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The Multilevel Switched Capacitor Power Converter. Experimental Proof of Concept.

Abstract. *The main scope of the paper is experimental assessment of feasibility of the switched capacitor multilevel converter (MLSCC). The converter operates as a resonant charge pump and represents the specific relationships between the resonant circuit parameters, and performance of the converter. Thus, measurements of performance of the converter for the different sets of the LC components are presented. The impact of the specific features of the ceramic capacitors is shown and analyzed. The limitations of the real converter are analyzed and design guidelines are formulated. The measurements and the analysis of the experimental setup include voltage gain, efficiency, voltage ripple, as well as resonant circuit operation.*

Streszczenie. *Przedmiotem artykułu jest eksperymentalne sprawdzenie wykonalności przekształtnika DC-DC typu MLSCC (Multi Level Switched Capacitor Converter). Przekształtnik pracuje, jako rezonansowa pompa ładunku i charakteryzuje się szczególnymi zależnościami pomiędzy parametrami układu rezonansowego a osiągami. Z tego powodu przeprowadzono pomiary przekształtnika dla kilku parametrów obwodu LC. W artykule zaprezentowano i przenalizowano wpływ właściwości kondensatorów ceramicznych na pracę przekształtnika. Przeanalizowano ograniczenia przekształtnika i przedstawiono zalecenia projektowe. Pomiary i analiza układu laboratoryjnego obejmowały wzmocnienie napięciowe, sprawność, tętnienie napięcia jak i warunki pracy układu rezonansowego.(**Wielopoziomowy Przekształtnik o Kondensatorach Przełączanych. Eksperymentalna Weryfikacja Koncepcji**).*

Słowa kluczowe: Przekształtnik wielopoziomowy, przekształtnik DC-DC, przełączane kondensatory, pompa ładunku
Keywords: Multilevel converter, DC-DC converter, switched-capacitor, voltage multiplier, charge pump

Introduction

Switched-capacitor DC-DC boost converters, in some applications, can be an alternative solution to switching-mode topologies. The major advantage of the switched-capacitor converter is the high voltage gain ability and nearly inductorless design. There are numerous of concepts of the power converters based on the switched-capacitor circuits [1]-[12] mostly in the step-up converters.

Calculation of efficiency of the switched-capacitor power converters is complicated [10-12], and high efficiency can be achieved by ZCS operation (Zero Current Switching) when the switched capacitors are recharged in oscillatory circuits. To achieve that, inductances are introduced to the circuits, as a dedicated or parasitic component. However, from the efficiency standpoint it is very important to achieve high quality factor of circuits and switching frequency near to the oscillation frequency [10]-[12]. Thus the process of the oscillations in the switched-capacitor converter should be in-depth recognized because it can vary depending on design and topology of a converter. In [1] the problem of oscillation model was analyzed in the MLSCC topology theoretically and with the use of simulations. This type of switched-capacitor converter (Fig. 1) is also analyzed here, for confirmation of the feasibility and presentation of the operation of experimental setup. Such issues as presentation of the design concept, feasibility and verification of operation, efficiency measurements and variation of oscillation period are addressed here. The problems of operation of the MLSCC is strongly related to the type of capacitors used in the switching cells which is demonstrated by comparison the test results of cases with the use of polypropylene and ceramic dielectrics capacitors.

The theoretical concept of operation

The MLSCC operates by charging the series output capacitors from the input source (Fig. 2). Each the output capacitor can be charged individually (Fig. 2, 3) or in pairs (Fig. 4, 5). Thus the converter can achieve the double or quadruple voltage gain ratio. In [1] operation of the converter is deeply analyzed by mathematical analysis and simulation.

Experimental setup of the MLSCC

The experimental setup consists of power module (Fig. 7, 6) and control module (Fig.6) The modules are connected with 8 wires that provide an auxiliary power supply for MOSFET drivers and digital control signal. The power module is composed of the main printed board that contains all the diodes, LC components and four switches modules with 2 MOSFET transistors, drivers and isolated auxiliary DC-DC converters. The control module is designed with the use of ALTERA FPGA DE0 evaluation kit. This solution of the setup is flexible and convenient for verification and development of concepts. However, presented hardware solution does not allow for high density and low parasitic designing, but that is not very important in context of feasibility study. Tab.1 presents the assumed parameters of the converter. The key components used in the experimental setup are listed in Tab 2. There two types of capacitors were used for the tests, with ceramic and polypropylene dielectrics in four different values in all. The test with three different inductance values was also performed. All the six tested LC components sets are listed in Tab. 3 and are numbered according to the result of the measured power efficiency of the converter for maximum power (LC1 is the highest).

