electronics

Review

Multiple-Output DC–DC Converters: Applications and Solutions

Salvador P. Litrán [1,2], Eladio Durán [2,3,*], Jorge Semião [4] and Cristian Díaz-Martín [2]

[1] Department of Electrical and Thermal Engineering, Design and Projects, University of Huelva, 21007 Huelva, Spain; salvador@uhu.es
[2] Centro Científico-Tecnológico de Huelva (CCTH), University of Huelva, 21007 Huelva, Spain; cristian.diaz@diesia.uhu.es
[3] Department of Electronic Engineering, Computer Systems and Automation, University of Huelva, 21007 Huelva, Spain
[4] Instituto Superior de Engenharia (ISE), Universidade do Algarve, 8005-139 Faro, Portugal/INESC-ID, 1000 Lisboa, Portugal; jsemiao@ualg.pt
* Correspondence: aranda@uhu.es; Tel.: +34-959217655

Abstract: Multiple-output DC–DC converters are essential in a multitude of applications where different DC output voltages are required. The interest and importance of this type of multiport configuration is also reflected in that many electronics manufacturers currently develop integrated solutions. Traditionally, the different output voltages required are obtained by means of a transformer with several windings, which are in addition to providing electrical isolation. However, the current trend in the development of multiple-output DC–DC converters follows general aspects, such as low losses, high-power density, and high efficiency, as well as the development of new architectures and control strategies. Certainly, simple structures with a reduced number of components and power switches will be one of the new trends, especially to reduce the size. In this sense, the incorporation of devices with a Wide Band Gap (WBG), particularly Gallium Nitride (GaN) and Silicon Carbide (SiC), will establish future trends, advantages, and disadvantages in the development and applications of multiple-output DC–DC converters. In this paper, we present a review of the most important topics related to multiple-output DC–DC converters based on their main topologies and configurations, applications, solutions, and trends. A wide variety of configurations and topologies of multiple-output DC–DC converters are shown (more than 30), isolated and non-isolated, single and multiple switches, and based on soft and hard switching techniques, which are used in many different applications and solutions.

Keywords: DC–DC converters; multiple outputs; applications; solutions

check for updates

Citation: Litrán, S.P.; Durán, E.; Semião, J.; Díaz-Martín, C. Multiple-Output DC–DC Converters: Applications and Solutions. *Electronics* **2022**, *11*, 1258. https://doi.org/10.3390/electronics11081258

Academic Editor: Kai Fu

Received: 10 March 2022
Accepted: 13 April 2022
Published: 15 April 2022

1. Introduction

Multiple-output DC–DC converters are fundamental in electric power supply, distribution, management, and power delivery systems. They are essential in applications such as: Intermediate Bus Architecture (IBA), Distributed Power Architectures (DPA), Dynamic Bus Architecture (DBA), Central Control Architecture (CCA), Datacom and Telecom, Light-Emitting Diodes (LEDs), consumer electronics products, battery chargers, or even Electric Vehicles (EV). These converters are used for USB power delivery, I/O, CPUs, FPGAs, ASICs, and other low-voltage devices, applications where controllability, efficiency, reliability, and miniaturization are critical.

Undoubtedly, the development of power switch semiconductor technologies has also contributed significantly to more efficient switching and has facilitated a higher frequency operation. This has allowed the development of applications where multiple-output DC–DC converters are used, considering mainly three aspects: high-power density, high efficiency, and small size. The increase in the rating of power devices, such as Insulated

Gate Bipolar Transistors (IGBT) and Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) technologies, has allowed innumerable applications to be addressed in the last 40 years. They have helped to improve energy efficiency and CO_2 reductions, in commercial, residential, transportation systems, industrial, military, aerospace, computer systems, lighting, and vehicle applications. MOSFET and IGBT, either as power modules or within discrete devices, have been the preferred technologies for high and medium power applications. IGBTs are used in applications of high-current, with voltages over 1 kV and up to 10 kVA, while MOSFETs are used in applications below 1 kV, but they are the most suitable in applications of high switching frequency, between 10–100 kHz.

Although silicon-based technologies have improved enormously in the recent years, and still continue to improve, this development will be restricted, ultimately, by silicon technology limitations [1]. Among the semiconductor materials with the greatest future potential are those with a Wide Band Gap (WBG), particularly Gallium Nitride (GaN) and Silicon Carbide (SiC). The physical properties of WBG materials make them especially suitable for high switching frequency and high-power applications, also giving them high resistance to high temperatures, lower switching losses, with low reverse recovery and low on-resistance, a better relationship between breakdown voltage (VBD) and on-resistance ($R_{DS(ON)}$), lower cooling requirements, and with low parasitic inductance. Applications where broadband technology is experiencing a considerable growth are: in the lighting sector (using GaN based LEDs); in the generation (transmission and distribution of electrical energy, where SiC devices present significant improvements in energy efficiency of the electrical network); and hybrid and fully electric vehicles (where GaN and SiC-based devices are essential elements, both in the propulsion and energy distribution systems of the vehicle).

The interest in DC–DC converters with multiple outputs is reflected in the sub-cited analysis and numerous publications, both from the academic, research, and economic/business world [2–11], as well as from industry and manufacturer publications [12–17]. The most recent forecasts estimate that the market for DC–DC converters is expected to increase at a CAGR (Compound Annual Growth Rate) of 12.1% in the next five years, from $9.9 billion in 2021 to $17.6 billion in 2026, and that the market for industrial power supply is expected to increase at a CAGR of 6.9% in the same period, from $7.0 billion in 2021 to $9.7 billion in 2026, with multiple-output DC–DC converters being one of the segments with the highest growth rate during the same period [18–30]. This growth is due to very different sectors and applications, such as storage and servers, battery management, healthcare and medical equipment, railway traction, beverage and food, information technology and telecom, transportation, consumer electronics, energy and utilities, defense and aerospace, machine tools, and security systems. Mobile Phone Industry and Internet of Things (IoT) are applications where DC–DC converters help to extend battery life. Also, the lighting sector through technology Light-Emitting Diode (LED) and Organic LED (OLED), which has provided more reliable and efficient light sources, is also an important sector. Moreover, the demand for DC–DC converters with multiple outputs in the automotive industry is driven by electric vehicles, such as Fuel Cell Electric Vehicle (FCEV), Battery Electric Vehicles (BEV), Plug-in Hybrid Vehicles (PHEV), and Hybrid Electric Vehicle (HEV).

All these applications contemplate various aspects and types of DC–DC converters, such as output number (dual-output, bipolar output, three- and four-output-type converters), power (<1 kW, 1–10 kW, 10–20 kW, and >20 kW) including low, medium, and high power, input voltage (<40 V, 40–70 V, and >70 V), output voltage (24 V, 15 V, 12 V, 5 V, and 3.3 V), isolated (one switch, two switches, and four switches converters) and non-isolated (one switch or several switches) DC–DC converters. In low-power applications, the two main trends are related to high-power density and low voltage, while in high power, with high efficiency and reliability. But the main trend is related to miniaturization for integration. Small size and weight, together with high-power density are very important items in power supplies for small format applications, mobile electronic systems, and onboard systems, driven by applications with facilities with space restrictions such as More-Electric

Aircraft (MEA), Electric Vehicle (EV), Robotics, Electric Ship (ES), Robotics, Solid-State Lighting, Integrated DC–DC Power Supply and Monolithic Power Systems, Intelligent DC–DC Power Distribution (micro or nano grids), On-chip Power Supply, Wireless Remote Sensing Node and Power Transfer, New Transport Technologies, Energy Harvesting, and IoT. In these applications, multiple or single power systems are used, which distribute energy to different loads, with converters operating in power ranging from hundreds of kilowatts to a few watts. This focus on multiple-output DC–DC converter applications has also led to the development and commercialization of integrated solutions by many electronic manufacturers [31–42], and to different tutorials, webinars, on-line publications, white papers and some surveys, reviews, and overviews papers being reported in the literature.

In this paper, an overview of the most important topics related to multiple-output DC–DC converters based on their main topologies and configurations, applications, solutions, and trends are presented. The work is organized as follows: Section 2 reviews multiple-output DC–DC converters: topologies and configurations and some of their main characteristics are analyzed. Section 3 presents some of the most important applications and solutions of multiple-output DC–DC converters. Finally, in Section 4 some conclusions are presented.

2. Multiple-Output DC–DC Converters: Topologies and Configurations

The main objective of DC–DC power conversion is to transfer electric power from a DC source into another DC source, which can be a load, with the highest efficiency and therefore lowest losses. The DC–DC converters are widely used at all power levels (from mW to kW), current levels (from nA to hundreds of amps) and voltage levels (from mV to kV) and have been very popular for the last three decades, they can invert the polarity of the DC voltage and increase or decrease its magnitude. The topologies and properties of DC–DC converters are reported in the literature and are well known. Topology describes how source, load, inductive and capacitive elements, and switches are interconnected in the converter, while the configuration establishes the DC conversion relation between the input and output current/voltage and according to the operating mode and the converter topology. Efficiency depends on how close converter elements are to ideal condition; assuming that the same elements are available, efficiency is related to the converter topology. Switch electrical stress (current and voltage) decides the choice of semiconductor devices used to implement the switches. For lower losses on parasitic resistances, lower generated noise, and more efficient filtering, it is preferred that input and output waveforms be continuous (ideally, DC only). Complexity of a converter is measured by the number of inductors, capacitors, and switches. Efficiency and density (watts/volume) have long been the metrics used to compare the performance of power converters.

DC–DC converters can be classified depending on the number of inputs as Multiple-Input and Single-Output (MISO), or Single-Input and Single-Output (SISO), depending on the number of outputs as Single-Input and Multiple-Output (SIMO), or Multiple-Input and Multiple-Output (MIMO). In all cases, they can provide one or more output voltages, from one or more input voltages. Multiple-output DC–DC converters are of interest in applications that require several outputs, from one or more input voltages, which include configurations MIMO [43–46] and SIMO [47–51].

As it is showed in Figure 1, SIMO DC–DC converters can be classified into isolated and non-isolated, depending on whether they are implemented with or without an electrical isolation, by means of a transformer, generally operated at high frequency. The output/input power range is often used as the main aspect when selecting a topology. However, there are many other factors that influence the topology selection for an isolated multi-output DC–DC power converter, such as: electrical stress, size, cost, input voltage range, and output noise. The size of an isolated multi-output power converter mainly depends on the transformer size and the number of active switches employed, while for a non-isolated converter depends on the number of active switches employed. The utilization of the power transformer affects the size of the power converter. A high-frequency transformer provides galvanic isolation between input and output, and allows increasing the step-up conversion ratio, while coupled inductors can also be used to increase the step-up ratio in a DC conversion and provide different output voltages from several secondary windings.

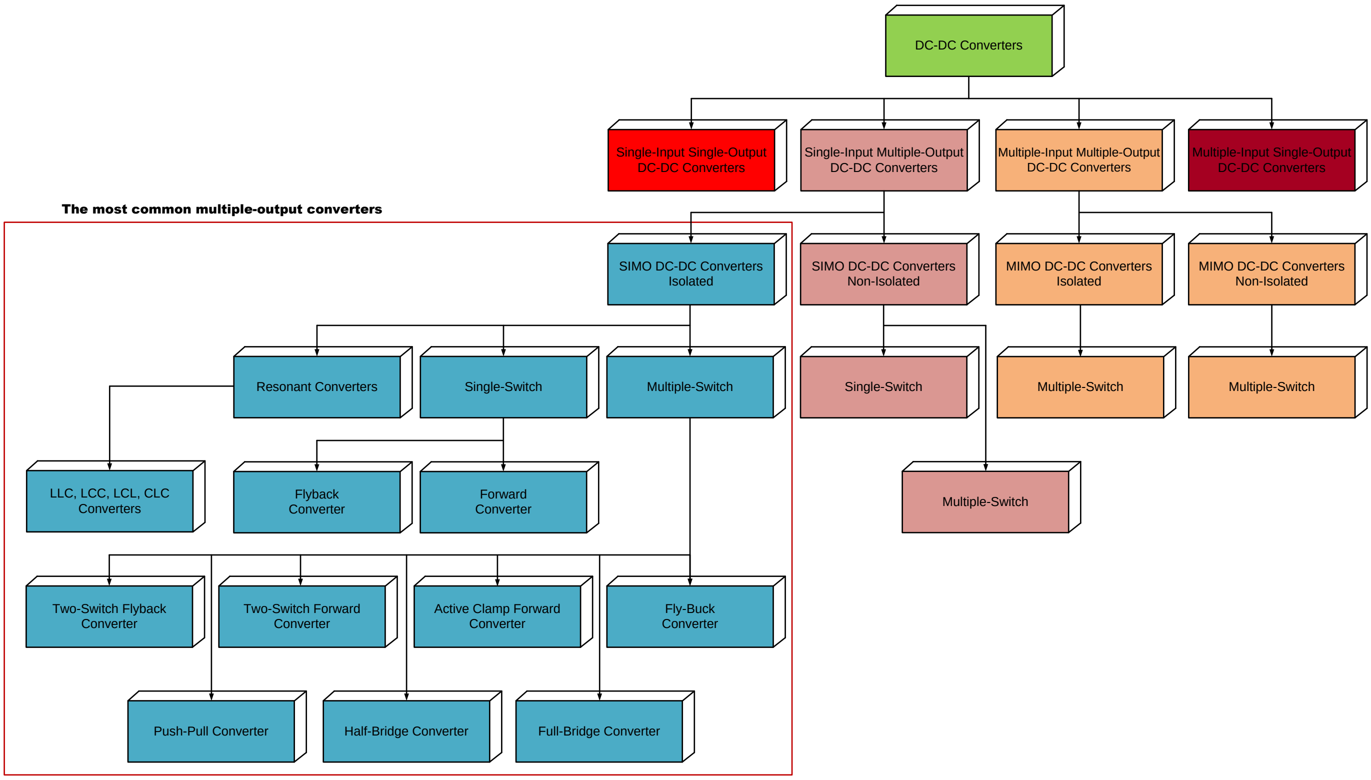


Figure 1. Multiple-Output DC–DC Converters Classification.

Control over DC conversion relation can be obtained by PWM (Pulse-Width Modulation) technique, usually using a Constant Frequency (CF). *D* (Duty Cycle) is the ratio between T_{ON} (Conduction Time) of switch/es and T_S (Switching Period). In PWM, the output voltage regulation is corrected (adjusted) by changing the T_{ON} of the switching element in the converter. Other control strategies used in DC–DC converters are: Variable Frequency and Constant on-Time (VF-C-on-T), Variable Frequency and Constant off-Time (VF-C-off-T), and variable frequency and variable pulse width. In VF-C-on-T, the operating frequency varies as a function of the input and load current. In VF-C-off-T conduction, the operating frequency varies (implying variable on-time conduction) as a function of the input and load current. CF is usually preferred over VF control since filtering components can be optimized to suppress voltage and current ripples at switching frequency and its harmonics. Also, noise generated by VF converters is more difficult to handle, and, in some applications, it cannot be tolerated. There is a wide variety of modes, techniques (linear and nonlinear), and types of controllers used for DC–DC converters: Voltage Mode Control (VMC), Current Mode Control (CMC), Sliding Mode (SM) or Hysteretic Mode (HM), and Band-Band Control (BBC), and controllers such as PID (Proportional-Integral-Derivative), Fuzzy Logic (FL), and Neural Network (NN) in different variants and their advantages and disadvantages are well understood and described in the literature.

When several outputs must be regulated it appears a mutual Cross Regulation (CR) effect, and this is one of the critical challenges in multi-output converters, when there is a load change in any one or more of its outputs. Among the different techniques implemented to regulate multiple DC outputs, cross regulation technique is very used by its simplicity. In this technique, one of the output voltages is directly sensed by the controller and regulated to the desired value. The other output voltages are indirectly regulated (quasi-regulated) by the main inductor and switch. Of course, the non-controlled outputs have lower regulation capacity and can present a variation with respect to their nominal values (CR = $\triangle V_{oi}/\triangle I_{oj}$). On the other hand, cross regulation allows the reduction in size, weight, and cost, and circuitry simplicity in several applications since it shows many advantages in terms of flexibility and integration in power-management systems. To suppress cross regulation, some methods have been reported in the literature [52,53].

2.1. SIMO DC–DC Converters Isolated

Isolated SIMO DC–DC converter topologies can be denominated as either double-ended or single-ended, based on the use of the magnetization curve (*B-H* curve, flux density versus magnetic field strength), as shown in Figure 2. During the operation, if the flux oscillates in two quadrants of the *B-H* curve (Figure 2a), then the topology is called as double-ended. While, if the flux oscillates in only one quadrant of the *B-H* curve (Figure 2b), then the topology is called as single-ended. In general, for given operating conditions, a single-ended topology requires a greater core than a double-ended topology and needs an additional reset winding.

