

Towards SC-enabled high density highly
miniaturized power LED drivers: A model-centric
optimization framework

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Part I

Towards Highly Miniaturized LED Power Systems

Chapter 1

The new coming LED based lighting industry

The appearance of light in the beginnings of the 19th century and the posterior commercialization was clearly a remarkable fact of the past history. The light bulbs contributed in two major facts that impacted peoples life . First, they enabled to have clear, reliable and safe source of light at home, extending our activity hours longer than the natural sun light. As a matter of fact we can not live without the use of artificial light. Second, the necessity of electric power helped to develop the first electric power distribution systems. Actually, that fact can be still evidenced since people, generally our grand parents, often use the word *light* when they actually are refereing electricity.



Figure 1.1: Early incandescent light bulb

From the first incandescent light bulb, the lighting industry has not had any big disruptive change to our perception of lighting till the last decade with the apparition of the LED lamps. Besides as many of us thing, it has been done a large effort to improve the efficiency of the light sources while keeping a the

quality of the light as good as the incandescent light bulb. Being the florescent lamps one of the biggest contributions during the past century, beginning to be commercialized around 1930. Later becoming a disruptive change in the lighting market with the introduction the low consumption lamps where Philips was one of the first player launching to the market the first screw-in fluorescent lamp. Although the prices of these lamps has been dropping to become commercially attractive for the costumers, their poorer color rendering factor and the longer setting time compared to the incandescent lamps prevented this lamps to be one-to-one replacement. Therefore the lighting industry has been keep without not too much attention till the introduction the LED based lamps.

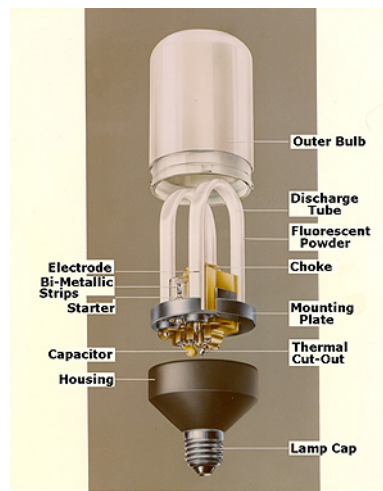


Figure 1.2: Components of the Philips SL compact fluorescent lamp.

The discovery of the high-efficiency blue LED [?] by Shuji Nakamura in 1994 enabled the quick development of the first efficient white LED. These early high power LEDs demonstrated that LEDs were a suitable technology for illumination. The relevance of Nakamura's work has been recognized last year being him awarded with the 2014 Nobel prize in physics. Looking farther we can also confirm the relevance of his invention since the apparition of the LED lamps, lighting is impacting again in our everyday life by changing our traditional concept of luminaries and lighting possibilities.

LED based lamps created a frenetic rush in the lighting industry into bring that technology to the end consumers. Actually the advantages of the LED based lighting, or also known as Solid State Lighting (SSL), are so relevant that in the close future they will replace any of the present lighting technology, that movement has been already named as the *LEDification*. The advantages of SSL are:

Efficiency The light generation inside an LED is produced by the direct mechanism of hole-electron recombination, the supplied energy is a better use of

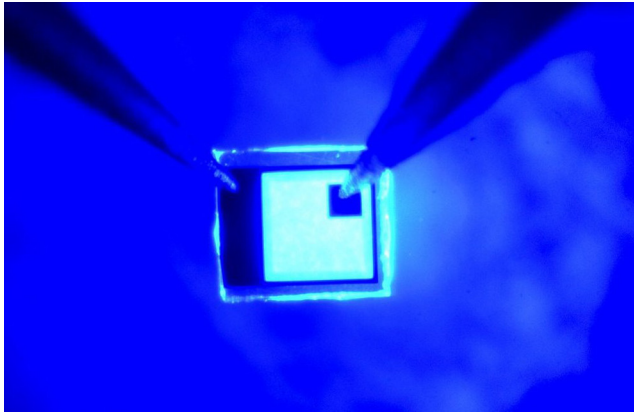


Figure 1.3: Picture of a blue laser LED researched by Shuij Nakamura.

