Switched Capacitor Based Hybrid DC-DC Converter: A Review

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Abstract: This paper provides an overview of the major topologies of switched capacitors (SCs), which are used in DC-DC power conversion. Initially, the basic configurations of voltage doubler, series-parallel, Dickson, Fibonacci, and ladder are examined. Some aspects of the semiconductors and capacitors used in the circuits, as well as their impact on the converter behaviour, are addressed. The operation of the structures is investigated in terms of full charge, partial charge, and no charge conditions. It is worth noting that these factors have a direct impact on the converter design and efficiency. Because voltage regulation is an inherent difficulty with SC converters, some control methods for this purpose are presented. Finally, some practical applications are discussed, as well as the possibility of designing DC-DC converters with higher power levels are analyzed.

Keywords: Switched Capacitors, DC-DC Converters, Integrated Circuits.

I. Introduction

Residential, commercial, and industrial applications for DC-DC converters include renewable energy conversion systems, electric traction devices, and, most notably, power supplies. Electronic devices are thought to process more than 70% of electricity today [1]. In this context, increasing the power processing capacity and power density of converters while lowering manufacturing costs is of critical importance.The advancement of low-power electronics is primarily due to increased material purity and advanced techniques used in the fabrication of integrated circuits (ICs) [2]. This has a direct impact on power electronics, which seeks to increase power levels and maximum operating frequency associated with smaller power converter dimensions [3]. New semiconductors have recently become commercially available. which are silicon carbide (SiC) and gallium nitride based (GaN). Because of their higher efficiency and operating frequency, these elements have promising properties that allow for the gradual replacement of silicon-based (Si) devices. Furthermore, it is possible to combine both manufacturing technologies in a single component [4].In turn, energy storage devices such as capacitors and inductors, which are typically used as filters, directly contribute to improved power converter performance. This is because capacitors use dielectric materials with optimised characteristics [5]. Furthermore, new ferrosilicon alloys can achieve higher magnetic permeability with lower hysteresis and eddy current losses in inductor cores . Topologies are constantly evolving in order to achieve higher power density in power converters. The application of switched capacitors (SCs) has recently piqued the interest of industry and academia. These structures have found use in low-power electronic applications, particularly in systems with small physical dimensions and high energy density. Their properties enable monolithic integration reduced electromagnetic interference (EMI) and reduced weight and volume.Despite the benefits mentioned above, these circuits may be inefficient [6]. The intrinsic characteristics of the switches and capacitors used in the circuit have a strong influence on this aspect, and the number of components must also be carefully considered . Another challenge is regulating the load voltage because, under certain operating conditions, the duty cycle does not have a linear relationship with the output voltage. implies an increase in control system complexity.When compared to topologies composed only of capacitors and semiconductors, SC circuits can also be combined with traditional structures based on inductors to produce families of hybrid converters with improved load voltage regulation and extended conversion ratio. also contains an example of a pseudo SC bandpass filter. Another hybrid approach is resonant SC converters, which can increase power processing capacity and power density. This analysis is beyond the scope of this work because the combination of SCs and inductors results in a wide range of topologies.

