

NATURAL CAPACITOR VOLTAGE BALANCE IN MULTILEVEL FLYING CAPACITOR CONVERTERS. A REVIEW OF RESEARCH ACHIEVEMENTS*

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Abstract: The flying-capacitor (FC) topology is one of the more well-established ideas of multilevel conversion, typically applied as an inverter. One of the biggest advantages of the FC converter is the ability to naturally balance capacitor voltage. When natural balancing occurs neither measurements, nor additional control is needed to maintain required capacitors voltage sharing. However, in order to achieve natural voltage balancing suitable conditions must be achieved such as the topology, number of levels, modulation strategy as well as impedance of the output circuitry. Nevertheless this method is effectively applied in various classes of the converter such as inverters, multicell DC-DC, switch-mode DC-DC, AC-AC, as well as rectifiers. The next important issue related to the natural balancing process is its dynamics. Furthermore, in order to reinforce the balancing mechanism an auxiliary resonant balancing circuit is utilized in the converter which can also be critical in the AC-AC converters or switch mode DC-DC converters. This paper also presents an issue of choosing modulation strategy for the FC converter due to the fact that the natural balancing process is well-established for phase shifted PWM whilst other types of modulation can be more favorable for the power quality.

Keywords: *flying-capacitor converter, natural capacitor voltage balance, multilevel converter, inverter, DC-DC converter*

1. INTRODUCTION

Multilevel converters have become a very important solution for power electronic applications in recent years. Using the multilevel converter, several advantages can be achieved by the decrease of voltage stresses on the switches and improvement of power quality.

The flying-capacitor (FC) converter has attracted the interest of researchers for many years. In the majority of applications the FC topology is applied to FC inverters and DC-DC step down converters termed multicell converters [1]–[3]. Many other ideas of multilevel conversion, such as stacked multicell converters,

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rectifiers, AC-AC or switched-mode DC-DC also utilize FC topologies and are presented in this paper.

The FC converter uses many auxiliary capacitors, and thus the voltage balancing of the converter is especially important in this topology. The flying capacitors determine the potential level necessary for the reduction of voltage stress on the switches and for modulation. The flying-capacitor voltages should be maintained in suitable proportion to the voltage on the terminals (output or input, depending on topology). A voltage imbalance may cause an increase of voltage stress on switches and can lead to damage of a converter. To avoid this, a method of reducing the imbalance is needed (in a converter). Under normal operation, the average power of the flying capacitor should be zero. Thus the large capacitance is typically unnecessary which makes the converter sensitive to factors that can cause an imbalance.

From the many methods of voltage imbalance reduction in multilevel converters, natural balancing methods are very attractive for the FC converters. The FC converter with adequate modulation achieves a natural balancing ability [1]. Under adequate modulation, the unbalanced FC converter introduces unique current components to the output circuitry which further affect the average voltages of the flying capacitors. This phenomenon occurs with the assistance of the load, but the efficacy is dependent on the output impedance. In order to achieve the required dynamics of the natural balancing process, an auxiliary circuit can be introduced to the converter which triggers the adequate current under the unbalancing conditions. Such a balancing circuit can be composed of a series RLC branch to achieve the required sensitivity for unbalancing conditions. Another very important issue concerns the modulation of the FC converter.

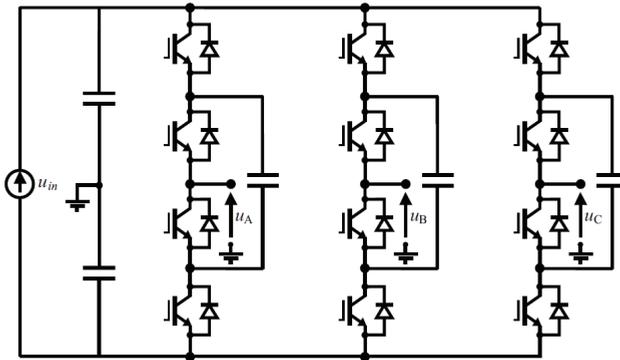


Fig. 1. A three-level three-phase FC inverter

Natural balancing exists in FC topologies with Phase Shifted PWM (PS PWM). Application of other PWM strategies in order to improve the output voltage spectrum is possible, and for natural balancing, redistributions of the switching signals can be

introduced. The modulation can also be modified to improve the dynamics of the balancing process.

Section 2 presents one of the approaches for an analytical proof of the natural balancing of the FC converter. Further analytical achievements and approaches addressed in references are also described in this section. In Section 3, the research achievements in the field of natural balancing of FC converter are gathered, presenting cases for inverters, DC-DC converters, rectifiers and AC-AC converters. This paper also addresses the issue of initial charging of the capacitors in FC converters and start-up control.

2. NATURAL VOLTAGE BALANCE IN A FLYING CAPACITOR TOPOLOGY

2.1. BASICS OF THE NATURAL VOLTAGE BALANCING IN AN FC CONVERTER

In-depth analytical solutions for the natural balancing process are addressed in many research works [1]–[30].

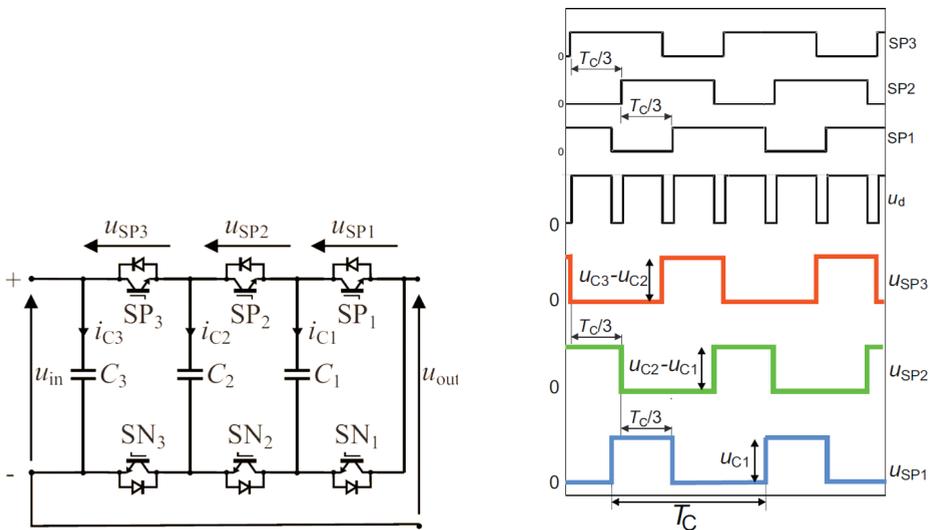


Fig. 2. A branch of the five-level FC inverter as a three-cell converter. Idealized waveforms of the control signals of the SP_n switches, output voltage and voltages on switches under the phase-shifted modulation

A single branch of the five-level inverter can be represented as a multicell topology, which is suitable for the natural balance analysis (Fig. 2). Analyzing the 3-cell

converter (Fig. 2) when the converter is modulated with the phase-shifted carriers (PS) the control signals of the SPn switches are also 120 deg phase shifted. Control of SNn is inverted in relation to the corresponding signals for SPn switches to avoid short circuits in the cells. The converter operates under the balanced state when the average value of voltages on the flying capacitors remains in the suitable proportion to the input voltage

$$u_{C2} = (2/3)u_{in}, \quad u_{C1} = (1/3)u_{in} \quad (1)$$

From (1) and Fig. 2 it is clear that when the converter operates under balanced conditions the voltage stresses across the switches are limited to the values

$$u_{SP1max} = u_{C1} = (1/3)u_{in}, \quad u_{SP2max} = u_{C2} - u_{C1} = (1/3)u_{in}, \quad u_{SP3max} = u_{in} - u_{C2} = (1/3)u_{in}, \quad (2)$$

$$u_{SPnmax} = (1/3)u_{in}. \quad (3)$$

However, under unbalanced conditions, when (1) is not met, the voltage stresses across switches exceed the rated voltage $(1/3)u_{in}$. Thus the unbalanced state can lead to failure conditions and should be avoided.