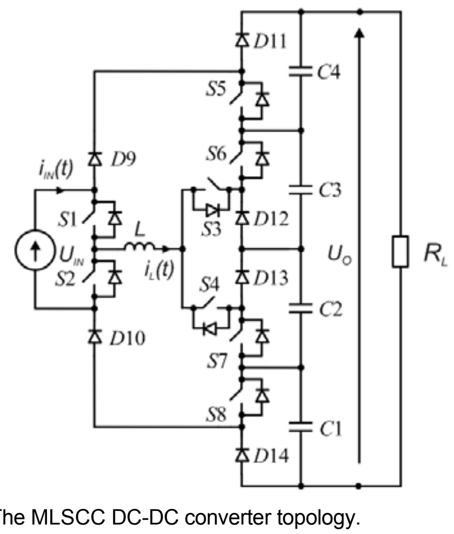

Fig. 1. The MLSCC DC-DC converter topology.

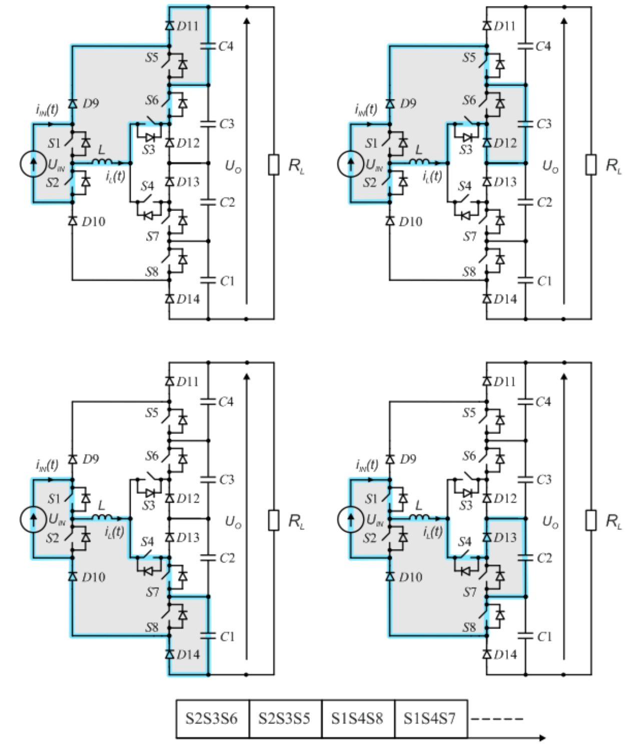

Fig. 2. The operation cycles of the MLSCC at k_U=4. [1]

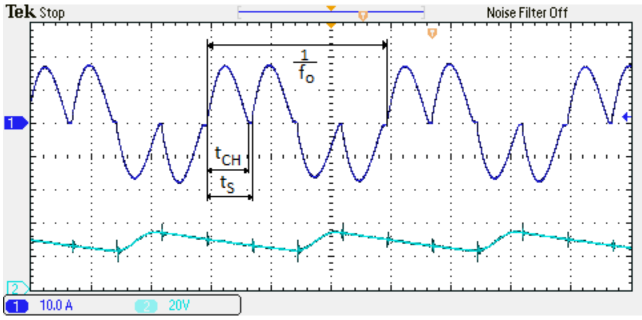

Fig. 3. Waveforms of inductor current (i_L, wav. 1) and voltage of one output capacitor (U_{C4}; wav.2) for $k_U = 4, U_{in} = 30V$, $I_{in} = 10A$. The most important time intervals are indicated.