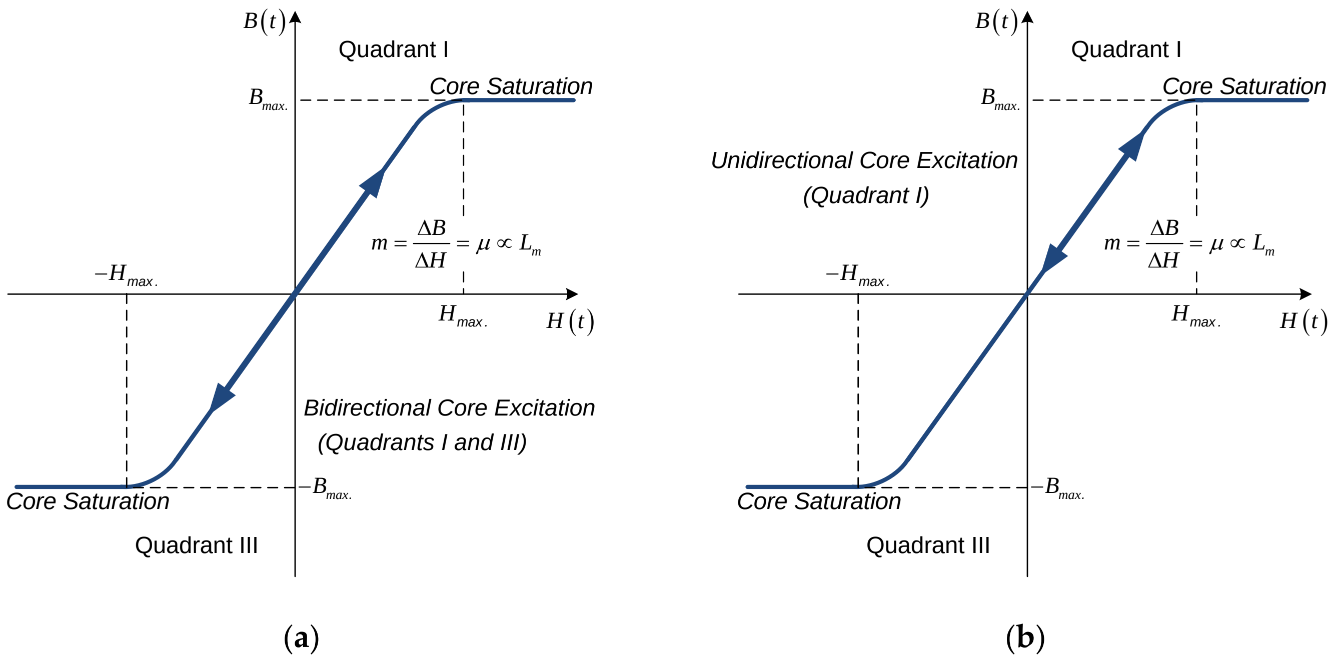


Figure 2. *B-H* Curve (without hysteresis) of Transformer Core. (**a**) Bidirectional Core Excitation. (**b**) Unidirectional Core Excitation.

Among Buck and Buck–Boost derived DC–DC converters, the most popular single-switch are Forward and Flyback converter, while those employing multiple switches include Full-Bridge, Half-Bridge, and Push–Pull converter. Figures 3–5, show the basic isolated SIMO DC–DC converters. The conversion relations for DCM (Discontinuous Conduction Mode) and CCM (Continuous Conduction Mode) are summarized in Table 1. The output filter inductor in Full-Bridge, Half-Bridge, and Push–Pull converters acts as the inductance in a Buck converter, and thus the equation for critical inductance for the Buck is valid for these Buck-Derived converters, as long as the appropriate transformation of the input voltage due to the transformer turns ratio and topology is applied. As a result, Isolated Buck (Fly-Buck) converter is used in applications below 15 W, Flyback, and Buck-Derived converters in 10–100 W, Forward in 50–300 W, Half-Bridge, and Push–Pull converters in more than 500 W, while Full-Bridge is used in applications with a power range of 1 to 5 kW. Table 2 summarizes some features of the converters shown in Figures 3–5.

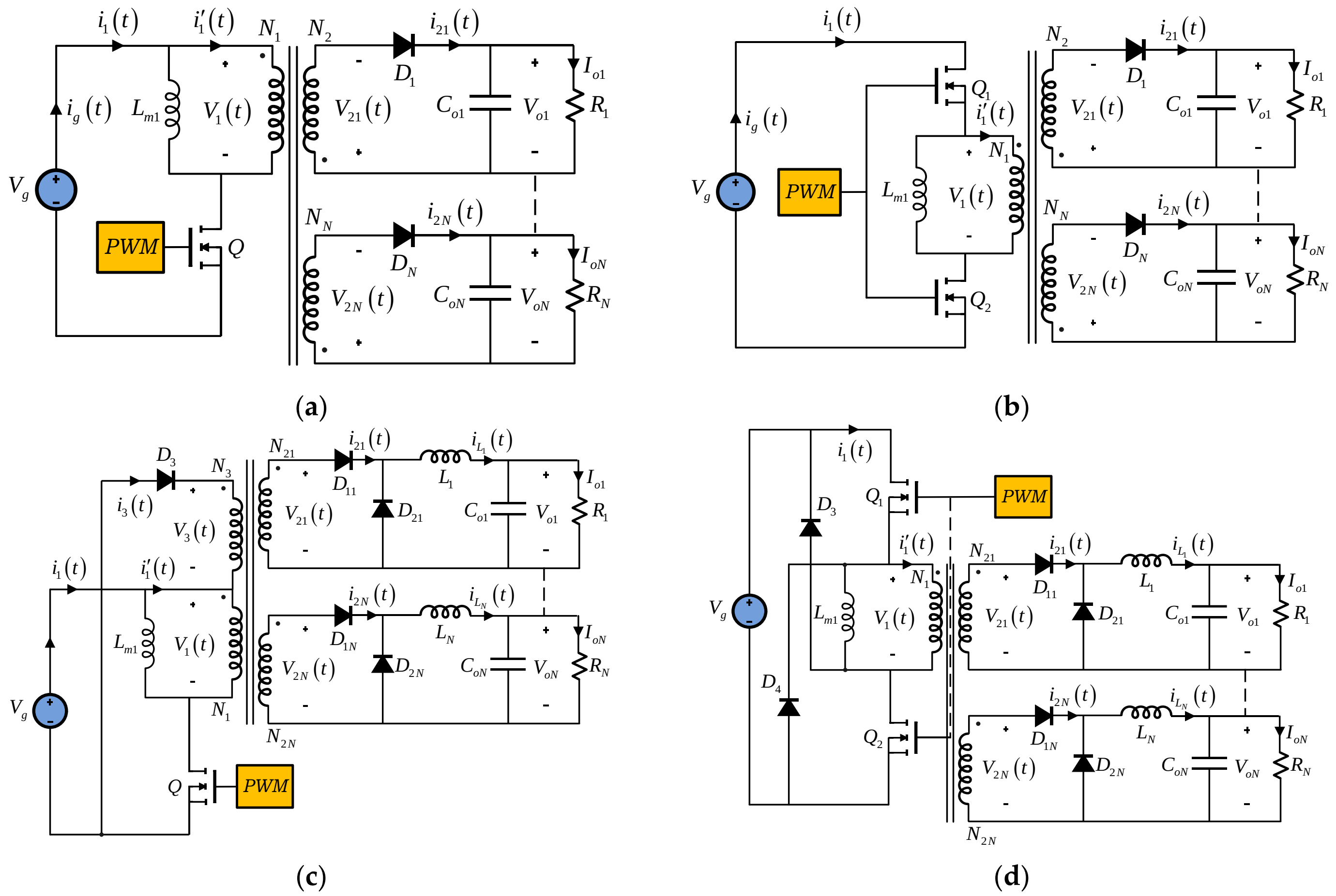


Figure 3. Multiple-Output Isolated DC–DC Converters Topologies. (**a**) Single-Switch Flyback Converter. (**b**) Two-Switch Flyback Converter. (**c**) Single-Switch Forward Converter. (**d**) Two-Switch Forward Converter.

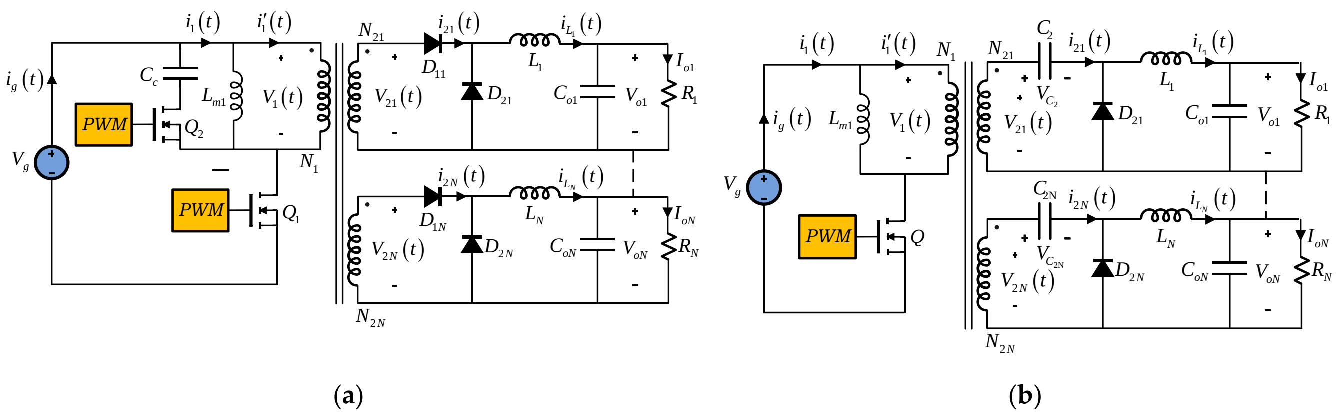


Figure 4. *Cont.*

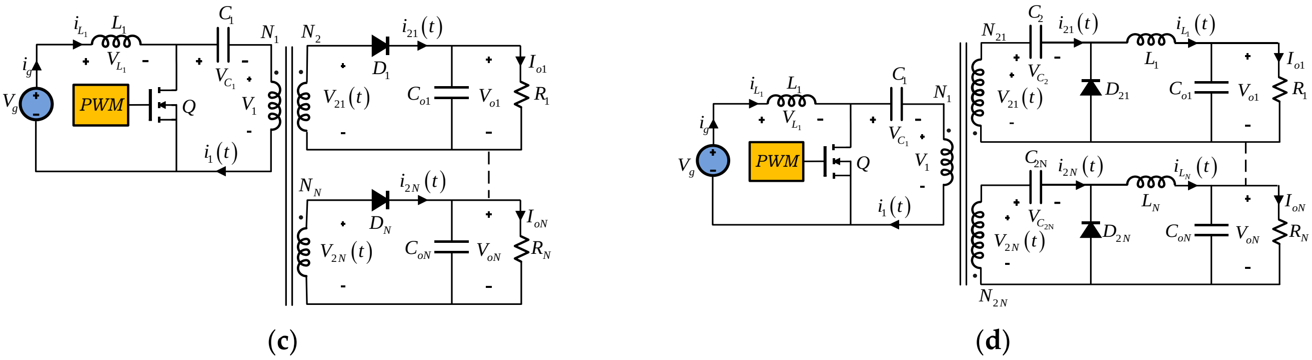


Figure 4. Multiple-Output Isolated DC–DC Converters Topologies. (**a**) Active Clamp Forward Converter. (**b**) Isolated Zeta Converter. (**c**) Isolated SEPIC Converter. (**d**) Isolated Ćuk Converter.

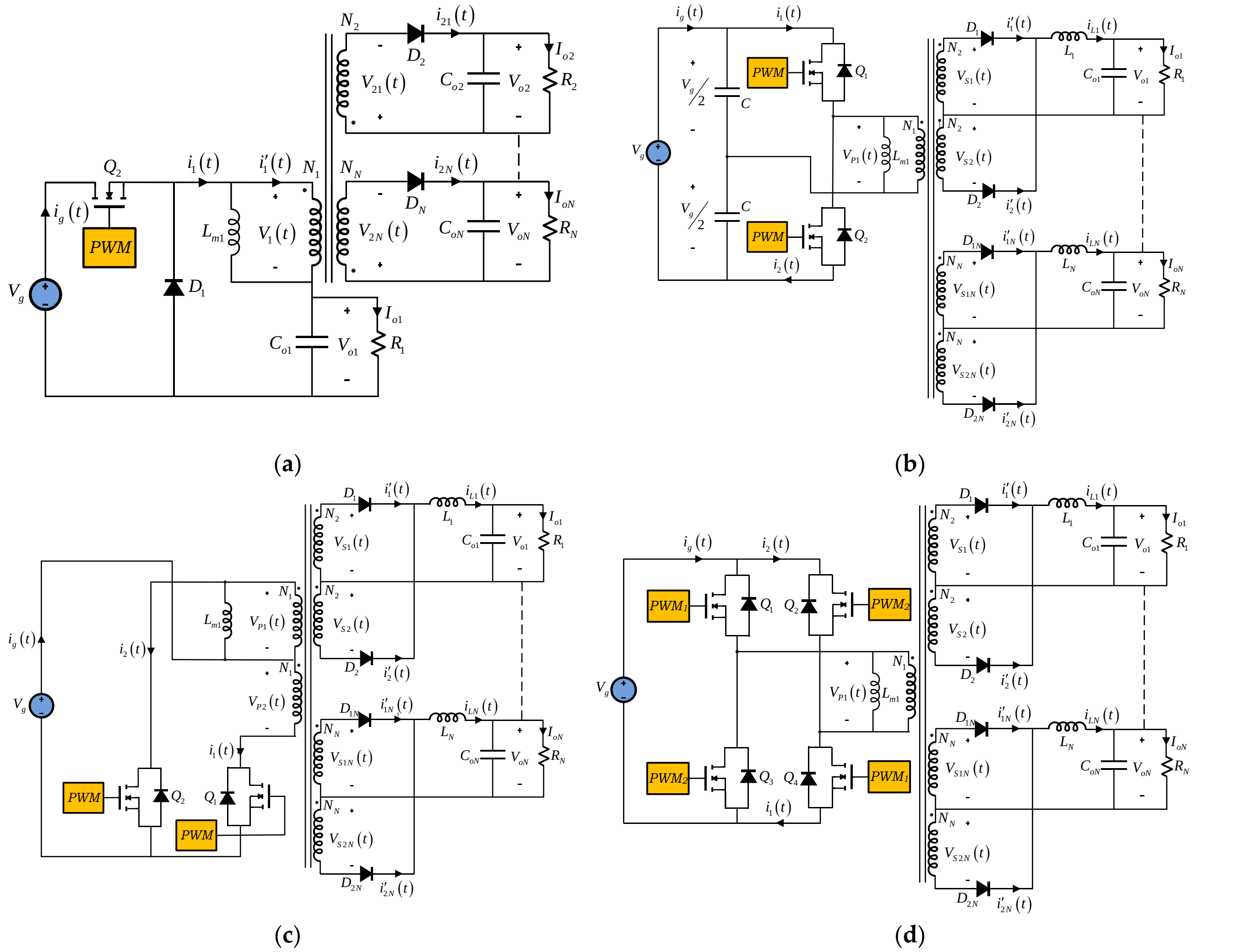


Figure 5. Multiple-Output Isolated DC–DC Converters Topologies. (**a**) Isolated Buck (Fly-Buck) Converter. (**b**) Half-Bridge Converter. (**c**) Push–Pull Converter. (**d**) Full-Bridge Converter.

Table 1. Conversion relations for Multiple-Output Isolated DC–DC Converters.

Converter	CCM	DCM
Flyback Converter (Figure 3a,b)	$V_{o1} = V_g \cdot \frac{N_2}{N_1} \cdot \frac{D}{1-D}, \ldots,$ $V_{oN} = V_g \cdot \frac{N_N}{N_1} \cdot \frac{D}{1-D}$	$V_{o1} = D \cdot V_g \sqrt{\frac{R_{eq.1} \cdot T_s}{2 \cdot L_{m1}}}, \ldots, V_{oN} = D \cdot V_g \sqrt{\frac{R_{eq.N} \cdot T_s}{2 \cdot L_{m1}}}$ $With: \frac{1}{R_{eq.1}} = \frac{1}{R_1} + \frac{1}{R_2}\left(\frac{N_3}{N_2}\right)^2 + \cdots + \frac{1}{R_N}\left(\frac{N_{N+1}}{N_2}\right)^2, \ldots$ $\ldots, \frac{1}{R_{eq.N}} = \frac{1}{R_1}\left(\frac{N_2}{N_{N+1}}\right)^2 + \frac{1}{R_2}\left(\frac{N_3}{N_{N+1}}\right)^2 \cdots + \frac{1}{R_N}$
	$0 < D < 1$	
Isolated Buck Converter (Figure 5a)	$V_{o1} = D \cdot V_g$ $V_{o2} = \frac{N_2}{N_1} \cdot V_{o1}, \ldots, V_{oN} = \frac{N_N}{N_1} \cdot V_{o1}$	$V_{o1} = \frac{2 \cdot V_g}{\left(1+\sqrt{1+\frac{8 \cdot L_{m1}}{R_1 \cdot D^2 \cdot T_s}}\right)}$ $V_{o2} = \frac{N_2}{N_1} \cdot V_{o1}, \ldots, V_{oN} = \frac{N_N}{N_1} \cdot V_{o1}$
	$0 < D < 1$	
Forward Converter (Figure 3c,d)	$V_{o1} = \frac{N_{21}}{N_1} \cdot D \cdot V_g, \ldots, V_{oN} = \frac{N_{2N}}{N_1} \cdot D \cdot V_g$	$V_{o1} = \frac{\left(\frac{N_{21}}{N_1}\right) \cdot 2 \cdot V_g}{\left(1+\sqrt{1+\frac{8 \cdot L_1}{R_1 \cdot D^2 \cdot T_s}}\right)}, \ldots, V_{oN} = \frac{\left(\frac{N_{2N}}{N_1}\right) \cdot 2 \cdot V_g}{\left(1+\sqrt{1+\frac{8 \cdot L_N}{R_N \cdot D^2 \cdot T_s}}\right)}$
	$0 < D < 0.5\, for\, N_1 = N_3$	
Active Clamp Forward Converter (Figure 4a)	$V_{o1} = \frac{N_{21}}{N_1} \cdot D \cdot V_g, \ldots, V_{oN} = \frac{N_{2N}}{N_1} \cdot D \cdot V_g$	$V_{o1} = \frac{\left(\frac{N_{21}}{N_1}\right) \cdot 2 \cdot V_g}{\left(1+\sqrt{1+\frac{8 \cdot L_1}{R_1 \cdot D^2 \cdot T_s}}\right)}, \ldots, V_{oN} = \frac{\left(\frac{N_{2N}}{N_1}\right) \cdot 2 \cdot V_g}{\left(1+\sqrt{1+\frac{8 \cdot L_N}{R_N \cdot D^2 \cdot T_s}}\right)}$
	$0 < D < 0.5$	
Push–Pull Converter (Figure 5c)	$V_{o1} = 2 \cdot \frac{N_{21}}{N_1} \cdot D \cdot V_g, \ldots,$ $V_{oN} = 2 \cdot \frac{N_{2N}}{N_1} \cdot D \cdot V_g$	$V_{o1} = \frac{\left(\frac{N_{21}}{N_1}\right) \cdot 4 \cdot V_g}{\left(1+\sqrt{1+\frac{8 \cdot L_1}{R_1 \cdot D^2 \cdot T_s}}\right)}, \ldots, V_{oN} = \frac{\left(\frac{N_{2N}}{N_1}\right) \cdot 4 \cdot V_g}{\left(1+\sqrt{1+\frac{8 \cdot L_N}{R_N \cdot D^2 \cdot T_s}}\right)}$
	$0 < D < 0.5$	
Half-Bridge Converter (Figure 5b)	$V_{o1} = \frac{N_{21}}{N_1} \cdot D \cdot V_g, \ldots, V_{oN} = \frac{N_{2N}}{N_1} \cdot D \cdot V_g$	$V_{o1} = \frac{\left(\frac{N_{21}}{N_1}\right) \cdot 2 \cdot V_g}{\left(1+\sqrt{1+\frac{8 \cdot L_1}{R_1 \cdot D^2 \cdot T_s}}\right)}, \ldots, V_{oN} = \frac{\left(\frac{N_{2N}}{N_1}\right) \cdot 2 \cdot V_g}{\left(1+\sqrt{1+\frac{8 \cdot L_N}{R_N \cdot D^2 \cdot T_s}}\right)}$
	$0 < D < 0.5$	
Full-Bridge Converter (Figure 5d)	$V_{o1} = \frac{N_{21}}{N_1} \cdot D \cdot V_g, \ldots, V_{oN} = \frac{N_{2N}}{N_1} \cdot D \cdot V_g$	$V_{o1} = \frac{\left(\frac{N_{21}}{N_1}\right) \cdot 4 \cdot V_g}{\left(1+\sqrt{1+\frac{8 \cdot L_1}{R_1 \cdot D^2 \cdot T_s}}\right)}, \ldots, V_{oN} = \frac{\left(\frac{N_{2N}}{N_1}\right) \cdot 4 \cdot V_g}{\left(1+\sqrt{1+\frac{8 \cdot L_N}{R_N \cdot D^2 \cdot T_s}}\right)}$
	$0 < D < 0.5$	
Buck–Boost-Derived Isolated Converters (Figure 4b–d)	$V_{o1} = V_g \cdot \frac{N_2}{N_1} \cdot \frac{D}{1-D}, \ldots,$ $V_{oN} = V_g \cdot \frac{N_N}{N_1} \cdot \frac{D}{1-D}$	$V_{o1} = D \cdot V_g \sqrt{\frac{R_{eq.1} \cdot T_s}{2 \cdot L_{m1}}}, \ldots, V_{oN} = D \cdot V_g \sqrt{\frac{R_{eq.N} \cdot T_s}{2 \cdot L_{m1}}}$ $With: \frac{1}{R_{eq.1}} = \frac{1}{R_1} + \frac{1}{R_2}\left(\frac{N_3}{N_2}\right)^2 + \cdots + \frac{1}{R_N}\left(\frac{N_{N+1}}{N_2}\right)^2, \ldots$ $\ldots, \frac{1}{R_{eq.N}} = \frac{1}{R_1}\left(\frac{N_2}{N_{N+1}}\right)^2 + \frac{1}{R_2}\left(\frac{N_3}{N_{N+1}}\right)^2 \cdots + \frac{1}{R_N}$
	$0 < D < 1$	
	Nomenclature: V_g: Source voltage N: Winding turn number D: Duty cycle	R: Load resistance L: Inductance T_s: Switching period