Source: <http://www.newsweek.com/how-blue-led-changed-world-and-won-nobel-prize-275977>

the energy compared to the incandescent lamps. The power consumption can be up to an order of magnitude lower of an incandescent light.

Size LEDs are tiny and flat devices, which can be considered as 2-D elements and do not need any vacuum chamber to work. They are much more flexible devices to assembly, and can easily replace the old glass made bulb design.

Color LED light has a very narrow light spectrum, that can be used to produce directly colored light. Colored lights are becoming more popular in domestic homes becoming a piece of decoration or mood tweaking device.

This section will make a little dissertation about what is the way to go:

1. Cost driven driver production the cheapest the better
2. Miniaturization + smart driver integration

this section should gasp the current efforts done in order to introduce the LED light to the market. And say that the present way is retrofitting.

The section should close facing the dilemma that once the retrofitting is done where it will be the new market cases, and point that highly integrated drivers can be one of the possible scenarios where integration and connectivity are part of a single solution.

Chapter 2

Introducing switched capacitors in LED drivers

Presenting the concept of using a SCC with an inductor in order to enable integration and reduction in the size of the inductor.

Part II

Switched Capacitor Converters for LED drivers

Chapter 3

Introduction

Switched Capacitor Converters (SCCs) are *dc-dc* power circuits composed only by switches and capacitors that provide efficient voltage conversion. SCCs have been long known and utilized, initially for voltage multiplication and more recently for voltage regulation as well. Compared to inductor based power converters, the absence of magnetic elements makes them suitable for high density power systems and integrated solutions, such as Power-System-in-Package (PSiP) or Power-System-on-Chip (PSoC).

The high level of miniaturization of these circuits has been the motivation to combine them with the growing necessities of the emerging Solid State Lighting (SSL) industry, where high miniaturized drivers close to the Light Emitting Diodes (LEDs) can enable new applications and solutions for the coming years. The paradigms of using SCC to drive LEDs archiving high density, fiercely and current regulation are the motivation of the presented work and will be further discussed in the following chapters.

3.1 Switched Capacitors applications for LED driving

SCC for LED driving had an initial and broad usage in the portable industry, where miniaturization and efficiency was a must. White-LEDs (W-LEDs) are widely applied for back-lighting Liquid Crystal Display (LCD) for portable devices such as laptops, mobile phones and tablets. The problem to adjust the battery levels to the forward voltage (V_f) of the LEDs could not be solved using just linear drivers, therefore switched capacitors were a simple solution to implement in an Integrated Circuit (IC) to boost the voltage above V_f and then adjust the current by means of a linear regulator.

There is a large portfolio of available ICs, designated as Charge-Pumps

(CPs), for driving LEDs in portable devices for instance the *MAX88779*¹ or the *MCP1252/3*². These circuits can drive with, RGB or Flash LEDs from a Lithium-Ion battery only by adding a few external capacitors. Generally these chips integrate an multi-target SCC with different conversion ratios (x1,x1.5,x2) along with a series current regulator for each LED branch as shown in the block diagram of the Fig. X. Different publications [14, 38, 39] proposed variations in the architectures that reduced the parasitic losses bringing the efficiency close to the theoretical limit defined by the linear regulator. The application of these circuits is limited for powers below a Watt and currents below a hundred of milli-Amperes and the theoretical efficiency is limited by the linear regulator.

There are few relevant publications within the scope of Solid State Lighting targeting mains connected drivers. In 2008, K.H. Lee *et al.* [21] presented a SC step-down converter composed of several cascaded Series-Parallel that supplied from rectified $220V_{rms}$ an LED string of 75V at 15W. The load is directly supplied by the flying capacitors producing pulsating currents in the string and its average values is controlled modulating the frequency of the converter. The cascaded topology minimized the number of components (switched and capacitors) for the required conversion ratio (fixed by the LED string).

In 2012, M. Kline *et al.* [17] proposed a isolated *DC/DC* converter that combined a SCC stage with series-LC resonant converter. The SCC stage decreased the rectified mains voltage, reducing the voltage stress in switches, capacitors and the elements of the resonant tank. The lower voltage stress allows a reduction in the volume of the passive components and the total area in the silicone. By controlling the frequency and the duty cycle of the SCC stage current through the LEDs can be regulated, resulting in a very efficient solution. In a recent publication they presented an implementation where power train and control were integrated in an stackable IC [19].