Natural balancing is a mechanism that leads the converter to the balanced state by the current flow which is triggered under the unbalanced state. In the case of the multicell converter (Fig. 1, Fig. 2) the output voltage and the output current play a significant role in this process.

The output voltage is the sum of the input voltage and voltages on switches SPn

$$u_{out} = u_{in} - (u_{SP1} + u_{SP2} + u_{SP3}). \quad (4)$$

The switches are modulated with the switching frequency (f_c) but at the output voltage a switching component at the three times the switching frequency should appear ($3f_c$). However, the unbalanced state will differ from these conditions which will be the basis for the natural balancing proof. Using the analysis in the switching frequency (f_c) domain there can be found the difference in the output voltage spectrum under the balanced and the unbalanced state. These cases are presented in Fig. 3, with the use of complex amplitude diagrams [84]. From the diagrams presented in Fig. 3, it follows that under the unbalanced state the component with the f_c frequency appears in the output voltage. This component triggers the output current which should affect the voltages of flying capacitors. The direction of current through the capacitors is dependent on state of the neighboring switches, which can be described in the following way [25]:

$$i_{C1} = i_{out}(SP2 - SP1), \quad (5)$$

$$i_{C2} = i_{out}(SP3 - SP2). \quad (6)$$

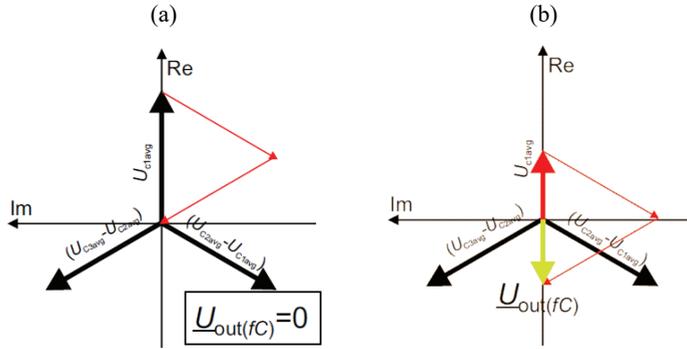


Fig. 3. A complex representation of the output voltage (u_{out}) components in the switching frequency domain (f_c) of the 3-cell DC-DC converter under the balanced (a) and unbalanced state (b)

In the switching frequency domain (f_c) the switching functions (SP2–SP1) and (SP3–SP2) are 120 degrees phase shifted (or 240 degrees) sinusoidal functions

$$(SP2-SP1)_{f_c} = B \sin(2\pi f_c - 2\pi/3) - A \sin(2\pi f_c), \quad (7)$$

$$(SP3-SP2)_{f_c} = C \sin(2\pi f_c - 4\pi/3) - B \sin(2\pi f_c - 2\pi/3), \quad (8)$$

where A , B , C are the amplitudes of the components, and are proportional to voltages on capacitors.

From (7) and (8) it follows that:

- The component of f_c frequency of the output current affects the average value of the flying capacitors.
- If the f_c frequency output current exists it can affect the average voltages of one or two flying capacitors. The case where any of the capacitors average voltage varies does not exist when the f_c frequency of the output current flows.
- Because the switching functions do not include the constant components or the $3f_c$ frequency these components of the output current do not affect the flying capacitors average voltages. This is important due to the fact that these components as well as the low frequency component dominate the output current. From the instance of an unbalanced state, presented in Fig. 3b, it is seen that the balancing voltage is created by an error in the voltage component which uses the voltage u_{C1} . In this case, the balancing voltage triggers the balancing current to become out of phase to the u_{SP1} voltage (in relationship (1)), which means that capacitor C_1 is charged by the balancing current when SP1 is in the off state and the system is led to the balanced conditions. Figure 4 presents simulation results which show the components of the output voltage under the balanced as well as unbalanced state. The voltage u_{bal} is extracted in Fig. 4 as the difference between the output voltage under the balanced and unbalanced conditions for the same setup and this is the voltage $u_{out(f_c)}$. It is clearly seen in Fig. 4

that $u_{\text{out}(fC)}$ has three times lower frequency than the output voltage switching component under the balanced conditions.

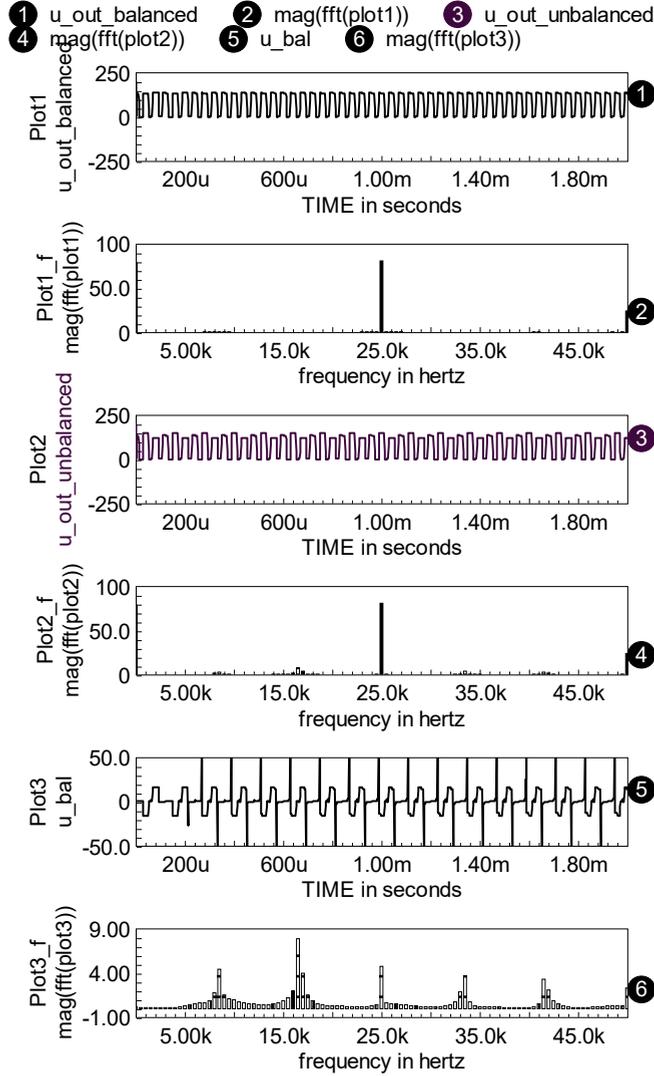


Fig. 4. The output voltage waveform in the three-cell FC converter under the balanced state (Plot 1), and the unbalanced state (Plot 2). The difference between the voltage under the balanced and unbalanced state (Plot 3) and spectrum of all the waveforms. $U_{\text{in}} = 400$ V. Under the balanced state: $u_{C1} = 266.6$ V, $u_{C2} = 133.3$ V. Under the unbalanced state: $u_{C1} = 250$ V, $u_{C2} = 133.3$ V

Presented in this section is the proof of the balancing process, which demonstrates a mechanism of triggering the output current with a unique frequency under the unbal-

anced conditions and an impact of this current on average voltage on the flying capacitors.

These approaches are addressed in the literature [25] but for the complete model of the natural balancing, the following issues should also be proven:

- An influence of the various components of the output current (e.g., low frequency 50 Hz) on the flying capacitors voltages.
- Stability of the balancing process, i.e., whether the triggered balancing circuit leads the flying capacitor voltages to the balanced state or causes a dipper imbalance.
- The dynamics of the balancing process.

The in-depth analysis of the natural balancing process including the influence of the harmonic of the output current on the natural voltage balance dynamics can be found in [1]–[27]. In [9]–[12], the dynamics of the natural balancing process is described by the linearized circuit model where the flying capacitor voltage is the following

$$\dot{V}_c(t) = AV_c(t) + BV_{in}(t). \quad (9)$$

The circuit model (9) is determined by the use of a Double Fourier solution of the PWM switching signals.