II. Related Work

Traditional SC converters are widely used in practise, particularly at low power levels and when high power density is required . These characteristics make them particularly appealing for embedded electronic systems, biomedical equipment, energy harvesting, and general-purpose microelectronics. It is worth noting in this context that some modern portable electronic devices have extremely low power consumption. Smartphones, for example, consume about 1 W, whereas cardiac pacemakers consume 50 W .Several studies have been conducted to examine the importance of utilising the available energy in the environment where a device or equipment is placed. To power the aforementioned devices, various forms of energy can be harvested and converted into electrical energy. Photovoltaic solar energy is a common example [7], but other, more unusual sources are possible. be taken into account, including pyroelectric and blood sugar.Regardless of the source, the use of SC converters in these applications has piqued the interest of researchers in other low-power applications It can also be used to power sensors or very-low-power circuits, which is useful in situations where space is limited Hybrid vehicles, which combine fossil fuels with energy storage devices such as supercapacitors and batteries, are also a promising scenario for the use of SC converters [8]. In this case, the topologies can be used to increase the voltage across the batteries as well as to control the bidirectional power flow with the goal of energy management and battery charging . Because of the Because of its small size, the entire set can even be integrated into the battery system as a consolidated solution.SCVDs are frequently reported in the literature for milliwatt-rated applications such as electrically-erasable programmable read-only memories (EEPROMs), VLSI systems VLSI energy harvesting and liquid crystal display (LCD) technology.Because this is the only type of SC configuration available in the form of commercial ICs, this technology can be used to supply electronic circuits such as operational amplifiers and analog-to-digital (A/D) converters. The shows some voltage doubler ICs that are available on the market and have low output currents and input voltages.With an array of encapsulated SPC structures, SPC structures can be configured more easily. capacitors with a wide range of options for use not only in series to increase gain, but also in parallel to reduce current ripple [9]. Because of the control complexity, existing applications are reported in fewer publications. Some of them include circuits for energy harvesting in and biomedical systems [10]. Because the SP topology is so versatile in terms of voltage gain, the output voltage can remain constant even when the input voltage varies greatly.The Dickson converter was one of the first structures designed for practical memory applications. Existing circuit evolution is primarily concerned with increasing energy density and efficiency. Some devices can even be linked together.the same memory chipThe FC is similar to the SPC, but requires more switches and capacitors. As an emerging application, [11] proposed an emergency power supply for a computer system based on this structure, but LCD drivers can also be found in [12].The ladder topology is also adequate for some specific applications, despite the fact that it is not as commonly used in DC-DC power conversion as its remaining counterparts [13]. This topology has the highest efficiency and versatility of the topologies presented. Even at power levels of 1 kW, the efficiency in experimental tests can be greater than 90% with low voltage ripple . As a result, this is the only promising So far, only one topology has been developed for high-power applications, while the others are only feasible at low power levels [14]. Another solution that has a lower impact on efficiency is voltage regulation via pulse width modulation (PWM) . This technique is widely used in conventional buck, boost, and buck-boost converters to control the output voltage. This operation mode is divided into two stages per cycle in SC circuits. The capacitor is charged in the first stage, and the duty cycle can range between 0 D 0.5. The capacitor is connected to the load in the second stage, and the discharge process begins. This situation occurs during each cycle. It should be noted that as the duty cycle approaches zero, the voltage ripple increases, as do the input current peaks .The interleaved strategy is another strategy presented in the literature. [15] Cell connection This arrangement, however, may or may not work with overlapping phases [16]. The main benefit is that this method reduces output voltage ripple, providing not only voltage regulation but also an increase in efficiency. However, as previously stated, an increase in the number of components causes an increase in losses. Because the current is shared among the interleaved cells, this technique has the advantage of increasing power levels.In electronics, the pulse frequency modulation (PFM) control technique is also well known. The simplicity of producing a variable frequency signal from monitoring the output voltage or output current is the advantage of this strategy. This signal increases the switching frequency. The frequency is determined by the load current [17]. However, under heavy load conditions, this technique does not guarantee reduced voltage ripple [18]. Another important point to remember is that when using MOSFETs, increasing the switching frequency can increase switching losses.The term quasi-switched capacitor refers to a popular control technique that makes use of MOSFET transconductance. This strategy was previously introduced as a new SC cell in [19]. Subsequent work applied this concept in a somewhat ambiguous manner, using the terms "QSC cell" and "QSC control." It is, however, a technique for controlling the gate-source voltage in a MOSFET. The drain current is proportional to the gate-source voltage when operating in the active region, that is, in the triode region [20]. The drain current can be controlled if the MOSFET always operates in that region. The main difference between this technique and the others mentioned above is that the input current waveform does not change during the charge stage, whereas in other cases, there are short-term current peaks. This reduces the current stresses on the switches and prevents the occurrence of conducted EMI. This control strategy has no effect on converter efficiency because efficiency during the charge stage is only determined by the difference between the voltage on the capacitor during the charging process and the source voltage.