The different applications show an increasing interest in using SCC for LED drivers. It is evident that the approach used in portable devices can no be further extended in for high powers and higher voltages. The use of a bear SCC can never satisfy the requirements of LED drivers due to the following facts:

- Only provide voltage-to-voltage conversion
- Fixed conversion ratios
- Regulation is provided by series shunting.

These limitations combined with the abrupt characteristics I-V of the LEDs makes barely impossible to provide high efficient solutions with the single use of SCC. The converters would require to have a large number of conversion ratios

¹Maxim® Charge Pump for Backlight/Flash/RGB LEDs with Safety Timer

²Microchip® Low noise, Positive-Regulated Charge Pump

with a very large granularity to avoid uncontrolled currents flowing through the LEDs.

the only means of regulation out of the fixed conversion ratio is by dissipating power

Therefore the SCC sta Actually the already existing publications targeting LED drivers combine the SCC stage with an inductive stage in order to provide a better integration of the switches and reducing the requirements of the magnetic passives. The research presented in this work aims to explore the possibilities of the SCC for LED drivers and the conducting path is based in the combination of the with inductors. The overall solution improves the power density and reduced form factor of the present solutions.

3.2 Hybrid Switched Capacitor Converters

Bla bla bla bla!!!

3.3 A chronological vision of Switched Capacitor Converters

The first Switched Capacitor circuit was proposed in 1919 by Heinrich Greinacher. The Voltage Multiplier Rectifier multiplied the peak voltage of an AC supply to a DC voltage proportional to the number of stages. In 1932 J.D. Cockcroft and E.T.S. Walton used this circuit to generate very high voltage potentials, up to 800 kilovolts, for their particle accelerator [11]. Subsequently, this circuit become widely used in television sets to supply high voltage to the cathode ray tube [5] and later it was used in space applications [37]. D.L. Waidelich and J.S. Brugler made some contributions to determine equivalent series resistance [36, 4] and Brugler and L. Chua proposed a unified approach to generate and analyse new topologies [4, 24].

In 1976, J.F. Dickson [13] introduced a modification of the Cockcroft-Walton circuit to enable the integration of a voltage multiplier in an MNOS non volatile memory IC. The so-called Dickson charge-pump boosted the DC supply voltage proportionally to the number of stages in the pump. At same time, the new circuit mitigated the effects of the integrated capacitor stray capacitances on the voltage gain and reduced the output impedance of the converter increasing the current throughput. After the Dickson charge-pump other topologies [32] have been reported, such as the series-parallel converter [29, 9], which allowed rational conversion ratios. F. Ueno *et al.* [35] presented a SC converter with conversion ratios corresponding to Fibonacci series, $k = 1, 2, 3, 5, 8, \dots$, achieving higher conversion ratios using fewer capacitors [26, 40]. F.L. Luo [25] proposed a topology cascading voltage doublers cells where the conversion ratio follows a quadratic relationship with the number of cells, and J. A. Starzyk [34] reviewed the same concept with a multi-phase topology that can achieve the same gain with fewer capacitors.

Two important concepts have been introduced to SC converters in order to reduce the current ripples and conducted Electromagnetic Interferences (EMI): These are the Interleaved SC converters, with reported implementations of 2-phase [7, 10], 16-phase [3] and 32-phase [20] and the Current Mode Charge-Pumps [41, 12] where the process of charge or discharge -or both- are controlled with a current source.

Extending the possibilities of SC converters hybrid combinations of Inductor-Based (IB) converters have been also used to achieve large conversion ratios with tighter regulation. There are a large number of hybrid solutions where a SC cell is integrated into an inductor based converter [1, 2, 27, 28, 17]. Lately, a couple of papers [23, 16] presented a Maximum Power Point Tracking (MPPT) converter for Photovoltaic (PV) cells employing a SC converter in parallel with an inductor based converter. In 2001 K.W.E. Cheng [8] reported another hybrid solutions which made use of the inductive elements, in this case to limit the currents through the capacitors, charging and discharging the capacitors with resonant transitions. The Resonant Switched Capacitors (RSC) converters, improved the converter efficiency when the converters operated in the SSL reducing at same time the current stress in the switches. Subsequently, many publications appeared [22, 6, 15, 33] presenting applications and uses of this converter family.