The state-space analysis of the natural balancing process of the FC converters is presented in [13].

The time-domain solution and analysis of the flying-capacitor voltage natural balancing dynamics is demonstrated in detail in [15]–[25], [33]. The time domain approach presented in [15], [23] utilizes analytical solutions in switching intervals with appropriate initial conditions, which makes it possible to obtain a time-averaged model of the voltage balancing of the flying capacitors. The application of the time averaging analysis of the FC converter voltage balancing is also demonstrated [17]–[20], [24], [25] for various number of level converters.

In general, from the solutions presented in the literature it follows that the dynamics of the natural balancing depends on the imbalance ratio, flying capacitances and load. The balancing booster (described in Section 2.3) creates specific conditions of balancing and has a substantial impact on the dynamics of the process. For the switching frequency (f_c), the impedance is approximately equal to the resistance of the booster, which can be as low as the parasitic value of the balancing circuit.

2.2. MODULATION STRATEGY AND SUITABLE NUMBER OF LEVELS FOR THE NATURAL BALANCING CAPABILITY

In the general case for the natural balancing ability it is necessary to modulate the cells by the set of the interleaved signals [1]–[7]. The signals can be generated using various methods but the most intuitive is Phase Shifted PWM (PS PWM) strategy.

In [1]–[31], the natural balancing is achieved by the use of PS PWM strategy (Fig. 5). The PS PWM is a subject of investigation and modification [32]–[38] to improve the output voltage or the flying-capacitor voltage balance. In a method proposed in [32], [35], an additional balancing control algorithm is used with the PS PWM strategy.

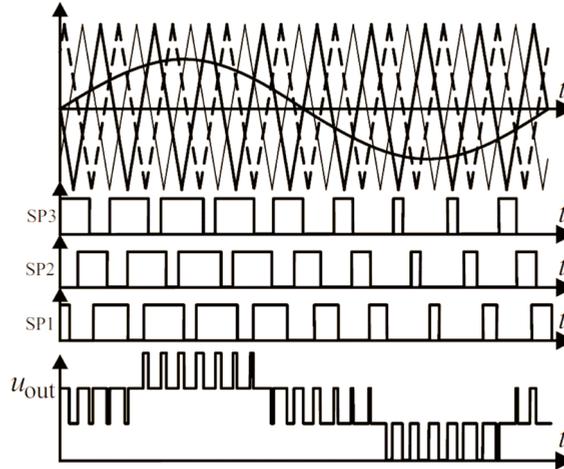


Fig. 5. PS PWM strategy suitable for the natural balancing conditions. Control signals and the output voltage of 3-cell DC-DC converter (Fig. 2)

The algorithms adjust the duration of switching cells necessary for the voltage balance, utilizing a redundancy of switching states. The method proposed in [38] utilizes two sets of phase shifted carriers, and the use of a given carrier depends on the value of the reference signal. As a result, the quality of the line-to-line voltage is improved and the converter maintains the natural voltage balancing ability. In [33], the voltage balance dynamics is improved by the use of modified PS-PWM. The method proposed in [33] is based on a switch-state sequences modification and can be achieved using carriers.

Aside from the PS PWM technique, other PWM strategies can be attractive from the standpoint of output voltage harmonic content or hardware implementation. In [39]–[44], an in-depth study of Phase Disposition (PD) PWM strategy is presented. In [42], [43], it is demonstrated that the application of additional state machine-based processing for suitable distribution of the switching signals makes it possible to achieve the natural balancing ability using PD and CSPWM methods. PD PWM applications for FC converters are also an issue addressed in [44], where natural balancing is also achieved by the reconfiguration of the basic carriers of the PD technique. In [45], the PD PWM application in FC converters is proposed, where a single triangular carrier is used. In [46], the natural balancing dynamics is compared for the PS PWM, and modified level-shifted PWM in H-bridge FC converter. An in-depth ana-

lytical solution for the voltage balancing dynamics and very good performance of the modified LS PWM method is demonstrated in [46]. From other solutions in [47], a modified Carrier-Redistribution PWM method using symmetric carrier technique is proposed for the voltage balance of the flying-capacitor multilevel inverter. In [48], the voltage balancing in FC converter with the hysteresis current control is presented and in [49], [50] the FC system uses hybrid PWM methods where PD PWM, as well as selective harmonic elimination (SHE PWM) are applied. The hysteresis current control with further state machine-based voltage balancing is presented in [51]. In [52], a precalculated switching pattern is used for a low switching frequency IGBT-based FC converter. In [53], a comparison of three carrier-based PWM methods, namely Modified Carrier-Redistribution (MCR) PWM, the Saw-Tooth-Rotation (STR) PWM, and the typical Phase-Shifted (PS) PWM with an analysis of output voltage harmonic and the voltage balance problem is presented.

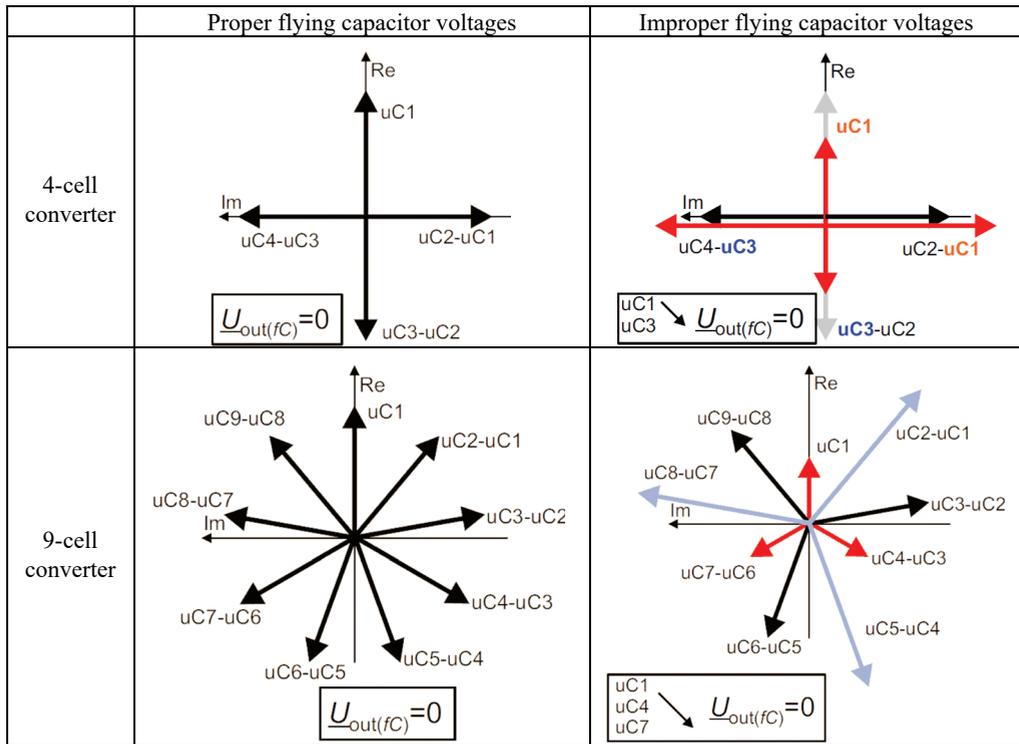


Fig. 6. A complex representation of the output voltage components of the 4-cell and 9-cell converters. Cases of proper flying capacitor voltages and possible improper flying capacitor voltages, where the unbalanced component in the output voltage is not present

The PS PWM strategy makes it possible to achieve the natural balancing in the FC converter, however, the effectiveness of the method can be reduced in for some con-

verters, such as the typical multicell branch with unsuitable number of cells and, duty ratio. This issue is addressed in detail in [54].

