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

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Towards Highly Miniaturized LED Power Systems

Chapter 1

LEDification: Transition towards LED lighting

The light bulb is one of the most relevant inventions from our past history. Electrical lighting was definitely a revolution in the early $19th$ century society; for the first time in history people had a clear, reliable and safe source of artificial light was embedded in a single device easy to distribute and control. The apparition of the electrical light bulb was also, without doubt, the trigger for the commercialization of electric power and the deployment of the first power distribution networks [24]. The impact was to such a degree that it settled two capital sectors of the present industry, the lighting and the electric power distribution, with world recognized companies such as Philips, General Electric and Osram. Actually, both sectors have been so close related that often we use the word *light* when we actually mean *electricity*. In short, a single invention changed our society forever, bringing light and electricity to our homes.

Figure 1.1: Philips advertisement from 1900 comparing what was before - *Vroeger*, an oil lamp- and now - *Today, the* incandescent light bulb [1].

From the initial invention of the first incandescent light bulb onwards, to most people bulbs have simply been a commodity device to generate light which have not arose any sense of innovation. Despite the impression of simplicity that the lights can produce, important research has continuously been done to improve the most important characteristic of the incandescent light bulb, the efficacy. Incandescent light bulbs are extremely inefficient at generating light, with a luminous efficacy between $12.6lm/W$ for a tungsten incandescent bulb, and up to $24lm/W$ for a quartz halogen lamp (see Table 1.1). In a more comprehensive way, we can say that in general incandescent lights convert just at most 5% of the supplied energy in light and at least 95% in heat. Knowing that lighting represents 17% of world energy consumption, we can account that 15% of the world's consumed power is transformed to heat and only 1.7% is transformed real light [1]. Although generating heat is not intrinsically negative, specially for spaces that have to be heated, the propose of a light is to illuminate the space in the most efficient meaner; that is why there is a motivation and necessity to improve the efficacy/efficiency of light bulbs.
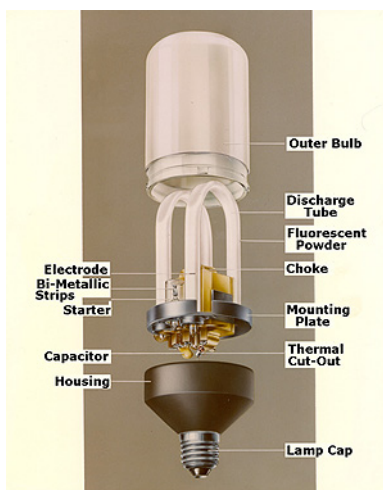
Figure 1.2: Exploded view of Philips SL the first compact fluorescent lamp launched to the market [1]

Gas-discharge lamps were one of the first alternatives for incandescent lamps that proved a better efficacy, with the fluorescent tub the most popular in this family. The low pressure mercury-vapor gas-discharge lamp, commonly called *fluorescent*, was considered an innovation in the lighting industry [15]. Initially the tubes where mainly used for the interior lighting of industrial buildings, offices, schools and similar [7, 23], and after, in the late 1980's, started populating households with the appearance of the *compact fluorescent lamps*[2] (CFLs) [7],

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[1]Estimated values for the year 2008
[2]Screw-in version of a fluorescent tube. Now a days you can find a CFL replacement for almost the majority of sockets in the market.

being currently the market standard for energy efficient light bulbs [10]; as shown in Figure 1.2. Fluorescent lamps are indeed a big improvement in efficacy with respect to the incandescent lamps. The luminous efficacy ranges between 52-100 lm/W depending on the *Color Rendering Index* (CRI), converting about 22% of the input power to visible light. More details of other gas-discharge bulbs are presented in Table 1.1. Notwithstanding the better efficiency of the CFLs, due to the following reasons they have not yet fully replaced the inefficient incandescent ones [10]:

- Standard CFLs are not *dimmable*. *Dimmable* CFLs are more expensive, their behavior is not standardized among manufacturers, producing mismatches in the light output between lamps, what does not satisfy consumer's desires.

- CFLs have a slow warm-up time[3]. Not being suitable for places where lights are turned on for short times.

- CFLs have unappealing form and look. Some can not fit in existing fixtures that mount incandescent lamps. The *pig tail* appearance is not attractive when bulbs are exposed.

- The low price of the incandescent light bulb compared to a CFL is more attractive for the consumer. Although CFLs save more money due to power savings, the end consumers are still repelled by the retail price of the lamps.

Therefore, in 2012 it was estimated that in residential environments more than 50% of the installed light bulbs were still incandescent [21]. Thus a need for a another lighting technology capable of replacing the old inefficient incandescent lamps.
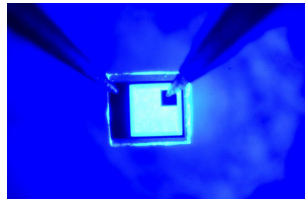
Figure 1.3: Bare die of a working blue LED .

It was not till 1994, with the invention of the high-efficiency blue *light-emitting diode* (LED) (Fig. 1.3) by Sush Nakamura's [18]. Actually, Nakamura's work was initially triggered by Isamu Akasaki and Hiroshi Amano [5] demonstrating that was possible to generate blue light from semiconductor materials; blue light was fundamental to generate withe light for LED lamps [20].

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[3]Gas-discharge lamps have to be warm in order to volatilise and mix chemical elements that compose the gas. Depending on the chemical elements this process can take from a minute up to ten minutes.

They were awarded with the 2014 Nobel prize in physics [4]; their inventions were revolutionary and are already transforming the future of artificial lighting, thus settling the base of a new player in the lighting industry, the *Solid State Lighting* (SSL) technology.

The advantages of SSL are:

Efficiency The light generation inside a LED is the direct mechanism of hole-electron recombination. The supplied energy is better used compared to an incandescent lamp. The power consumption can be up to an order of magnitude lower than 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 in the assembly process and can easily replace the old glass-based bulb design.

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

Dynamics Compared to any of the traditional sources of light, LEDs have no dynamics. Actually they have, but they are so fast that cannot be tracked by the human eye. They do not have any setting time when turned on, contrary to the CFLs. Their fast dynamics allow to modulate the light and even transmit data without disturbing human beings [16, 26].

Lifetime Solid State devices do not wear out, therefore they can be considered to have an infinite lifetime. In practice LEDs make use of organic phosphores, thus the light quality degrades over used time. The practical life expectancy of the LED is rated from 20.000 - 100.000 hours, 20 to 100 times longer than the life expectancy of the classical light bulbs. In order to take advantage of this long life, the different elements of lighting systems must be properly designed otherwise the lamps can experience a short life [19].

Just looking at the benefits that LEDs offer LED in terms of efficiency, the projected energy savings for 2020 are $297 TWh$ only in USA. The *United States Environmental Protection Agency* [22] published that reducing the household lighting energy consumption by half - easy to achieve by using LED lighting - more than \$13 billion a year in energy costs could be saved, more than 80 million metric CO_2 tones would be avoided each year, and the need for over 30^4 power plants could be eliminated. The advantages of LED lamps are so relevant that the *United States National Lighting Bureau* [22] forecasts a market penetration growth from 5% in 2015, to 74% in 2020 and reaching 88% in 2030, as shown in the graph of Figure 1.4. Hence in the near future almost all lighting technology will be LED based.

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[4]To be further detailed

The transition towards LED based lighting technologies, referred as *LEDification* [9, 12], will come in two waves [17], the first wave will be a replacement period. The main focus will be to bring fast and simple LED technology in form of light to the consumers in order to remove the inefficient old lighting technologies. The second wave will include more intelligence to the light fixtures, transforming the lights from a simple light sources to connected nodes within an infrastructure of interconnected lights, what is already crystalizing with *The Connected Lighting Alliance*. This second phase will be a revolution making the lighting infrastructure a crucial element in the future smart houses and in the internet-of-things era [13]. Therefore LED lighting will bring not only efficient lighting, but also interconnect light fixtures. This is similar to what happened before, in the late 1800s, when a single invention brought simultaneously light and electricity to our homes [24].
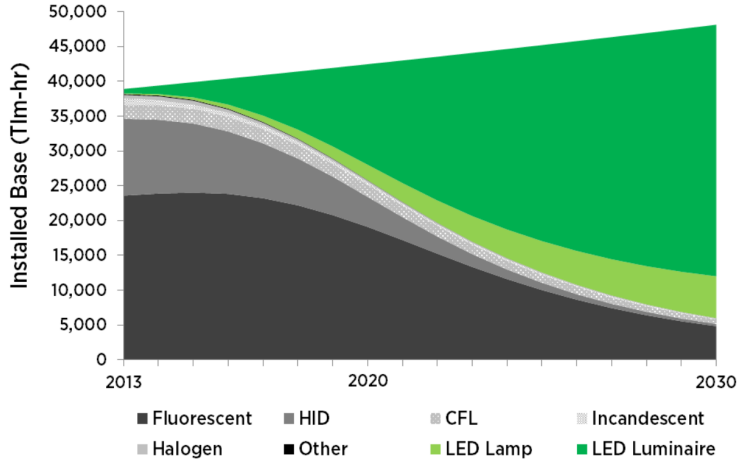
Figure 1.4: U.S. Lighting Service Forecast, 2013 to 2030 [22].

During the last decade, the lighting industry has been in a rush to bring LED light to the market, making *LEDification* a reality. Initially LED lighting was only used for decorative lights and with the advance of the LED technology with higher efficiency devices, they started to be applied in general lighting applications. With the progression of efficiency of the LEDs, in May 2008 the U.S. Department of Energy (DOE) established the Bright Tomorrow Lighting Prize (L-Prize) [2, 27] competition in order to encourage the industry to spur development of ultra-efficient SSL products awarded with US\$10 million cash prize. In the L-Prize competition the industry was challenged to develop replacement technologies for two most widely used and inefficient bulbs: *A19 60W* incandescent lamps and *PAR38* halogen lamps. On September 2009, Philips Lighting North America became the fist to submit LED lamps in the category to replace the standard 60W screw-in lamps, becoming the winer in that category [3, 31]; the other category is still empty. Only three years later, in 2012, Philips had al-

ready covered the whole range of incandescent bulbs up to 100W [17]. Today in 2015, all these replacement lamps are available in almost all of the supermarkets and retail shops, although they are not yet adopted as the preferred solution by consumers. Despite of the advantages of LED lighting, end consumers are still very reluctant to make the change towards SSL products due to their elevated price [11, 29]. Currently a 100W LED replacement costs between \$20 - \$40 compared to less than \$3 for an halogen incandescent.

Actually, the majority of end consumers do not yet understand that even incandescent lamps are cheaper, LED replacements save money over the life time of the product due to energy savings. With the help of Table 1.1 we can easily demonstrate this statement.