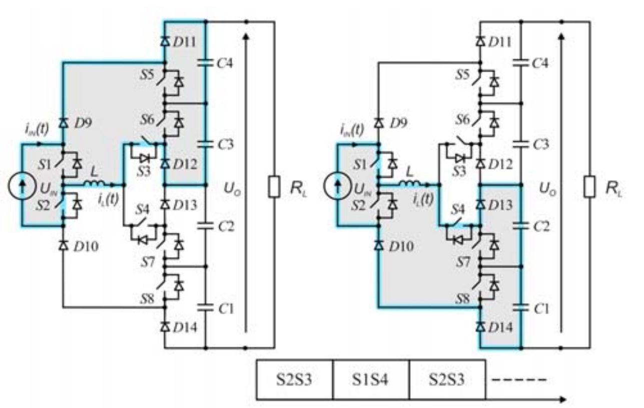

Fig. 4. The operation cycles of the MLSCC at k_U=2. [1]

The measurements and results discussion:

In Tab.3 the parameters of the used LC sets are demonstrated with the measurements of the converter's performance for maximum load. The table consists of the following items:

- V_c – physical volume of capacitors
- t_{CH} – length of charging time of one output capacitor (fig. 3)
- U_{rpp}- peak-peak value of ripple of the output voltage related to mean value of output voltage
- η – power efficiency
- K – voltage efficiency:

$$\kappa = \frac{U_{OUT}}{U_{IN} \cdot 4}$$

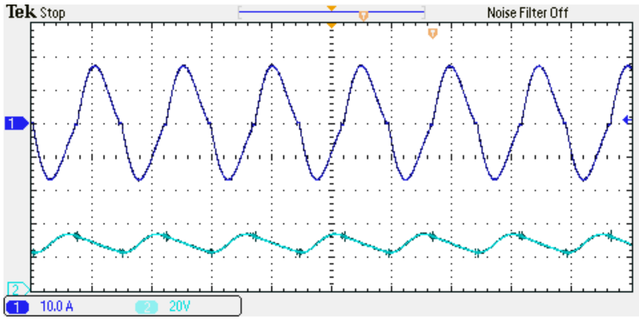

Fig. 5. Waveforms of inductor current i_L (1) and voltage of two (U_{C4}+U_{C3}) output capacitor (2) for $k_U = 4, U_{in} = 30V$, I_{in} = 10A.

Table 1 The assumed parameters for the MLSCC.

Parameter			Mode k_U = 2	Mode k_U = 4	
Input voltage		U_{IN}	30		V
Output voltage (ideal)		U_{OUT}	60	120	V
Nominal power		P	300		W
Operating frequency of the converter	LC1	f_o	75	16	kHz
	LC2		108	23.5	
	LC3		158	34.7	
	LC4		106	26.3	
	LC5		135	33	
	LC6		83	39	

Table 2 The key components used for laboratory setup.

	Type		Pcs
C	MKP10	WIMA MKP1D044706J00KSSD	8
		WIMA MKP1D051007G00KSSD	4
	X7R	TDK C3225X7R1H335K250AB	16
L	0.22 µH	BOURNS SRP1250-R22M	1
	0.47µH	WURTH ELEKTRONIK 74477009	1
	1 µH	COILCRAFT SER2009-102MLD	1
Sx	INFINEON IPB037N06N3GATMA1 3.7mΩ, 60V, 90 A		8
Dx	VISHAY MBRB1660-E3/45		6

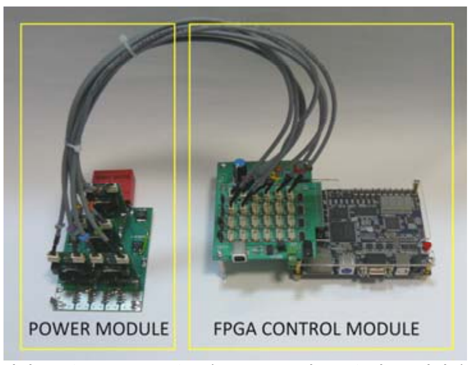

Fig.6 The laboratory converter (power and control module).

It should be noticed that two types of capacitors has been utilized, namely polypropylene and ceramic dielectric. There is the great difference in the physical volume between them, even if the difference in maximum voltage is considered (the maximum voltage of MKP10 capacitors is twice oversized because of availability of the components).

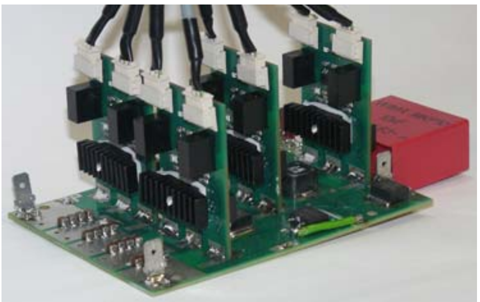

Fig.7 Power module of the converter. The X7R output capacitors can be seen on the PCB.