Figure 6 presents diagrams of the vectors that create the output voltage in the domain of switching frequency of a single cell (f_c) in a four-cell DC-DC converter (Fig. 7). In both cases, the balanced as well as unbalanced one, the sum of the vectors equals zero, meaning that the f_c component will not appear in the output voltage in such specific unbalanced conditions, and the balancing current is not triggered. Similar conditions can occur for other specific number of cells such as the nine-cell, presented in Fig. 6. To overcome the problem of ineffectiveness of the natural balancing in the FC converter with PS PWM strategy, it can be modified to change the order of redundant states. In the output voltage, the level varies according to a defined order. In a single switching period (T_c – Fig. 2), a given level can be realized in a redundant way from the voltage of different capacitors. When PS PWM is utilized, the redundant states in the output voltage appear in a fixed order (Table 1). Thus the conditions presented in Fig. 6 can occur when the unbalanced voltage is canceled for a unique phase shift of the voltage components of the output voltage. Because the imbalance voltage is cancelled for a particular order of the switching states in a switching period the unbalanced voltage will appear when the order is changed using redundant level realization (Table 2).

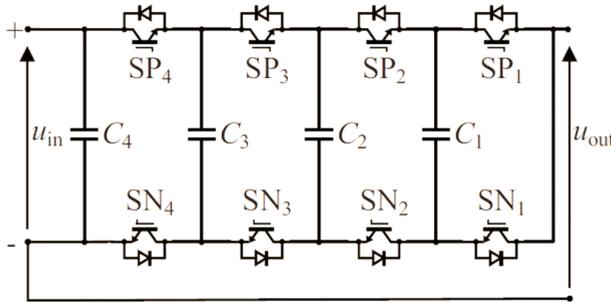


Fig. 7. A four-cell FC inverter

Table 1. Realization and order of switching states in 4-cell converter for PS PWM on the 1st level

Switching state	S1a	0	S1b	0	S1c	0	S1d	0
Turned-on switches	SP1	SN1	SP2	SN1	SP3	SN1	SP4	SN1
	SN2	SN2	SN1	SN2	SN1	SN2	SN1	SN2
	SN3	SN3	SN3	SN3	SN2	SN3	SN2	SN3
	SN4	SN4	SN4	SN4	SN4	SN4	SN3	SN4
Output voltage components	u_{C1}	0	$u_{C2}-u_{C1}$	0	$u_{C3}-u_{C2}$	0	$u_{in}-u_{C3}$	0

Table 2. PS PWM and an example of modified switching order in 4-cell converter on the 1st level

Fixed sequence	State	S1a	0	S1b	0	S1c	0	S1d	0	S1a	0	S1b	0	S1c	0	S1d	0	...
Variation of sequences	State	S1a	0	S1b	0	S1c	0	S1d	0	S1a	0	S1c	0	S1b	0	S1d	0	...

2.3. AUXILIARY CIRCUITRY FOR THE NATURAL BALANCE BOOSTING

In many research works presented in the literature, an additional balancing booster is proposed to improve the conditions for the natural balancing process [1]–[3], [5]–[8], [26]–[31], [54], [76], [77], (Fig. 8).

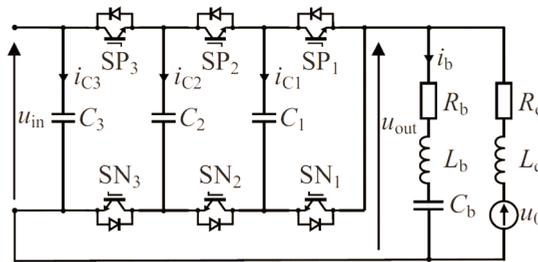


Fig. 8. The balancing circuit ($R_bL_bC_b$) application in the multicell converter

The balancing booster, in a simple way, can be designed as an RLC series branch with the resonant frequency equal to the switching frequency of a single cell (f_c). Thus, under the unbalanced state the balancing circuit creates low impedance for the current flow, triggered by the balancing component (frequency f_c). In the balanced state the balancing circuit represents substantial impedance which limits its unnecessary current flow.

Utilization of the balancing current can increase the cost of the converter. However, it brings some important advantages:

- The dynamics of reduction of the imbalance state can be predicted;
- The level of the imbalance can also be predicted;
- The imbalance state is reduced independently of the load of the converter.

The effectiveness of the balancing circuit and the voltage balancing process is demonstrated in Fig. 9, for the test where the flying capacitor C_2 is discharged by the parallel capacitor. Despite the 300 W discharging, the average voltages on the flying capacitors remain constant. The ripples in the voltages of the capacitors show that the balancing effectiveness depends on the duty cycle. A selection of parameters of the balancing booster is not trivial, and in the literature, much attention is devoted to selection of parameters of the balancing circuit [26]–[31]. It is a critical issue for nominal operation in the case of AC-AC converters (Fig. 23) [3], [27], [28], [76].

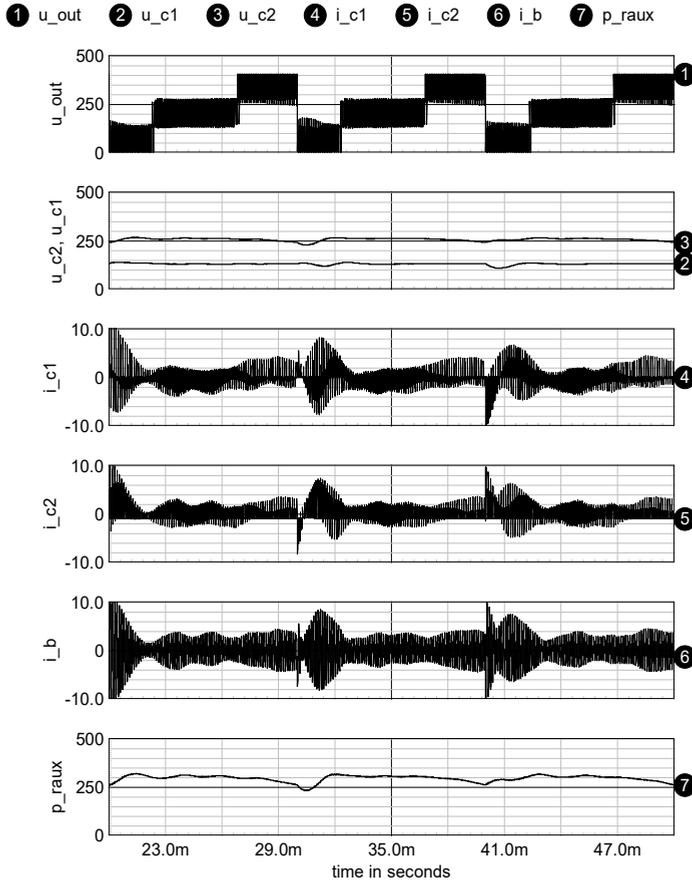


Fig. 9. Waveforms of the three-cell FC converter under the discharge of the flying capacitor C_2 by parallel auxiliary resistor (R_{aux}): (1) the output voltage, (2) the voltage on capacitor C_1 , (3) the current of capacitor C_1 , (4) the voltage on capacitor C_2 , (5) the current of capacitor C_2 , (6) the balancing current, (7) power of auxiliary resistor R_{aux} $C_1 = C_2 = 20 \mu\text{F}$, $U_{in} = 400 \text{ V}$

3. UTILIZATION OF THE NATURAL BALANCING IN FC CONVERTERS

3.1. FLYING-CAPACITOR INVERTERS AND MULTICELL CONVERTERS

The natural balancing of single-phase inverters, as well as multicell converters is well established for multicell converters as well as inverters. However, the problem is still in the current track of research and various types of modulation, as well as the topologies of converters, are investigated.

