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DC–DC boost converter with high voltage gain and a low number of switches in multisection switched capacitor topology

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Abstract: This paper presents a concept and the results of an investigation of a DC–DC boost converter with high voltage gain and a reduced number of switches. The novel concept assumes that the converter operates in a topology composed of series connection switched-capacitor-based multiplier (SCVM) sections. Furthermore, the structure of the sections has significant impact on parameters of the converter which is discussed in this paper. The paper demonstrates the basic benefit such a multisection SCVM idea in the converter, which is the significant reduction in the number of switches and diodes for high voltage gain in comparison to an SCVM converter. Aside from the number of switches and diodes, such parameters as efficiency and volume of passive components in the multisection converter are analyzed in this paper. In figures, the analysis is demonstrated using the example of 100 kW thyristor-based converters. All the characteristics of the converter are compared between various configurations of switching cells in the particular sections, thus the paper can be useful for a design approach for a high voltage gain multicell converter.

Key words: DC–DC converter, boost converter, switched-capacitor, high voltage pulsed power

1. Introduction

Switched-capacitor (SC) power converters represent a large family of circuits which is intensively developed in recent years. The basic idea of the charge pump can be applied into power electronic converters in various topologies. In such converters the capacitors charge and discharge in series or parallel configurations, in resonant circuits, which makes it possible to achieve the required voltage ratio [1–17].

When using reconfigurable topologies with switched capacitors, a large number of switches are usually required. In topologies such as voltage multipliers, in which the voltage ratio equals

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four, reported in [3–6], six transistors or thyristors, four diodes and three switched capacitors are required. In such converters an increase in voltage gain by one requires two additional switches and one diode. This problem also affects other topologies, such as Dickson [7–10], or Fibonacci [11–14] SC converters.

How to reduce the number of switches in SC converters is an important problem that is addressed in the literature [17, 18]. In [18] canonical SC topologies with a minimum number of capacitors are analyzed. This paper presents a method to reduce the number of switches in the converter by introducing a multisection converter composed of SC-based units. The benefits of such a method are demonstrated in the class of SC voltage multipliers (SCVMs). By comparing high voltage gain SCVMs and multisection SCVMs (MSCVM), a reduction in the number of switches is proven and demonstrated. The total number of passive components, their volume and the efficiency of the MSCVM are also analyzed in this paper.

Module-based topologies, also called multistage or multisection, are used in the generators of high voltage pulses [19–23]. However, the SC generators have different purposes to converters and usually do not conduct significant current. The proposed topology (MSCVM) is dedicated to converters which can be loaded with significant current. It can operate as a resonant converter with a low number of switches, but also with zero current switching (ZCS) mode operation, and it is highly efficient. The analysis of the converter is included in Section 2 and subsections. Such issues as the basic concept of the multisection converter, its voltage gain, number of switches, efficiency of the converter, as well as its volume and number of passive components are investigated. The analysis is performed for various configuration of the number of switches in sections which can be useful for optimization of the converter design. The increase in the current capability of the SC converter can be achieved by parallel connection of sections of the converter [24]. The specific array of switches [24] may enable to achieve different conversion ratios [24].

2. Basic concept and benefits of multisection SC resonant converter

The concept of the SC multisection resonant converter assumes a series connection of converters, as presented in Fig. 1.

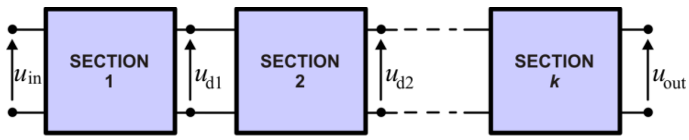

Fig. 1. The composition of a converter in the multisection system

2.1. Voltage ratio of MSCVM

In the basic concept, the multisection converter is investigated as a module-based topology composed of resonant switched capacitor voltage multipliers (Fig. 2).