The *Lumen cost of owner ship*[5] for incandescent technologies is below 60 $klm/€$ and for LED technologies is easily above $200klm/€$. Translating these figures to total costs[6], it is estimated that in a productive year (around $2000h$), for a $25m^2$ office space[7], costs of lighting would be above 420€ for incandescent lamps and below 140€ for LED lamps. It is true that linear fluorescent and *(* High-Intensity Discharge Sodium) (HID-SON) represent the best option regarding costs below 80€, but the projected performance gains in efficacy, color quality and light distribution point that LED technology will be come the best choice [8]. HID-SON lamps are out of discussion since they have a very poor CRI (25) what does not allow to properly recognise colors. Based on the aforementioned facts is predicted that LED is going to be the future lighting technology [22, 28], but still the industry has find the manner to motivate the end consumers to buy LED lamps as their first choice [29].

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[5]Lumen cost of owner ship is expressed in $klm/€$ indicating how many lumens you can produce per € during thousand hours. Using this metric the different light technologies can be compared independently of the lamp power consumption.

[6]Lamp amortization are included in the costs

[7]Recommended illumination for productive office spaces is $500lm/m^2$

Table 1.1: Characteristics for different lamp technologies (winter 2015).

	Units	Incandescent	Halogen	Cold-White Fluorescent	Warm-White Fluorescent	Compact Fluorescent	HDI SON	Retrofit LED Budget	Retrofit LED Dimmable	Retrofit LED	Retrofit Tube LED
Power	W	100	53	36	39	11	70	10	13	5	10.5
Flux	lm	1203	845	3100	3100	600	5600	600	1055	350	950
Efficacy	lm/W	14.3	14.42	57.14	57.14	55	80	60	81.15	70	90.5
Color Temperature	K	2700	2800	4000	3000	2700	2000	2700	2700	3000	3000
Color Rendering Index		100	100	85	85	82	25	87	80	80	85
Lifespan	h	1000	2000	20000	24000	15000	28000	2500	25000	15000	50000
Retail price	€	1	3	5.6	4.8	8.78	14.26	4.5	37.1	17	43
Lumen cost of ownership	$klmh/$€	48	59	348	324	186	324	233	229	182	281
Cost of ownership	€$/kh$	25	14.2	8.9	9.6	3.2	17.3	2.6	4.6	3.3	3.4
Cost for a $20m^2$ office	€$/kh$	260	210	36	39	67	39	54	55	69	43

Figure 1.5: 900 lumens LED light bulb.

Different factors can help the adoption of LED as the preferred lighting solution for consumers [29]. On the one hand, it is reducing the end product price; on the other hand, bringing more value than traditional lighting sources. Indeed, as previously mentioned, LED light bulbs already bring more value compared to the old light bulbs. They are much more efficient, almost one order of magnitude lower in power consumption, and have a longer lifetime, easily twenty times more operating hours. However, that is not yet well explained to be a valuable argument for the end consumers. New *Smart* bulbs concepts are starting to populate the market, such as LIFX, Philips Hue and Easybulb, offering color tuning, light output dimming, remote control and other wireless services. This position SSL in line with the current trend of the *internet-of-things*(IoT) [6, 25, 30], for the specific lighting case: The *internet-of-lights* [13, 14]. Moreover, LED lighting is also growing the luminaries industry, bringing more and more popular products where the light fixture directly incorporate LEDs without offering alternative technologies. These products benefit from design advantages that the small form factors of the LEDs allows. As a matter of fact the *U.S Department of Energy* (U.S.DoE) estimates that LED luminaries will be the big player in the lighting market (Figure 1.4).

In general three main factors are identified to influence the market penetration of SSL:

- End lamp/luminaire price

- Intelligence: Interactivity, connectivity and controllability

- Light fixture size: Luminaire design, shape and application

It is necessary to describe the different elements in an LED lamp in order to relate this three factors with current LED bulbs and understand the challenges in their development. The system can be grouped in six main elements described below and shown in the Figure 1.7.

LED From its acronym, a *Light-Emitting Diode* is a two-lead semiconductor device that generates light when a current flows through it. Internally

light is produced by the electroluminescence effect, where an electron recombines with an electron-hole releasing energy in form of photons. The color of the light is determined by the energy band gap of the semiconductor. The mounted LEDs in the lamp will determine light color, power, efficiency and load characteristics.

Optics Optical device that mixes and distributes the light from the LED to the illuminated space.

Driver Electronic circuit designed to transform the electrical power of the input source to properly supply the LEDs. LED drivers are considered voltage-to-current$(v - i)$ power supplies. Commonly used power supplies are voltage sources and LEDs need to be supplied by current. The must driver control the current through the load, hence the light output, and it is the active part of the system that essentially controls the lamp.

Heat sink Mechanical element that acts as a passive heat exchanger to cool the hot elements inside the lamp by dissipating the heat into the surrounding medium. In the LED bulb the energy that is not transformed to light becomes heat and must be extracted from inside the lamp. The hot spots areas in the lamp are the LEDs chips and some of the driver components.

Body assembly Mechanical element that hold alls the different subsystems in one single device. In many cases this is the heat sink.

Connector Mechanical element that provides connection with the energy source. The most popular one is the Edison connector present in all screw-in lamps. There are many other popular ones, such as GU10, MR16, MR11, coming from the halogen multifaceted reflector bulbs, or the 2-pin connector of the fluorescent tubes.

In many cases, the standardized connectors restrict the mechanical design of the lamp. Their old-fashioned design is not optimal for the new lamps.

With an understanding of the different elements of a LED lamp we can relate them back to the three factors that influence the market penetration previously mentioned. First, the price of the lamps. Figure 1.6a shows the cost breakdown for different lighting applications. The three main elements Driver, LED package and Thermal/Mechanical/Electrical interface[8] share almost equally the costs of the lamp, and it is predicted to be similar or even a bit better distributed as shown in the forecast of Figure 1.6b. Based on these figures, it is evident that in order to achieve the predicted cost reduction, one half for 2020, actions have to be started at the system level, ensuring an equal research and development effort for all elements in the lamp.

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[8]The Thermal/Mechanical/Electrical group comprises the heat sink, socket connector and *Printed circuit Boards* (PCBs) that interconnect and mount the input socket, LEDs and driver.
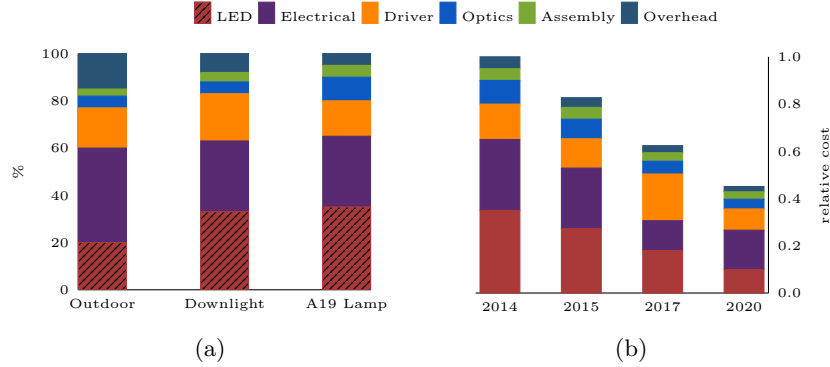
Figure 1.6: *Left*-Comparison of cost breakdown for different lighting applications; *right* - Cost breakdown projection for a typical A19 replacement lamp *Source: DOE SSL Roundtable and Workshop attendees*

The LEDs or LED package [9] are in continuous evolution in order to fit the requirements of the luminarie manufacturers and driver requirements in terms of price, efficacy and package. Innovations are on the market with three available technologies based on current capability of the dies: low, mid and high power range. The different offer in chip packages brings more flexibility at the system level in terms of optical design, luminarie light projection, color, and driver design. However full potential of the reduced profile of the LED has not yet been explored in regard to the luminaire design. Further research at the die level will improve the reliability of manufacturing process, and the efficiency needed to reduce the costs of the lamps. It is, however, in the better use of the small size of the LED what will provide more value for the future lamp designs and competitions like *Next Generation Luminaires* (`http://www.ngldc.org/`) challenge the industry to innovate in that field.

The Mechanical/Thermal/Electrical group - comprising heat sink, socket connector, PCBs and *Electromagnetic Interference* (EMI) filters - still plays a dominant role in the design of the lamp. The heat sink and the connector are in many cases the body of the lamp where the heat sink and assembles form the entire lamp. Traditional sockets, which are not design friendly, are currently kept in order to provide a fast transition for the current first wave of the *LEDification*, the replacement period. Replacement lamps are also known as *retrofit*[10] lamps. The current offer of *retrofitted* LED bulbs proves the successes achieved in that area. Nowadays is already possible to find a replacement lamp for almost all old lamps. However *retrofitted* lamps will have only an small market share as predicted in the lighting forecast of Figure 1.4. That is why

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[9]Electronic part composed by an assembly of LEDs connected in series or parallel and mounted on a single substrate

[10]Adding the new LED technology to the older light bulb systems. In that way the end user can directly replace an old lamp or tube by a LED one without needing to make any change in the current installation.
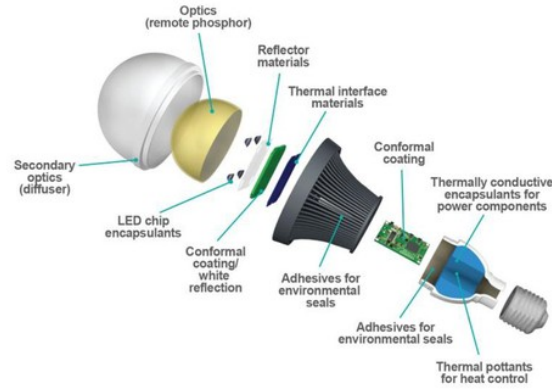
Figure 1.7: Exploded vision of an LED light bulb.

innovations in the Mechanical/Thermal/Electrical group will be necessary for the coming light fixtures, to evolve and reinvent the future LED luminaries, where the small size, the low profile and the colored light of the LEDs will play an relevant role.

The driver is, with no doubt, the most *special* component of the entire lamp. It is referred to as *special* because it is the only element of the lamp that plays a role in each of the three factors of influence for market penetration: Intelligence, Design and Costs. First, the driver is the only element that brings active functionality to the lamp, hence the only one that can incorporate the control and interactivity to the system. Second, its volume and its location influence the design of the lamp. The closer the driver to the LEDs is, the better the controllability and the intelligence of the system becomes. Finally, the manufacturing costs, what up-to-now has been the main research interest for LED drivers.

For the past years cost down reduction has enabled to bring the prices for simple *retrofitted* lamps down to competitive levels. However the chosen circuit architectures for low cost drivers are very cost sensitive towards more intelligent drivers, as it can be seen with the different prices for the *dimmable*, *non-dimmable* and *smart* lamps of Table 1.1. That is why a different approach in the driver architectures must be taken in order to respond to the challenges for the future intelligent and connected LED lamps. In other words, the driver architecture that will provide power management, intelligence and connectivity together, assembled in a reduced volume, and at low cost will be, with no discussion, the key element to carry the future of LED lighting technology.