3.1.1. DOUBLE FLYING CAPACITOR MULTICELL CONVERTER

In [55], the concept of the double flying-capacitor multicell converter (Fig. 10) as well as the modulation strategy are presented. The proposed converter utilizes two additional low frequency switches with the multicell converter which assures an increase in the number of levels and makes it possible to improve its operational features.

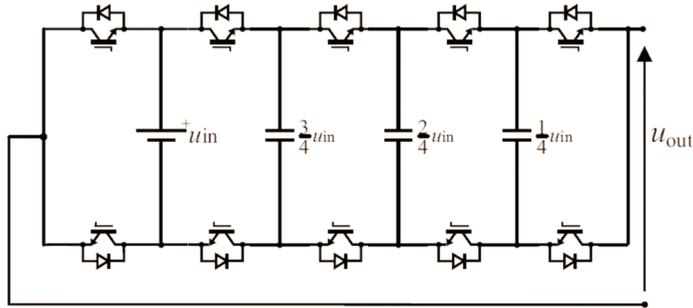


Fig. 10. The double flying-capacitor multicell converter

The modulation based on the PS PWM makes the natural balancing possible in the converter. The results of double flying-capacitor multicell converters are also presented in [56]–[58]. Natural balancing is achieved by the application of PS PWM in the modified flying-capacitor multicell converters (Fig. 11) presented in [59]–[61].

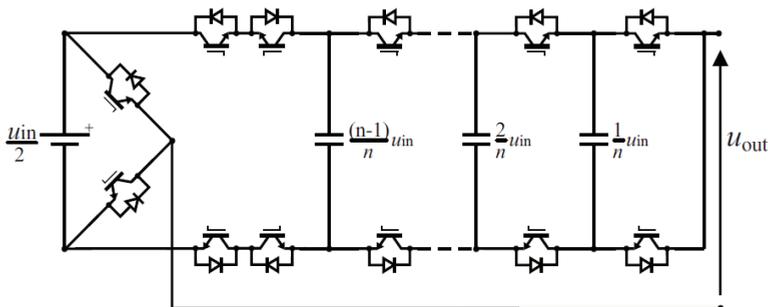


Fig. 11. The concept of the flying-capacitor multicell converters (FCMC)

3.1.2. HIGHER LEVEL INVERTERS AND H-BRIDGE CONVERTER

The FC topology is suitable for applications with a higher number of levels and in many references the multicell converters, stacked converters and inverters are analyzed for levels higher than three. If the number of levels is suitable, it does not affect the natural balancing capability of the converter [54]. An analysis of the voltage balancing dynamics for four-level to seven level single leg FC converters is clearly demonstrated in the series of publications [16], [19], [24], [25].

In single-phase systems, the number of levels can be additionally increased by the use of the H-bridge topology. An in-depth study of the H-bridge FC inverter is presented in [36] and [62] (Fig. 12). In [36], the natural balancing conditions are analyzed for improved carrier-based PWM strategies in 4-level H-bridge FCC. An application of the proposed improved PWM improves the natural balancing dynamics when a small output voltage is realized. The proposed modulation strategy introduces improved switching states redundancy.

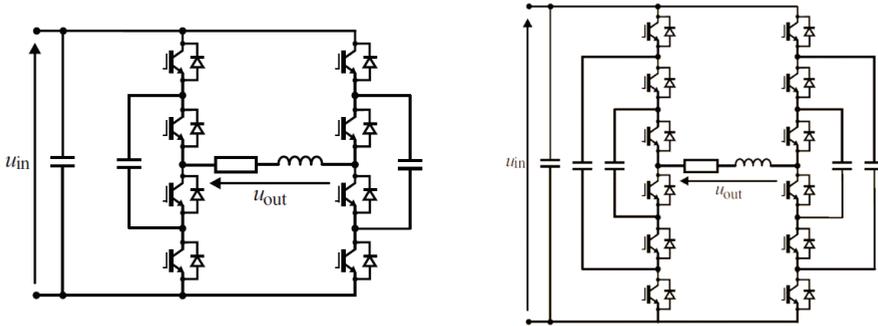


Fig. 12. H-bridge flying-capacitor inverters [36], [62]

The advantages of the proposed PWM strategy were demonstrated and the need for further investigations was suggested in the conclusions due to the new findings during operation under the large modulation indices [36]. The authors in [62] demonstrate a comparison of the H-bridge balancing ability and dynamics for 3-level FC and NPC converter. In [17], [18], [21], [22], four level and five-level FC H-bridge converters are analyzed.

3.1.3. STACKED FLYING-CAPACITOR CONVERTERS

The stacked multicell converter (SMC), [63], presented as an example in Fig. 13, is a composition of two multicell converters which enable an increase in the number of the output voltage levels in comparison to a single multicell converter.

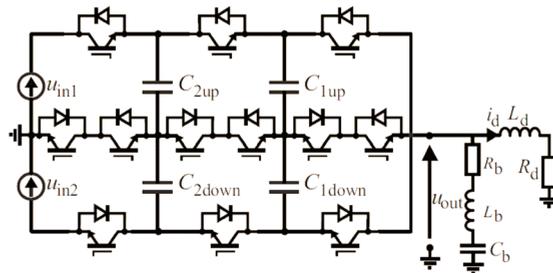


Fig. 13. The flying-capacitor 3-level stacked multicell converter with a balancing circuit

The SMC allows higher input voltages to be utilized and the volume of the capacitors to be reduced. The natural balancing of the SMC is also a subject of investigation. Figure 14 presents examples of waveforms of a 3-level stacked multicell inverter with balancing circuit.

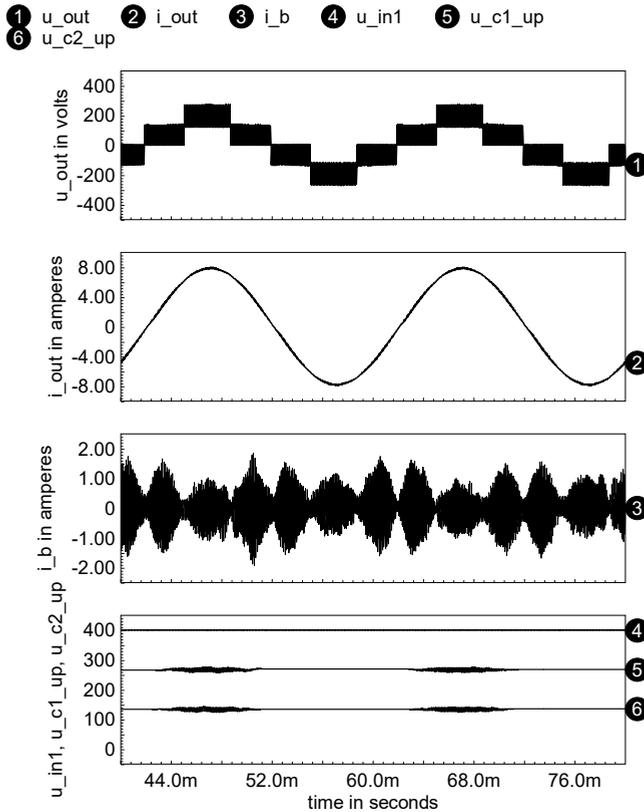


Fig. 14. An operation of the flying-capacitor 3-level stacked multicell inverter. Exemplary waveforms of the output voltage, the output current, the balancing current and voltages of the upper part (u_{in1} , u_{C1up} , u_{C2up}). ICAP/4 simulation results

An in-depth analysis of the natural balancing in the SMC can be found in [64]–[66]. In [65], the study of the voltage balancing dynamics under the phase disposition phase shifted carrier pulse width modulation (PD-PSC-PWM) technique is demonstrated with the use of an analytical model. In [42], [43], the analysis of the natural balancing in SMC is achieved and an in-depth analysis of the modulation strategy related to the balancing in multicell converter, as well as SMC, is demonstrated. The proposed strategy is a modification of conventional PD and CSV PWM with finite state machine algorithms responsible for suitable transitions in the converter branches. An algorithm

of a correction of a state machine decoder for MC and SMC converter for optimal distribution of switching transitions among cells is presented in [50]. In [66], selected topologies with resistive and RL loads using time domain averaging methods are analyzed. The basics of the natural voltage balance in the SMC are similar to the multicell converter case [1]–[31].

