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PERFORMANCE AND ANALYSIS OF A NOVEL MODULAR MULTILEVEL SWITCHED CAPACITOR UNITS

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Abstract: This paper presents the research results of a multilevel switched capacitor DC-DC converter (MLSCC). The converter, for power electronic applications, can operate in ZCS mode by utilizing resonant circuits for recharging the switched capacitors. The switched capacitor multi-level inverter can produce the desired output voltage and also can boost the input voltage without any bulky transformer. Also, the number of switches and DC voltage sources are reduced in this topology. This reduces the size and cost of the inverter. This topology uses series and parallel combination of the basic unit to produce higher level output voltage. The main focus of this article is an in-depth original analysis of the waveforms and the converter voltage ratio. The concept of the converter is verified by simulation results of the circuit in MATLAB/Simulink Sim Power Systems. The present analysis is important for the converter design process and can be used for numerical multi-object optimization to further improve the converter design. This new multilevel inverter using switched capacitor units can also be used for renewable energy applications.

Keywords: Multilevel inverter, series inverters, series– parallel connection, switched capacitor units.

I.Introduction

Switched capacitor technology is commonly used in chip scale electronic circuits for measurements and supply purposes. Using switched-capacitor topologies in power electronics makes it possible to create a specific class of converters. Advantages of using such converters include less inductive topologies, fast dynamics, small dimensions and fair efficiency. On the other hand, switched capacitor converters usually utilize many more semiconductor switches than conventional switched-mode converters, so they are characterized by having more complicated topology and drivers. The specific energy conversion which uses recharging of capacitors is still a subject of in-depth analysis related to the operational condition, selection of parameters or efficiency [1]–[5]. For instance, a detailed analysis for multilevel-modular capacitor clamped DC-DC converter towards the highest efficiency and the smallest size is presented in [1]. In [2], a selection of components of the switched capacitor voltage multipliers are analysed. It is very important because the fast increase of recent years' scientific papers where switched capacitor power converters are analysed in various topological configurations [1]–[16] is observed. Thus, various methods are used for analysis of various topologies and the presented approach for the MLSCC gives original findings The multilevel topologies of switched-capacitor converters are also implemented [11]–[14] in power converters as resonant ZCS circuits. In many cases [14], [15], the novel multilevel converters originate from the basic switched capacitor multilevel topology. Thus, an in-depth analysis of the operational conditions, resonant circuits utilization, and control and voltage ratios of proposed converters is very important. This paper addresses such an analysis based on a multilevel switched capacitor converter (MLSCC). It focuses on a steady state analysis of oscillation conditions of resonant circuits and the converter's voltage ratio under two types of control. The analysis utilizes a mathematical approach partially supported by numerical methods. A set of figures is presented for arbitrarily selected parameters of the converter. The concepts of the converter topology as well as its driving strategy have been verified by computer simulations. The analysis and findings are original in the case of the MLSCC circuit proposed.

This paper proves that an important impact of resonant circuit parameters on the converter operational conditions as well as novel findings included in obtained models can be very useful in the design process of the converter and control.

II. Hybrid Multilevel Inverter Using Switched Capacitor Units

The term "hybrid" means 'a thing made by combining two different elements, of mixed characteristics, composed of different elements'. Thus the hybrid multilevel inverter is a combination of a switched capacitor topology and an H-Bridge.

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A.Switched Capacitor Unit

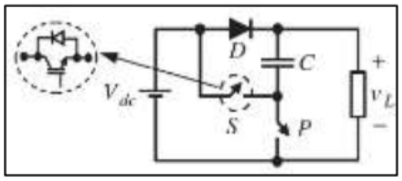
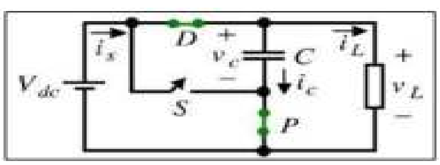
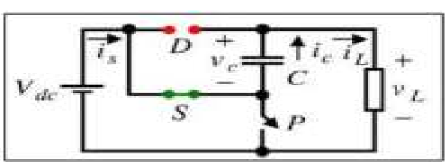