Other classification of isolated multiple-output DC–DC converters can be realized depending on the switching technique: hard-switching (PWM converters) and soft-switching (resonant converters) [54–56]. They are traditionally used in applications such as very high frequency power supplies, induction heating, ballasts for fluorescent lamps, sonar transmitters, ultrasonic generators, and power supplies for laser cutting machines. Isolated resonant converters can be defined as converter networks to which resonant (L and C)

elements are added. In contrast to square wave switch waveforms in PWM converters, resonant topologies exhibit smooth quasi-sinusoidal waveforms and, therefore, reduced switching losses. The incentive to increase the frequency at which DC–DC converters are operated is motivated by the fact that correspondingly smaller values and, hence, weights and sizes of energy storage components should result in lighter and smaller converters. However, the inevitable increase in power losses due to switching establishes a practical upper limit in the frequency range. Resonant isolated converter topologies overcome some of the switching loss mechanisms attributed to PWM converters and offer the possibility of extending the usable frequency range toward higher frequencies (typically 100 to 500 kHz). In contrast to sharp transitions in current and voltage waveforms of PWM converters, the resonant converters operate with smooth, quasi-sinusoidal, resonant waveforms, leading to reduced losses ascribed to switching transitions. Soft-switching converters can exhibit reduced switching loss, at the expense of increased conduction loss.

Table 2. Comparative summary of SIMO Isolated DC–DC Converters.

Type Converter	Number Switches	Number Components	Voltage Stress	Transformer Utility	Floating Switches	Input/Output Feature
Single-Switch Flyback	Low	Low	High	Moderate	No	Discontinuous input current Discontinuous output currents
Two-Switch Flyback	Medium	Low	Medium	Moderate	Yes	Discontinuous input current Discontinuous output currents
Single-Switch Forward	Low	Medium	High	Moderate	No	Discontinuous input current Continuous output currents
Two-Switch Forward	Medium	Medium	Medium	Moderate	Yes	Discontinuous input current Continuous output currents
Active Clamp Forward	Medium	High	Medium	Moderate	Yes	Discontinuous input current Continuous output currents
Isolated Zeta	Low	Medium	High	Moderate	No	Discontinuous input current Continuous output currents
Isolated SEPIC	Low	Medium	High	Moderate	No	Continuous input current Discontinuous output currents
Isolated Ćuk	Low	Medium	High	Moderate	No	Continuous input current Continuous output currents
Isolated Buck (Fly–Buck)	Low	Low	Medium	Moderate	Yes	Discontinuous input current Discontinuous output currents
Half-Bridge	Medium	Medium	Medium	Good	Yes	Continuous input current Continuous output currents
Push–Pull	Medium	High	Medium	Good	No	Continuous input current Continuous output currents
Full-Bridge	High	High	Low	Good	Yes	Continuous input current Continuous output currents

Resonant converters use resonant L-C elements that cause sinusoidal variation of voltage and current waveforms in order to reduce switching losses. They were developed as an alternative to simple rectangular switching, the power devices switch at high frequency, maintaining acceptable converter efficiency by minimizing the significant switching losses associated with hard-switching. In these converters, the size and weight are reduced (mainly, magnetic and filtering components) and the power density is increased, with low stress on the switching devices. In addition, the soft-switching technique utilizes Variable Frequency (VF) for regulation, with constant on-time or constant off-time, which creates an oscillating circuit that allows power device transitions to occur at zero voltage (Zero Voltage Switching, ZVS) or zero current (Zero Current Switching, ZCS), eliminating or reducing the switching losses in the converter, higher-frequency operation and reducing the size of magnetic and filter components. Both resonant techniques are widely used in many applications.

In isolated multiple-output DC–DC converters, the resonant components can be placed either on the primary or on the secondary side. When a resonant capacitor is placed on in some winding, the leakage inductance and magnetizing inductance of the transformer can be used as a resonant element in order to reduce the number of discrete magnetic components and, therefore, increase the power density of the converter.

Although there is a wide variety of isolated multiple-output resonant converter topologies, the most widely used are those based on three reactive elements, being LLC and LCC, shown in Figure 6, the most popular. The conversion relations for these topologies are summarized in Table 3 [56]. Table 4 shows some features of the LLC and LCC converters.

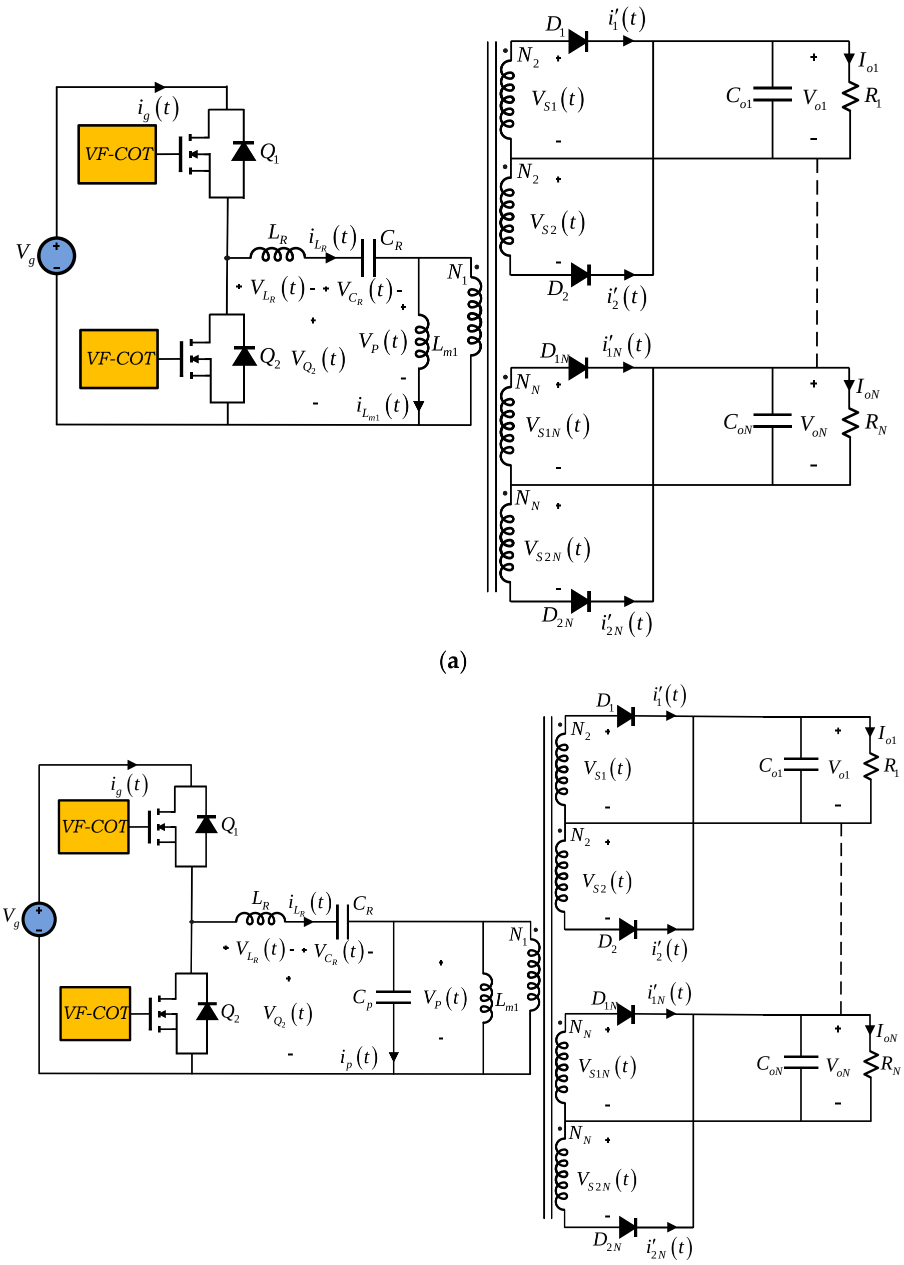


Figure 6. Three-element Multiple-Output Isolated Resonant DC–DC Converters: LLC and LCC. (**a**) LLC Resonant DC–DC Converter. (**b**) LCC Resonant DC–DC Converter.

Table 3. Conversion relations for Multiple-Output Isolated Resonant DC–DC Converters.

Converter	Output Voltages
LLC Resonant DC–DC Converter (Figure 6a)	$V_{o1} = \frac{\frac{N_2}{N_1}\cdot\frac{V_g}{2}}{\sqrt{\left[(L_n+1)-\frac{1}{f_n^2}\right]^2\cdot\frac{1}{L_n^2}+\left(f_n-\frac{1}{f_n}\right)^2\cdot Q^2}}, \ldots, V_{oN} = \frac{\frac{N_N}{N_1}\cdot\frac{V_g}{2}}{\sqrt{\left[(L_n+1)-\frac{1}{f_n^2}\right]^2\cdot\frac{1}{L_n^2}+\left(f_n-\frac{1}{f_n}\right)^2\cdot Q^2}}$ $V_{oN} = \frac{N_N}{N_1}\cdot\frac{V_g}{2} \leftarrow \text{Mode I } \left(f_S = f_{R_1}\right).$ $V_{oN} = \frac{N_N}{N_1}\cdot\frac{V_g}{2} \leftarrow \text{Mode II } \left(f_S > f_{R_1}\right).$ $V_{oN} > / < \frac{N_N}{N_1}\cdot\frac{V_g}{2} \leftarrow \text{Mode III } \left(f_S < f_{R_1}\right).$
	$f_s = \text{Switching Frequency}, f_{R_1} = \frac{1}{2\pi\sqrt{L_R C_R}}\ and\ f_{R_2} = \frac{1}{2\pi\sqrt{\left(L_R+L_{m_1}\right)C_R}}$ $f_n = \frac{f_S}{f_{R_1}}, L_n = \frac{L_R}{L_{m_1}}, Q = \frac{\pi^2}{8R_{eq.}}\cdot\sqrt{\frac{L_R}{C_R}}\ and\ \frac{1}{R_{eq.}} = \frac{1}{R_1}\left(\frac{N_2}{N_1}\right)^2+\cdots+\frac{1}{R_N}\left(\frac{N_{N+1}}{N_1}\right)^2$
LCC Resonant DC–DC Converter (Figure 6b)	$V_{o1} = \frac{\frac{N_2}{N_1}\cdot\frac{V_g}{2}}{\sqrt{\left[\frac{C_n+1}{C_n}-f_n^2\right]^2\cdot C_n^2+\left(f_n-\frac{1}{f_n}\right)^2\cdot Q^2}}, \ldots, V_{oN} = \frac{\frac{N_N}{N_1}\cdot\frac{V_g}{2}}{\sqrt{\left[\frac{C_n+1}{C_n}-f_n^2\right]^2\cdot C_n^2+\left(f_n-\frac{1}{f_n}\right)^2\cdot Q^2}}$ $V_{oN} = \frac{N_N}{N_1}\cdot\frac{V_g}{2} \leftarrow \text{Mode I } \left(f_S = f_{R_1}\right).$ $V_{oN} = \frac{N_N}{N_1}\cdot\frac{V_g}{2} \leftarrow \text{Mode II } \left(f_S < f_{R_1}\right).$ $V_{oN} > / < \frac{N_N}{N_1}\cdot\frac{V_g}{2} \leftarrow \text{Mode III } \left(f_S > f_{R_1}\right).$
	$f_s = \text{Switching Frequency}, f_{R_1} = \frac{1}{2\pi\sqrt{L_R C_R}}\ and\ f_{R_2} = \frac{1}{2\pi\sqrt{L_R\left(\frac{C_R\cdot C_P}{C_R+C_P}\right)}}$ $f_n = \frac{f_S}{f_{R_1}}, C_n = \frac{C_P}{C_R}, Q = \frac{\pi^2}{8R_{eq.}}\cdot\sqrt{\frac{L_R(C_R+C_P)}{C_R\cdot C_P}}\ and\ \frac{1}{R_{eq.}} = \frac{1}{R_1}\left(\frac{N_2}{N_1}\right)^2+\cdots+\frac{1}{R_N}\left(\frac{N_{N+1}}{N_1}\right)^2$
	Nomenclature: V_g: Source voltage N: Winding turn number D: Duty cycle R: Load resistance L: Inductance f_s: Switching frequency f_R: Resonance frequency Q = Quality factor

Table 4. Comparative summary of SIMO Isolated DC–DC Resonant Converters.

Type Converter	Number Switches	Number Components	Voltage Stress	Transformer Utility	Floating Switches	Input/Output Feature
LLC Resonant	Medium	Medium	Medium	Good	Yes	Discontinuous input current Continuous output currents
LCC Resonant	Medium	High	Medium	Good	Yes	Discontinuous input current Continuous output currents

2.2. SIMO DC–DC Converters Non-Isolated

Multiple-output converters without transformers are an alternative in applications where galvanic isolation is not required. In this sense, non-isolated multiple-output converters can be implemented with single switch or multiple switches, with their advantages and disadvantages. As an example, multiple switches require several control switches, which increases the cost, losses, and number of gate drivers in the converter, while single-switch converters cause higher stress in terms of voltage and current.

SIMO non-isolated with multiple switches converters have been developed for many applications and in different configurations and topologies [57–64]. They can provide space savings, while maintaining high efficiency. They are generally based on traditional Single-Input Single-Output (SISO) structures such as Buck, Boost, Buck–Boost and cascade Buck–Boost, as shown in Figure 7. Each output voltage is a function of a fraction of the duty cycle of the switch to which it is connected. By having several switches, different switching strategies (time sequencing [65] and time-multiplexing [66]) and operation modes (CCM and DCM) are applicable.