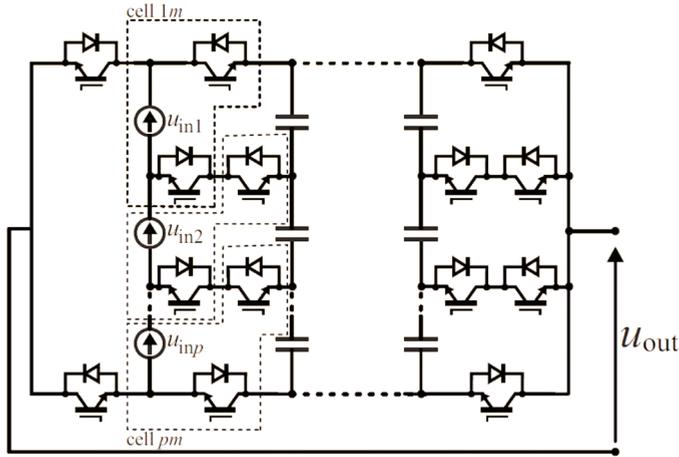


Fig. 15. The flying-capacitor multi-level SMC [67]

In [67], the concept of a higher level SMC converter is presented (Fig. 15) with a reduction in the number of switches as well as the energy stored in flying capacitors. The converter maintains the natural balancing ability by the use of modified PS PWM, proposed in [67]. Examples of operation in cases of 9-level and 13-level converters are presented. In [68], an application of SMC in STATCOM is demonstrated. For self-balancing, the PS PWM is used in the system [68].

In [69], [70], the STC is reconfigured and utilized as a rectifier with sinusoidal input current (Fig. 16).

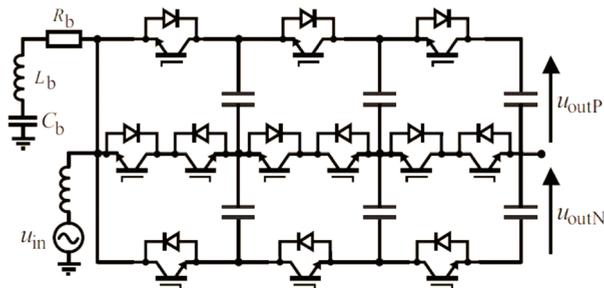


Fig. 16. A flying-capacitor rectifier with sinusoidal input current [69], [70]

3.2. HYBRID-CLAMPED CONVERTER

The four-level hybrid-clamped converter (Fig. 17) proposed in [71] utilizes a flying capacitor as well as dc-link capacitors. Thus the natural balancing of the capacitors is especially attractive in such converter. In [71], the natural balancing of voltages across the flying capacitor and the dc-link capacitors can be achieved in this converter under the fair modulation.

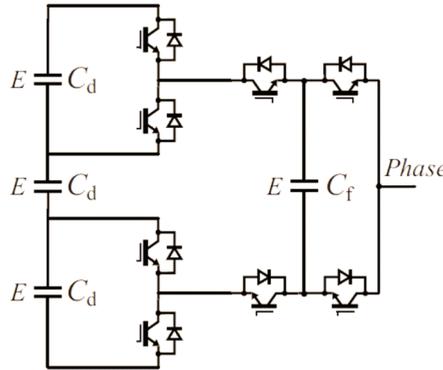


Fig. 17. The four-level hybrid-clamped converter [71]

3.3. SWITCH-MODE DC-DC FLYING CAPACITOR CONVERTER

Aside from the inverters and inductiveless multicell step-down converters (Fig. 2), the flying-capacitor topologies can be introduced to the switch-mode DC-DC converters. In [72]–[75], various topologies are demonstrated and in [75] the natural voltage balance is analyzed in detail for boost and buck-boost FC converter. The advantages of the flying-capacitor topologies versus typical switch-mode DC-DC are as follows:

- A decrease of the stresses on switches,
- An increase of the frequency of the current and voltage of an inductor.

Figure 18 presents the flying-capacitor boost DC-DC converter supported by two flying capacitor cells [75]. This balanced state can be maintained when the natural balancing of the converter occurs. In both the converter voltages on the switches are then reduced (Fig. 19), which is proven in [75]. In [75], many analytical, simulation and experimental results are also presented for the natural balancing ability of the converter, demonstrating very good performance of this method. Figures 20–22 present experimental results of the operation of the flying-capacitor boost converter with two auxiliary capacitor cells. From the waveforms presented in Fig. 20 it is seen that the frequency of the voltage and current of the choke is three times higher than the switching frequency of a single cell. It is the biggest advantage of the FC boost converter aside the voltage limitation on switches.

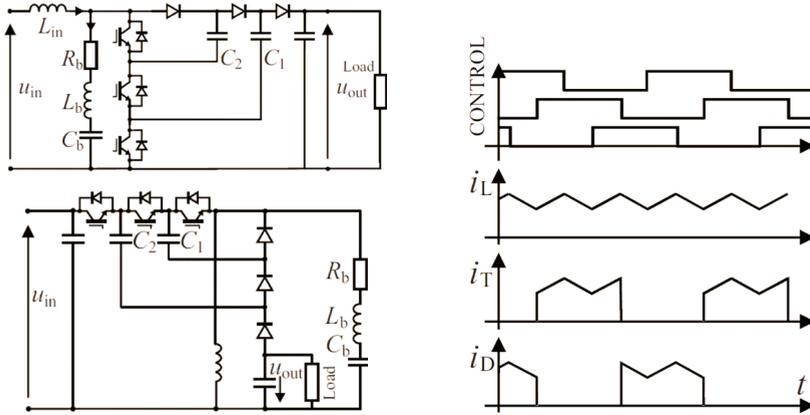


Fig. 18. The flying-capacitor DC-DC boost and buck-boost converter [75].
Application of a balancing circuit and theoretical waveforms in the FC boost converter

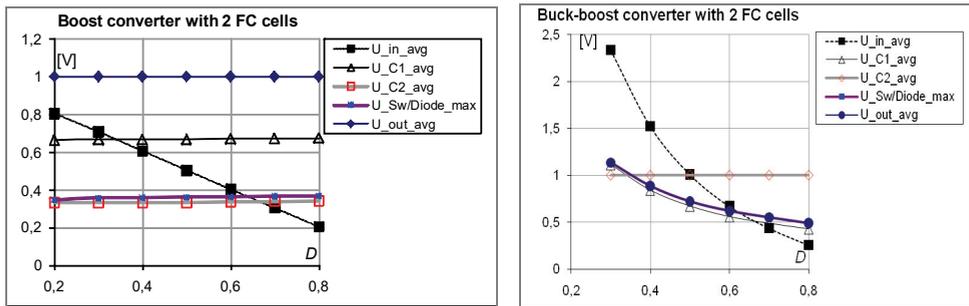


Fig. 19. Examples of simulation results (ICAP/4 software) of input and output voltages, voltages on the capacitors and voltage stress on a switch and a diode [75]. The values related to the output voltage U_{out}

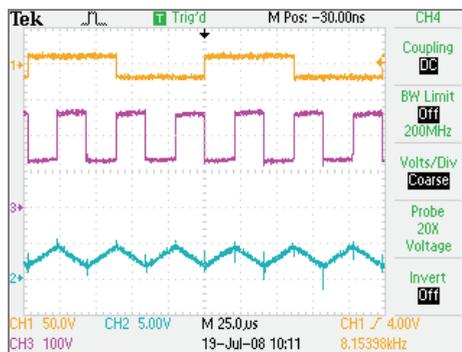


Fig. 20. Experimental results of the flying-capacitor boost converter with two auxiliary capacitor cells (Fig. 18). Waveforms of a control signal of a switch, voltage on a branch of switches (voltage on a balancing circuit), and inductor current (i_L). $U_{in} = 200$ V, $P_{out} = 1$ kW