In a single section of the SCVM, capacitors are charged from the source U_{in}, via the inductor L_1, after switching-on the charging switches (with SN symbols) [3, 4]. As the capacitors are

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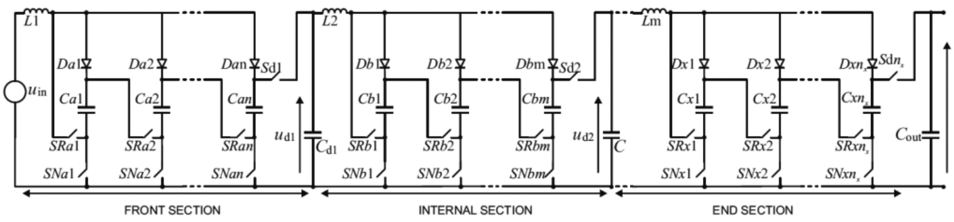

Fig. 2. The multisection SCVM converter (MSCVM)

charged, the SN switches are switched-off and SR and Sd switches are switched-on, but with the delay necessary to achieve blocking by the turned-off switches. This causes discharging of the capacitors connected in series with the source and the output capacitor C_d. Thus, in the n-cell single-section converter the output voltage can reach the following value, for the whole range of the rated load (discounting voltage drops at the semiconductor switches):

$$U_{d1} = U_{\text{in}}(1 + n), \tag{1}$$

where n is the number of switching cells in an SCVM.

Thus a single section of the MSCVM operates with the following voltage gain:

$$G_s = (n + 1). \tag{2}$$

When each section of the MSCVM represents a converter with the voltage gain G_s the series connection of the SCVM converters yields the voltage gain:

$$G_{\text{MSCVM}} = G_{s1} \cdot G_{s2} \cdot \ldots \cdot G_{sk}\,, \tag{3}$$

where k is the number of sections in the converter.

In the particular case of the MSCVM converter the multicell composition causes a substantial reduction in the number of components in high voltage gain systems.

To compare the basic SCVM with the MSCVM converter for a required voltage ratio, such qualities as the number of switching devices (switches and diodes), the volume of passive components, efficiency and cost should be considered.

2.2. The number of components in the MSCVM

In the two-section converter the output voltage of the first section is the input voltage for the second section. Thus, the average value of the output voltage in the second section is as follows:

$$U_{d2} = U_{d1}(1 + m) = U_{\text{in}}(1 + n)(1 + m), \tag{4}$$

where n is the number of cells in the first section and m is the number of cells in the second section of the converter.

In the dual-section converter, in which each section includes more than one switched-capacitor cell, the voltage gain of the entire converter is higher than in a single-section converter using

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the same number of cells. Therefore, using a given number of switched-capacitor cells the dual-section converter achieves higher voltage gain than the single-section converter which is the key advantage of the proposed converter. Relationships (3) and (4) also show the general advantage of the multisection concept, in which the number of components can be substantially reduced versus a typical single section converter. This is extremely important because switched capacitor converters usually use a large number of switches and capacitors.

Fig. 3 presents the results of the analysis of the number of required switching cells for a converter operating as an SCVM or MSCVM, with voltage gains up to 16. Not all gains can be achieved in a multisection converter, e.g. voltage gains of 5, 7, 11 and 13 (prime numbers), are unavailable from the multiplication of natural numbers. From the results presented in Fig. 3 and Table 1 it also follows that the number of switching cells in an MSCVM is always lower than in an SCVM and for a voltage ratio of 16 the proportion of the SCVM to FSCVM equals 15:4 when the number of switching cells is considered. A voltage ratio of 8 or of 12 can be achieved using 2 combinations of cell numbers in sections, while a voltage ratio of 16 can be achieved using 4 combinations of cell numbers in sections.