III. Structures of SC

Despite the fact that voltage multiplier circuits are simple structures that are widely known and described in analogue electronics textbooks, they are still used in applications that require high DC voltages from an AC voltage source. Because voltage multipliers are simple and low-cost circuits, they are commonly used in X-ray machines, scanning electron microscopes, and particle accelerators, among other devices .There are some SC structures dedicated to specific applications in the literature, which are frequently derived from basic converters provides a description of SC topologies and voltage multipliers used in the design of non-isolated dc-dc converters for high step-up applications. However, the focus of this research is on a thorough examination of existing techniques for extending the conversion range of dc-dc converters with no isolation Some important issues for the design of SC-based converters are not addressed in such as component selection, capacitor charging mode, efficiency evaluation in relation to relevant practical aspects, and control techniques aimed at achieving output voltage regulation.It is worth noting that there is a wide range of circuits that use inductors and SCs in hybrid topologies, particularly for wide conversion range applications. Because of the wide variety of combinations with distinct properties, this work is devoted to the analysis of classical topologies based on the use of only semiconductors and capacitors, resulting in "pure SC" converters [21].

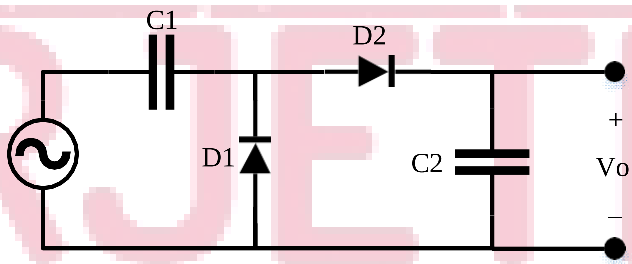

Figure 1. Greinacher voltage doubler.

The Greinacher voltage doubler is the most basic structure of a step-up converter that uses switches and capacitors, as shown in Figure 1 [22]. This circuit is powered by an alternating current source and operates in two stages. The capacitor is charged to the peak value of the source voltage in the first one. The previously charged capacitor is connected in series with the source and supplies a load in the second. This combination produces a voltage that is ideally twice as high as the input voltage.This was one of the first topologies capable of stepping up the voltage across a load powered by an AC source using only passive semiconductors and capacitors due to its simple structure[23]. This circuit or cell may be linked. in a modular manner in series or parallel with phase opposition, allowing for high voltages SC Voltage BoosterAlthough the voltage step-up circuit depicted in Figure 1 may be useful in some applications, it can only be used when an AC voltage source is available. However, many electronic circuits are powered by direct current (DC). In this case, the SC voltage doubler (SCVD) circuit shown in Figure 2 is a suitable alternative.

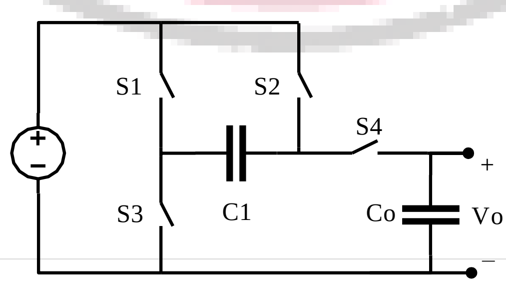

Figure 2. SCVD.