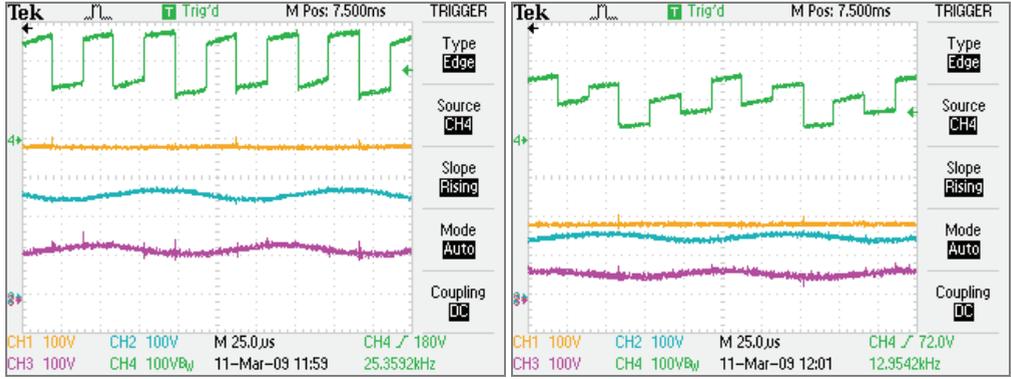


Fig. 21. Experimental results of the flying-capacitor boost converter with two auxiliary capacitor cells and the balancing circuit (Fig. 18). Waveforms of the voltage on the balancing circuit, output voltage and voltages on the flying capacitors u_{C2} , u_{C1} . $U_{in} = 200$ V, $P_{out} = 1$ kW, $D = 0.5$.

(a) Balanced state, (b) exemplary unbalanced state (capacitor C2 discharged by parallel 120 Ω resistor)

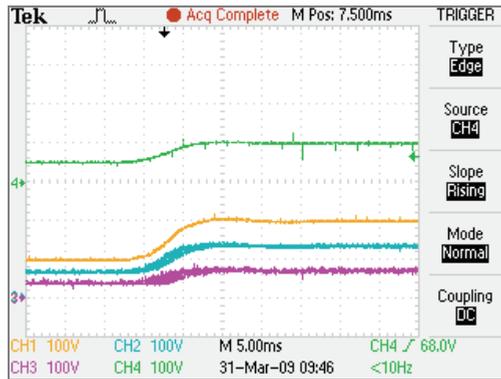


Fig. 22. Experimental results of the flying-capacitor boost converter with two auxiliary capacitor cells and the balancing circuit (Fig. 18) under the variation of the input voltage from $U_{in} = 500$ V to $U_{in} = 100$ V. Waveforms of the input voltage, output voltage and voltages on the flying capacitors u_{C2} , u_{C1}

Figure 21 demonstrates that the voltage on the balancing circuit will be destroyed by lower frequency harmonics when the voltage sharing on the flying capacitors is improper. The efficacy of the balancing process of the FC boost converter with the balancing circuit is demonstrated in Fig. 22. It is evident that the waveforms of the output voltage and the voltage on capacitors remain in constant proportion in this test.

3.4. AC-AC MULTICELL CONVERTER

The multicell AC-AC converter [2], [6], [27], [28], [84] is a constant frequency step-down voltage regulator with the following features:

- Regulation of rms value of the output voltage,
- Reduction of voltage stress on the switches,
- Reduction of the value of the switching component in the output voltage,
- Increase of frequency in the switching component in the output voltage.

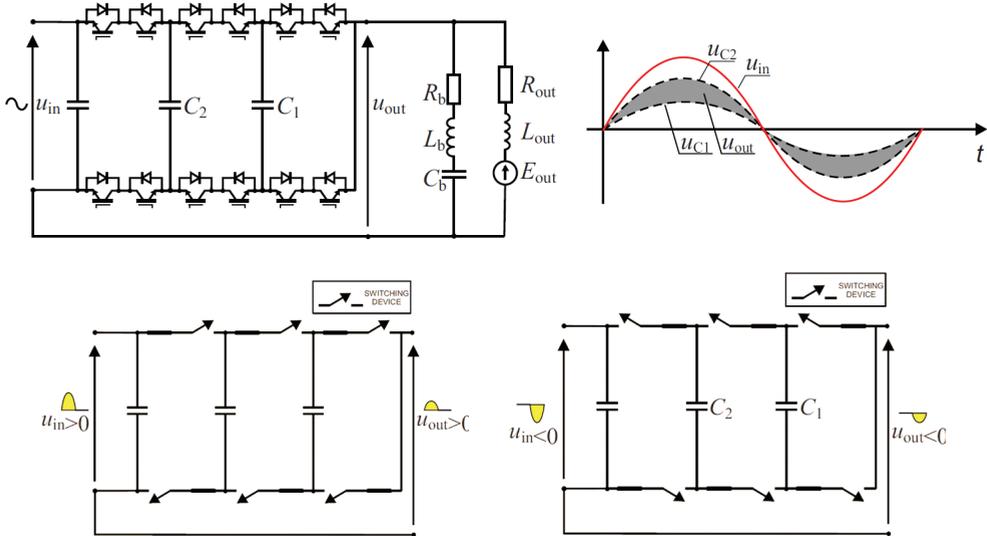


Fig. 23. The multicell AC-AC converter and the concept of operation

The converter can be suitable for power supplies with AC voltage regulation as well as for voltage stabilization in a power transmission line.

Figure 23 presents the topology and the concept of operation of the multicell AC-AC converter. The operation is proceeding under the variation of the input voltage. Positive and negative input voltages are managed by the shorting and switching of the suitable section of switches. The critical aspect for the nominal operation of the AC-AC converter is the suitable variation of voltages on the flying capacitors to stay in a constant proportion to the input voltage, which for the 3-cell case, should be the following

$$u_{C1} = (1/3)u_{in}, \quad u_{C2} = (2/3)u_{in}. \quad (10)$$

The conditions of (10) can be met via proper application of the balancing circuit. Reference [27] is devoted to this issue, where the selection of the characteristic impedance of the balancing circuit for the multicell AC-AC converter is presented, and problems of the quality of operation, stresses of the balancing circuit and converter components, as well as the possible impact on the efficiency is analyzed. Figure 24 presents the case of a proper and improper balanced converter as a consequence of selection of the balancing circuit parameters [27]. Figure 25 presents experimental results which confirm the feasibility of the converter.

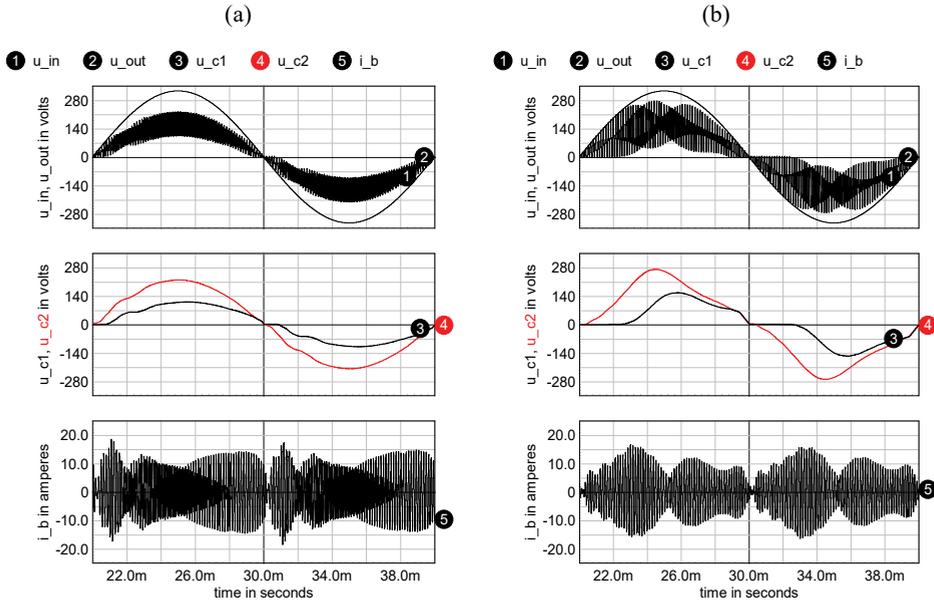


Fig. 24. Instances of properly and improperly balanced converter depending on the parameters of the balancing circuit. ICAP/4 simulation results. (a) $L_b = 0.09375$ mH, $C_b = 4.4$ uF, $R_b = 0.1$ Ω , (b) $L_b = 0.375$ mH, $C_b = 1.1$ μ F, $R_b = 0.1$ Ω , $f_c = 6.8$ kHz