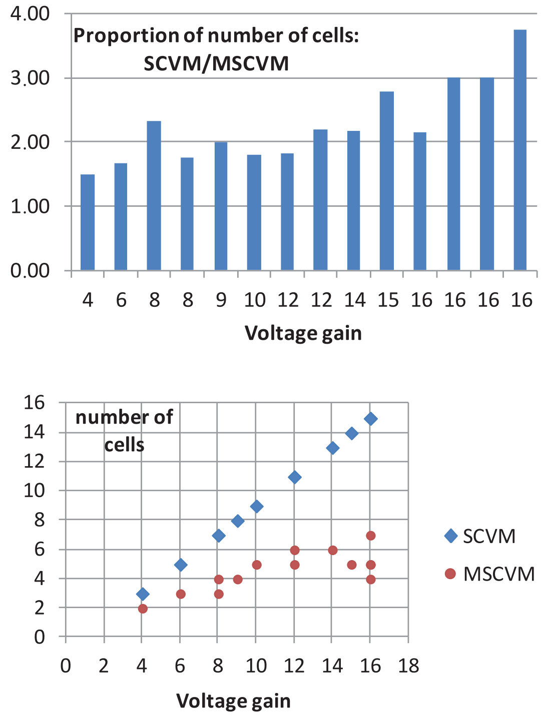

Fig. 3. Number of switching cells in SCVMs and MSCVMs versus voltage gain

Fig. 4(a) presents selected minimum numbers of switching cells in an MSCVM achieved by suitable selections of sections for voltage ratios from 1 to 16. From these results (Fig. 4(a)) it follows that the voltage $G = 16$ can be achieved with the use of a lower number of switching cells

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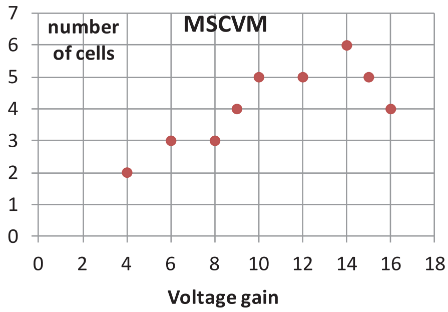
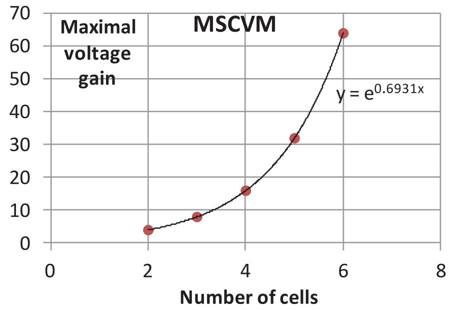


(a)



(b)

Fig. 4. The minimal number of switching cells in an MSCVM that is required for particular voltage gains

Table 1. Voltage gain and number of switching cells in SCVMs and MSCVMs

Gain	**SCVM**	**MSCVM**					
	Number of cells	**gain1**	**gain2**	**gain3**	**gain4**	**Number of cells**	**Number of SCVM to MSCVM**
2	1	–	–	–	–	–	–
4	3	2	2	–	–	2	1.50
6	5	2	3	–	–	3	1.67
8	7	2	2	2	–	3	2.33
8	7	2	4	–	–	4	1.75
9	8	3	3	–	–	4	2.00
10	9	2	5	–	–	5	1.80
12	11	2	6	–	–	6	1.83
12	11	3	4	–	–	5	2.20
14	13	7	2	–	–	6	2.17
15	14	3	5	–	–	5	2.80
16	15	8	2	–	–	7	2.14
16	15	4	4	–	–	5	3.00
16	15	2	2	4	–	5	3.00
16	15	2	2	2	2	4	3.75

than for $G = 10$ to $G = 15$. In fact, it requires the same number of cells as for $G = 9$. Fig. 4(b) presents the maximal voltage gain that can be achieved using a multisection topology versus the number of switching cells. These results were obtained using multisection converters composed of single-cell sections.

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2.3. Efficiency of MSCVM

For the thyristor-based SCVM the following formula can be used to calculate its efficiency [3]:

$$\eta = 1 - \frac{nU_D + (2n+1)U_T}{(n+1)U_{\text{in}}} - \frac{\pi^2 \left(R_L + \dfrac{R_C}{n}\right)}{8U_{\text{in}}^2} \left(1 + \frac{2n}{n+1}\frac{t_d}{t_{ps}}\right) P_{\text{in}}, \tag{5}$$

where: U_D and U_T represent the forward voltage on diodes and thyristors, R_L and R_C are the resistances of capacitors and diodes, t_{ps} is the duration of current pulse during charging of switched capacitors and t_{pd} is the duration of the current pulse during discharging of switched capacitors [3].