Active switches are used in this structure to control the charge and discharge of the capacitors. The circuit works in the same way as a voltage multiplier, with two stages. The charge of capacitor C1 occurs in the first. Capacitor C1 is connected in series with the source and the load in the second. It is possible to obtain a given gain 2n by connecting several cells in series, where n is the number of associated stages. As a result, high voltage gains can be obtained, allowing high output voltage loads to be supplied. Cockcroft and Walton used an AC-powered circuit to supply a particle accelerator with a voltage of 1 MV, significantly increasing the output voltage. This circuit became known as the Cockcroft and Walton voltage multiplier (CWVM), or simply voltage multiplier, and is illustrated in Figure 3 in several stages. Because of the simplicity of the circuit, low cost, and simple implementation, this is one of the most well-known structures in electronics for obtaining high gains. Using ideal components, the output voltage Vo can be calculated as nVi, where n is the number of associated cells and Vi is the input voltage [24].

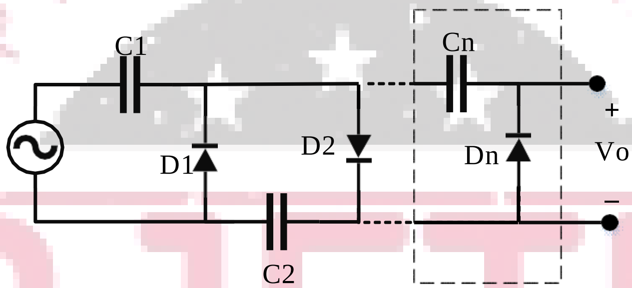

Figure 3. CWVM.

Recent research suggests that this structure could be used in a variety of modern applications, including high-gain DC-DC converters linked to photovoltaic modules and even high power factor rectifiers.The source supplies some charge Q to capacitor C1 in the CWVM, and the charge Q is transferred from capacitor to capacitor (C2, C3,...) until it reaches the last element Cn in each half cycle of the AC input voltage. This process involves shifting the charge through each diode in a manner similar to a ladder, thus justifying the circuit's name.One inherent problem with this topology is that as the number of stages increases, the output impedance increases by an n3 factor[25]. This property restricts the output current to low values, as seen in the In the case of high currents, the output voltage will drop rapidly due to losses [23]. The series-parallel converter (SPC) shown in Figure 4 is one proposed alternative to overcome the CWVM's main limitations in voltage regulation. Because each cell can be connected in series or parallel, and the output voltage can be changed at any time, this converter is extremely versatile.

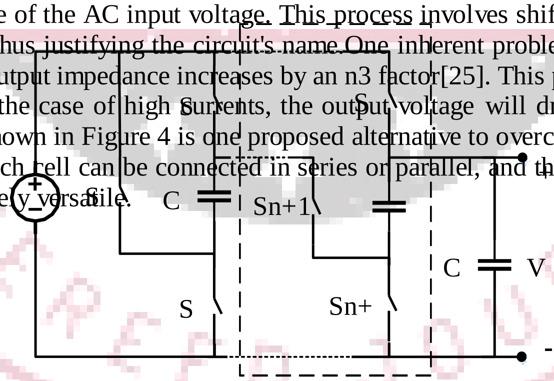

Figure 4. SPC.

The energy transfer from the input to the output occurs, as the name implies, when some of the capacitors are connected in parallel with the source during the charge stage. The capacitors are connected in series and supply the load in a second moment. This arrangement has some notable advantages because it does not have the same issues as the CWVM, particularly with regard to the high output impedance[26]. However, there are some disadvantages, such as the simultaneous charging of many capacitors, which can draw a large amount of current from the source in a short period of time. Furthermore, if many capacitors are charging, the voltage ripple at the output may be high, reducing converter efficiency. Depending on how long the connection tracks are on the Regardless of the printed circuit boards (PCBs), the arrangement of the elements, and the number of capacitors, parasitic capacitances may cause problems, drastically educing the efficiency of the circuit in the event of high voltage gains. The series-parallel multiphase converter (SPMC) [24] is another option for overcoming the problems presented by the CWVM and the SPC. In this way, the transients of the input current and the effect of parasitic capacitances can be reduced. During the charge cycle, a portion of the capacitors is connected to the source, while the remaining fully charged components are connected to the load. Meanwhile, a portion of the other series-connected capacitors is still charging. As a result, there are at least two or three phase-shifted signals controlling the capacitors' connection to the source and load.