The current driver architectures are based on discrete implementations. In such an approach driver circuits are composed by different discrete components all assembled on a single *printed-circuit-board* (PCB), which enables a fast development and cheap costs, because the mounted parts are general propose components sold by millions; however this approach has several limitations. First the performance of old and cheap components limits the volume reduction of

the required passive components in the drivers filters and magnetics. Second, as the circuit increases in complexity, the *bill of materials* (BOM) and there fore the costs increases, also the costs, therefore reducing the possibilities to offer more functionality in the driver circuit, such as connectivity and controllability at reduced costs. In resume, fulfilling the driver requirements for the second generation of LED lamps will be very challenging using discrete driver architectures.

The approach to meet the requirements for the future lamps will probably rely on an integrated driver solution; meaning by integrated an *application-specific integrated circuit* or ASIC. This approach from the perspective of the integrated power supplies brings the focus of the research to drivers where the power converter can be partially or fully integrated in a single package. There are two approaches of integrated power converters: *Power System on Chip* (PSoC) or *Power System in Package* (PSiP). The first integrates all required power components, active and passive, on a single die. The second assembles all the components within the same package, keeping the appearance of an unique *Integrated Circuit* (IC), see Figure 1.8. The advantages of having an integrated power management unit align with the necessities of the LED drivers, therefore the trend of the drivers will be going towards having *Power LED Drivers in Package* (PLDiP).
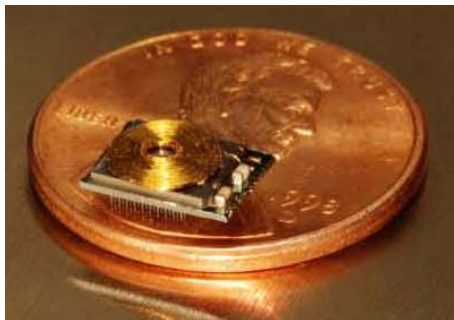
Figure 1.8: Power System in a Package buck converter.

Besides the size reduction that an integrated driver would offer, such an approach would also bring other benefits in terms of control and connectivity. The power management unit and driver control unit could be integrated together, providing the necessary intelligence for light control and the connectivity optimized for the requirements of the coming connected lighting industry. *Smart lamps* are a clear example of the requirements of the so called *smart drivers*. The *smart lamps* are wireless connected to a network providing remote control for the light intensity level and color from a web interface, a mobile application or a dedicated remote control. The internal electronics has normally four LED drivers - one per each color channel: red, green, blue and amber - and, at the same time, a wireless interface. The electronic board is populated with discrete power drivers and micro-controller units. A solution capable to integrate all

the functions in a single IC, or few ICs (one per channel), will definitely reduce packaging and assembling costs and still providing the same functionality. At the same time, the expected market volume for SSL technologies will, with no doubt, justify costs of a dedicated ASIC design for LED drivers. All-in-all it has been the goal of this PhD thesis with the goal to explore and identify new architectures suitable for integration that can efficiently power LEDs. The rational to explore the architectures that enable high density highly miniaturized power LED drivers, such as switched capacitor converters, developing a design framework based on a model-centric approach.

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Chapter 2

Introduction

The challenges in powering LED loads are so relevant that have an impact in functionalities and design of the future *Solid-State-Lighting* (SSL) products. So much, that the user adoption of such a beneficial technology by is far slower than comparable disruptive technologies [21]. In a part, that could be attributed due to the difficulties in achieving the high miniaturization and performance necessary in the LED drivers, at low cost, in order to outcompete the cheaper old technologies.

From the power management standpoint power a LED load is a trivial task, however the different requirements of SSL products make the design of them a complex task. Initially the main driving forces in the driver designs where: manufacturing cost, power quality, light quality. Reducing manufacturing costs can enable to decrease the lamp prices to the entry point for the consumers. The drivers have to fulfill with the legislation in terms of power quality not exceeded the minimum *Power Factor* (PF) and *Total Harmonic Distortion* (THD). From the consumer point of view the light quality is measured in terms of: flickering, color consistency and *Color Rendering Index* (CRI), being the flickering a parameter related to the driver design. Flickering must be kept under certain limits to do cause health concerns [24]. Recently two other factors are becoming more relevant in the driver: miniaturization and controllability. The volume of the drivers is currently, in many cases, limited by the old lamp shapes in order to provide retrofit solutions. There are solutions for all incandescent lamps, however there are still challenged for small halogen cases. Anyway the miniaturization requirements of the lamps have been relaxed by redefining the shape and look of the old lamps, the new design take large part of the lamp volume for the heat sink body, what allows a large volume for the driver. Further reduction of the driver will enable higher freedom in the lamp design. The future connected lamps [7] will require control and connectivity, what challenges the driver to provide multiple color channels, current control and power management for added intelligent circuitry such as MCUs and sensors.

The high and diverse level of requirements for the LED drivers has made the design process a complex task, further than just a pure power management

problem. The initial driving forces in driver design, cost, power and light quality, found effective solutions based on discrete components. The new driving forces where miniaturization, controllability and connectivity brings to research in the context of *Power Systems on-Chip/in-Package*(PSoC/PSiP), where miniaturization and integration of functionalities can be easily achieved. This chapter starts with an analysis of the LED characteristics to understand why is a driver necessary. Subsequently, the three different driver technologies are studied: Linear, switched inductor converters and switched capacitor converters. An state-of-the-art for each technology will be provided in order to construct a rational of the technology toward miniaturization. Switched capacitor converters will be thoroughly studied, since constitute the central conversion technology selected for this dissertation.

2.1   The LED load

The LED is just a special diode that emits light as the acronym stands for *Light Emitting Diode*. It is well known that a diode has a very *voltage-current* $(v - i)$ curve as shown in Figure 2.1. For voltages below the *forward voltage*, v_f, there is practically no current flow and the LED behaves as an open circuit. The same characteristic applies when reversed bias until the breakdown voltage, v_{break}, is reached. For voltages above v_f the curve becomes very steep and the current increases dramatically with respect to the voltage, thus the LED behaves as a short circuit. The similar behaviour happens when the LED is reverse biased and the voltage is above v_{break}, however in this case there is no light generation. The LED has to be supplied at an specific point P in order to provide a desired light output as shown in Figure 2.1, depending on the bias current light colour and intensity will vary. Due to the steepness in the $v - i$ curve, the practical way to bias a LED is supplying them with a *dc*-current. Since the common used energy sources are voltage supplies, it is necessary to select a circuit that converts the input energy from the voltage source to a constant current.

At first glance, keeping a constant bias current, i_{bias}, through the LED does not seems to be challenging, however the LED's electrical characteristics are not static and have some tolerances. On the one hand, a LED has different sources of deviations that the driver circuit has to deal with them in order to keep them delivering the desired light output. First, v_f has a negative dependence with the temperature, drooping its values as the *pn*-junction temperature increases. Second, the LED has an aging factor which derates the light output over time, and which has to be adjusted by changing the bias point. And last, during production LEDs will vary in colour, flux, and forward voltage; even for products from the same batch. The manufacturers have reduced the tolerances between devices by binning [1], but after binning, the parts suffer deviations, *e.g.* up to 10% in v_f. Figure 2.1 shows graphically how deviations in v_f produce a displacement in the $v - i$ characteristic, which require to modify the v_{bias} within

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[1]Quality control performed at LED production line, where each LED is individual tested and sorted in groups (bins) that have the same electrical and lighting characteristics.
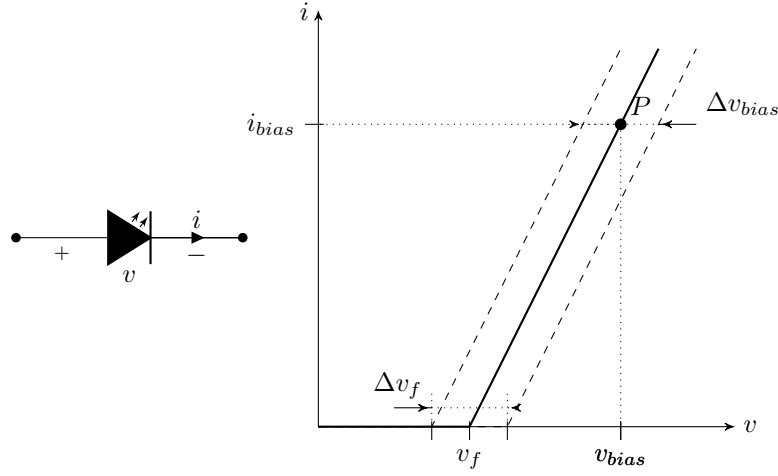
Figure 2.1: Idealized LED voltage-current characteristic, with the *forward voltage* v_f identified and a projection of the *bias point* P

a certain range Δv_{bias} in order to keep i_{bias} constant. On the other hand, the voltage provided by the energy supply has some tolerances. Depending on the nature of the energy supply, *ac* or *dc*, the driver has to provide line regulation, filter high frequency perturbations and accept the voltage tolerances of the source, without affecting the light output. In general, LEDs lamps have to provide a certain desired light output range despite variations in the LED characteristics or the voltage supply, and therefore that control function is what adds complexity to the driver circuit. The three families of LED drivers will be presented in the subsequent sections.

2.2   Linear Regulators

Linear drivers place a shunt element between the source and the load(*i.e* the LED). The shunt element limits the LED current providing the necessary voltage droop between the source and the load. The excess of voltage between the source and the load is dissipated in the series element, literally burned in form of heat; therefore these drivers become very inefficient if the LED voltage is not close to the source. Other limitation is that linear drivers only provide step-down conversion, thus they cannot work when the voltage at the load is higher than the input supply.

The circuit of the Figure 2.2a shows the schematic of a linear driver. The shunt element can be implemented with just a resistor of with an active device. The first will impose a current depending on the input source and the load conditions; the second will provide regulation of the bias point for variations in the source and in the load. Linear drivers are very simple to implement, with
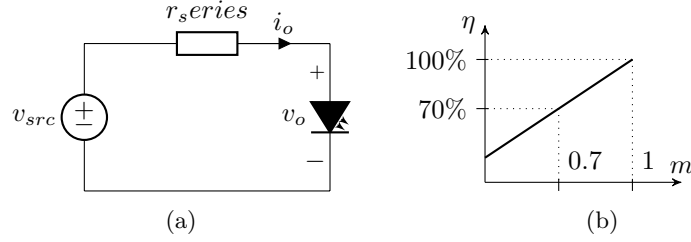
(a)   (b)

Figure 2.2: Linear driver, *left*- schematic; *righ*- conversion ratio vs. efficiency characteristics

very low costs and taking almost no volume, being indeed the perfect solution for integration since they do not make use energy storage components for power processing.