For a multisection converter composed of k sections the overall efficiency is the multiplication of the components described by the formula (5):

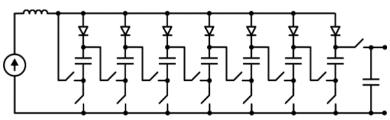
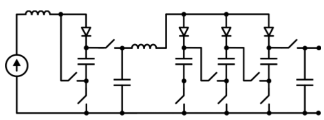
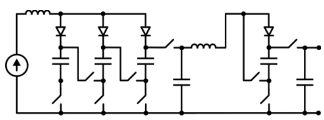
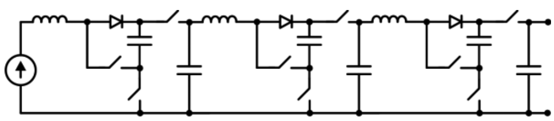
$$\eta = \prod_{i=1}^{k} \eta_i\,, \tag{6}$$

where i is the number of a section, η_i are the efficiency values for particular sections and $\eta_i < 1$.

From (6) a method for the calculation of the efficiency of a multisection converter can be derived. However the efficiency of particular components of (6) can differ, because it depends on the parameters of devices in a given section, determined by voltage and current stresses.

In this paper an example efficiency analysis of a thyristor-based converter with gain $G = 8$ is demonstrated (Fig. 5). This is a very interesting example because it can be composed of a single, two- or three section converter, and it is presented in Table 2.

Table 2. Parameters for a thyristor-based converter with $G = 8$

	U_{in} [V]	V_{Tn} [V]	V_{FD1} to V_{FD8} [V]	$V_{\text{FD out}}$ [V]
	500	0.82	1	1
SCVM Single-section (acronym 1-sect)				
SCVM Two-sections (2-sect 3-1)				
SCVM Two-sections (2-sect 1-3)				
SCVM Three-sections (3-sect 1-1-1)				

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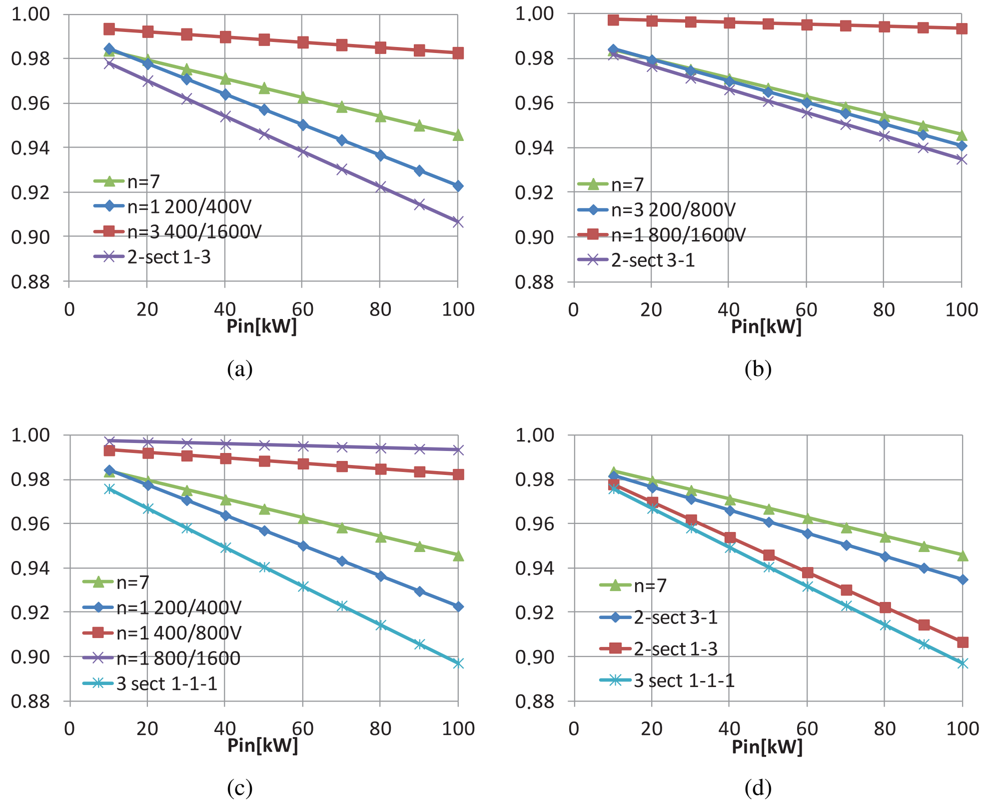