IV. Design variables

The main design parameters of SC converters are addressed in this section, including operation modes, main components, efficiency, and control techniques.
3.1. Components
3.1.1. Switches
In general, the intrinsic resistances of the switches and the dielectrics that comprise the capacitors determine the efficiency and regulation of SC converters. Metal-oxide-semiconductor field-effect transistors (MOSFETs) are widely used in low- and medium-power DC-DC converters due to their high frequency operation. Isolated gate bipolar transistors (IGBTs) are better recommended for higher power levels because they support higher currents and voltages, but switching losses increase significantly with switching frequency. According to some studies, SiC MOSFETs perform similarly to Si-based IGBTs. As a result, the analysis presented in this work takes Only MOSFETs are used.Table 1 compares some of the characteristics of various commercial Si and SiC MOSFETs [27]. Conduction losses in these semiconductors must be carefully analysed because they are dependent on the drain-source on-resistance Rds (on). The manufacturer's datasheet includes this parameter, can be used to calculate conduction losses.

Table 1. Comparison of the characteristics of different MOSFETs.

Component	Type	(V)	(A)	(mΩ)	(ns)	(ns)	(pF)	(pF)
IRFP240	Si	200	20	180	51	36	400	1300
IRF530	Si	100	14	160	34	24	250	670
IRFP460	Si	500	20	270	51	36	430	1300
IRF840	Si	500	8	850	21	20	200	1225
C2M0080120D	SiC	1200	36	80	22	14	92	1130
SCT3080KL	SiC	1200	31	80	22	24	75	785
IMW120R045M1XKSA1	SiC	1200	52	59	24	13	115	1900
NTHL080N120SC1	SiC	1200	44	80	20	10	80	1112

Table 2 summarizes the main parameters associated with some diode models, which include the maximum value of the repetitive peak reverse voltage VRRM, the average forward current IF(avg.), the forward voltage drop VF, the reverse recovery time trr, and the reverse recovery charge Qrr as informed by the manufacturer at 25 ◦C. It is worth mentioning that the total capacitive charge QC of SiC diodes is equivalent to Qrr in Si ones. Only ultrafast Si diodes are listed because SC converters often operate at high switching frequencies. Besides, only SiC Schottky diodes are described since this technology presents improved characteristics when compared with other solutions.

Table 2. Comparison of the characteristics of different diodes.

Component	Type	(V)	$I_{F(avg.)}$	V^F (V)	T_r (ns)	Q_{rr}/Q_C(nC)
MUR860	Si	600	8	1.20	60	195
RHRP8120	Si	1200	8	3.2	70	165
HFA15TB60S	Si	600	15	1.2	50	84
60EPU04	Si	400	60	1.05	85	375
IDT08S60C	SiC	600	8	1.5	-	20
C4D10120A	SiC	1200	33	1.5	-	52
SCS210KGHR	SiC	1200	10	1.4	-	34
IDH15S120	SiC	1200	15	1.65	-	54

Table 3 presents a comparison among eight commercially available capacitor models that use different types of dielectrics, which have a capacitance of 1 μF. Also, the maximum operating voltage varies according to the type of material used. An analysis is then per- formed considering important aspects such as volume, energy density, and the maximum loss angle measured at 1 kHz, so that the designer can be assisted in choosing the most adequate type of capacitor. The energy density has an impact on the size of the converter and, therefore, it is important to know how these parameters vary from one capacitor to the other according to the type of dielectric.

Table 3. Comparison among different types of capacitors.