Power Levels and Integration

There are not intrinsic implications that limit the output power of a Switched Capacitor converter, but the boundary conditions. There are implementations ranging from tens of milliwatts to tens of kilowatts, where the difference only relies in the used technology. They can be classified in 3 groups: Fully integrated circuits, integrated circuits with external capacitors and discrete solutions.

Full integrated converter are suitable for very lower power applications from some microwatts up to some tens of milliwatts. These solutions are implemented in standard processes (CMOS, BiCMOS or Bipolar) where the priority is in achieve an integrated solution rather than efficient. These converters have very poor efficiency up to 60%, due to the low energy density and poor quality of the capacitors available in those processes. The second group overcomes this problem using external capacitors. These converters integrate the control and the power train in a single chip with a standard CMOS process, offering output power up to one watt and peak efficiencies of 95%. In this case, the CMOS switches limit the converter efficiency and scalability in power. The implementations with discrete components enable output powers up to kilowatts with peak efficiencies above 95%. Discrete semiconductor switches can offer lower channel resistance and better switching characteristics, reducing ohmic resistance and enabling higher switching frequencies. *Silicon power MOSFET are the dominant in discrete implementations, but recent publications used Gallium-Nitride HEMT switches [30, 31].*

The limiting factor of the output power of a SC converter is driven by the

boundary conditions of the technology. Up to now, integrated SC converters designs have been covered addressing the problem with the standard process in VLSI, in order to have compact power conversion units at the lowest cost. The current technologies can easily improve the present solutions, for instance, a Power-System on Package (PSoC) integrating switches and capacitors would already reduce the series resistance of the pins and optimize the silicon die area of the present integrated converters with external capacitors. The current technologies offer the possibility to achieve integrated SC converters processing higher powers, but it would require to combine them in non-standard processes.

Missing refs!

Chapter 4

Advanced Modeling of Switched Capacitor Converters

4.1 Introduction

4.2 Single Output Converters

Switched Capacitor Converters (SCCs) are considered to be a two-port converter with single input and a single output as shown in Fig.???. The input port is connected to a voltage source and the output port feeds the load. The SCC provides between input, v_i , and output, v_o , a voltage conversion, m , that steps up, steps down or/and inverts the polarity of the input voltage. Up to present all the circuit theory devoted SCCs is valid only for the two-port configuration, therefore this section is dedicated to revisit the classical concepts of single output SCC and to introduce new ones that enable a broader use of such converters.

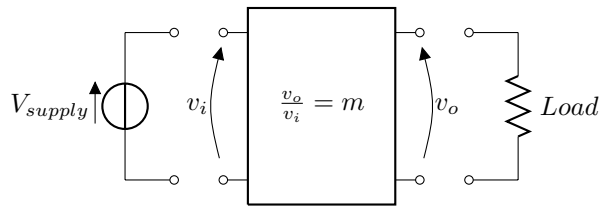


Figure 4.1: General two port configuration of a Switched Capacitor Converter.

4.2.1 The Hybrid-SCC: Identifying Outputs in Switched Capacitor Converters

Two types of nodes can be identified in a Switched Capacitor Converter, as shown in Fig. 4.2:

- Fixed voltage *dc*-nodes, node *a*
- Floating voltage *pulsed width modulated*-nodes (*pwm*-nodes), node *b*