Table 3 Parameters of various LC components for the MLSCC.

	L	C		V_C	t_{CH}	U_{rpp}	η	K
					U_{in} = 30V I_{in} = 10A k_U = 4			
	μH	μF		cm^3	μs	%	%	%
LC1	0.47	19.4	MKP10 100V	310	15.2	2.2	93.9	93.8
LC2	0.47	9.4		190	10.3	2.8	93.6	93.6
LC3	0.47	4.7		95	6.95	3.2	93.5	93.1
LC4	1	13.2	X7R 50V	0.3	9.15	4.5	93.3	93.2
LC5	0.47	13.2		0.3	7.00	4	92.8	92.6
LC6	0.22	13.2		0.3	5.9	3.4	92.7	92.6

Fig. 8 presents the power efficiency vs the input current characteristics for six different LC components selections, listed in Tab.2 and Tab.3, and for k_u = 4 mode. In all the presented power efficiency measurements the power consumption of control circuits and drivers is not included. For each LC set the switching period t_S was adjusted to the shortest possible value without hard switching. According to the results the ceramic capacitors (X7R) can be considered as less efficient when two LC sets with the same frequency of operation are compared (LC3 and LC5). The lower efficiency can be accepted in many designs since superior physical volume is taken into account. In Fig.9 the efficiency curves for two similar LC sets and both modes of operation can be seen. The converter is definitely low efficient in k_u=2 mode. There are three main reasons for that:

- In k_u=2 mode the switching frequency is much higher due to lower equivalent capacitance (the two of the output capacitors are charged in series Fig.4)
- The equivalent resistance of charging path is higher because the capacitors are charged in series connection.
- All of the charging paths for k_u=2 *mode* has three diodes and two switches while for k_u=4 *there is* 2 diodes and three switches in a circuit. The diodes should be considered as definitely less efficient components than MOSFET switches due to the relatively high forward voltage (Fig.12). For higher voltage circuit this difference in efficiency should not be so substantial.

The important feature of ceramic capacitors is a relatively high dependency of capacitance across the applied voltage. This effect explains the notable difference in capacitance between LC3 and LC5 sets where both utilize the same inductor and both have very similar time of charging interval t_{CH} (Tab.3). Fig. 10 shows that the input voltage of the converter has strong influence on t_{CH} in the case of ceramic capacitor (Fig.10a), and has almost no influence for polypropylene (MKP10) capacitors (Fig.10b). The phenomenon limits the efficiency of converter for higher input voltage of the converter due to shorting the charging time and increasing peak value of current. In such conditions the resistive power losses are significantly increased. This notice can be confirmed by Fig.11 where characteristics of power losses among converter input voltage for two types of capacitors and constant I_{in} are shown. The characteristics (Fig.11) correspond to waveforms (Fig.10) (measured for the same operation conditions and in the same time).

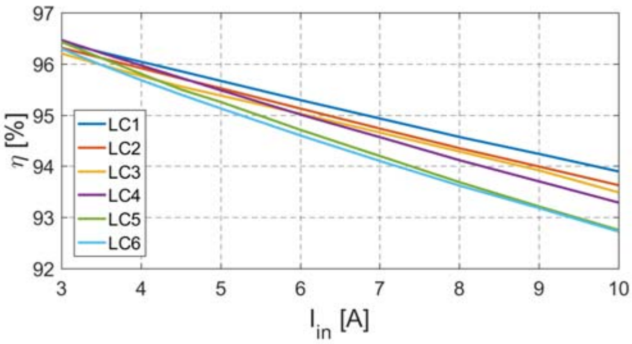

Fig.8 Power efficiency for k_u=4 for different types of the LC components (Tab.3)

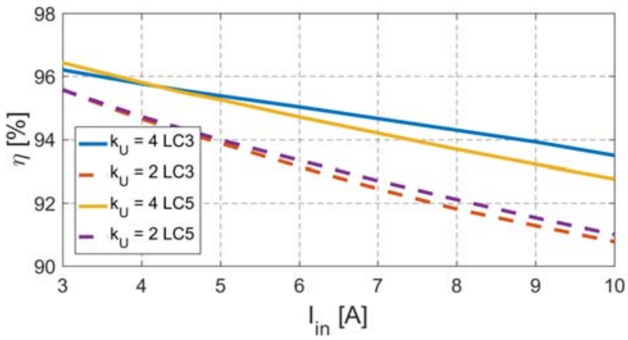

Fig.9 Power efficiency for k_u=2 and ku=4 for two types of the LC components (Tab. 3)