The plotted graph in Figure 2.2b presents the variation of the driver efficiency with respect to the conversion ration m. Here m is the ratio between the input voltage, v_{src}, and the output voltage, v_o, being defined as

$$m = \frac{v_o}{v_{src}}. \tag{2.1}$$

The efficiency of the driver is the ratio between the input power and the output power

$$\eta = \frac{P_o}{P_i} = \frac{v_o i_o}{v_{src} i_o} = \frac{v_o}{v_{src}}, \tag{2.2}$$

hence for this case the efficiency is indeed equal to the conversion ratio

$$\eta = m. \tag{2.3}$$

Owing to the fact that LED drivers have to be efficient, and assuming that a worst case 80% efficiency can be accepted, linear drivers could only be suitable where the ration between input voltage and load voltage is higher than 0.8.

2.3   Inductor Based Converters

Inductor Based Converters (IBCs) are *Switched Mode Power Supplies* (SMPS) [2] that employ magnetic passive elements (i.e. inductors and transformers) to store energy and provide efficient electrical power conversion. Since IBCs are very efficient with respect to voltage-to-current conversion, they are ideal as LED drivers.

The inductor is the main element in these converters and it allows voltage conversion by storing energy in form of magnetic field. In the case of the converter of the figure 2.3a the inductor is charged during

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[2]Electronic power supply that provides efficient electric power conversion by commuting between different circuit configurations (modes).

These converters can provide step-up and step-down conversion for large dynamic ranges while keeping the efficiency very high. On top of their power conversion capabilities, such converters can also provide galvanic isolation, which in many applications is compulsory in order to guarantee the safety of the users against electrical hazards. Such characteristics suggest these drivers as the preferred solution for the LED industry. Figure 2.3a shows one of the most popular implementations for LED drivers: The *buck* converter. Figure 2.3b presents the regulation characteristic of a generic inductor based converter. As shown, the theoretical efficiency of these converters is 100% for all the conversion ratio range. In practice, due to parasitics in switches and inductors, the efficiency drops to a certain value with small fluctuations with respect to the conversion range.
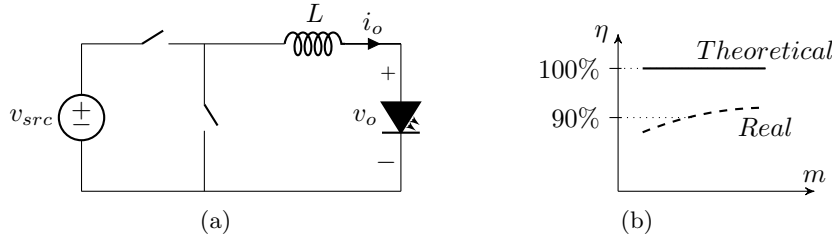

(a) (b)

Figure 2.3: Inductor based converter, *left* - buck converter schematic; *right* - conversion ration *vs.* efficiency curve comparing the *theoretical* and a *practical* limit.

One of the disadvantages of these converters is the magnetic components, and the volume related to them. In practice, inductors dominate the entire volume of the LED drivers as shown in Figure 2.4. Integrated implementations of these converters suffer the challenges of using integrated magnetic components. The present *very-large integration scale* (VLSI) technologies do not yet offer power inductors in the commercial implementations, and other integrated inductors are not yet mature enough for non-research products.

Yet another disadvantage for integration is the voltage stress in the switches of the converter. Switches in inductive converters have to withstand the full operational voltage, which depending on the application range, is from tens to a few hundreds of volts. Using high voltage devices has three main drawbacks: First, the losses in the devices scale quadratically with the voltage stress. Second, bad switching performances, because high voltage devices are less efficient and slower switching. Third, the standard VLSI technologies do not offer these *high voltage* (HV) devices and the VLSI technologies that offer them are less performant and more expensive than the dedicated discrete technologies.
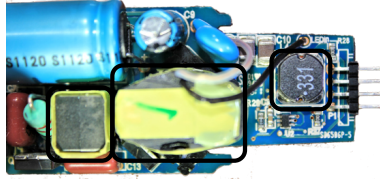
Figure 2.4: Magnetic components marked with a black square in a mains connected LED driver. These components dominate the volume of the converter.

2.4   Capacitor Based Converters

Switched Capacitor Converters (SCCs) are SMPS composed only of switches and capacitors. SCC were initially used for voltage multiplication [3, 4, 22] and more recently in applications that need voltage regulation as well [14]. Compared to inductor based converters, the absence of magnetic elements places them in a good position for high density power systems and integrated solutions, such as Power-System-in-Package (PSiP) or Power-System-on-Chip (PSoC).

SCCs have a fixed ratio of conversion between the input and the output determined by the topology. The output voltage of the converter under no load conditions is defined as the *target voltage* v_t. The converter performs at high efficiency when the load is supplied close to the *target voltage*. Similar to the linear drivers, if the output voltage goes below the *target voltage* the efficiency drops and when the output voltage is above the *target voltage* the converter cannot operate. Figure 2.5a shows a step-down converter with a conversion ratio of one half.

A common practice to extend the regulation margins of these converters is to have topologies with multiple conversion rations [12, 19]. From Figure 2.5b it can be seen that the efficiency increases as the ration m gets close to the first fixed conversion ration of the converter m_1; right after m_1 the efficiency drops again dramatically and it again linearly increases as it approaches the second fixed conversion ratio of the converter m_2. Beyond m_2 the converter does not work.

The main advantage of these converters is that they use no inductors, which makes them suitable for integration. Integrated capacitors have a better energy density than integrated inductors. The mechanical structure of the capacitors, a stack of isolator-metal-isolator, is much easier to replicate on a small scale. Yet another advantage of the switch capacitors is that they split the voltage applied to the converter among the different components, thus reducing the voltage stress in the switches and capacitors. Such voltage stress reduction is very interesting from the point of view of integration. First, lower voltage capacitors have better performances: higher energy density, less derating and better chances of integration. Second, lower voltage switches have better switching performances. Finally, low voltage devices take less silicon area and there is more to offer in the standard VLSI technologies, thus reducing the production
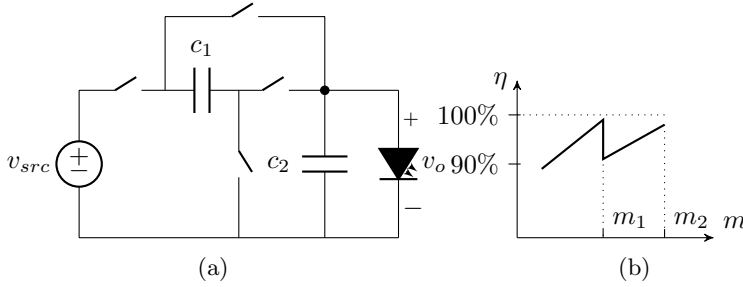
Figure 2.5: Switched capacitor converter, *left* - 2:1 converter schematic; *right* - conversion ration *vs.* efficiency curve for of a generic multiple conversion ration stage

costs.

The big disadvantage of these converters is that they can not directly provide the voltage-to-current conversion required for the LEDs to work. Nevertheless they are still used as LED drivers in backlighting applications for battery supplied devices. In such cases, the SCCs steps-up or steps-down the battery voltage and afterwards a linear driver provides current regulation to properly bias the LEDs. Adopting that architecture for general lighting could be a solution, but when voltages and currents are scaled to the values used in these applications the number of necessary conversion steps of the SCC would make it totally infeasible and inefficient.

Based on the previous arguments adopting an SCC architecture for a general solution for LED drivers seems to be, a priori, not an evident choice. On the one hand, their limitation in voltage-to-current conversion would directly disqualify switched capacitors. On the other hand, the advantageous characteristics of switched capacitors for integration made these circuits very attractive. Actually, if the initial limitations in voltage-to-current conversion could be overcome, such architecture would be an interesting candidate to explore as a solution for a *Power System on-Chip/in-Package* LED driver. Exploring the possibilities that switched capacitor converters can offer in terms of integrated and miniaturized LED drivers with efficient voltage-to-current conversion was the rational of this dissertation.

2.5 State of the art LED Drivers

Screen backlighting, Automotive and General Lighting are currently the three main areas of applicaiton of LEDs. Looking into these three areas of application gives a broad overview about the different driver architectures currently used and the approaches towards integration and miniaturization.

With regard to the miniaturization of power supplies, we can indemnify two clear approaches: *Power System on Chip* (PSoC), and *Power System in Package* (PSiP). The PSoC approach aims for the integration of the all con-

verter in a single monolithic *Integrated Circuit* (IC). In this approach the power management and the control control circuits are integrated in the same semi-conductor die along with energy storage components, with poor energy storage that have on-die inductors and capacitors. The PSiP approach aims for the integration all the necessary functionalities in the same IC package including the passives. This second approach allows to use a large variety of technologies enabling multi-die chips and the integration miniaturized discrete passives in the same package. In line with PSiP, it could be considered a third approach with off-package passives, and an IC integrating power management, control and processing. Actually, this solution is widely spread among the current IC manufacturers regarding power management solutions, however the current solutions only provide the integration of the power train and control circuit or just merely the control circuit.

Van Breussegem and Steyaert [18] and Villar-Pique et al. [20] provide a comprehensive overview and analysis over the stat-of-art regarding integrated converters, this section provides the overview targeted specific to LED drivers from two points of view application and driver technology.

2.5.1   Commercial LED drivers

Generalist IC manufacturers such as NXP, TI, ST, etc. have a large portfolio of dedicated LED drivers for the this three main applications: Backlighting, Automotive and General Lighting. Innovation from the perspective of the IC manufacturers is very limited just providing the two standard integrated circuit solutions with regard to power management for LED drivers: controller or controller and power train. This approach facilitates the driver development by reducing component count and design time, however using this circuits the possibilities to reduce the size of the off-chip passives if very limited, topologies are fixed. Currently there is any commercial IC that solves the challenges of the smart drivers, offering connectivity and power management.

Currently the most innovative approach is taken by the startup *Gooee* that proposes connected lighting platform consisting of two ICs. The control chip integrates a micro-controller unit (MCU) with to implement the communication and sensing, and the power chip with the LED driver that interfaces with the LED; the platform is completed with a cloud service that enables from a web application to have access to the lamp fixture data logs. The technical details of the power chip are no yet available [2].