Fig. 1: Basic Switched Capacitor Unit

Figure 1 shows the basic unit of a switched capacitor topology. The basic circuit contains one DC power supply, one capacitor, one power diode and two series/parallel unidirectional power switches. The switches P and S connect the capacitor in parallel and series with the DC voltage source, respectively. When the switch P is turned ON, the capacitor is charged to the voltage V_{dc} , and when the switch S is turned ON, the capacitor starts to discharge. The switches P and S have complementary operation with each other, which means that, when the switch P is ON, the switch S must be OFF and vice versa. Otherwise, a short circuit occurs across the DC voltage source. When the switch S conducts, the diode D becomes reverse biased and prevents capacitor discharging to the DC voltage source. Thus, in the case of series connection of the capacitor and DC voltage source (S is ON), the capacitor current only flows to the load. Figures 2(a) and 2(b) shows the operating mode of the basic unit. The blocked voltage by each switch in Figure. 2 is V_{dc}.



(a)



(b)

Fig. 2 Operating Mode of Basic unit when Capacitor is charging (V_L=V_C=V_{dc}) and Discharging (i_L = i_C = i_s)

III.THE MULTILEVEL SWITCHED CAPACITOR DC-DC CONVERTER:

BASIC CONCEPT

Figure 3 presents the basic concept of the MLSCC converter. It is a kind of topology with a series connection of output capacitors. Each output capacitor (C1–C4) can be separately charged from the source, incorporating the output tank function and the resonant circuit part. The output capacitor charging processes occur successively with symmetrical distribution over time (not overlapping themselves), reduceducing a voltage ripple of the total output voltage. The output voltage ripple can also be minimized by applying an output LFCF filter. The converter can operate with a k_U = 2 or k_U = 4 voltage ratio which is verified by using computer simulation in MATLAB/Simulink Sim Power Systems. The simulation model consists of ideal switches and ideal diodes whichever way losses are modelled, by cumulated parasitic series resistance.

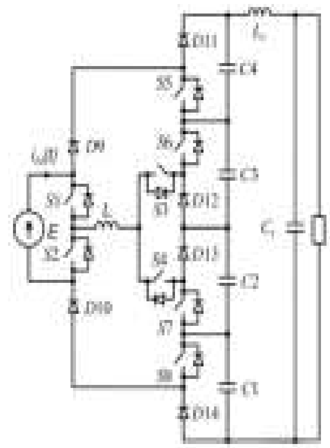


Fig. 3. The basic topology of the MLSCC DC-DC converter in the four-level case

k_U = 4 ratio All the output capacitors (C1–C4) are sequentially and separately charged. This mode of operation is presented in Fig. 2 and the simulation results are presented in Fig. 4.

k_U = 2 ratio The capacitors C1 and C2 (or C3 and C4) are charged together in a series connection. This mode of operation is clarified by Fig.7 and the results of simulation of the converter are presented in Fig. 8

Table 1 Parameters of the simulation model

Parameter		Mode		
		$k_U = 2$	$k_U = 4$	
Switching frequency	f	125	50	kHz
Inductance	L	200		nH
Capacitance of C_1,C_2,C_3,C_4	C	10		μF
Series parasitic resistance	R	45		mΩ
Length of charging interval	T_C	3.5	5	μs
Input voltage	E	30	30	V
Output current of the converter	I_o	3	3	A

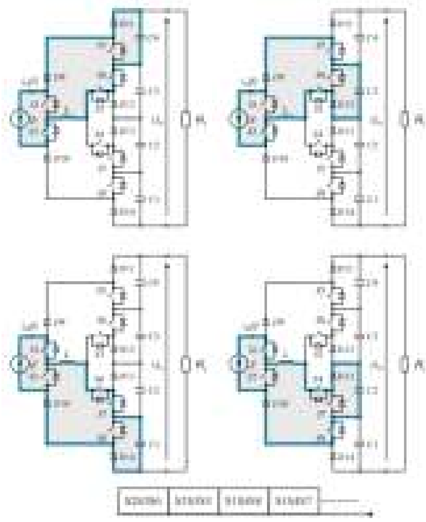


Fig. 4. Principle of operation of the proposed converter for voltage ratio $k_U = 4$