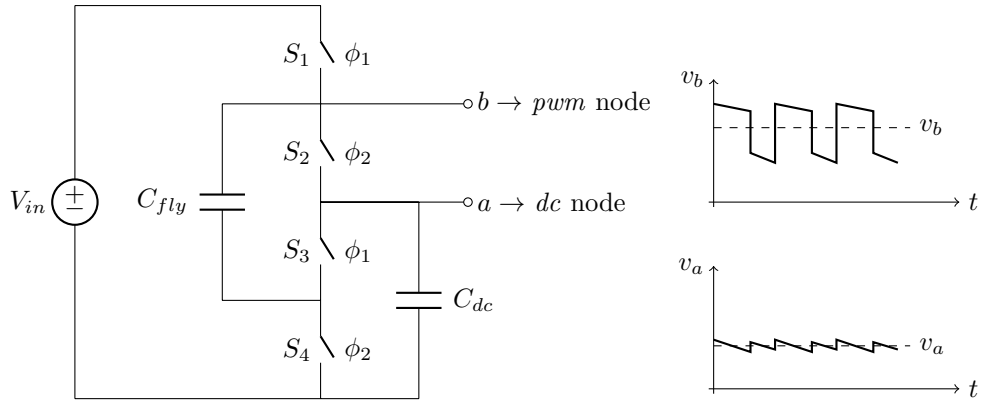


Figure 4.2: Nodes types in a SCC. Node *a* is a *dc*-node; its voltage, v_a is plotted in the bottom graph. Node *b* is a *pwm*-node; its voltage, v_b , is plotted in the top graph.

The fixed voltage *dc*-nodes are the common used nodes to supply a *dc* load. They provide a fixed voltage conversion defined by the topology with a low *ac* ripple, and they always have connected a capacitor between the node and the ground by the so called *dc*-capacitor as shown in the Fig. 4.2. Depending on the topology the number of *dc*-nodes can vary between one or more, however topologies that reduce the number of *dc*-capacitors (C_{dc}) trend to have a better utilization of the capacitors since *dc*-capacitors do not contribute to transport charge [32].

The floating *Pulsed Width Modulated*-nodes (*pwm*-nodes) have been rarely used as outputs until a recently couple of publications [18, 17] presented the advantages of using them. *pwm*-nodes have been normally considered just internal to the converter with any added value, but actually the conversion possibilities of SCCs can be further exploited by using these nodes as outputs.

A *pwm*-node is located at the terminal of a *flying capacitor* (C_{fly}) and provides a floating *Pulsed-Width-Modulate* voltage with an added *dc* offset of a fraction of the input voltage. The magnitudes are related to the SCC topology. The pulsated voltages can be filtered using an inductive-capacitive filter (LC) allowing to supply *dc* load with averaged voltage of the node. Actually the

pwm voltage at the node can be controlled adjusting the duty cycle of the SCC, enhancing the regulation capabilities of these outputs compared to the fixed value of the *dc*-nodes. The switched capacitor converters that combine the *pwm*-outputs with inductors will be referred from now on as *Hybrid-Switched Capacitor Converters* (H-SCC).

4.2.2 The Output Impedance Model

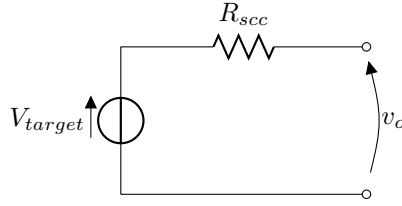


Figure 4.3: The Output Impedance Model for SCCs.

Figure 4.4: The Output Impedance Model for SCCs.

4.2.3 Identifying the source of losses in the charge transfer

4.2.4 Re-formulating the charge flow analysis

Slow Switching Limit: Re-defining the Capacitor Charge Flow Vectors

Fast Switching Limit: Re-defining the Switch Charge Flow Vectors

4.2.5 Load Model: Voltage Sink versus Current Sink

4.2.6 Sensitivity of the inductor current ripple

4.3 Multiple Output Converters

4.3.1 The Output Trans-Resistance Model

4.3.2 Obtaining the Trans-Resistance parameters with the charge flow analysis

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5.2 Study in the correlation of the design parameters and the Output Impedance

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5.4 Insights towards a complete optimization

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6.1 Small Signal Analysis

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7.1 Circuit description

7.2 Identifying the losses

7.2.1 Switching Losses

7.2.2 Characterization the switches R_{ON}

7.2.3 Fast Switching Limit Losses

7.2.4 Slow Switching Limit Losses

7.3 Playing with the design space

7.3.1 Validating the SSL optimization

7.3.2 Validating the FSL optimization

7.4 Results

7.5 Conclusions

Chapter 8

12W H-SCC LED Architecture

8.1 Introduction

8.2 Circuit Description

8.3 Design and Implementation

8.4 Results

Chapter 9

AC/DC Architecture

9.1 Introduction

9.2 Circuit Description

9.3 Design and Implementation

9.4 Results

9.4.1 Model verification

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