Backlighting for screens in phones, tablets, laptops and TVs was one of the first commercial application of high brightness LEDs (HB-LEDs). Backlighting applications require multiple LED channels, therefore these drivers are generally implemented with a two stage architecture as shown in Figure 2.6. The first stage - normally implemented with SMPS, inductive or capacitive- boosts the supply voltage above the highest voltage of the LED strings. The different strings are individually driven by a linear driver which enables to adjust and dim the currents for each channel individually [5, 8]. Current commercial solutions integrates power train and power management in a single IC package, using
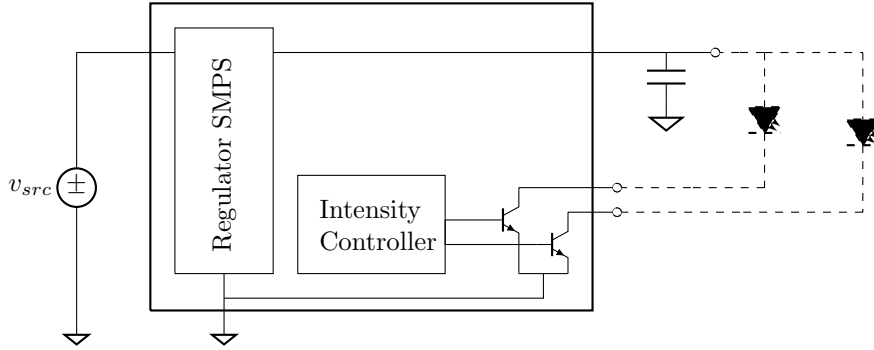
Figure 2.6: Block diagram of the common architecture used in drivers for back-lighting applications.

off-chip passives. Drivers for mobile devices, phones and tablets, accept low voltages between 2.5V to 5V, and implement the SMPS stage with an inductive or a capacitive converter. For bigger screens the drivers accept higher voltages between 5V to 45V, and the SMPS stage is normally implemented with an inductive boost converter. In both cases currents are in the low range between between 20mA to 100mA for each string channels, with the exception of the flash light that requires currents burst of up to 1A.

Signaling for the tail lights was the initial application of LEDs in the automotive industry, with the consolidation of the HB-LEDs, LED lighting is currently used also in headlights [6]. Drivers for automotive applications have to deal with a wide range in the input voltage from 6V to 42V between and provide immunity for the transients in the battery line [13, 16]. The currents change depending on the application, for signaling currents are between 20mA to 100mA, and for head lighting around 1A. These drivers are implemented with the popular inductive converters such as Boost, Back, Back-Boost or SEPIC. The available commercial products control ICs using off-chip passives and switches for scalable solutions, or power train and control ICs using off-chip passives. A new trend in the automotive lighting field is the matrix LED technology for headlamps [1], where a matrix of individually driven LEDs provide high-precision illumination for the drivers, enabling higher safety during night conduction. Matrix LED headlights represent a new challenge for the LED driver, requiring individual control for each of the LEDs in the matrix. The current used architecture connects a switch in parallel of each individual LED, by closing the switches the LEDs can be short-circuited allowing to turn them off or dimming the light intensity [9].

General lighting is currently the main application of high brightness LEDs and the one with the most variants with respect to the drivers. Drivers for general lighting are supplied from the mains utility (ac source) and they require a buffer element in order to provide constant power to the LEDs, which is generally implemented with an electrolytic capacitor. This buffer capacitor is one

main contributors in volume and failures, limiting the lamp design and lifetime. Therefore reducing the volume of the capacitor is one of the important aspects in the miniaturizations of off-line drivers, and it can be done by reducing the operating voltage or the required value enabling to use other technologies with better reliability or energy density such us multi-layer ceramics chip capacitors (MCCC) or thin film plastic capacitors.

Three different architecture approaches are currently implemented in off-line drivers:

Single stage A SMPS, a buck or a fly-back, converts the input rectified mains voltage to a constant current to supply the LEDs. At the same time the driver keeps the power quality within the standards in terms power factor (PF) and total harmonic distortion (THD). This approach has the advantage of a reduced costs since it has a small number of components, just requiring one power transistor and one magnetic component. However it is necessary to use a big buffer capacitor in parallel to the LEDs in order to have an stable output voltage and avoid the flickering from the low frequency rectified mains voltage (100Hz - 120Hz). Currently it is one of the most popular solutions for domestic lighting products for powers up to 70W, and there is a large portfolio of ICs implementing the control or the control and power train, passives have to be used off-chip.

Two stage Rectified mains voltage is first converted to a *dc* bus voltage and stored in to the buffer capacitor with almost unity power factor. A second stage converts the power from the buffer capacitor to the LED strings. In this approach the size of the buffer capacitor can be optimized adjusting the voltage and ripple in the bus voltage, which leads to an smaller value than the single stage approach. As a draw back these architecture are more expensive and require double number of components, switches for two power train and at least two different magnetic components. Two stage drivers are used in professional lighting applications, for powers above 100W, and for domestic application for smart bulbs with color tuning, usually both applications require a drivers with multiple outputs to efficiently supply independent LED strings. There are not dedicated power factor controllers (PFC) ICs for lighting applications, therefore first stages are just designed and mounted with generic power management ICs for PFC. For the second stage, the IC manufacturer offer a portfolio of drivers for the standard inductive converters (back, boost and flyback), with the two common options in power management ICs: controller or integrated controller and power train, passives are mounted off-chip.

Tap linear Rectified mains is directly supplied two the LEDs by means a matrix of switches and linear regulators. The driver is continuously adjusting the LED string configuration in order to minimize the difference between the input voltage and the LED string, hence decreasing the voltage through a linear regulator. Tap linear drivers do not require the use of a buffer capacitor and magnetics, therefore can be fully implemented in

silicon. However, these circuit have a poor light quality in terms of flickering. TI launched in 2014 the first dedicated IC for tab linear drivers the TPS92410, currently there are no other commercial alternatives.

2.5.2 Linear LED Drivers

Linear Drivers are the excellent converters for a full integrated solution with a minimal die area, being possible to practically implement all the converter in silicon with the exception of the output buffer capacitor. Linear drivers are commonly used in *dc-dc* conversion for screen blacklighting [8, 11, 17], where different LED strings have to be supplied individually supplied from the same voltage buffer. Each string has a linear driver that permits to individually control and adjust their light level. The common voltage levels is generally supplied from a SMPS pre-regulator that can be adjusted to improve the efficiency of the system.

Regarding general lighting, full integrated implementations were reported for *ac-dc* conversion with the so called *tap*-linear drivers or matrix converters [10, 15, 23]. Tap-linear drivers implement a matrix of linear regulators and switches along with different LED strings. The matrix of switches adjust the voltage of the LED string and the linear regulators the currents in order to follow the input voltages and reduce the drop-out voltage across the linear regulators, achieving good efficiencies above 80% and power factors above 90%. Light quality was not reported with respect to flickering, however it can be anticipated that a low frequency ripple (100-120Hz) will be present since the current and the number of LEDs varies with the mains voltage. Neither dimmablility in the drivers were reported. Another requirement of the tab-linear drivers is that led strings are designed with an overhead to cope with the mains line variations(±10%), which leads to poor utilization of the LED chips, some can conduct for short or null periods of time, increasing the costs for the LEDs.

2.5.3 Inductor Based LED Drivers

Inductor based converters are, without doubt, most used solution for LED drivers. Inductive converters have an excellent current-to-voltage regulation at high efficiencies, and at the same time can provide galvanic isolation. That is why, the majority of IC manufacturers offer a large portfolio of ICs for LED driving, with two approaches of integration: Control circuit alone, or Control circuit with the power switches. In both cases, buffer capacitors and magnetics have be mounted externally. Different flavors of control circuits can be found, covering the usual architectures (buck, boost or fly-back) and with different control schemes providing Power Factor Correction (PFC) and dimmability. Practically SSL products already in the market have build the electronics around these, circuits.

2.6   Conclusions

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

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.

This thesis is divided in the four main sections that where necessary to build a switched capacitor LED driver. The first section introduces the new LED driver architecture used during the entire thesis, the *Hybrid-Switched Capacitor Converter*, H-SCC from now on. The second part of this book, the core of the PhD. work, presents the methodology to model H-SCC. The methodology extends the previous works in the topic providing an enhanced modeling for the design of SCCs and H-SCCs. The third section is devoted to the practical use of the new methodology, thus for the design phase of a converter. The modeling is used to help in the development facilitating the sizing and optimization of the design variables. The last section presents a discrete implementation of 12W H-SCC LED driver and the design procedure. Although is not a regular practice, experimental work is not only presented in the in the last section. The experimental work has been also used to validate the presented modeling and methodology. The final section is the conclusion of the entire work and the future opportunities that the presented work can offer.

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Chapter 3

Hybrid Switched Capacitor Converter

The integration and miniaturization characteristics of Switched Capacitor Converters (SCCs) have an application for LED drivers, already in commercial ICs and also in research. Commercially, there is a large portfolio of available ICs, designated as Charge-Pumps (CPs), for backlighting in portable devices, *i.e.* *MAX88779* [1], *MCP1252/3* [2]. These circuits can drive withe, 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 (1:1, 3:2, 2:1) along with a linear regulator for each channel a shown in the block diagram of Figure 2.6. Various publications [1, 7, 8] proposed enhancements in the architectures in order to reduce the parasitic losses bringing the efficiency close to the theoretical limit. The power ratings in these drivers are below a $1W$ and currents below hundred mili-Amperes with efficiencies between 70%-90% depending on the operation point.

With respect to general lighting there are few research publications that rapport the use of SCCs. In 2008, Lee et al. [5] presented a step-down converter supplied from rectified $220V_{rms}$ providing 15W with a 95% peak efficacy. The proposed architecture supplied directly the LED string from the capacitors, controlling the output power by changing the switching frequency. In 2012, Kline et al. [2] proposed a isolated converter that combined a SCC stage with series-LC resonant converter delivering 15.5W with an efficiency of 92%. The SCC stage decreased the rectified mains voltage, reducing the voltage stress in switches, capacitors and the elements of the resonant tank, allowing to diminish the volume of the passive components and the total silicone area. The LED current is regulated using frequency and the duty cycle modulation. A recent publication presented modular implementation in silicon with a stackable ICs [4].

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[1] Maxim® Charge Pump for Backlight/Flash/RGB LEDs with Safety Timer
[2] Microchip® Low noise, Positive-Regulated Charge Pump

Driving high power LED using a switched capacitor converter challenges the operation of these converters. SCC provide a good performance in voltage-to-voltage conversion, but they can not directly provide a voltage-to-current. In low power applications, that is solved by using a linear regulator in series with the LED string, however it is not a valid solution for general lighting where high power and currents are needed. Combining switched capacitor with inductors can provide efficient converters for LED lighting, where the use of inductors provide a tight and efficient regulation, and the use of a switched capacitor allows to reduce the voltage stress in the components reducing switching losses and size.

The *Hybrid* switched capacitor converter (h-SCC) is a merge of a switched capacitor and an inductive converter, and it will be introduced in this chapter. The first section will introduce the reader to basic operation of the switched capacitor converters and the common used model. The second section, will present the H-SCC architecture and their operation. In the third section, different LED driver architectures will be presented along with architecture and control modifications that extends the range of operation of the converter.