Manufacturer	Type	Series	V_{dc}	(Vol mm^3)	E(mJ)	Dens (μJ/mm^3)	Max tan($)@1 kHz
Hitano	Electrolytic	ECR	47	215.98	1.25	5.78	0.10 *
Nichicon	Electrolytic	UMA	50	62.83	1.25	19.89	0.10 *
TDK	Polyester	B32560	63	244.8	1.98	8.10	0.008
Panasonic	Polyester	ECQE	100	1125.6	5	4.44	0.01
TDK	Polypropylene	B32672L	250	3663	31.25	8.53	0.0008
Hitano	Polypropylene	MKT	100	2592	5	1.92	0.01
TDK	Ceramic (ML)	FA24	50	67.5	1.25	18.51	0.03
Hitano	Ceramic (ML)	R25	50	132	1.25	9.46	0.1

V. Comparison among SC Topologies

Different In terms of constructive aspects, existing SC topologies are very similar, though they may differ in terms of voltage gain, number of components, and stresses. Table 4 shows the component count associated with the capacitors and switches required by a given basic cell for a generic number of cells N = 1, 2, 3,...F(N 1) is also the (N 1)-th Fibonacci number, with F(0) = F(1) = 1. It is also worth noting that Table 4 summarises the main characteristics of basic topologies used in the design of SC dc-dc converters, which can help the designer decide which configuration is best for a given application.

Table 4. Comparison among SC topologies.

Parameters	SCVD	SPC	SPMC	Dickson	FC	Ladder *
Capacitors	N	N	$3N$	$2N$	N	$2N$
Switches	$4N$	$3N$	$3N$	$2N$	$3N$	$2N$
Maximum voltage on the	$2^{(N-1)}V_i$	V_i	V_i	NV_i	$(N-1)V_i$	V_i
Maximum voltage on the	$2^{(N-1)}V_i$	NV_i	NV_i	V_i	$(N-1)V_i$	V_i

In the SVCD and FC configurations, the voltage stresses on the capacitors increase as more cells are added to increase the conversion ratio. In Dickson and ladder converters, the maximum voltage stress on the active switches is constant and equal to the input voltage Vi, making them suitable for applications requiring high output voltages. Current stresses cannot be estimated in this manner because they are affected not only by the characteristics of the load connected to the converter, but also by the charge modes of the capacitors.When the capacitors are charged, SC circuits in full charge mode exhibit high short-term current peaks. The maximum charging current must be carefully considered because it may damage the switch. Furthermore, the pulsating nature of the input current may increase conducted electromagnetic emissions. High-frequency operation and/or the use of large capacitances to ensure full charge or no charge are two possible solutions for mitigating such undesirable problems. As explained the QSC is a control approach that can be used for this purpose. It enables obtaining a nearly continuous input current, resulting in reduced current stresses on the switches. Interleaved converters are also less susceptible to the undesirable effects caused by capacitor voltage ripple.

VI. Conclusion

SC converters have recently received a lot of attention from academia and industry because of their unique characteristics such as high energy density and low EMI levels in DC-DC, DC-AC, AC-DC, and AC-AC conversion. Given the prevalence of hybrid SC topologies comprised of capacitors, semiconductors, and inductors reported in the literature, this work has been focused on providing a general overview of important concepts associated with "pure SC" DC-DC converters. The existing configurations were thoroughly examined, and a brief explanation of voltage multipliers was included, as some structures are derived from popular circuits used in low-power ac-dc power conversion. It is critical to understand the inherent characteristics of SC converter operation modes during the design stage. There are three distinct modes, each with a different impact on circuit performance in terms of efficiency and regulation. With prior knowledge of the intrinsic resistances of both capacitors and switches, a proper time constant aimed at achieving an adequate operating frequency for the converter can be defined. This aspect is also directly related to the behaviour of the circuit's output resistance, which is inversely proportional to the conversion efficiency. Control and voltage regulation techniques for SC DC-DC converters are still reported in fewer numbers in the literature than those for classic isolated DC-DC converters.

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