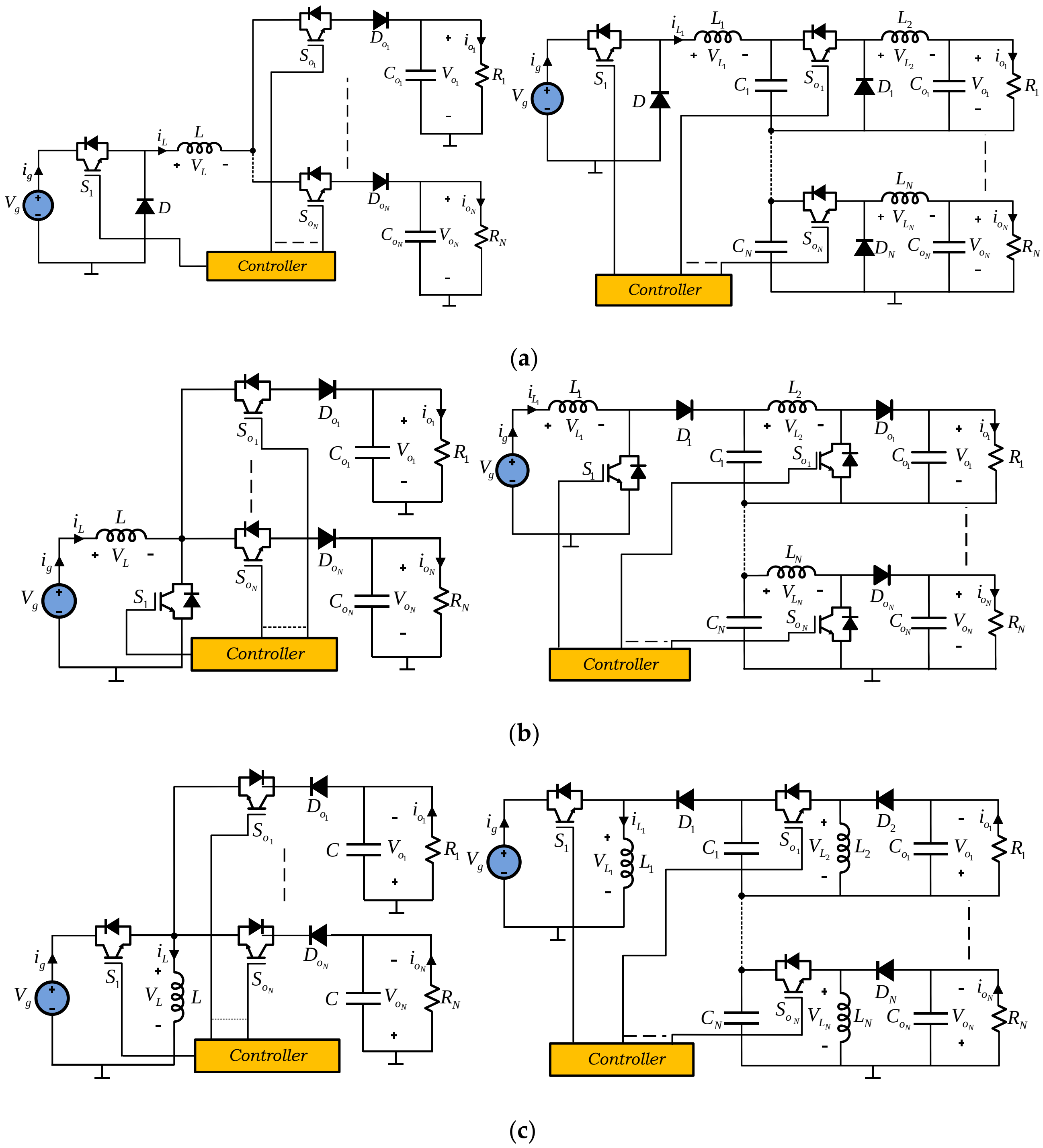


Figure 7. Single Input Multiple-Output (SIMO) non-isolated multiple switches DC–DC converters. (**a**) SIMO Buck Converter versions [57]. (**b**) SIMO Boost Converter versions. (**c**) SIMO Buck–Boost Converter versions.

Within SIMO non-isolated with multiple-switch converters, special attention should be paid to Single Input Dual Output (SIDO), Symmetric Outputs DC–DC Converters or Bipolar Output DC–DC Converters, as shown in Figure 8. Not only because of the interest of its applications, but also because of the different topologies that have been developed [67–77]. The conversion relations SIDO Boost and Buck–Boost converters based are summarized in Table 5 [67].

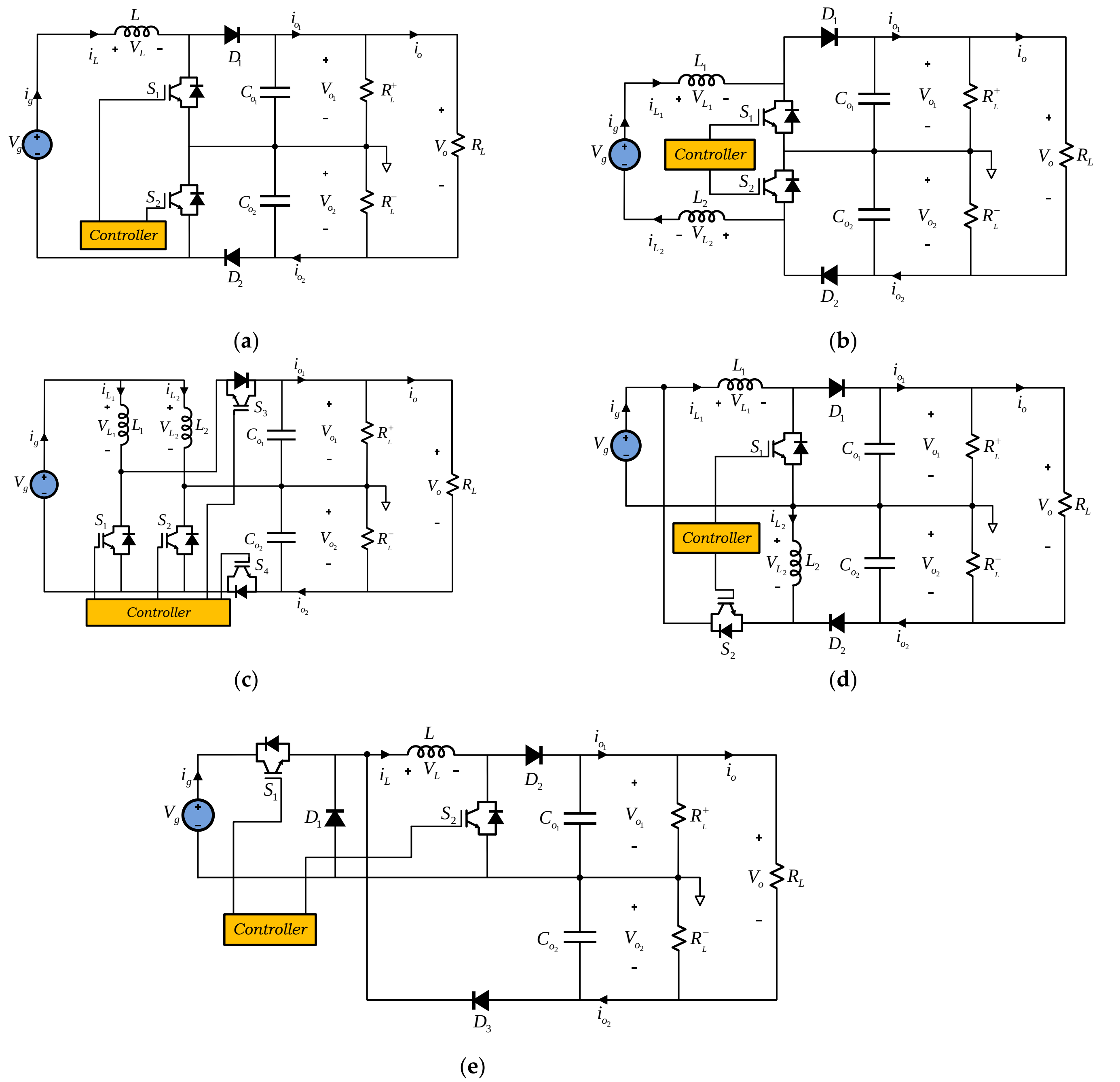


Figure 8. Single Input Dual Output (SIDO) DC–DC Converters. (**a**) Three-level Single-inductor Boost Converter [69]. (**b**) Three-level Two-inductors Boost Converter [70]. (**c**) Dual-output DC–DC Boost Converter [71]. (**d**) Series-combined Boost and Buck–Boost Converter [72]. (**e**) Single-inductor Buck–Boost Converter [73].

SIMO non-isolated with single-switch converters [78–80] try to avoid some of the disadvantages of using multiple controlled switches. They are also based on the combination of SISO structures, using their front end, as shown in Figures 9 and 10. In these cases, each output voltage is a function of the duty cycle of the single switch, operation modes (CCM and DCM) and of the combined configuration.

Table 5. Conversion relations for SIDO DC–DC Converters.

Converter	CCM	DCM
Boost Converter (Figure 8a)	$V_o = \frac{V_g}{1-D} = 2V_{o1} = 2V_{o2}$ $I_g = \frac{I_o}{1-D}$	$V_o = \frac{V_g}{2}\left(1+\sqrt{1+\frac{2R_L \cdot D^2 \cdot T_s}{L}}\right)$ $I_g = \frac{I_o}{2}\left(1+\sqrt{1+\frac{2R_L \cdot D^2 \cdot T_s}{L}}\right)$
Buck–Boost Converter (Figure 8e)	$V_o = \frac{V_g\,D}{1-D} = 2V_{o1} = 2V_{o2}$ $I_g = \frac{I_o\,D}{1-D}$	$V_o = D \cdot V_g \sqrt{\frac{R_L \cdot T_S}{2 \cdot L}}$ $I_g = D \cdot I_o \sqrt{\frac{R_L \cdot T_S}{2 \cdot L}}$
	Nomenclature: V_g: Source voltage I_g: Source curren D: Duty cycle	R: Load resistance L: Inductance T_s: Switching period

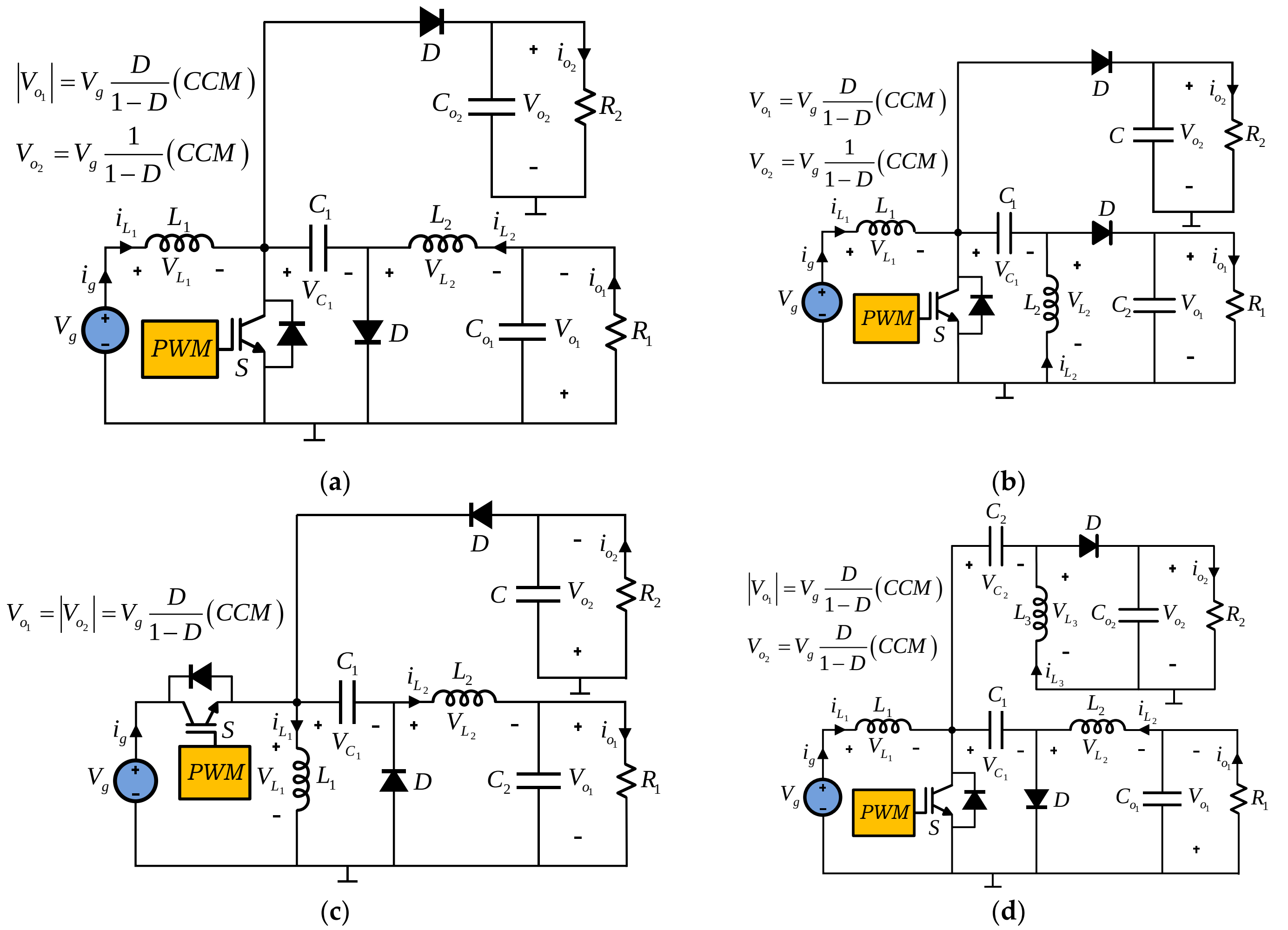


Figure 9. Two-output-type converter combinations. (**a**) Boost–Ćuk converter combination. (**b**) Boost–SEPIC converter combination. (**c**) Buck–Boost–Zeta converter combination. (**d**) SEPIC–Ćuk converter combination.

Table 6 summarizes some features of the converters shown in Figures 7–10.

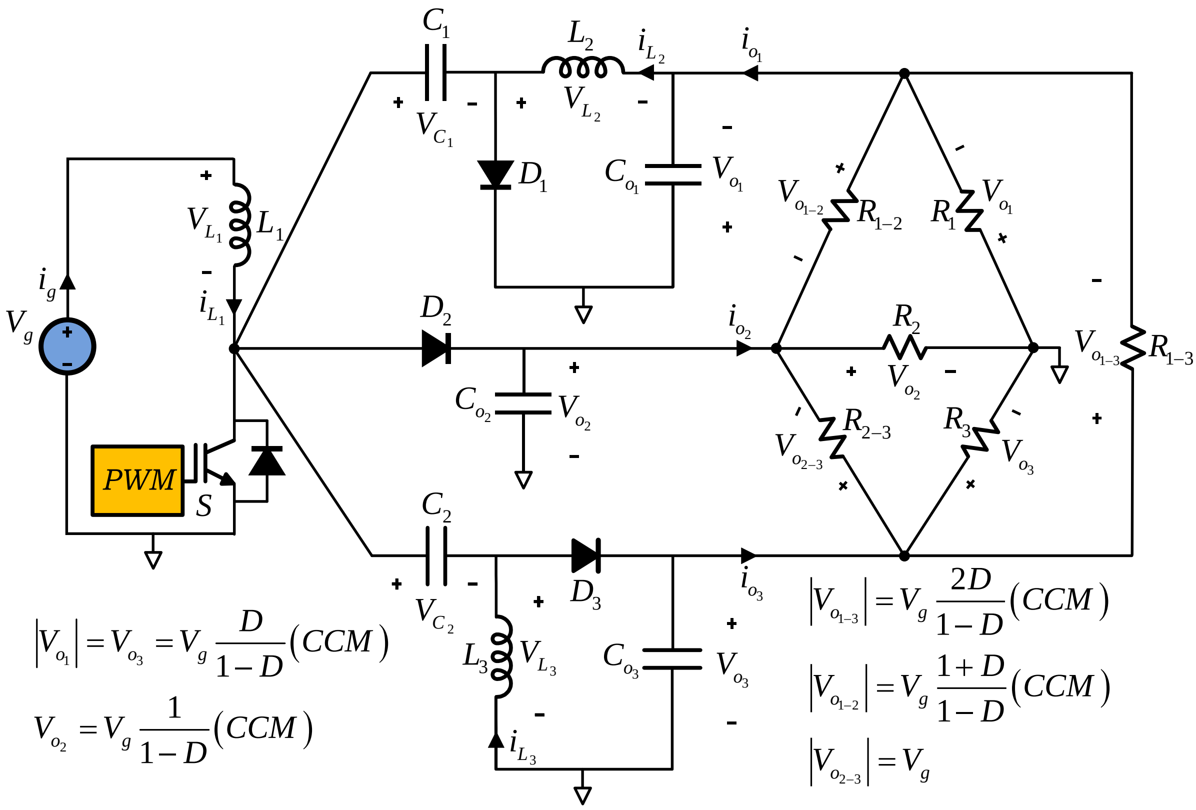


Figure 10. Three-output-type converter combination for six loads.

Table 6. Comparative summary of SIMO DC–DC Converters Non-Isolated.