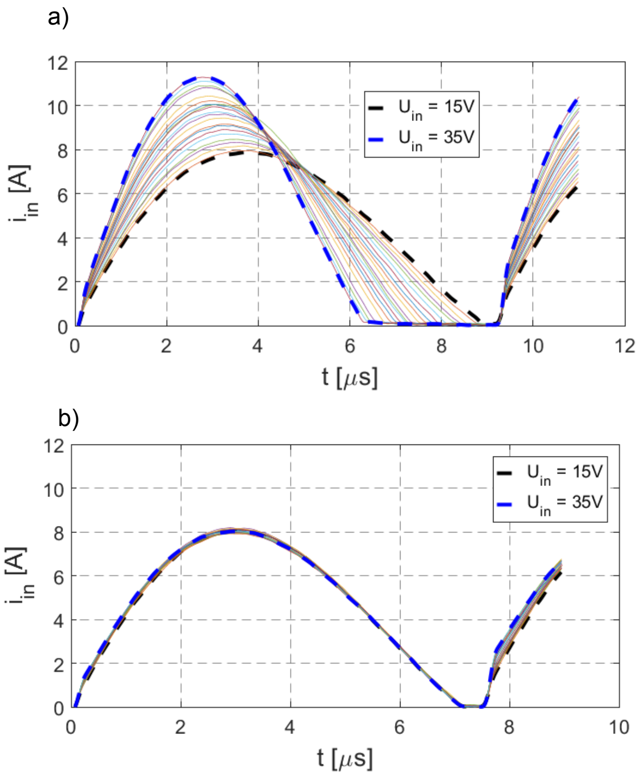

Fig.10 The waveforms of the charging of one output capacitor for different input voltage and constant input current I_{in}=*5A:*. a) LC5(X7R) b) LC3(MKP10)

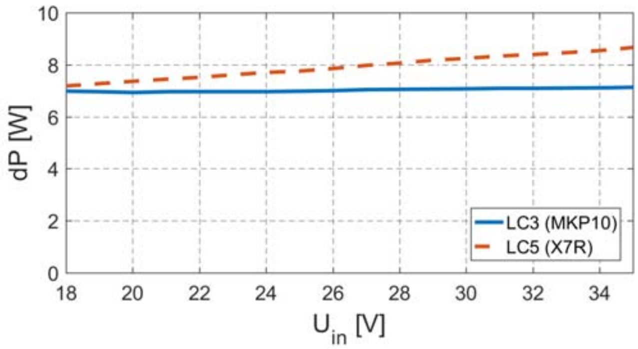

Fig.11 Power losses for k_u=4 for two types of the LC components with different technology of capacitor.

If the converter is designed with ceramic capacitors for operation in wide input voltage range, the active switching frequency adaptation should be considered for the highest possible power and voltage efficiency as well as the lowest output voltage ripples. The main equipment used for measurements is the following:

1. Oscilloscope Tektronix DPO2024B
2. Current probe Tektronix TCP0030
3. Precision Power Analyzer Yokogawa WT1800

Fig.12 IR Thermograph of the converter operating with maximum power. The hottest points are the diodes. Steady state at 300W operation.

Conclusions

The presented results confirm the feasibility of MLSCC converter. The converter operates with relatively low power efficiency 92.5-94% (for k_u=4 mode and peak power) and has relatively low power density. The main reasons are:

- The topology consists of many diodes which strongly affect the power efficiency for low voltage designs like presented in the paper. The efficiency can be increased by application of MOSFETs instead of diodes but presented solution is much more cost effective.
- The presented hardware solution of power module is not optimal but very flexible and suitable for proof of concept purpose. For target application the converter can be design with significantly higher power density.
- The converter has not been optimized.

The presented results show that the adaptive frequency control algorithm may be needed in case of ceramic (X7R) capacitors for achieving the highest power and voltage efficiency in various operation conditions.

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