Fig. 5. Efficiency calculated for an SCVM and various configurations of MSCVMs; in each example the converter is designed for minimal switched capacitance optimization [3, 4]

2.4. Volume of resonant circuit LC components

Resonant circuits of the analyzed SCVM converters are composed of an input choke and switched capacitors in particular cells. The capacitance of the switched capacitors should be large enough to transfer the rated power in the converter with a given number of cells, switching frequency, and value of the resonant inductor, according to the relationship presented in [3]:

$$C \geq \frac{P_{\text{in}}}{2(n+1)U_{\text{in}}^2 f_s}\,. \tag{7}$$

The inductance of the SCVM converter is a function of the capacitance of switched capacitors, the number of cells and the frequency of oscillation of current in resonant cells (expressed by t_{ps} parameter) [3]:

$$L = \left(\frac{t_{ps}}{\pi}\right)^2 \frac{1}{nC}\,. \tag{8}$$

In a single section, the energy of all the switched capacitors is the following:

$$W_{C\,\text{sec}\,t} = 2nCU_{\text{in}}\left(U_{C\,\text{max}} - U_{\text{in}}\right). \tag{9}$$

Assuming: $U_{C\,\max} = 2U_{\text{in}}$ (for a converter designed with the minim capacitance):

$$W_{C\,\text{sec}\,t} = 2nCU_{\text{in}}^2 = W_{L\,\text{sec}\,t}\,. \tag{10}$$

In the MSCVM more than one resonant choke is applied (one choke per section). The total energy of the capacitors, as well as of the inductors should be calculated for each section and added together. Fig. 6 presents the total energy of the switched capacitors in the analyzed converters with $G = 8$, and a possible configuration of the sections.

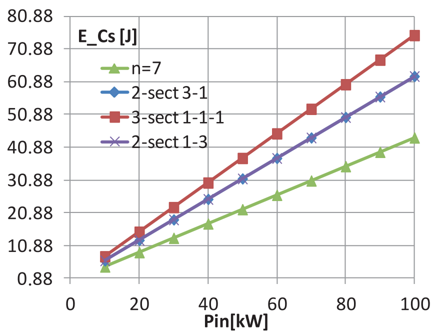

Fig. 6. The total energy of the switched capacitors in the analyzed 100 kW thyristor-based converters in various configurations of sections when $G = 8$

2.5. Voltage ratio decrease in a real converter

In a real converter a voltage gain is lower than in a theoretical one (1), due to voltage drops on components and power losses during the charge pump operation. In [3] many experimental results of voltage gain versus power is presented for SCVM-type converters. These results show a linear voltage drop versus the load power. The intensity of the voltage drop can depend on the number of switching cells in the SCVM converters.

In the MSCVM converters a voltage drop of a given section is multiplied by other sections, therefore it should be designed as low as possible to minimize the total voltage drop:

$$G_{\text{MSCVM}} = U_{\text{in}}(G_{s1}\,D_1)(G_{s2}\,D_2),\ \ldots,\ (G_{sk}\,D_k) = U_{\text{in}}G_{s1}G_{s2}D_1D_2,\ \ldots,\ G_{sk}D_k\,, \tag{11}$$

where $D_k \in (0 \div 1)$.

As the MSCVM uses a lower number of switches than the SCVM, the voltage drops of particular sections $(G_{sk}D_k)$ can be insignificant and the total voltage drop of the MSCVM can be comparable to the SCVM.