Type Converter	Number Switches	Number Components	Voltage Stress	Floating Switches	Input/Output Feature
SIMO Buck	Medium	Medium	High	Yes	Discontinuous input current Discontinuous output currents
SIMO Boost	Medium	Medium	High	Yes	Continuous input current Discontinuous output currents
SIMO Buck–Boost	Medium	Medium	High	Yes	Discontinuous input current Discontinuous output currents
Three-level Single-inductor Boost	Medium	Low	Medium	Yes	Continuous input current Discontinuous output currents
Three-level Two-inductors Boost	Medium	Low	Medium	Yes	Continuous input current Discontinuous output currents
Dual-output DC–DC Boost	Medium	Low	Medium	No	Continuous input current Discontinuous output currents
Series-combined Boost and Buck–Boost	Medium	Low	Medium	Yes	Continuous input current Discontinuous output currents
Single-inductor Buck–Boost	Medium	Medium	Medium	Yes	Discontinuous input current Discontinuous output currents
Boost–Ćuk combination	Low	Low	High	No	Continuous input current Discontinuous/Continuous output currents

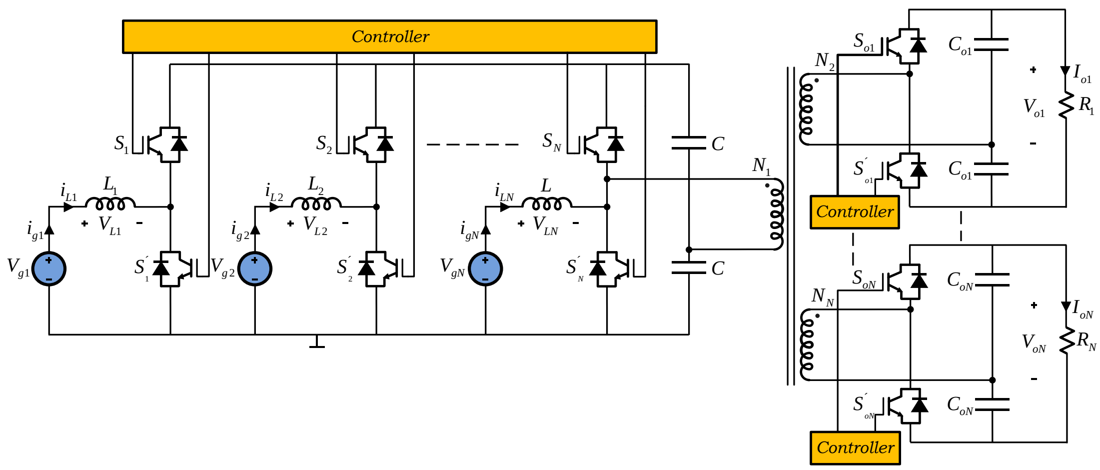
Table 6. *Cont.*

Type Converter	Number Switches	Number Components	Voltage Stress	Floating Switches	Input/Output Feature
Boost–SEPIC combination	Low	Low	High	No	Continuous input current Discontinuous output currents
Buck–Boost–Zeta combination	Low	Low	High	Yes	Discontinuous input current Discontinuous/Continuous output currents
SEPIC–Ćuk combination	Low	Low	High	No	Continuous input current Discontinuous/Continuous output currents
Three-output-type converter for six loads	Low	Medium	High	No	Continuous input current Discontinuous/Continuous output currents

2.3. MIMO DC–DC Converters Isolated

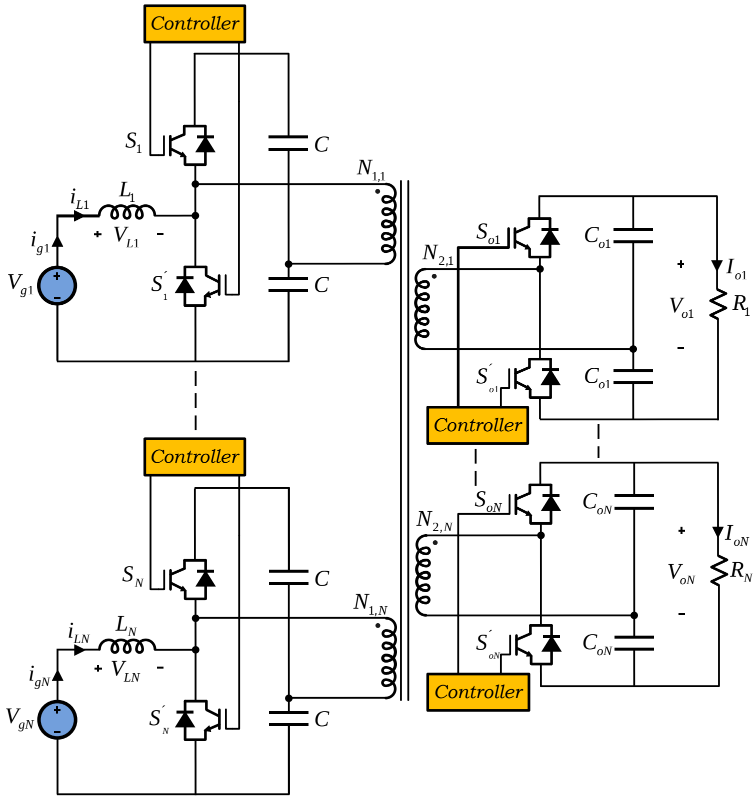
In the same way, MIMO DC–DC converters for combining various output loads and input sources, they have become an interesting alternative in recent years, especially because they allow the integration of different sources, such as: Rectifiers, Photovoltaic Systems, Fuel Cells, Batteries, Supercapacitors, and, in some cases, Wind Energy Systems. Fundamentally, MIMO converters are implemented according with two structures: sharing a high voltage or low voltage common DC bus; and sharing one or more transformers; or both architectures are also possible.

MIMO isolated configurations use a multi-winding transformer to transfer the energy from the primary side to the secondary side and to couple the different sources and loads, with several power switches and centralized or distributed control signals. Several configurations can be derived from Full-Bridge, Half-Bridge Push–Pull Forward and Flyback topologies, and other such as those shown in Figure 11 [81,82]. These converters consist of Boost, Half-Bridge, or the called Boost–Dual-Half-Bridge (BDHB) topologies. In these converters, the conversion ratio and output voltages depend on the control strategy of the power switches, operation modes, and the turns ratio between the transformer windings. Normally, the power switches are controlled by phase-shifted PWM operating at 50% duty cycle, in CCM and DCM. Table 7 shows some features of the MIMO isolated converters.

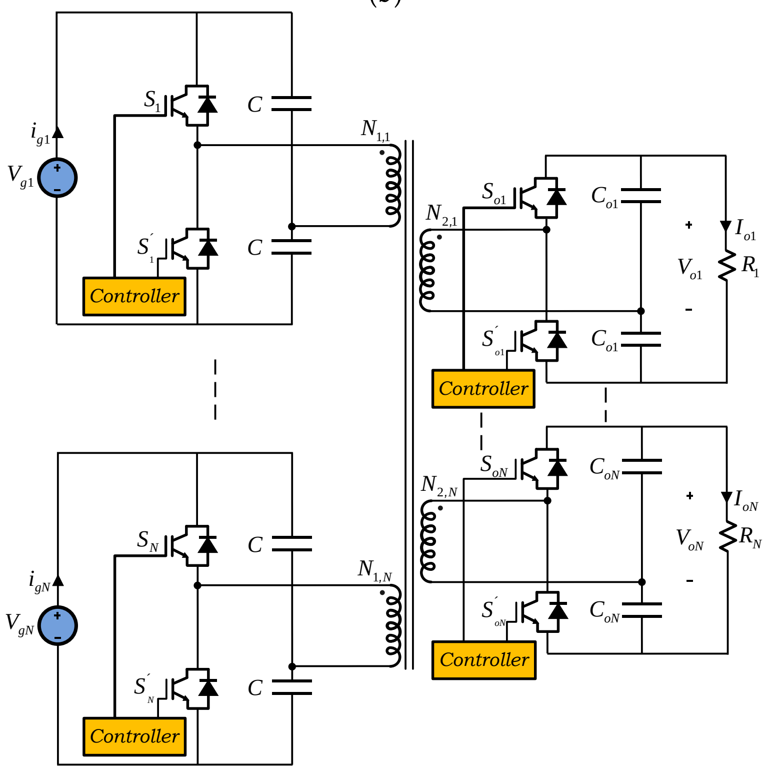


(**a**)

Figure 11. *Cont.*

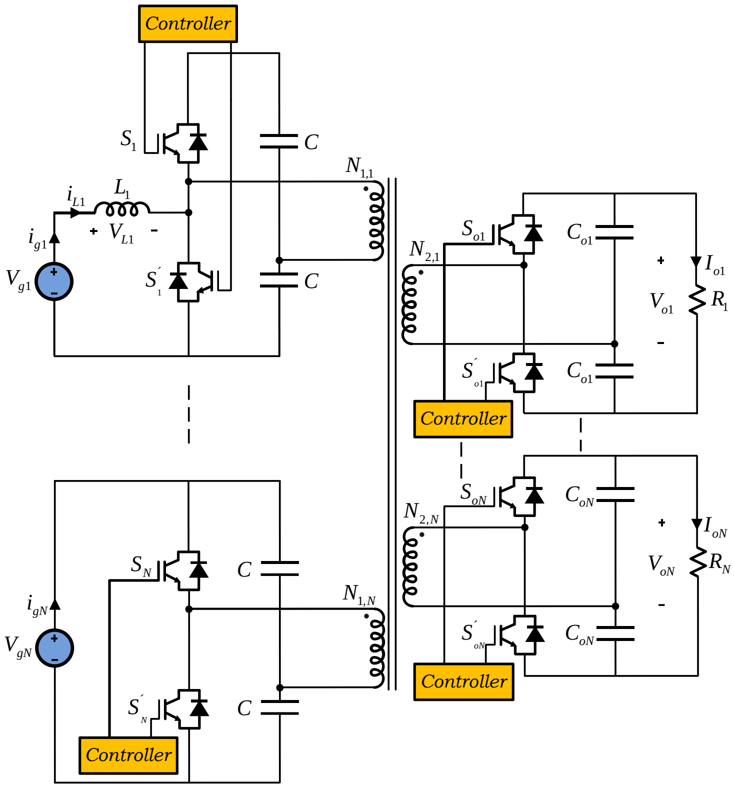


(**b**)



(**c**)

Figure 11. *Cont.*



(**d**)

Figure 11. MIMO isolated. (**a**) Boost parallel converter. (**b**) Boost ports converter. (**c**) Half-Bridge converter. (**d**) Boost–Half-Bridge converter combination.

Table 7. Comparative summary of MIMO DC–DC Converters Isolated.

Type Converter	Number Switches	Number Components	Voltage Stress	Transformer Utility	Floating Switches	Input/Output Feature
Boost parallel	High	High	Medium	Good	Yes	Continuous input currents Continuous output currents
Boost ports	High	High	Medium	Good	Yes	Continuous input currents Continuous output currents
Half-Bridge	High	Medium	Medium	Good	Yes	Continuous input currents Continuous output currents
Boost–Half Bridge	High	High	Medium	Good	Yes	Continuous input currents Continuous output currents

2.4. MIMO DC–DC Converters Non-Isolated

In the same sense, for MIMO transformerless configurations, based on high-voltage or low-voltage common DC bus, two architectures are established: independent and/or integrated DC–DC converters. MIMO non-isolated integrated uses a single conversion stage, simplifying architecture and control, and have been proposed as an alternative to independent architecture connection. These converters are based on single-input single-output configurations such as: Boost, Buck, Buck–Boost, SEPIC, and Ćuk, as well as combinations of these configurations, with common ground [83–85] or series connections [44,86], as shown in Figure 12. Table 8 summarizes some features of the non-isolated MIMO DC–DC Converters.

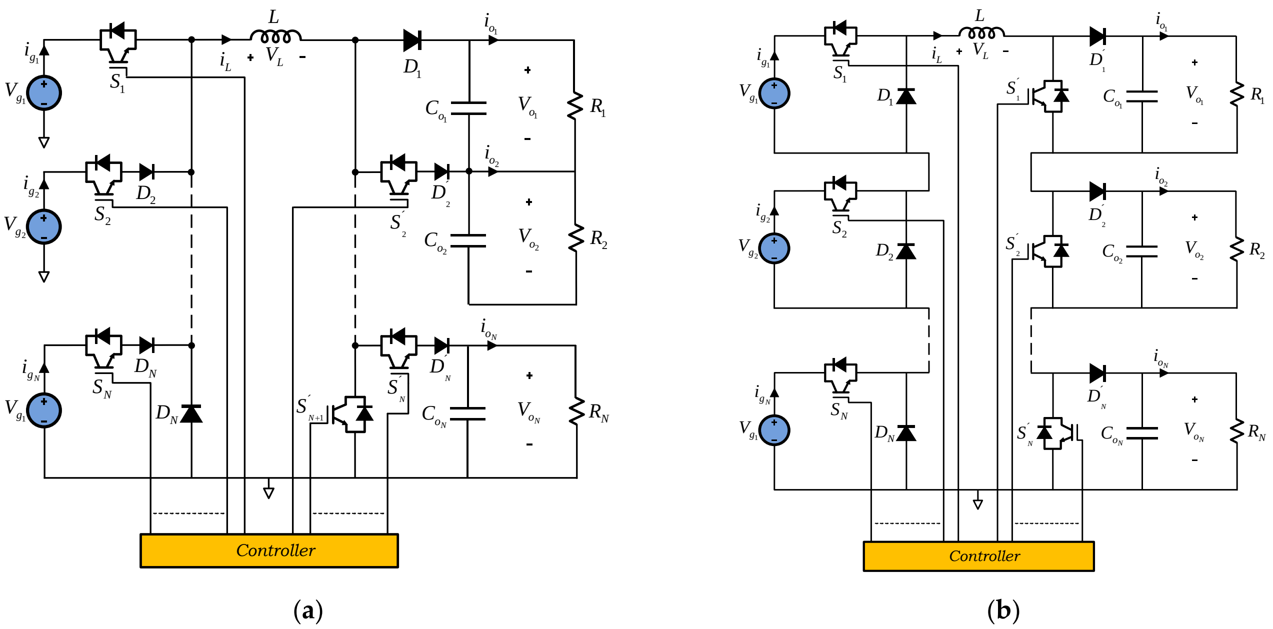


Figure 12. Non-isolated single-inductor MIMO Converters. (**a**) Series outputs [83–85]. (**b**) Series inputs and series outputs [44,86].

Table 8. Comparative summary of MIMO DC–DC Converters Non-Isolated.

Type Converter	Number Switches	Number Components	Voltage Stress	Floating Switches	Input/Output Feature
Series outputs	Medium	Low	High	Yes	Discontinuous input/ output currents
Series inputs and series outputs	Medium	High	High	Yes	Discontinuous input/ output currents

Compared with independent architecture connection, integrated MIMO DC–DC converters have the advantage of smaller size, fewer power conversion stages, and lower cost. On the other hand, both the series inputs and the series inputs and series outputs connection, with a single inductor, require a complex control system to avoid cross-regulation problems, and the simultaneous application of different voltages coming from the input sources, which limits the connection of a large number of sources and loads.

The current trend in the development of DC–DC converters with multiple outputs follows general aspects, such as low losses, high-power density, and high efficiency, as well as the development of new architectures and control strategies. Certainly, simple structures with a reduced number of components and power switches will be one of the new trends, especially to reduce the size. However, the incorporation of devices with a Wide Band Gap (WBG), particularly Gallium Nitride (GaN) and Silicon Carbide (SiC), will establish future trends, advantages and disadvantages, in the development and applications of DC–DC converters with multiple outputs.

3. Multiple-Output DC–DC Converters Applications and Solutions

In this section, we present the applications of multiple-output DC–DC converters. Although it's impossible to list all type of applications, we try to present a wide variety that can represent the most important types of applications and solutions that use multiple-output DC–DC converters. Figure summarizes some DC–DC converters' applications, grouped in three major categories: High Power, Medium Power, and Low Power. Again, a partition like this will never be straightforward or even definitive, but it represents the typical mindset when one thinks of general DC–DC converters.

Also, in Figure 13, we can identify areas of applications like: telecommunication, medical, automotive, energy and power, robotic, UAVs, and drones. In the next sections, some of these areas are detailed, giving concrete examples of applications and solutions used with multiple DC–DC converters.

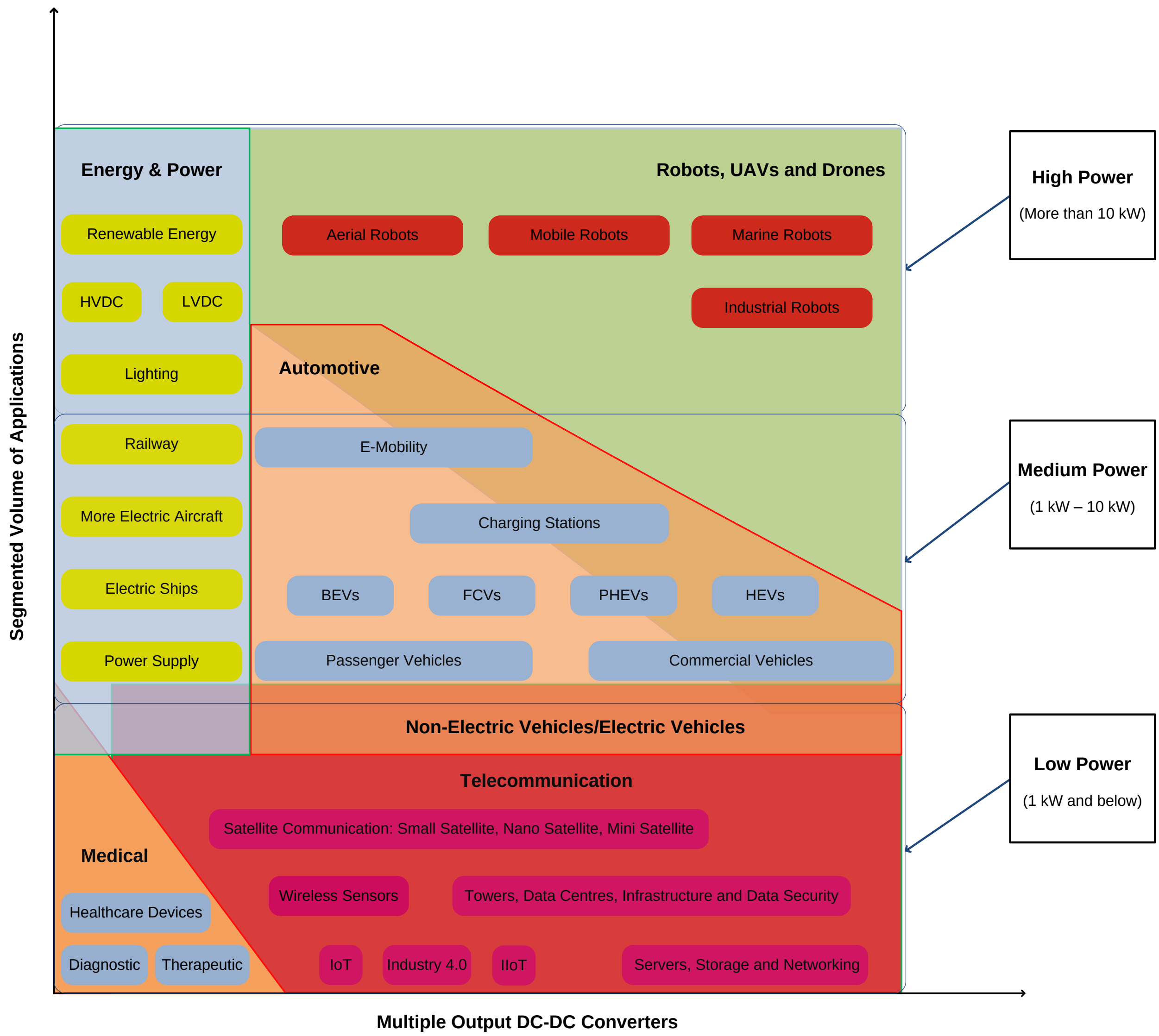


Figure 13. Multiple-Output DC–DC Converters Applications.