3.1 Switched Capacitor Converter

A SCCs are a family of SMPS circuits that provide power conversion using only switches and capacitors as shown in figure 3.1a. A SCC has two or more operation modes, referred as phases, each operating mode is associated with a different circuit arrangement of the capacitors , and sequentially switching between the different modes provides a voltage conversion between input and output. The circuit in figure 3.1a is a two phase 3:1 Dickson that provides a step down conversion ratio of $\frac{1}{3}$. During the first phase the odd switches are closed, resulting with the circuit of figure 3.1b. During the second phase, the even switches are closed, resulting with the circuit of figure 3.1c.

3.1.1 Conversion ratio

The conversion ratio of the converter and the steady state voltages in the capacitors can be obtained applying Kirchhoff's voltage law (KVL) of each phase and solving the system of linear equations that provide the different equations. Therefore KVL equations of the first phase are:
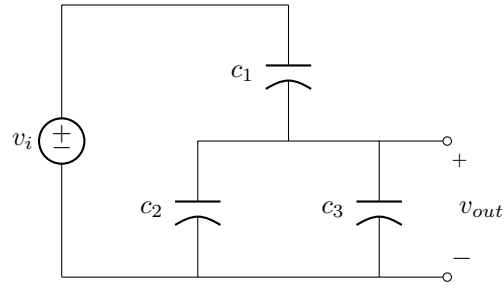
$$
\begin{aligned}
v_{src} - v_{c_1} - v_{c_2} &= 0, \\
v_{out} - v_{c_2} &= 0, \\
v_{out} - v_{c_3} &= 0.
\end{aligned}
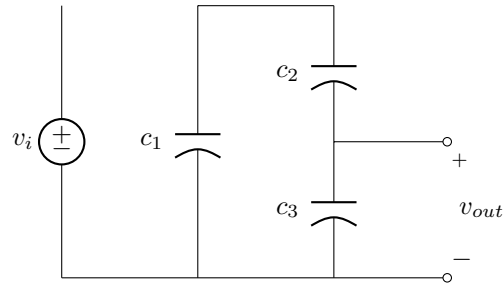\tag{3.1}
$$

The KVL equations of the second phase are

$$
\begin{aligned}
v_{c_1} - v_{c_2} - v_{c_2} &= 0, \\
v_{out} - v_{c_3} &= 0.
\end{aligned}
\tag{3.2}
$$
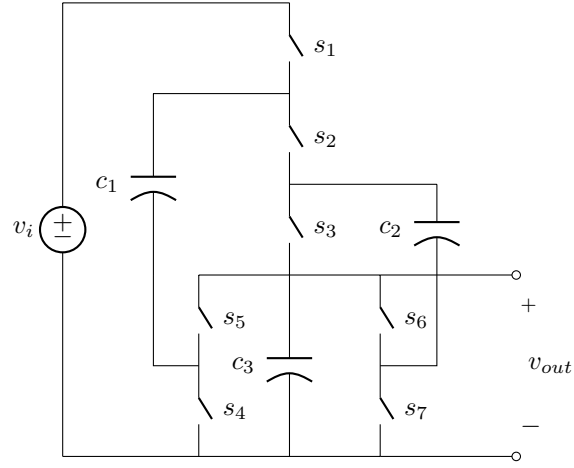
(a) Circuit diagram the two phase 3:1 Dickson Converter.

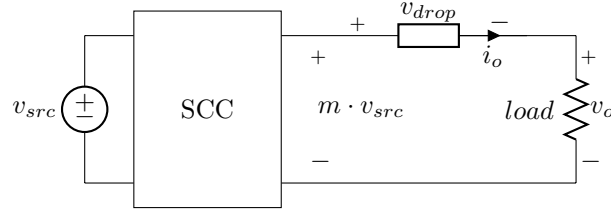(b) First phase, odd switched are closed and even switches are open.

(c) Second phase, even switched are closed and odd switches are open.

Figure 3.1

Selecting the linear independent equations from eq.(3.1) and eq.(3.2) the

Figure 3.2: Linear regulated switched capacitor

system can be solved, yielding

$$v_{out} = v_{c_3} = vc_2 = \frac{V_{src}}{3},$$
$$v_{c_1} = \frac{2V_{src}}{3}, \tag{3.3}$$

thus the converter conversion ratio is

$$m_i = \frac{v_{out}}{v_{src}} = \frac{1}{3}. \tag{3.4}$$

This result shows that the conversion ratio is defined by the topology of the converter and independent of the switching operating regime. From now on, the conversion ratio defined by the topology will be referred as the *intrinsic* conversion ratio and defined as m_i.

3.1.2   Output voltage regulation

A SCC has a fixed conversion ratio only defined by its topology and not by its operation regime. The conversion ratio of the converter can not be adjusted changing frequency or pulse width as in the case of inductive based converters, therefore the converter can not directly provide voltage regulation.

Indirectly, there is the possibility to regulate the output voltage by means of a linear regulator, thus the output voltage is adjusted by drooping the excess voltage (v_{drop}) in a series element with the load, as shown in the schematic of figure 3.2. This can be achieved in two ways: Using an external liner regulator connected between the converter output and the load, or what is more common, using or *'misusing'* the behaviour of the SCC in order to provide this linear regulation characteristics. Regulating the load in this way the efficiency of the converter is affected, the efficiency decreases as the difference between $m \cdot v_{src}$ and v_o increases. Actually, like a linear regulator, the efficiency of the converter can be written as function of v_{src} and v_o as

$$\eta = \frac{P_o}{P_i} = \frac{v_o \cdot i_o}{m \cdot v_{src} \cdot i_o} = \frac{v_o}{m \cdot v_{src}}. \tag{3.5}$$

Figure 3.3 plots the theoretical maximum efficiency with respect of the effective conversion ratio of the power converter $m_e = v_o/v_s rc$. Comparing the characteristics of a single linear regulator and a linear regulated 2:1 SCC shows
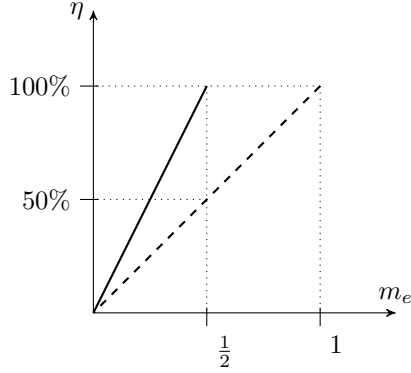
Figure 3.3: Comparison of the conversion ratio vs. maximum theoretical efficiency curve: *dashed line* - linear regulator ; *thick line* - 2:1 linear regulated SCC

that for conversion ratios below 1/2 the SCC converter has 50% better efficiency, however above 1/2 the SCC is not longer operative.
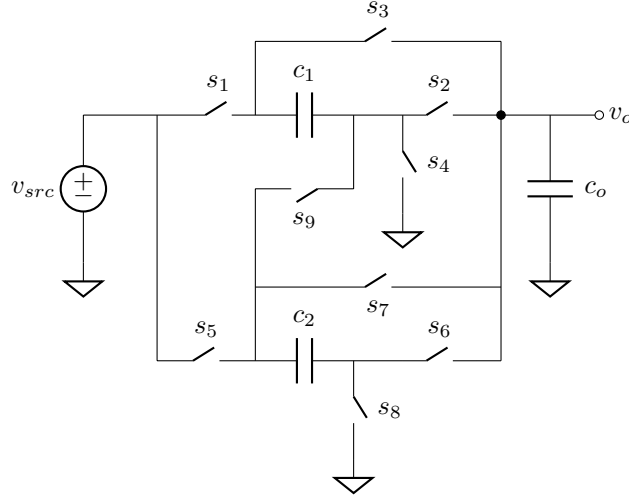
3.1.3 Multiple conversion ratio converters

Multiple conversion ratio converters enable to extend the regulation margins and increase the conversion efficiency. Figure 3.3 shows the limitations of a 2:1 SCC. First, the converter is only operative for conversion rations below 1/2. Second, as the conversion ratio moves below the intrinsic conversion ratio of the converter (1/2) the efficiency linearly decreases. Topologies, like the one of figure 3.4a, have multiple conversion ratios - $\frac{1}{3}$, $\frac{1}{2}$, $\frac{2}{3}$ and 1 - that extend the operation margins and increase the efficiency of the converter as shown in the plot of figure 3.4b.

3.1.4 Converter output nodes

The precedent section has presented switched capacitor converters with the load connected to a node that provides a fixed conversion ratio. Actually that is the most common and extended way of employing such converters, however a SCC can supply the load from other nodes internal nodes of the converter with special characteristics. In truth, two types of nodes can be identified in a Switched Capacitor Converter: Fixed voltage *dc*-nodes, node *a* in figure 3.5, and floating voltage *pulsed width modulated*-nodes (*pwm*-nodes), node *b* in figure 3.5.

Fixed voltage *dc*-nodes are the common output nodes of a SCC. With a fixed conversion ratio defined by the topology, they supply the output load with a low voltage ripple with a capacitor in parallel connected to ground. The capacitors that are connected between a *dc*-node and ground are *dc*-capacitors as shown in the Fig. 3.5. A converter have one or more *dc*-capacitors, however topologies with a reduced number of them (C_{dc}) trend to have a better utilization of the capacitors, since these capacitors do not contribute to the charge transportation [6].
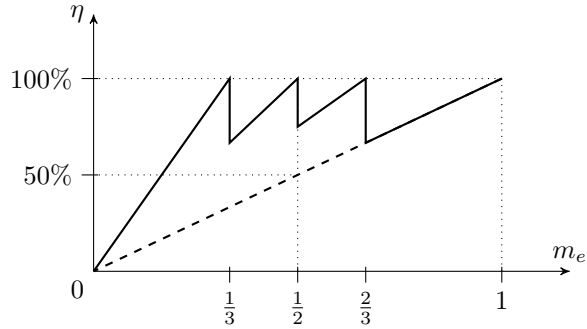
(a) Multiple conversion ratio SCC.

(b) Comparison of the conversion ratio vs. maximum theoretical efficiency curve: *dashed line* - Single linear regulator ; *thick line* - Linear regulated multiple conversion ratio SCC.