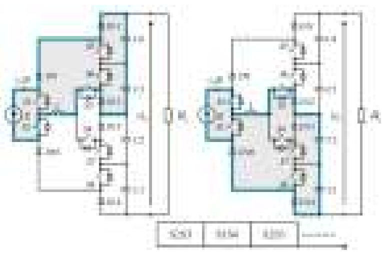


Fig. 5. Principle of operation of the proposed converter for voltage ratio $k_U = 2$

IV.An Analysis Of Mlscc Operation

Waveforms In The Converter

The following assumptions have been introduced to simplify the analysis: all the output capacitors (C1–C4) have equal capacitances; driving signals are symmetrically distributed within the time domain, all output capacitors' charging circuits have equivalent parameters, and all switches operate in the ZCS mode (Zero Current Switching). The converter is loaded by the current source with the value of I0, which represents the real system when the converter is equipped with an output LC filter for output voltage ripple minimization (however, within the analysis, the output filter influence is not considered in detail). Under such assumptions, analyzing the converter in a steady state of operation can be limited to only analyzing one of the output capacitors because they do not interact with each other. The other capacitor waveforms are the same as the analyzed ones, but with a time shift. In Fig. 6, the equivalent circuit for analyzing the output capacitor charging is presented. The resistance R represents the sum of all components' parasitic series resistances in the charging path. The parameter L is the inductance of the converter's resonant inductor and the capacitor C represents one of the output capacitors which is being charged. The current source I_0 is the load of the converter. The diode D is an equivalent of the multiple series connected diodes which exist in the charging path considered. Within the following model, forward voltage of the diodes is neglected.

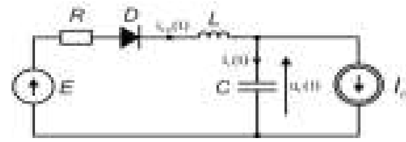


Fig. 6. Equivalent circuit of charging one output capacitor

V.RESULTS & DISCUSSIONS

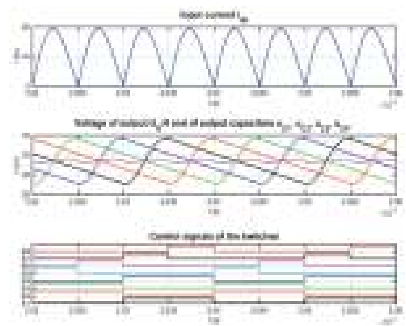


Fig. 7. Simulation result of the MLSCC for mode

$k_U = 4$

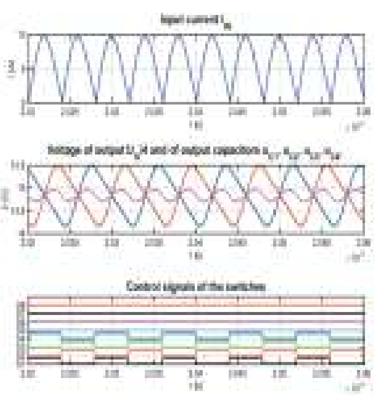


Fig. 8. Simulation result of the MLSCC for mode

$k_U = 2$

Conclusions

The main focus of this article was the mathematical analysis of multilevel switched capacitor DC-DC converters' topology under a steady state operation.

The impact of particular parameters of resonant circuits, including series parasitic resistance, on the operational features of the converter is very important for the design. The analytical solutions to obtain clear relationships can be very complicated; thus the original assumptions have been proposed to simplify the analysis. The important influence of the parasitic resistance on the converter operation is identified and a mathematical model taking the resistance into account is presented. Due to the limitations of mathematical modelling, the numerical approach is proposed for solving a few of the given equations.

The obtained relations are evaluated with the example parameters of the converter and a set of curves is plotted for further reference. Based on the plots, the influence of different parameters on performance of the converter is analyse. The unexpected dependence of the charging interval TC on the switching period TS has been discovered and explained, based on a prepared analytical model. The possible optimization of output capacitors and an input inductor has been identified and discussed. The conclusions derived allow for a careful design of the MLSCC converter regarding component selection. The present analysis can be used for numerical multi-object optimization to further improve the converter design. The concept of topology and drive has been proven by simulation in MATLAB/Simulink software.

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