3.1. Converters for More Electric Aircraft

In an airplane, the necessary power generated by an engine is converted into four types of energy: hydraulic, mechanical, pneumatic, and electrical. In addition to the power required for pushing, the current trend is to replace mechanical, pneumatic, and hydraulic systems with an electric alternative [87,88]. This has led to a significant increase in the electrical power of an aircraft, reaching values of the order of megawatts in some models [89]. As a consequence, the electrical system has increased in complexity with a large number of electronic converters, electrical machines, switches, protections, and a variety of loads [90,91]. These systems are similar to a ground-based microgrid, although there are some differences that make them unique. In this sense, a system with a high level of reliability and safety is required with the advantage of having more predictable loads, changing their priority during the flight.

The electrical power system of an airplane is a system of multiple voltage levels, connected through electronic power converters. The different voltage levels are standardized [92]:

- DC Voltages: 28 V, 270 V (±135 V) and 540 V (±270 V); and
- AC Voltages: 230/115 V with fixed frequency of 400 Hz and 230/115 V with variable frequency (350–800 Hz).

There are different configurations of power systems for this type of application, one of them is the one shown in Figure 14. The two generators (coupled to each motor) and the Auxiliary Power Unit (APU) are connected to a three-phase AC 230 V network at variable frequencies (350–800 Hz). Several AC–DC converters supply the ±270 V DC bus from this network. High power loads are directly fed from this bus, a low-voltage DC bus (28 V) and an AC network at a frequency of 400 Hz, by means a DC-AC converter.

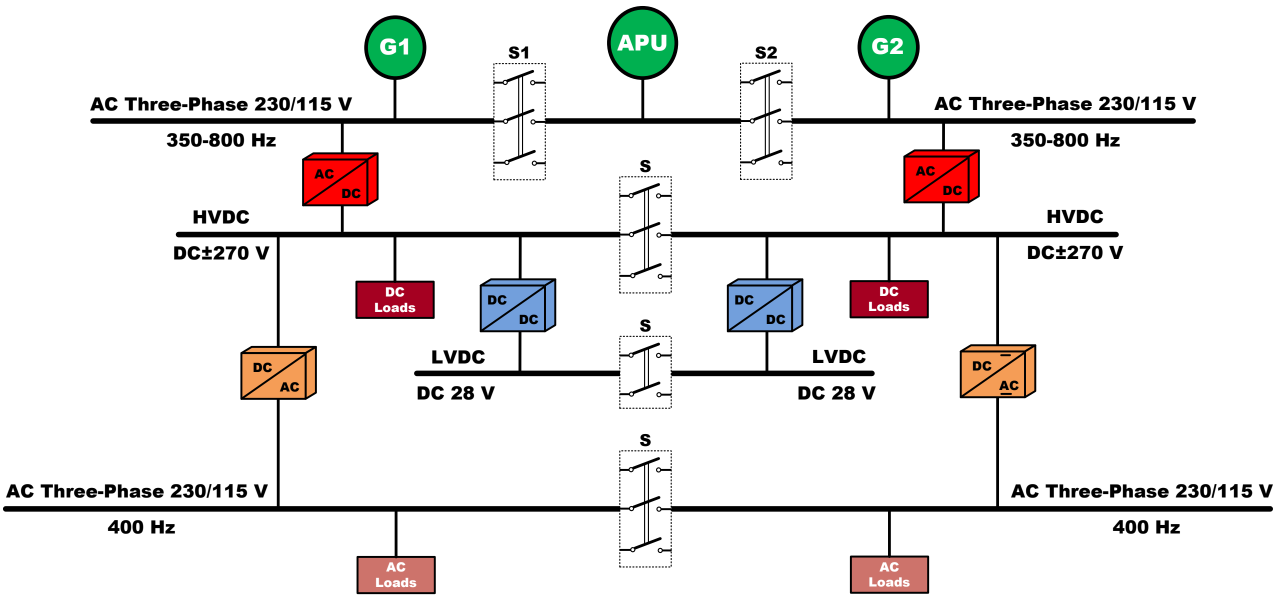


Figure 14. Electric scheme for a More Electric Aircraft.

In theses type of applications, the converters used are numerous and different, but they all have in common that they are reliable, that they have high efficiency, and in their designs the weight and size of the converter must be reduced [93,94]. In this sense, multi-port converters are a solution that meets these design restrictions [95–97].

3.2. Converters for All Electric Ships

Recently, in ship design, the concept of All Electric Ship (AES) has emerged [98,99]. These types of applications include different loads, electric generators governed by diesel engines, energy storage systems, renewable energy sources, and a distribution network that manages the energy of the entire system [100].

Traditionally, systems based on the AC system have been used, however, recently, there is a trend towards the use of DC distribution systems, due to the advantages that these present compared to AC distribution systems [101–103].

An example of a ship's electrical system topology based on a DC distribution is shown in Figure 15. Generally, the main power source is based on Synchronous Generators (GS) driven by diesel engines (fuel). The AC-DC converters feed the DC network that can be monopolar or bipolar [104]. Virtually the entire system is powered from the DC bus. Through DC–DC converters, the Renewable Energy Sources (RES), Energy Storage System (ESS), and different loads of the DC type are connected. The Electric Propulsion (EP) system is connected via a DC–AC converter. This can also have a small isolated AC network.

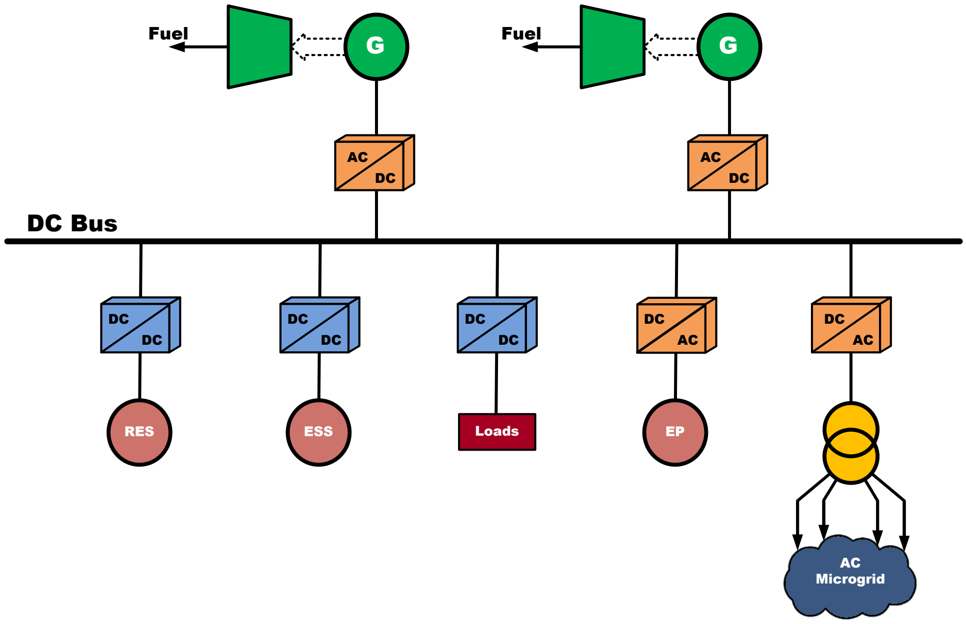


Figure 15. Electric scheme for all Electric Ships.

Therefore, the electrical system of an AES is made up of a microgrid where the power converters are a fundamental part of the system [105,106]. An adequate control allows the system to function properly, with suitable DC bus voltage regulation and balancing the power flow between sources and loads. In this sense, the use of multiple-output converters plays an important role since they allow the control of the system when the DC network is bipolar type or to establish a common power strategy to different loads through the converter itself.

3.3. Converters for Electric/Hybrid Vehicles

The number of electric/hybrid vehicles is increasing considerably every year. In this type of application, power electronics plays a fundamental role, both from the point of view of efficiency and having lighter and smaller systems [107,108].

An important evolution has been the development of new semiconductor devices that have made it possible to increase power, switching frequencies, and performance, at the same time with reduced losses, weight, and cost [109,110].

Modern vehicles often have similar power schemes. Figure 16 represents a simplified diagram of an electric vehicle. The main source of energy is the battery, which is usually of relatively high voltage. This feeds the traction motor of the vehicle through a DC–DC converter and the traction control converter [111,112]. These converters are usually bidirectional to return energy in the event of vehicle braking [113,114]. In some cases, there are several sources of energy storage (Li-Ion batteries, fuel cells, etc.) so the DC converter is usually of the type of multiple input and single output [115,116].

A DC–DC converter makes it possible to supply vehicle auxiliary elements, such as pumps, heaters, cooling system, lighting, etc., at lower voltages [117]. In addition, a low-voltage auxiliary battery is usually included to power the entire control and safety system of the vehicle.

In the case of electric or plug-in hybrid vehicles, the design of electronic systems for charging batteries is of special interest. This has probably been one of the main reasons why the electric vehicle has not been widely used in many countries. This has given rise to research in two lines: the development of efficient and fast charging systems and the development of network infrastructures that integrate the generation, transmission, distribution, and charging of vehicles [118]. In this sense, the possibility of designing smart battery charging systems that are bi-directional is being studied, so that they not only act as loads connected to the grid but at some point they can inject energy into the grid and, thus, can contribute to the stability of the electrical system [119,120], such as Grid to Vehicle (G2V) and Home to Vehicle (H2V), as well as Vehicle to Vehicle (V2V), Vehicle to Home (V2H), Vehicle to Building (V2B), Vehicle to Grid (V2G), and Vehicle to Everything (V2X) concepts.

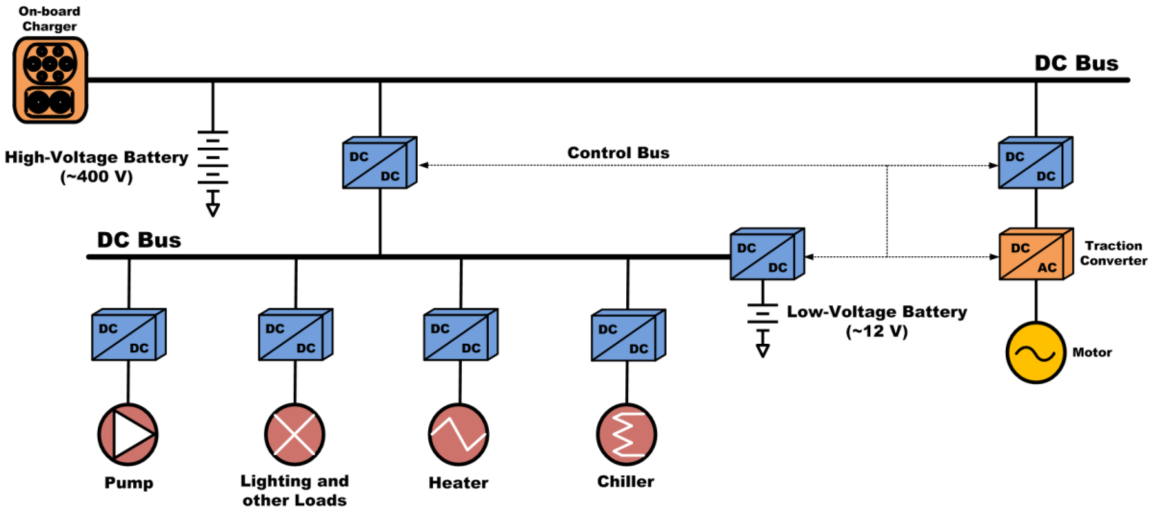


Figure 16. Scheme of an electric vehicle.

3.4. Converters for DC Microgrids

For almost a century, an electrical system model based on AC system has been followed. In this model, the energy is generated in large power plants and is transported through transmission networks to the places of consumption, which are usually far from the production centers. The advantage of AC is that it is easy to modify the voltage levels, which is necessary to reduce losses in energy transport.

With the proliferation of renewable energies, the electrical system has changed towards a system in which small power generators are incorporated, located close to consumers. This new model has been called a distributed generation system. Recently, a system has been proposed in which consumers have a net balance of zero energy. For this, electrical microgrids are proposed [121–123], where together with the loads and generators, energy storage systems are added to make the system self-sufficient and manageable. In many cases, the storage system is replaced by the public electricity grid so that energy is injected into it if it exceeds the microgrid and is absorbed from the grid if necessary.

Micrograms can be of the AC or DC type [124,125]. In this case, the debate between these two systems has been raised again, since most of the generation systems with renewable energies work in DC and on the other hand, currently, most of the loads work in DC form [126]. In addition, DC networks have the following advantages from a technical point of view:

- DC networks are more efficient, they have less loss in the transmission of energy, because the effective resistance, for equal section, is lower;
- Fewer conductors are required for distribution;
- They are more stable than AC networks;
- There are no line reactances, which results in lower voltage drops;
- The frequency is zero, thus eliminating the need for a synchronization system when connecting a generation system to the grid;
- There is no transient stability problem as in AC networks; and
- No electromagnetic interference is generated.

However, from an implementation point of view, it has two clear drawbacks [127,128]:

- Currently there are no infrastructures for this type of networks; and

- The protection of DC systems is usually more complex due to the constant value of the voltage.

It can be concluded that DC networks can be an alternative to AC networks when there are distributed generation systems and high quality and efficiency are sought in the system.

There are three different topologies for DC networks: homopolar, bipolar, and monopolar [69]. Among these topologies, the most versatile is the bipolar DC network, despite presenting greater complexity. In a bipolar DC network, there are three conductors "+", "−", and "0", Figure 17. The loads can be connected to two voltage levels. This is interesting in the case of loads with high consumption that, if connected to the highest voltage, reduce the absorbed current by half. On the other hand, part of the network could continue to function when a failure occurs in the other part. It is also interesting to note that the current through the "0" conductor is much smaller than through the other conductors, so the system could be designed for a smaller section of this conductor.

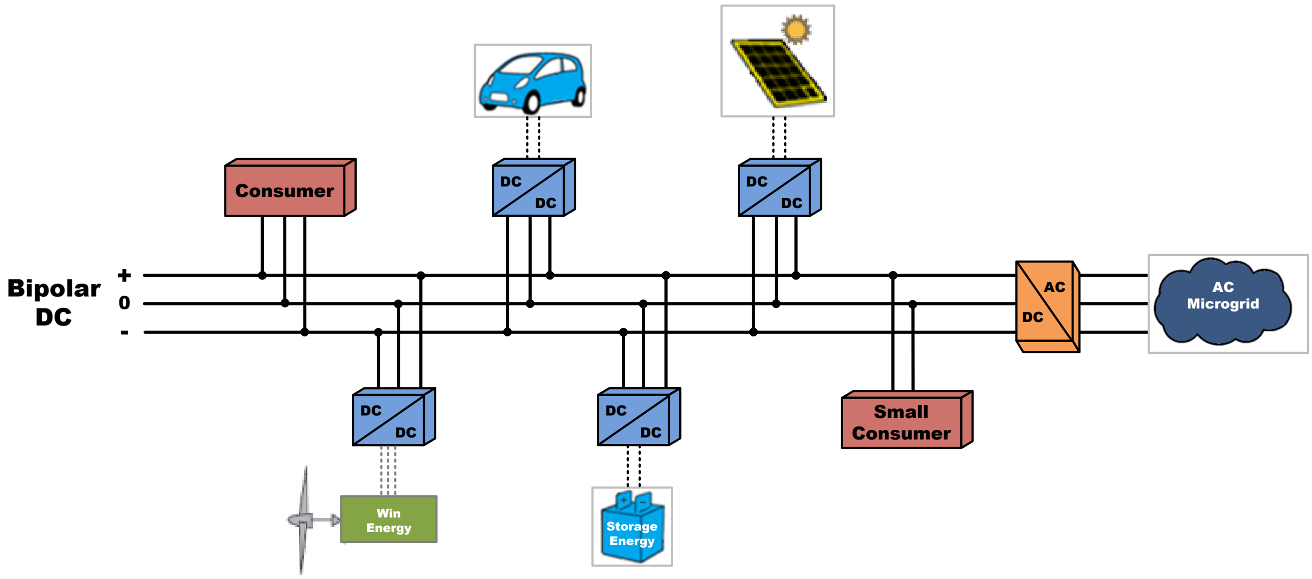


Figure 17. Bipolar DC microgrid.

For the connection of distributed generation systems to a bipolar network, reliable and efficient DC–DC converters with a bipolar input and output are required. The converter will make it possible to adapt the output voltage of the source and control the power flow between the source and the microgrid. Its design and control play a fundamental role for the proper functioning of the microgrid. There are many topologies proposed in the literature, both in their non-isolated and isolated versions, unidirectional or bidirectional, for applications in DC microgrids [129–131]. There are also many control strategies proposed, so as to ensure adequate power quality or the balance of system voltages [76,132].

3.5. Converters for LED Ilumination Systems

LED (Light Emitting Diode) lighting has become the main source of artificial light today. It is expected to be the primary source for decades to come due to its long service life, high luminous efficacy, and flexibility in color mixing. Above all this is the great energy savings compared to traditional light sources that together with the reduction in the cost of LEDs have made them widely used in the lighting of streets, buildings, homes, monuments, traffic signs, screens, etc. [133].