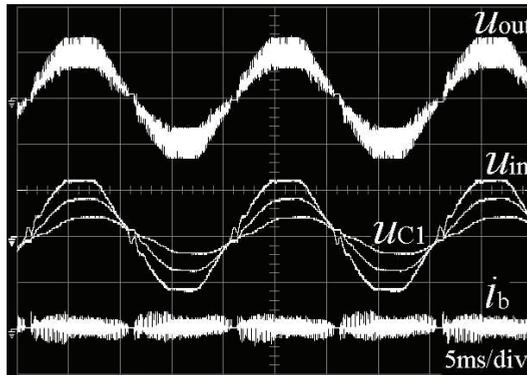


Fig. 25. An operation of the three-cell AC-AC converter. Experimental results for $D = 0.82$, $f_c = f_0 = 7052$ Hz, $\rho = 58.38$ Ω [78]

3.5. INITIAL CHARGE OF THE FLYING CAPACITORS

Initial charging of the flying capacitors assures that the voltage stresses on the switches are limited at the beginning of operation.

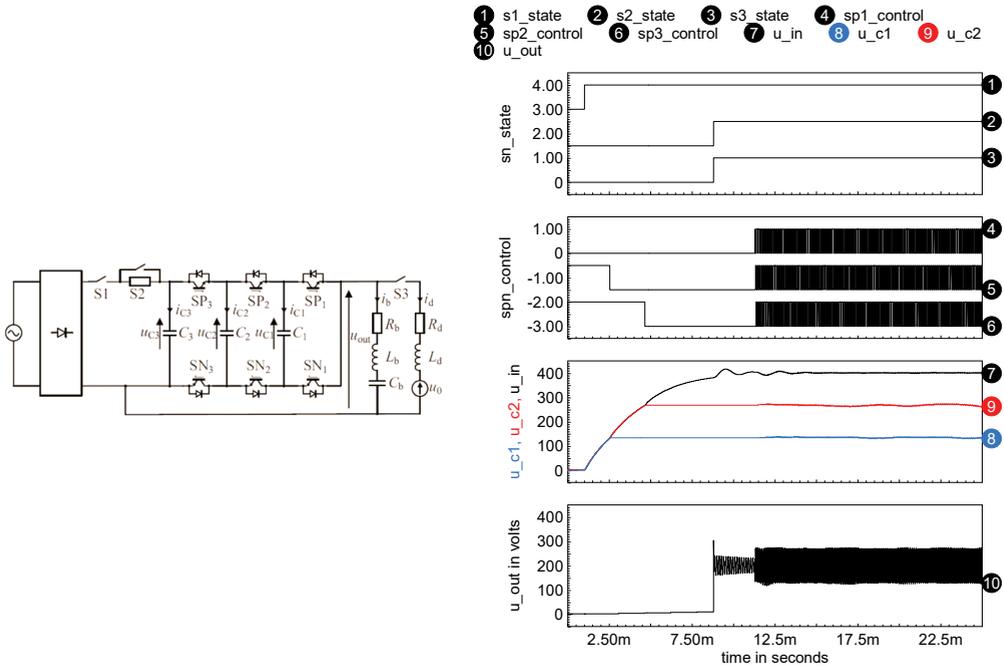


Fig. 26. Charging procedure of the flying capacitors with the use of auxiliary resistor with bypassing switch. ICAP/4 simulation results. The test achieved on the basis of [79]

The capacitors charging can be achieved with the use of auxiliary resistors after connecting the converter to the input source [79]–[85]. Figure 26 presents the results of charging procedure of the flying capacitors with the use of an auxiliary resistor with bypassing switch presented in [79]. Operation of the auxiliary switch S2 and the switches in cells makes it possible to charge the capacitors to adequate values. Aside the input resistor, the natural balancing mechanism can also be used for improvement of the charging of the flying capacitors during the start up [33], [80], [81] or suitable switching [82]–[84]. In [85], charging resistances are also used for the capacitors voltage balancing. However, contrary to other solutions, in [85], the resistors are connected in parallel to switches.

4. CONCLUSIONS

The flying-capacitor topology is a well established concept of the multilevel conversion [86], [87]. However, the basic concept of the FC topology is adopted into many new multilevel topologies of converters proposed in recent years. One of the significant qualities of FC converters is the ability for natural capacitor balancing, but the method

can only be used under the suitable conditions. Existing achievements in the field of natural voltage balance process in the FC converters focus of the following aspects:

- Mathematical modeling of the voltage balance and analysis of the process existence in a particular topology. The model can differ in a multicell converter and, e.g., a FC switch-mode DC-DC converter. The number of levels may also be important.
- Modeling of the dynamics of the balancing process and the impact of parameters of the converter. The response of the circuit to the conditions which can affect the voltage sharing on the capacitor should be sufficient to maintain safe voltage stresses on switches.
- Development of new FC topologies. This paper presents several types of FC converters where natural balancing exists (Table 3).
- Development of modulation methods which produce suitable output parameters, maintaining natural balancing abilities of the converter. Thus, the FC converter may operate with modulation other than PS PWM, which assures the natural balancing.
- Utilization of auxiliary balancing booster to improve the balancing ability of the converter. For instance, in a multicell AC-AC, the balancing booster with nominal parameters is critical for proper operation. Points of connection of the balancing circuit can also be very important, such as in the switch-mode DC-DC converters.
- Initial charging of the capacitors in FC converters to avoid overvoltage on switches during start-up of the FC converters.

Table 3. A summary of FC topologies and the natural balancing conditions

A case	Natural balancing conditions
Multicell DC-DC converter	<ul style="list-style-type: none"> • good balancing conditions with carrier-based PS modulation, • in some number of level topologies, the natural balancing can fail with the use PS PWM, • fully functional balancing conditions when special control with suitable order of states is introduced.
FC inverter, stacked multicell converters, and double flying-capacitor multicell converter	<ul style="list-style-type: none"> • the same balancing conditions as in multicell converters
Multicell AC-AC converter	<ul style="list-style-type: none"> • good balancing conditions with carrier-based PS modulation, • the balancing process is necessary for proper operation, • fair selection of parameters of the balancing circuit is critical for voltage stresses limitation and output voltage quality.
Switch-mode DC-DC flying-capacitor converter	<ul style="list-style-type: none"> • good balancing conditions in proven cases, • application of balancing circuit is possible and can importantly improve the balancing process.
Other FC topologies	<ul style="list-style-type: none"> • balancing conditions proven for particular cases.
Multicell topology with PD PWM	<ul style="list-style-type: none"> • possible balancing conditions but fully functional can be when special control with redistribution of active switches is introduced.

All these issues are addressed in the literature, but are still developed which is very important taking into consideration an industrial importance of the flying-capacitor topology.

It is worth pointing out that attempts are made to introduce the idea of natural capacitor voltage balancing to other types of multilevel converters.

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