Figure 3.4

Floating *Pulsed Width Modulated*-nodes (*pwm*-nodes) have been rarely used as outputs until a recently couple of publications [2, 3] 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. *pwm*-node are accessible from the terminals of flying capacitors (C_{fly}), delivering a floating pulsed-width-modulated (PWM) voltage with an added *dc* offset of a fraction
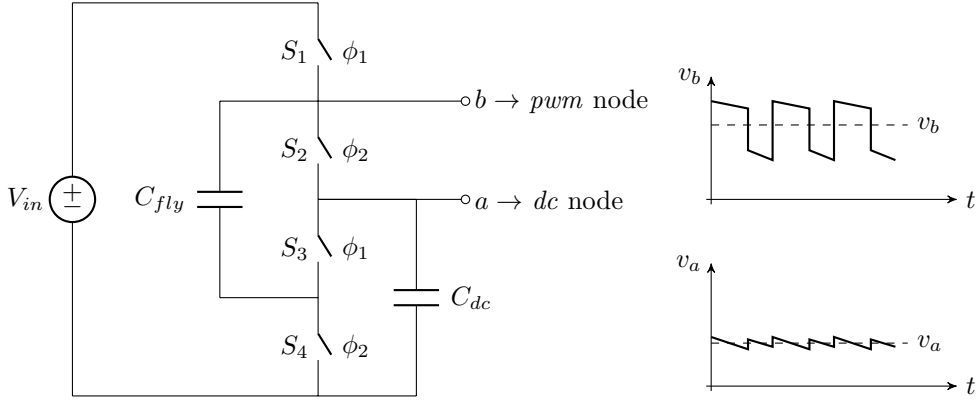
Figure 3.5: 2:1 switched capacitor and the two nodes types. Node a is a dc-node; its voltage, v_a is plotted in the bottom graph. Node b is a pwm-node; its voltage, v_b, is plotted in the top graph.

of the input voltage with respect to ground. 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. Furthermore 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.

3.2 Hybrid Switched Capacitor

A Hybrid Switched Capacitor Converter (H-SCC) uses a low pass filter to supply a dc voltage from a pwm-node, as shown in figure 3.6. The low pass filter is composed by inductor l_o and capacitor c_o, and averages the pwm-voltage of the switching node v_x.

As in the previous case, odd switches are closed during one phase (figure 3.9a) and even switches (figure 3.9b) are closed during the other phase. The switching between the two phases produces a pwm voltage at the switching node v_x as shown in the graph of the figure 2.1. Hence the voltage at the switching node v_x during an entire switching period T_{sw} is

$$
v_x(t) = \begin{cases} \frac{1}{3}v_{src} & : & 0 & < & t & \leq & DT_{sw} \\ \frac{2}{3}v_{src} & : & DT_{sw} & < & t & \leq & T_{sw}, \end{cases}
\tag{3.6}
$$

where D corresponds to the duty cycle. The output filter averages voltage at the switching node voltage, and the resulting mean value v_{out} is obtained by
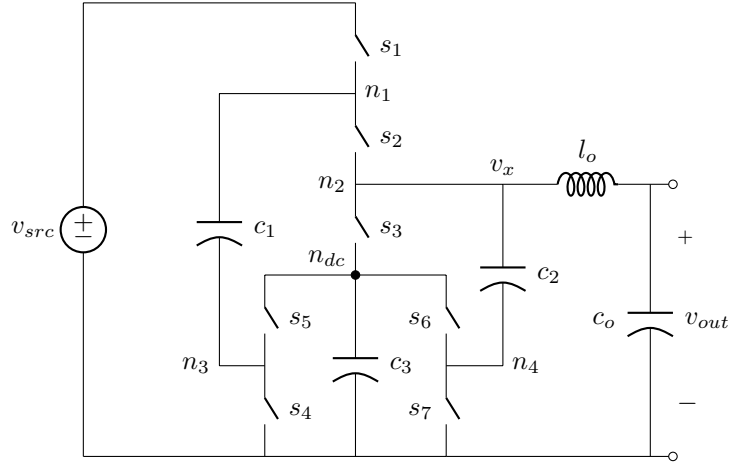
Figure 3.6: H-SCC with a 3:1 Dickson topology with the inductor connected to the second *pwm*-node.
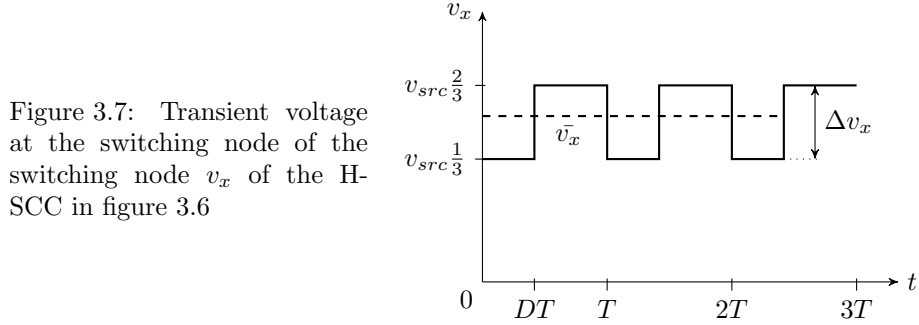

Figure 3.7: Transient voltage at the switching node of the switching node v_x of the H-SCC in figure 3.6

integrating eq.(3.6) during a switching cycle:

$$v_{out} = \frac{1}{T} \int_0^T v_x(t)dt \tag{3.7}$$

$$v_{out} = \frac{1}{T} \left(\int_0^{DT} \frac{1}{3} v_{src} \, dt + \int_{DT}^T \frac{2}{3} v_{src} \, dt \right) \tag{3.8}$$

$$v_{out} = \frac{2-D}{3} v_{src}, \tag{3.9}$$

thus the converter conversion ratio for the second node (n_2) is

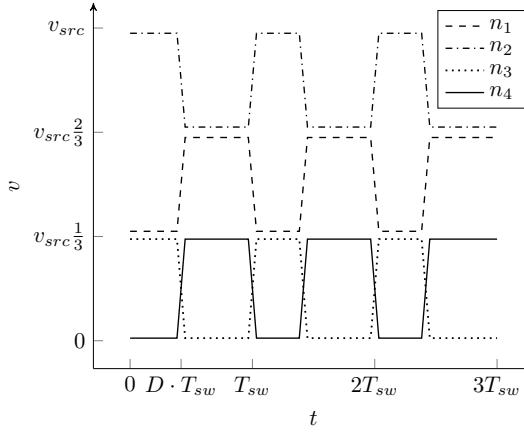$$m_2 = \frac{v_{out}}{v_{src}} = \frac{2-D}{3}, \tag{3.10}$$

Figure 3.8: Transient voltage from all the different *pwm*-nodes of the 3:1 H-Dickson converter of figure 3.6.

where the subscript in m denotes the node of the converter. The numbering of the nodes is made in the following order top-bottom and left-right, see circuit schematic of figure 3.6. Figure 3.8 plots all the switching voltages available in the converter. The square-wave voltages cover a the range from 0 to v_{src} equally divided with an amplitude of $v_{src}/3$. In fact, this equal spacing is one of the singularities of Dickson and Lader converters with respect to the other topologies. (That is why these two topologies were selected to implement all the H-SCC of this dissertation.) Therefore the amplitude of the voltage at the switching node is

$$\Delta v_x = m_i v_{src}. \tag{3.11}$$

In fact, a H-SCC share lots of the characteristics of a buck converter, the most common LED driver in dc-to-dc conversion. Adding the output filter to a SCC, complements the converter with tight current regulation overcoming one of the intrinsic limitations of these converters, however it requires new magnetic elements challenging again the integrability of the converter. In the following sections is introduced the characteristics of this new *hybrid* topology as a LED driver using the buck converter as the reference driver, since a H-SCC architecture can directly replace a buck converter LED driver providing the same regulation characteristics.

3.2.1 Output Regulation

In contrast with the classical SCC, the conversion ratio of the converter depends on D, the duty cycle of the converter, consequently the conversion ratio can be now intrinsically adjusted to provide regulation to the load without affecting the converter efficiency.

Figure 3.10 compares the idealized trend curves of the converter efficiency with respect to the conversion ratio for a H-SCC, a SCC and a buck converter. For example a 3:1 Dickson has an intrinsic conversion ratio of $m_i = \frac{1}{3}$ and provides regulation at costs of efficiency (see dashed line). Instead, using the
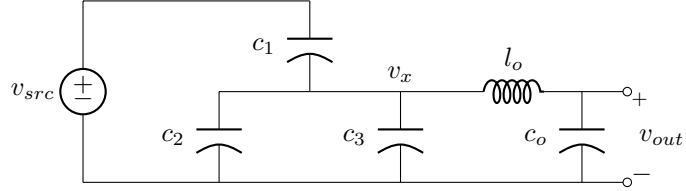
(a) First phase, odd switched are closed and even switches are open.
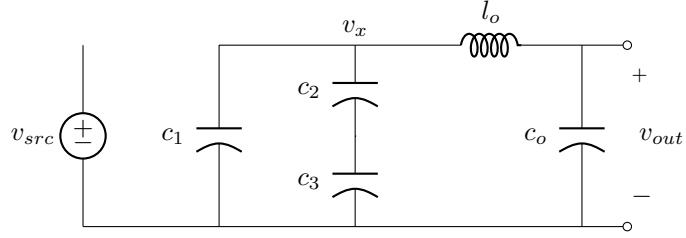
(b) Second phase, even switched are closed and odd switches are open.

Figure 3.9

third *pwm*-node (n_3), located at the negative terminal of capacitor c_1 in the schematic of figure 3.6, the converter has an adjustable conversion ratio of

$$m_3 = \frac{D}{3} \tag{3.12}$$

by changing the duty cycle D of the drive signal. In this case, the efficiency vs. regulation curve keeps flat within a regulation margins and drops for extreme duty cycles cause of the internal losses of the SCC (see solid line). The details of the loss mechanisms in SCC and H-SCC, are covered in chapter X dedicated to modeling. Indeed, the efficiency vs. regulation curve of a H-SCC is similar to the one of a buck converter (dotted line) but with a smaller dynamic range.

Ideally a buck converter can provide a conversion ratio between 0 and 1. It is the same case for a H-SCC, however the conversion ratio is segmented. Each segment is associated to a different *pwm*-node of the converter, and it has a limited dynamic range of regulation Δm. Table 3.1 presents the conversion characteristics for the different nodes of the 3:1 H-Dickson of figure 3.6. It can be seen that the dynamic range of conversion (Δm) is the same across all the *pwm*-nodes and equal to equal to the intrinsic conversion ratio of the converter m_i, this characteristic is shared with two topologies used in this dissertation: Dickson and Ladder.
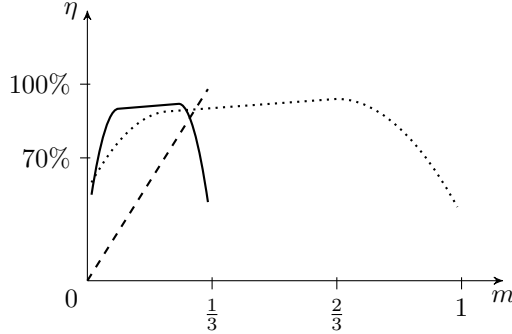
Figure 3.10: Comparison between converters of regulation vs efficiency (trend curves): 3:1 H-Dickson $3rd$ pwm-node (solid line), 3:1 Dickson (dashed line) and buck converter (dotted line).