In LED lighting, the driver circuit plays a fundamental role, mainly in the efficiency of the system [134,135]. The driver circuit basically consists of a DC–DC converter and a Power Factor Correction (PFC) circuit. A current loop is included in the converter in order to obtain a constant current control. The function of the PFC circuit is to eliminate possible current harmonics and to correct the power factor, which turns out to be an indispensable component in this type of system. Both circuits can be implemented in a single stage, in two stages or in integrated stages. The single stage LED driver is a DC–DC converter with constant current output that includes the power factor correction function [136–138]. The two-stage LED driver consists of a PFC circuit plus a separate DC–DC converter [139,140]. As an example, Figure 18 presents a block diagram of a LED illumination system. In the integrated stage topology, the PFC circuit and the DC–DC converter can be simplified in a single stage, sharing the active power switches and the control circuits [141,142].

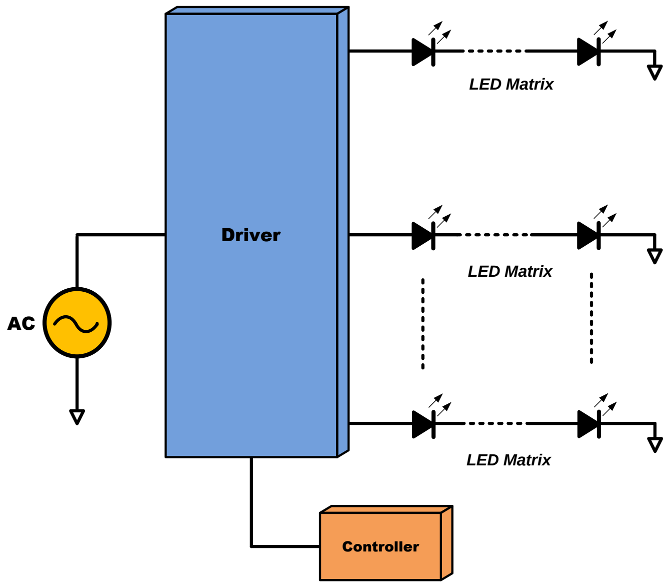


Figure 18. Block Diagram of LED illumination systems.

Multichannel LEDs are used to ensure a high intensity of illumination. In this way, high tensions of structures connected in series are avoided. This consists of several branches each made up of several LEDs connected in series (LED Matrix). In each branch the intensity is controlled from a DC–DC converter. There are several converter topologies that have been proposed, both in isolated and non-isolated versions, in order to obtain the maximum efficiency of the system [143–145]. In this situation it is where the DC–DC converters with multiple outputs can have a special relevance, which allows the power supply of each chain of LEDs and their control [146,147].

3.6. Multiple-Output DC–DC Converters for Satellite and Aerospace Applications

In aerospace and satellite applications, because it is an inhospitable and remote environment, power supplies should meet some important requirements, like size, weight, impossible/costly online repairs, severe radiation, a wide range of temperatures they have to withstand, and being a self-sustainable energy system, as the satellite should generate, distribute, and convert power to different levels in order to provide power to all the different blocks in the system, and they must have several different power-supply output voltage levels. Therefore, very often DC–DC converters with multiple outputs are used in this type of application.

Satellites are usually equipped with solar panels and rechargeable battery cells as their energy source and storage. Both are complementary to each other during two alternate phases. First, when a satellite faces the sun, photovoltaics in solar panels convert sunlight into electrical energy; the generated power is supplied to the satellite's sub-systems, and, then, the remaining power is stored in battery cells. On the other hand, during the eclipse phase (or the sun phase with a peak power demand), the stored energy in battery cells is used to operate the satellite sub-systems [148]. Moreover, power management is critical because power demands must never exceed the generated power.

Regarding the energy usage in satellites, each sub-system's power consumption is, typically, a periodic consumption task, repeatedly in a specified amount of time. As satellites are indispensable for navigation, weather forecast, broadcast, and many other applications, several switching and linear regulators are used, according to the sub-system to which they provide power. Figure 19 represents a typical block diagram of an Electric Power Supply subsystem of a satellite, in this case the CUBEsat [149]. As it can be seen, the Electric Power Supply subsystem contains solar panels, Boost converter with Maximum Power Point Tracker (MPPT), switching and linear regulators, over voltage protection and different load switches on the input of each subsystem. Boost converter steps up the solar panel voltage (4.4 V) to Power Distribution Bus (PDB) voltage level (14 ± 2 V). MPPT operates solar cells at maximum power point. Over voltage protection circuit keeps the PDB voltage within the operation limits. Switching and linear regulators step down the PDB voltage to different voltage levels required for all the subsystem components. Load switches supply and cutoff power from the subsystems through enable signal from an on-board processor.

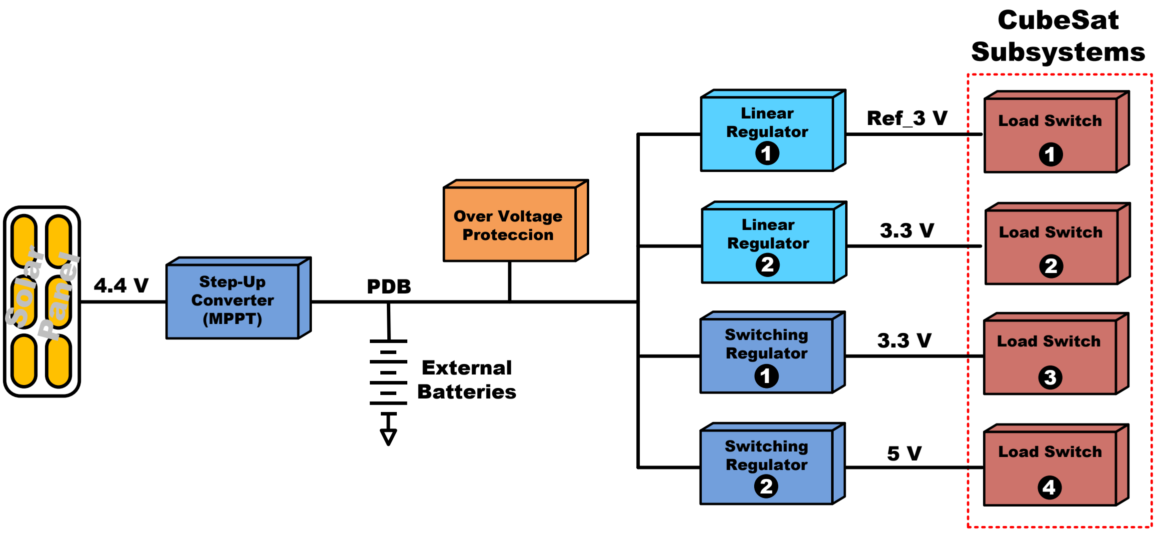


Figure 19. Block diagram of Electric Power Supply subsystem of a satellite (CUBEsat).

3.7. Multiple-Output DC–DC Converters in Computer Applications

Computer systems are probably the most important and widely used systems nowadays. Like any other electronic systems, computer systems need a Power Supply Unit (PSU) to convert an input voltage into one or several power supply voltages appropriate for its circuits. Systems like data centers, modems and communication networks, or even desktop computers, include some of the major applications and give support to the inter-net, provide data storage, support websites and databases, and support virtually almost every corporation and institution.

A computer system power-supply unit is a good example of application of multiple-output DC–DC converters, as every computer system needs to supply energy to different modules and, typically, several DC output values are needed. The most common type of today's PSU for computer systems is the Switch Mode Power Supply (SMPS). Regarding this type of PSU, there is a wide variety of topologies used by PSU manufacturers. However, all topologies use the same basic concepts [150]. For example, considering the application of DC–DC converters for a common desktop computer, Figure 20 presents a typical block diagram of a PSU. Usually, it consists of a front-end Power Factor Correction (PFC) stage and an isolated DC–DC stage [151]. The output blocks, as it can be seen, present multiple-output converters where three output DC voltages are available: 3 V, 5 V, and 12 V.

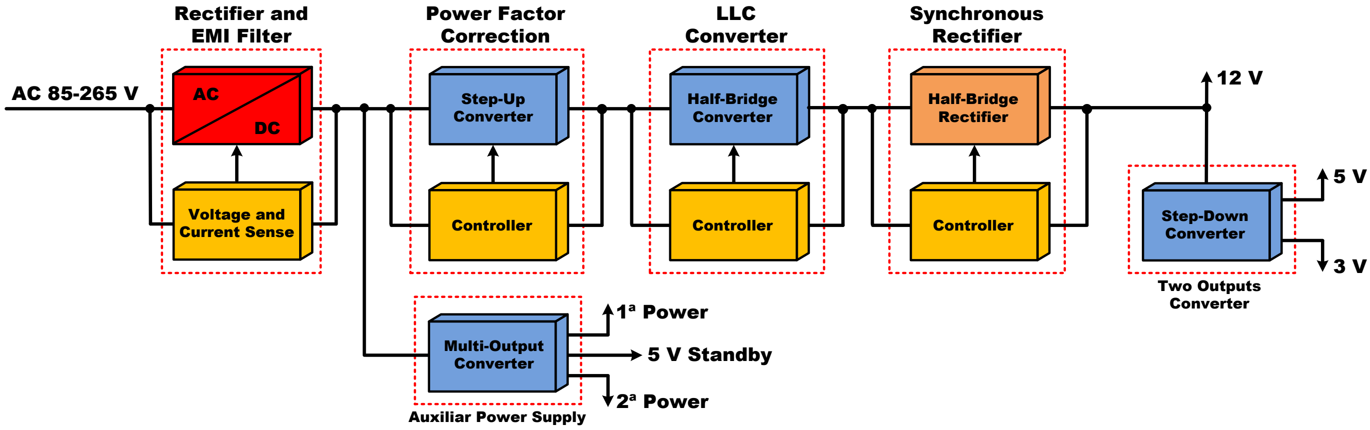


Figure 20. Desktop computer power-supply unit.

3.8. Multiple-Output DC–DC Converters in Systems-on-a-Chip (SoC)

The increase complexity of today's Systems-on-a-Chip (SoC) imposes the need to integrate in a single chip all the major features that in the past were only available in computer systems, which includes a power-management unit and, most likely, DC–DC converters. In fact, a SoC is an electronic circuit that can integrate all the necessary components present in a computer and other electronic systems, like a GPU (graphics-processor unit), memory, power management circuits, CPU (central processing unit), a USB controller, wireless radios (2G/3G/4G LTE, GPS, WiFi, FM radio, and Bluetooth) and many more, but all integrated in a single chip. Being a very complex circuit, an SoC needs a dedicated power-management unit that can be similar to typical computer systems, but although all integrated in silicon.

Several publications present PMU for SoC applications that have similar architectures to PSU in computer systems (e.g., [152]). Figure 21 presents a typical block diagram of a SoC and we can see the need of several linear regulators to supply different building blocks with different power-supply voltage levels.

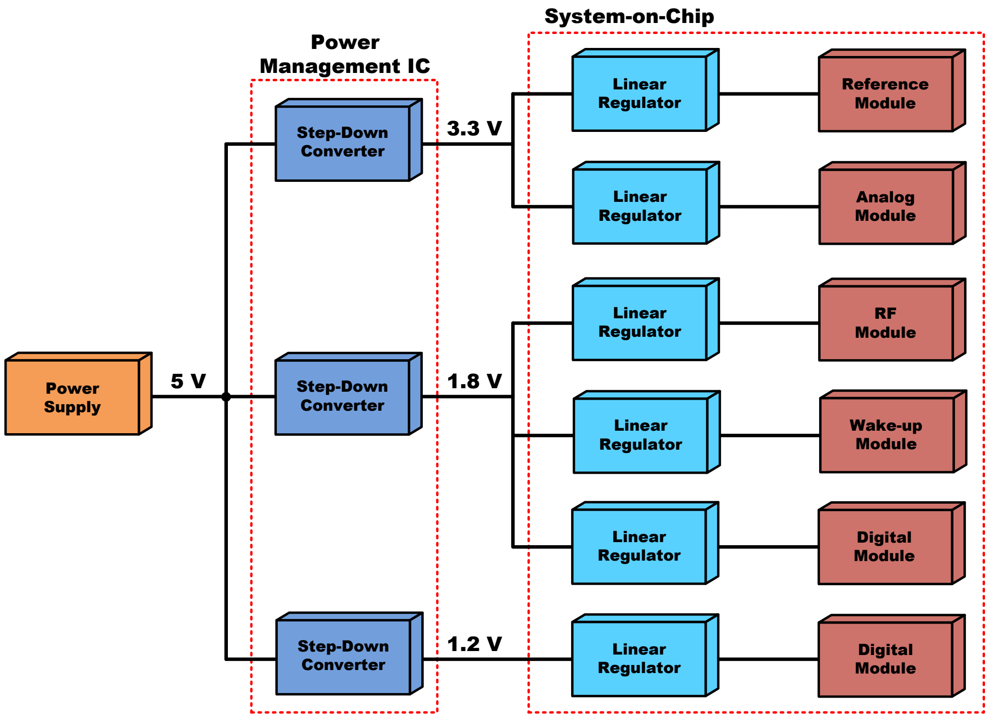


Figure 21. Block diagram showing general architecture of power supply in a SoC (System-on-a-Chip).

However, to facilitate the integration of all blocks, other type of DC–DC converters are used, like Switched-Capacitor (SC) based DC–DC converters, because they allow monolithic substrate integration due to the reduction of silicon surface required and size, and contribute towards reduced electromagnetic effects and power losses. As an example, in [153], Multiple-Output Switched-Capacitor DC–DC Combination Converters are presented, for use in SoC focusing IoT applications.

Moreover, the need to reduce power consumption in today's chips brings the use of aggressive power-reduction techniques, and multi-domain power supplies are increasingly being used to accomplish power reduction [154]. To achieve ultra-low-power consumption levels, especially in new SoC for IoT, Dynamic Voltage and Frequency Scaling (DVFS) techniques should be used, to work at different power-supply voltage (VDD) and clock frequency levels (as explained in [155]). These new low-power techniques demand new DC–DC converters, with adjustable output-voltage values, or with multiple simultaneous output values available. Therefore, SoC applications are a good example to show that DC–DC converters with multiple outputs have still a long way ahead for research and development.

4. Conclusions

In this paper, we present an overview of the most important topics related to multiple-output DC–DC converters based on their main topologies and configurations, applications, solutions, and trends. Our goal is to highlight a wide variety of configurations and topologies of multiple-output DC–DC converters. We show more than 30 topologies, isolated and non-isolated, single and multiple switched, based on soft- and hard-switching techniques, which are used in many different applications and solutions. However, the current trend in the development of multiple-output DC–DC converters follows general aspects, such as high-power density, high efficiency, and low losses, as well as the development of new architectures and control strategies. Certainly, simple structures with a reduced number of components and power switches are one of the new trends, especially to reduce the size.

Also, several applications of multiple-output DC–DC converters were presented in this paper. A wide variety of examples were presented, to characterize the most important types of applications and solutions that use these converters, showing High Power, Medium Power, and Low Power application examples.

Author Contributions: S.P.L., E.D., J.S. and C.D.-M. have written the original draft and have reviewed and edited the paper, the conceptualization, the methodology, and the analysis of the state of the art. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ballestín-Fuertes, J.; Muñoz-Cruzado-Alba, J.; Sanz-Osorio, J.F.; Laporta-Puyal, E. Role of Wide Bandgap Materials in Power Electronics for Smart Grids Applications. *Electronics* **2021**, *10*, 677. [CrossRef]
2. 360 Market Updates. Available online: https://www.360marketupdates.com/ (accessed on 1 April 2022).
3. Absolute Reports. Available online: https://www.absolutereports.com/ (accessed on 1 April 2022).
4. Allied Market Research. Available online: https://www.alliedmarketresearch.com/ (accessed on 1 April 2022).
5. DataM Intelligence. Available online: https://www.datamintelligence.com/ (accessed on 1 April 2022).
6. IDTechEx Research Reports. Available online: https://www.idtechex.com/ (accessed on 1 April 2022).
7. Market Research Future. Available online: https://www.marketresearchfuture.com/ (accessed on 1 April 2022).
8. Market Research Reports, Business Communications Company (BCC). Available online: https://www.bccresearch.com/ (accessed on 1 April 2022).
9. Omdia Research by Market. Available online: https://omdia.tech.informa.com/ (accessed on 1 April 2022).
10. Report Linker. Available online: https://www.reportlinker.com/ (accessed on 1 April 2022).
11. Valuates Reports. Available online: https://reports.valuates.com/ (accessed on 1 April 2022).
12. eeNews Europe (Electronics Europe News). Available online: https://www.eenewseurope.com/search/node/multiple%20output%20dc-dc%20converters (accessed on 1 April 2022).

