) unbalanced operation with undesired phase shift of 80 ns for S_1 and S_4 leading to an undesired flying capacitor voltage.



(a)

(b)

Fig. 7: (a) Control concept to adjust the flying capacitor voltage v_{FC} in the a2PSM. Depending on the counter slope, the compare values are altered; (b) Visualization of the adapted compare values to balance the flying-capacitor voltage by increasing the charging intervals.

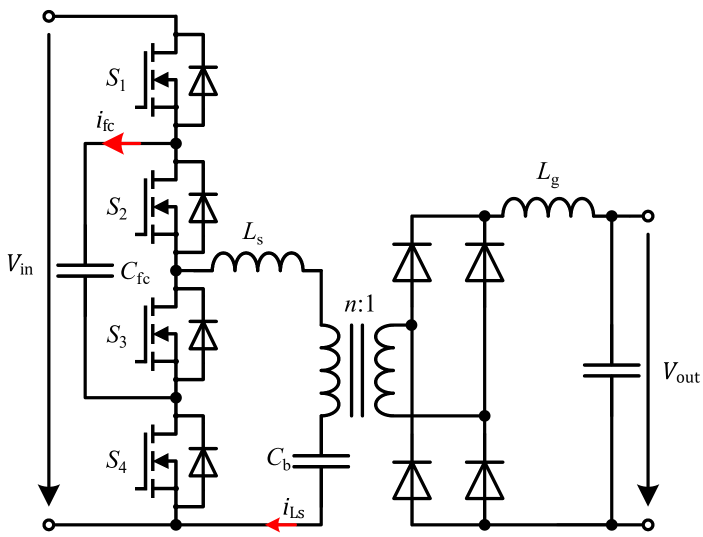


Fig. 8: Three-level phase-shift converter with a blocking capacitor C_b.

$\Delta D)N_{reg}/4$ where ΔD is determined as visualized in Figure 7a. The modified compare values are depicted in Figure 7b.

With the proposed modulation, it is possible to create a flying-capacitor phase-shift converter (*phase-shifted full bridge* as depicted in Figure 8. The blocking capacitor C_b is used to block half of the input voltage and is setup with a large capacitance. Simulation results are depicted in Figure 9 where Figure 9a shows a simulation with a introduced delay of 20 ns for S_1 and Figure 9b shows simulation results with the balance control resulting in the desired flying capacitor voltage.

4 Conclusion

Multi-level flying-capacitor converters are an attractive solution to exploit the beneficial figure of merit of semiconductors with a lower blocking voltage. Conventionally, they are employed in power-factor-correction stages or inverters. This paper proved that the flying-capacitor module can be successfully implemented to exchange the conventional half-bridge leg. It proved that the phase-shift modulation can be utilized to adjust the flying capacitor voltage of half-bridge LLC converter and proposed a modulation

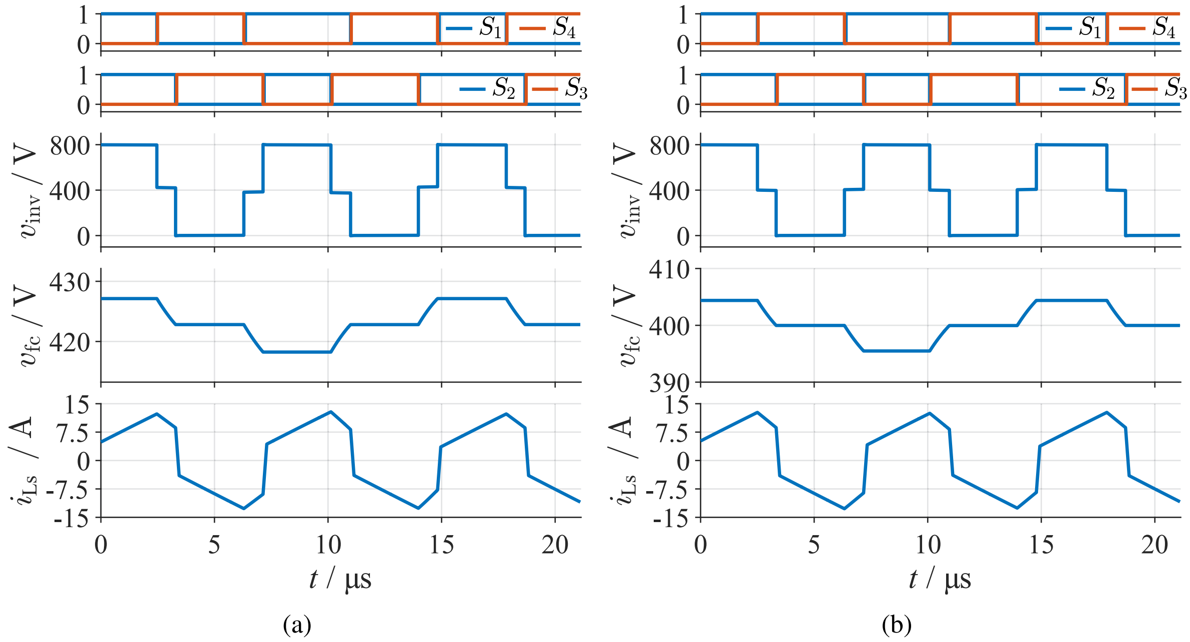


Fig. 9: 3-Level PSFB converter simulation results. (a) unbalanced operation with undesired delay of 20 ns for S_1 leading to an undesired flying capacitor voltage (b) balanced operation (controlled, $\Delta D = 0.01$) with undesired delay of 20 ns for S_1 leading to the desired operation.

to fully exploit the three-level structure of the FC module. Consequently, a FC phase-shift converter and a three-level LLC resonant converter were proposed along with a concept to control the voltage to the desired value.

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