2.6. Current stresses of components of MSCVM

In the multisection converter current stress of components is different in each section. The converter boosts the voltage thus the sections closer to the output operate with higher input voltage and currents in these sections are lower. The analytical representation of currents in the SCVM, presented in [3] shows that the values of currents of components (input current – $I_{\text{in avg}}$, peak of inductor current – $I_{L\,\max}$, current of thyristors and diodes – $I_{TD\text{ avg}}$ are inversely proportional to the input voltage:

$$I_{\text{in avg}},\ I_{L\,\max},\ I_{TD\text{ avg}} = f(1/U_{\text{in}}). \tag{12}$$

The multisection approach brings an important benefit from the current stresses standpoint, because the current of the switching components and switched capacitors in the sections closer to the output significantly decreases.

3. Conclusion

In this paper the concept of a modular converter composed of SC-based sections is presented (MSCVM). It has been shown that the MSCVM converter enables a substantial reduction in the number of switches and diodes in high voltage gain converters in comparison to SCVM converters. Furthermore, it has been shown that the MSCVM can be configured in various ways for the same total voltage gain.

The most effective reduction in the number of switches can be achieved in an MSCVM converter divided into sections with voltage gain $G = 2$. An analysis of other parameters relating to the MSCVM, such as efficiency and energy, as well as the number of passive components was undertaken using the example of a thyristor-based SC converter with $G = 8$. From this analysis it follows that the MSCVM with the lowest number of switches has the lowest efficiency, and requires the largest amount of energy in the passive components, as well as, more inductors and bulky capacitors. Fig. 7 presents a summary of the results generated.

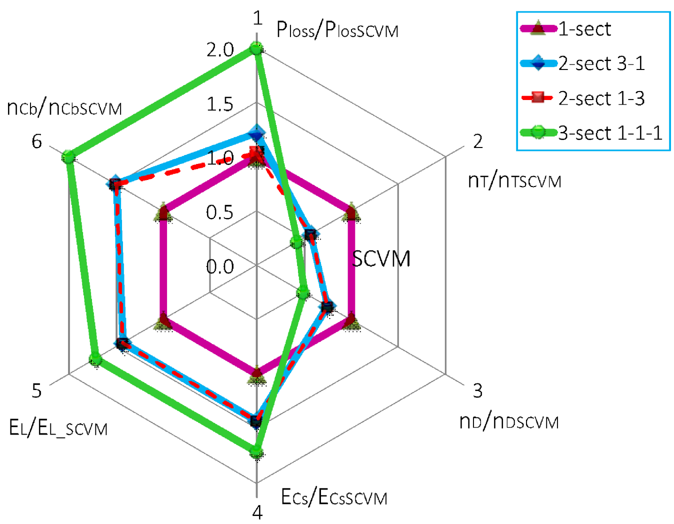

Fig. 7. Comparison of parameters of 100 kW thyristor-based converters in various configurations of sections; results are related to SCVM 7-cell converter where n_T denotes the number of thyristor, n_D is the number of diodes, n_{Cb} is the number of bulky capacitors (on the input and the output), E_{Cs} denotes the switched capacitors energy and E_L represents the energy of inductors

In future investigations, other switch technologies should be taken into consideration, such as those using metal-oxide semiconductor field-effect transistor (MOSFET) or wide band gap (WBG) switches. Especially interesting, from the efficiency standpoint, could be the use of a MOSFET-based SC converter. A model of efficiency of the MOSFET-based SCVM, presented in [5] contains a component related to switching losses, which are dependent on C_{oSS} capacitance. A decrease in the number of switches, achieved by the application of the MSCVM could lead to lower power losses in comparison to the SCVM.

Each section has a non-ideal voltage ratio and the voltage drop of a given section is further gained by other sections. However using sections with a low number of components can limit the total voltage drop of the MSCVM.

Current stresses of components decrease when a section is located closer to the output.

Such additional issues as current and voltage ripple filtering or a problem of synchronization of switching should also be investigated in further research.

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