Table 3.1: Conversion ratio characteristics at the different nodes of a 3:1 H-Dickson converter

Node		n_1	n_2	n_3	n_4	n_{dc}
Conversion ratio	m_x	$\frac{2+D}{3}$	$\frac{2-D}{3}$	$\frac{D}{3}$	$\frac{1-D}{3}$	$\frac{1}{3}$
Range of conversion		$1 \cdots \frac{2}{3}$	$\frac{2}{3} \cdots \frac{1}{3}$	$\frac{1}{3} \cdots 0$	$\frac{1}{3} \cdots 0$	-
Dynamic conversion range	Δm	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	-

3.2.2 Power Inductor

Actually the H-SCC is similar to a buck converter, where a LC low pass filter is excited with a square-wave voltage as shown in figure 3.11a. The size of the power inductor is directly proportional to the amplitude of the square-wave voltage at the switching node (Δv_x) that in a buck converter is equal to the source voltage as shown in the plot from figure 3.11b.

The value of the power inductor can be computed as

$$l_o = \frac{\Delta v_x \cdot DD'}{\Delta i}T, \tag{3.13}$$

where Δi is current *peak-to-peak* amplitude in the inductor. Particularizing it for the buck converter, yields to

$$l_{o,buck} = \frac{v_{src} \cdot DD'}{\Delta i}T. \tag{3.14}$$

Per contra, in the case of the H-SCC the square-wave voltage is floating with respect the ground (see figure 3.7) and its ripple amplitude Δv_x depends on the converter's topology. In the case of the Dickson and Ladder converters the amplitude of the voltage ripple Δv_x is the same for all of the *pwm*-nodes and equal to

$$\Delta v_x = m_i \cdot v_{src}, \tag{3.15}$$
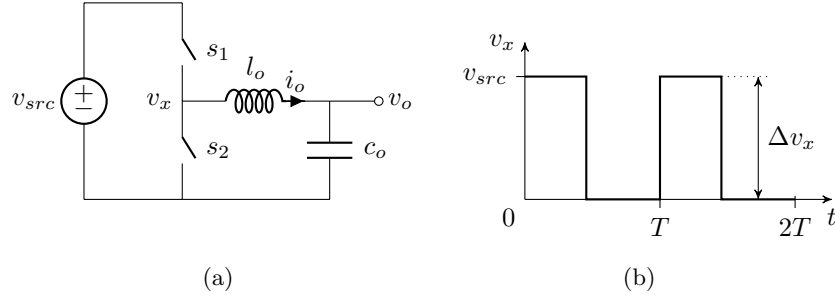
(a)   (b)

Figure 3.11: Inductor based converter, *left* - buck converter schematic; *right* - transient voltage at the switching node during two switching periods.

therefore particularizing eq.(3.13) for a Dickson or a Ladder H-SCC yields to

$$l_{o,hscc} = \frac{m_i \cdot v_{src} \cdot DD'}{\Delta i} T. \tag{3.16}$$

Actually using the *pwm*-nodes of an SCC reduces the amplitude of the voltage ripple at the filter inductor, what at the same time requires a smaller inductor value for a converter operating under the same frequency and current ripple conditions. The reduction ratio of the inductor can be obtained from eqs. (3.14) and (3.16) as

$$\frac{l_{o,hscc}}{l_{o,buck}} = \frac{m_i \cdot v_{src} \cdot DD' \cdot T/\Delta i}{v_{src} \cdot DD' \cdot T/\Delta i} = m_i. \tag{3.17}$$

In fact, the ratio coincides with the intrinsic conversion ratio (m_i) of the converter, that for a step-down is always smaller than 1. For the 3:1 Dickson H-SCC of figure '3.6 the inductor value is 3 times smaller than in a buck converter. As a matter of fact using a H-SCC introduces an new design parameter to reduce the value of the power inductor, providing a new architecture that improves the integration or power converters in this case by the reduction of the magnetic components.

3.2.3   Power Switches

The large number of switches used in a H-SCC has different advantages towards miniaturization of the converter. In fact in a H-SCC the voltage stress applied to the different switches is a fraction of the input voltage, in contrast with the buck converter that the two switches have to block the full input voltage. allows to implement H-SCC converters with switches rated at lower voltages than the input voltage. Table 3.2 shows the blocking voltages at the switches of the 3:1 H-Dickson of figure 3.6.

Reducing the voltage stress has several advantages. First, low voltage devices take less silicon area and have a larger offer in the standard integration processes.

Table 3.2: Stress voltages at the switches of the 3:1 H-Dickson of figure 3.6.

Switch #	Stress voltage
$s_1, s_3 \cdots s_7$	$\frac{1}{3}v_{src}$
s_2	$\frac{2}{3}v_{src}$

Second, switching performance of the devices are better since the devices are smaller in area, thus smaller in parasitic capacitances, as a consequence they can switch faster. Finally, the switching losses of the converter are reduced since they are quadratically proportional to the blocking voltages of the switches (v_{ds}). The switching losses ratio between the buck and the 3:1 H-Dickson are computed assuming that c_{ds} is equal for all the switches in both converters, using the switching losses formula associated to the parasitic capacitances [?]:

$$P_{sw} = \frac{1}{2}f_{sw} \cdot c_{ds} \cdot v_{ds}^2. \tag{3.18}$$

The blocking voltages of the switches in the buck converter of figure 3.11a is v_{src}, thus the switching losses are

$$P_{sw,buck} = f_{sw} \cdot c_{ds} \cdot v_{src}^2. \tag{3.19}$$

The blocking voltages of the 3:1 H-Dickson are in table 3.2, thus the switching losses for that converter are

$$P_{sw,hscc} = \frac{6}{2}f_{sw} \cdot c_{ds} \left(\frac{1}{3}v_{src}\right)^2 + \frac{1}{2}f_{sw} \cdot c_{ds} \left(\frac{2}{3}v_{src}\right)^2, \tag{3.20}$$

rearranging yields

$$P_{sw,hscc} = \frac{5}{9}f_{sw} \cdot c_{ds} \cdot v_{src}^2. \tag{3.21}$$

Dividing eq.(3.19) and eq.(3.22) yields the switching loss ratio between the two converters:

$$\frac{P_{sw,hscc}}{P_{sw,buck}} = \frac{5}{9}f_{sw} \cdot c_{ds} \cdot v_{src}^2. \tag{3.22}$$

We can generalize this result for the case of Dickson and Lader converters using the expressions for the blocking voltages of table 3.4.

3.2.4   Small Signal

3.3   LED Driver

The buck converter is usually the first choice that comes in mind when a LED has to be supplied from a *dc* source (see figure 3.12a). The converter provides a

Table 3.3: Switch blocking voltage of Dickson and Ladder converters.

Converter		# Switches	Blocking voltage (v_{ds})
N:1 Dickson	$N \geq 3$	$4 + N$	$\frac{v_{src}}{N} \rightarrow$ 6 switches $\frac{2v_{src}}{N} \rightarrow (N-2)$ switches
N:1 Ladder	$N \geq 2$	$2 \cdot N$	$\frac{v_{src}}{N}$

Table 3.4: Switch blocking voltage of Dickson and Ladder converters.

Converter	N:1 Dickson $N \geq 3$	N:1 Ladder $N \geq 2$
# Switches	$4 + N$	$2 \cdot N$
v_{ds}	$\frac{v_{src}}{N} \rightarrow$ 6 switches $\frac{2v_{src}}{N} \rightarrow (N-2)$ switches	$\frac{v_{src}}{N}$
P_{sw}	$\frac{4+N}{8 \cdot N^2} \cdot v_{vin}^2 \cdot f_{sw} \cdot c_d s$	$\frac{1}{N} \cdot v_{src}^2 \cdot f_{sw} \cdot c_d s$
$\frac{P_{sw}}{P_{sw,buck}}$	$\frac{4+N}{8 \cdot N^2}$	$\frac{1}{N}$

(a)   (b)
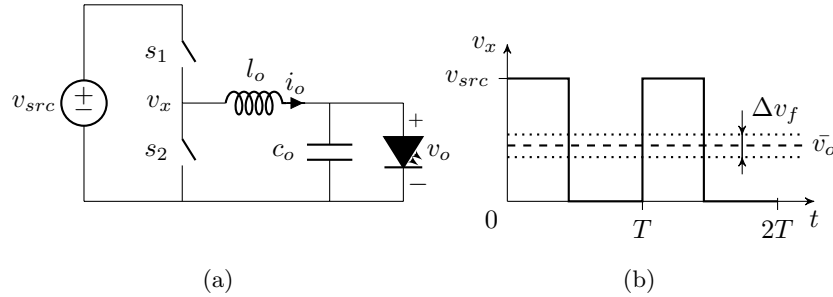
Figure 3.12: *Left* - buck LED driver schematic; *right* - transient voltage at the switching node with thick line. Average output voltage with a dashed line and forward voltage limits marked with dotted lines.

step-down conversion that can be adjusted to the LED voltage, and at the same time it provides an excellent current regulation since the inductor is in series with the LED load.

The plot of figure 3.12b shows the transient voltage at the switching node v_x, the average voltage at the LED, and the limits of the forward voltage variations Δv_f . It is evident that the margins of operation required by the LED Δv_f are much smaller than the regulation margins of the buck converter, which, indeed, is almost the full range of the input voltage from 0 to V_{src}. In fact, as aforementioned in the previous section this large voltage ripple at the switching

node requires a large inductor to filter.

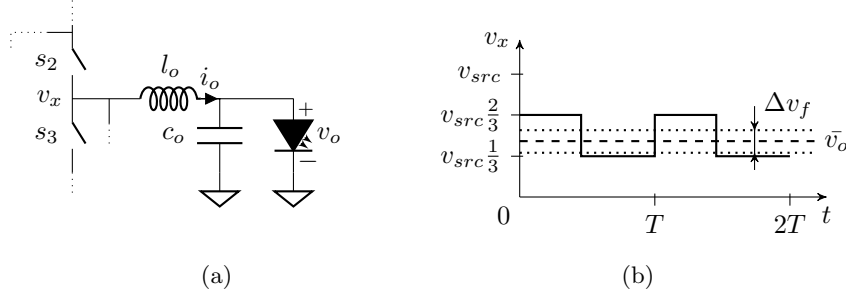(a)   (b)

Figure 3.13: *Left* - switching node detail of the 3:1 H-Dickson converter ; *right* - transient voltage at the switching node with thick line. Average output voltage with a dashed line and forward voltage limits marked with dotted lines.

On the contrary a H-SCC has a narrow excursion range of the switching node, what helps to decrease the value of the output inductor. The narrow margins of regulation that LEDs require due to their abrupt $v - i$ characteristics (see section 2.1) suits the reduced dynamic range that H-SCC offer. As a general practice in the design of a LED driver the voltage of the LED string is often optimized by selecting low, mid or high power LEDs and associating them in series or parallel. It is favorable to select a high voltages in the LED strings, but small enough to be driven by a buck converter. Increasing the voltage in the LED string decreases driving currents, which favors in lower conduction losses in the driver, mainly in switches and power inductors.

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