13. eeNews Embedded. Available online: https://www.eenewsembedded.com/search/node/multiple%20output%20dc-dc%20converters (accessed on 1 April 2022).
14. Electronics Design eNewsletter. Available online: https://www.electronicdesign.com/search?ebm_electronicdesign%5Bquery%5D=multiple%20output%20dc-dc%20converters (accessed on 1 April 2022).
15. EE Times Europe Magazine. Available online: https://www.eetimes.eu/?s=multiple+output+dc-dc+converters (accessed on 1 April 2022).
16. Power Electronics News. Available online: https://www.powerelectronicsnews.com/?s=multiple+output+dc-dc+converters (accessed on 1 April 2022).
17. Smart2.0. Available online: https://www.smart2zero.com/search/node/multiple%20output%20dc-dc%20converters (accessed on 1 April 2022).
18. DC–DC Converter Market by Vertical, Form Factor (SIP, DIP, DIN Rail, Box, Chassis Mount, Discreter, Brick), Input Voltage, Output Voltage, Output Power, Output Number, Product Type, Isolation Working Voltage and Region-Forecast to 2026. Available online: https://www.researchandmarkets.com/reports/5401801/dc-dc-converter-market-by-vertical-form-factor?utm_source=MC&utm_medium=Email&utm_code=mzrfk4g55&utm_ss=44&utm_campaign=1589384+-+dc-dc+converter+Market+-+Forecast+to+2026&utm_exec=cono266mtd (accessed on 1 April 2022).
19. Global Switching Power Supply Market Size, Trends & Growth Opportunity, by Voltage Rating, by Application, by Region and Forecast to 2027. Available online: https://www.researchandmarkets.com/reports/5437868/global-switching-power-supply-market-size-trends?utm_source=MC&utm_medium=Email&utm_code=mzrj5rgey&utm_ss=44&utm_campaign=1587831+-+Global+Switching+Power+Supply+Market+Size%2c+Trends+%26+Growth+Opportunity%2c+and+Forecast+to+2027&utm_exec=cono266mtd (accessed on 1 April 2022).
20. Global DC–DC Converters Market Research Report 2021, Forecast to 2026. Available online: https://www.360marketupdates.com/global-DC--DC-converters-market-19159087 (accessed on 1 April 2022).
21. Rugged Power Supply Market Global Industry Analysis, Size, Share, Growth, Trends, and Forecast 2017–2025. Available online: https://www.bccresearch.com/partners/transparency/rugged-power-supply-market-global-industry-analysis-size-share-growth-trends-and-forecast.html (accessed on 1 April 2022).
22. Medical Power Supply Market, Size, Share, Growth, Trends, Insight and Industry Forecast 2021–2028. Available online: https://www.datamintelligence.com/research-report/medical-power-supply-market (accessed on 1 April 2022).
23. DC–DC Converter Market by Vertical, Form Factor, Input Voltage, Output Voltage, Output Power, Output Number, Product Type, Isolation Working Voltage and Region-Forecast to 2026. Available online: https://www.reportlinker.com/p04180622/Global-dc-dc-Converters-Market-by-Application-Output-Number-Input-Voltage-Output-Voltage-Output-Power-Sales-Channel-Form-Factor-Product-Type-and-Region-Forecast-to.html (accessed on 1 April 2022).
24. 5G Small Cells 2021–2031: Technologies, Markets, Forecast. Available online: https://www.idtechex.com/en/research-report/5g-small-cells-2021-2031-technologies-markets-forecast/825 (accessed on 1 April 2022).
25. LED Supply & Demand Market Tracker—1Q21 Analysis. Available online: https://omdia.tech.informa.com/OM018423/LED-Supply--Demand-Market-Tracker--1Q21-Analysis (accessed on 1 April 2022).
26. Rugged Power Supply Market Research Report, by Component (Hardware and Software), System Type (Discrete and Integrated), Industry Vertical (Defense, Aerospace, Telecommunications, Manufacturing, Healthcare, and Transportation)—Forecast till 2027. Available online: https://www.marketresearchfuture.com/reports/rugged-power-supply-market-7150 (accessed on 1 April 2022).
27. DC–DC Converter Market by Input Voltage (5–36 V, 36–75 V, 75 V and Above), Output Voltage (3.3 V, 5 V, 12 V, 15 V and Above), Mounting Style (Surface Mount and Through Hole), Application (Smartphone, Servers & Storage, EV Battery Management Unit, Railway, and Medical Equipment): Global Opportunity Analysis and Industry Forecast, 2020–2027. Available online: https://www.alliedmarketresearch.com/dc-dc-converter-market (accessed on 1 April 2022).
28. Massive Multiple-Input Multiple-Output (MIMO) Market-Growth, Trends, COVID-19 Impact, and Forecasts (2021–2026). Available online: https://www.mordorintelligence.com/industry-reports/massive-multiple-input-multiple-output-mimo-market (accessed on 1 April 2022).
29. Global Power Supply Unit for Servers Market Size, Manufacturers, Supply Chain, Sales Channel and Clients, 2021–2027. Available online: https://reports.valuates.com/market-reports/QYRE-Auto-15M6756/global-power-supply-unit-for-servers (accessed on 1 April 2022).
30. Global Switching Power Supply Market 2021 by Manufacturers, Regions, Type and Application, Forecast to 2026. Available online: https://www.absolutereports.com/global-switching-power-supply-market-19180193 (accessed on 1 April 2022).
31. Aimtec. Available online: http://www.aimtec.com/manufacture-modular-ac-dc-dc-dc-switching-power-supplies (accessed on 1 April 2022).
32. CUI. Available online: https://www.cui.com/catalog/dc-dc-converters (accessed on 1 April 2022).
33. Delta Electronics. Available online: https://www.deltaww.com/en-US/products/dc-dc/ALL/ (accessed on 1 April 2022).
34. Flex Ltd. Available online: https://flexpowermodules.com/ (accessed on 1 April 2022).
35. Infineon Technologies AG. Available online: https://www.infineon.com/cms/en/product/power/dc-dc-converters/ (accessed on 1 April 2022).

36. Maxim Integrated. Available online: https://www.maximintegrated.com/en/products/power/switching-regulators.html (accessed on 1 April 2022).
37. MORNSUN Power. Available online: https://www.mornsun-power.com/html/products/1986/switching-regulator.html (accessed on 1 April 2022).
38. Murata Power Solutions. Available online: https://www.murata.com/products/power (accessed on 1 April 2022).
39. TDK Lambda. Available online: https://www.us.lambda.tdk.com/products/dcdc-converters/ (accessed on 1 April 2022).
40. Texas Instruments. Available online: https://www.ti.com/power-management/overview.html (accessed on 1 April 2022).
41. Traco Power. Available online: https://www.tracopower.com/dc-dc-converters (accessed on 1 April 2022).
42. Vicor Corporation. Available online: https://www.vicorpower.com/dc-dc (accessed on 1 April 2022).
43. Saman, D.T.; Peng, Z.; Lu, X.; Mohsen, H. Mutual Interactions and Stability Analysis of Bipolar DC Microgrids. *CSEE J. Power Energy Syst.* **2019**, *5*, 444–453.
44. Behjati, H.; Davoudi, A. A Multiple-Input Multiple Output DC–DC Converter. *IEEE Trans. Ind. Appl.* **2013**, *49*, 1464–1479.
45. Tong, Y.; Shan, Z.; Jatskevich, J.; Davoudi, A. Anonisolated multiple-input multiple-output dc–dc converter for dc distribution of future energy efficient homes. In Proceedings of the IEEE 40th Annual Conference of the Industrial Electronics Society, Dallas, TX, USA, 29 October–1 November 2014; pp. 4126–4132.
46. Taehyung, K.; Sangshin, K. Single pole switch leg based multi-port converter with an energy storage. *Power Electron. IET* **2016**, *9*, 1322–1330.
47. Patra, P.; Patra, A.; Misra, N. A single-inductor multiple-output switcher with simultaneous Buck, Boost, and inverted out-puts. *IEEE Trans. Power Electron.* **2012**, *27*, 1936–1951. [CrossRef]
48. Huang, M.H.; Chen, K.H. Single-inductor multi-output (SIMO) DC–DC converters with high light-load efficiency and mini-mized cross regulation for portable devices. *IEEE J. Solid-State Circuits* **2009**, *44*, 1099–1111. [CrossRef]
49. Dhananjaya, M.; Swapnajit, P. Design and implementation of a SIMO DC–DC converter. *IET Power Electron.* **2019**, *12*, 1868–1879. [CrossRef]
50. Dietrich, S.; Strache, S.; Wunderlich, R.; Heinen, S. Get the LED out: Experimental validation of a capacitor-free single-inductor, multiple-output LED driver topology. *IEEE. Ind. Electron. Mag.* **2015**, *9*, 24–35. [CrossRef]
51. Nami, A.; Zare, F.; Ghosh, A.; Blaabjerg, F. Multi-output dc–dc converters based on diode clamped converters configuration: Topology and control strategy. *IET Power Electron.* **2010**, *3*, 197–208. [CrossRef]
52. Lindiya, S.A.; Subashini, N.; Vijayarekha, K. Cross Regulation Reduced Optimal Multivariable Controller Design for Single Inductor DC–DC Converters. *Energies* **2019**, *12*, 477. [CrossRef]
53. Abraham, D.S.; Verma, R.; Kanagaraj, L.; Raman, S.G.T.; Rajamanickam, N.; Chokkalingam, B.; Sekar, K.M.; Mihet-Popa, L. Electric Vehicles Charging Stations' Architectures, Criteria, Power Converters, and Control Strategies in Microgrids. *Electronics* **2021**, *10*, 1895. [CrossRef]
54. Bose, B. Need a Switch? *IEEE Ind. Electron. Mag.* **2007**, *1*, 30–39. [CrossRef]
55. Outeiro, M.T.; Buja, G.; Czarkowski, D. Resonant Power Converters: An Overview with Multiple Elements in the Reso-nant Tank Network. *IEEE Ind. Electron. Mag.* **2016**, *10*, 21–45. [CrossRef]
56. Salem, M.; Jusoh, A.; Idris, N.R.; Das, H.S.; Alhamrouni, I. Resonant power converters with respect to passive storage (LC) ele-ments and control techniques—An overview. *Renew. Sustain. Energy Rev.* **2018**, *91*, 504–520. [CrossRef]
57. Li, T. Single Inductor Multiple Output Boost Regulator. U.S. Patent 6,075,295A, 13 June 2000.
58. Ma, D.; Ki, W.-H.; Mok, P.K.T.; Tsui, C.-Y. Single-inductor multiple-output switching converters. *Proc. IEEE PESC* **2001**, *1*, 226–231.
59. Ma, D.; Ki, W.-H.; Tsui, C.-Y. A pseudo-CCM/DCM SIMO switching converter with freewheel switching. *IEEE J. Solid-State Circuits* **2003**, *38*, 1007–1014.
60. Soyka, R.; Rall, W.; Schnaubelt, J.; Sieger, P.; Kulinna, C. Process for Preparing Amino Crotonyl Compounds. U.S. Patent 20,050,085,495A1, 21 April 2005.
61. Le, H.-P.; Chae, C.-S.; Lee, K.-C.; Wang, S.-W.; Cho, G.-H. A Single-Inductor Switching DC–DC Converter with Five Outputs and Ordered Power-Distributive Control. *IEEE J. Solid-State Circuits* **2007**, *42*, 2706–2714. [CrossRef]
62. Seol, K.-S.; Woo, Y.-J.; Cho, G.-H.; Gho, G.-H.; Lee, J.-W. A synchronous multioutput step-up/down dc–dc converter with return current control. *IEEE Trans. Circuits Syst. II Exp. Briefs* **2009**, *56*, 210–214. [CrossRef]
63. Kwon, D.; Rincon-Mora, G.A. Single-Inductor–Multiple-Output Switching DC–DC Converters. *IEEE Trans. Circuits Syst. II Express Briefs* **2009**, *56*, 614–618. [CrossRef]
64. Goder, D.; Santo, H. Multiple Output Regulator with Time Sequencing. U.S. Patent 5,617,015, 1 April 1997.
65. Ma, D.; Ki, W.-H.; Tsui, C.Y.; Mok, P.K.T. Single-inductor multiple-output switching converters with time-multiplexing control in discontinuous conduction mode. *IEEE J. Solid-State Circuits* **2003**, *38*, 89–100. [CrossRef]
66. Li, X.L.; Dong, Z.; Tse, C.K. Complete family of two-stage singleinput multi-output configurations of interconnected power converters. *IEEE Trans. Power Electron.* **2020**, *35*, 3713–3728. [CrossRef]
67. Litrán, S.P.; Durán, E.; Barroso, R.S.; Semião, J.; Ferrera, M.B. Analysis of Converters with Bipolar Output for DC Mi-crogrid. In Proceedings of the 2020 IEEE 14th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Setubal, Portugal, 8–10 July 2020; pp. 13–18.
68. Kakigano, H.; Miura, Y.; Ise, T. Low-Voltage Bipolar-Type DC Microgrid for Super High Quality Distribution. *IEEE Trans. Power Electron.* **2010**, *25*, 3066–3075. [CrossRef]

69. Zhang, M.; Jiang, Y.; Lee, F.; Jovanovic, M. Single-phase three-level boost power factor correction converter. In Proceedings of the 1995 IEEE Applied Power Electronics Conference and Exposition-APEC'95, Dallas, TX, USA, 5–9 March 1995; Volume 1, pp. 434–439.
70. Haddad, K. Three level DC–DC converters as efficient interface in two stage PV power systems. In Proceedings of the 2012 IEEE Energytech, San Diego, CA, USA, 29–31 May 2012; pp. 1–6.
71. Rezayi, S.; Iman-Eini, H.; Hamzeh, M.; Bacha, S.; Farzamkia, S. Dual-output DC/DC boost converter for bipolar DC microgrids. *IET Renew. Power Gener.* **2019**, *13*, 1402–1410. [CrossRef]
72. Durán-Gómez, J.L.; García-Cervantes, E.; López-Flores, D.R.; Enjeti, P.N.; Palma, L. Analysis and evaluation of a series-combined connected boost and buck-boost DC–DC converter for photovoltaic application. In Proceedings of the Twenty-First Annual IEEE Applied Power Electronics Conference and Exposition, 2006, APEC'06, Dallas, TX, USA, 19–23 March 2006; pp. 19–23.
73. Schoenbauer, S.; Martin-Lopez, F.R. Single Inductor Buck Boost Converter with Positive and Negative Outputs. U.S. Patent 20,100,039,080, 18 February 2010.
74. Kang, H.; Cha, H. A New Nonisolated High-Voltage-Gain Boost Converter with Inherent Output Voltage Balancing. *IEEE Trans. Ind. Electron.* **2017**, *65*, 2189–2198. [CrossRef]
75. Prabhakaran, P.; Agarwal, V. Novel Boost-SEPIC Type Interleaved DC–DC Converter for Mitigation of Voltage Imbalance in a Low-Voltage Bipolar DC Microgrid. *IEEE Trans. Ind. Electron.* **2019**, *67*, 6494–6504. [CrossRef]
76. Kumar, P.; Singh, R.K.; Mahanty, R. Performance of MPPT-Based Minimum Phase Bipolar Converter for Photovoltaic Systems. *IEEE Trans. Power Electron.* **2021**, *36*, 5594–5609. [CrossRef]
77. Zhou, X.; Wang, Y.; Wang, L.; Liu, Y.-F.; Sen, P.C. A Soft-Switching Transformerless DC−DC Converter with Single-Input Bipolar Symmetric Outputs. *IEEE Trans. Power Electron.* **2021**, *36*, 8640–8646. [CrossRef]
78. Sanjeevikumar, P.; Bhaskar, M.S.; Dhond, P.; Blaabjerg, F.; Pecht, M. Non-isolated Sextuple Output Hybrid Triad Converter Configurations for High Step-Up Renewable Energy Applications. In *Advances in Power Systems and Energy Management. Lecture Notes in Electrical Engineering*; Springer: Singapore, 2018; Volume 436, pp. 1–12.
79. Durán, E.; Litrán, S.P.; Ferrera, M.B. Configuration of DC–DC converters of one input and multiple outputs without trans-former. *IET Power Electron.* **2020**, *13*, 2658–2670. [CrossRef]
80. Ferrera Prieto, M.B.; Litran, S.P.; Aranda, E.D.; Gomez, J.M.E. New Single-Input, Multiple-Output Converter Topologies: Combining Single-Switch Nonisolated DC–DC Converters for Single-Input, Multiple-Output Applications. *IEEE Ind. Electron. Mag.* **2016**, *10*, 6–20. [CrossRef]
81. Tao, H.; Kotsopoulos, A.; Duarte, J.; Hendrix, M. Family of multiport bidirectional DC–DC converters. *IEE Proc.-Electr. Power Appl.* **2006**, *153*, 451–458. [CrossRef]
82. Tao, H.; Kotsopoulos, A.; Duarte, J.; Hendrix, M. Multi-input bidirectional DC–DC converter combining DC-link and magnetic-coupling for fuel cell systems. In Proceedings of the Fourtieth IAS Annual Meeting. Conference Record of the 2005 Industry Applications Conference, Hong Kong, China, 2–6 October 2005.
83. Li, X.L.; Dong, Z.; Tse, C.K.; Lu, D.D.-C. Single-Inductor Multi-Input Multi-Output DC–DC Converter with High Flexi-bility and Simple Control. *IEEE Trans. Power Electron.* **2020**, *35*, 13104–13114. [CrossRef]
84. Dong, Z.; Li, Z.; Lucia, X.; Chi, L.; Tse, K.; Zhang, Z. Single-Inductor Multiple-Input Multiple-Output Con-verter With Common Ground High Scalability and No Cross-Regulation. *Power Electron. IEEE Trans.* **2021**, *36*, 6750–6760. [CrossRef]
85. Chen, G.; Liu, Y.; Qing, X.; Ma, M.; Lin, Z. Principle and Topology Derivation of Single-Inductor Multi-Input Multi-Output DC–DC Converters. *IEEE Trans. Ind. Electron.* **2021**, *68*, 25–36. [CrossRef]
86. Nguyen, B.L.-H.; Cha, H.; Nguyen, T.T.; Kim, H.G. Family of integrated multi-input multi-output DC–DC power converters. In Proceedings of the 2018 International Power Electronics Conference (IPEC-Niigata 2018-ECCE Asia), Niigata, Japan, 20–24 May 2018; pp. 3134–3139.
87. Roboam, X.; Sareni, B.; De Andrade, A. More Electricity in the Air: Toward Optimized Electrical Networks Embedded in More-Electrical Aircraft. *IEEE Ind. Electron. Mag.* **2012**, *6*, 6–17. [CrossRef]
88. Ansell, P.J.; Haran, K.S. Electrified Airplanes: A Path to Zero-Emission Air Travel. *IEEE Electrif. Mag.* **2020**, *8*, 18–26. [CrossRef]
89. Madonna, V.; Giangrande, P.; Galea, M. Electrical Power Generation in Aircraft: Review, Challenges, and Opportunities. *IEEE Trans. Transp. Electrif.* **2018**, *4*, 646–659. [CrossRef]
90. Wheeler, P.; Bozhko, S. The More Electric Aircraft: Technology and challenges. *IEEE Electrif. Mag.* **2014**, *2*, 6–12. [CrossRef]
91. Brelje, B.J.; Martins, J.R. Electric, hybrid, and turboelectric fixed-wing aircraft: A review of concepts, models, and design approaches. *Prog. Aerosp. Sci.* **2019**, *104*, 1–19. [CrossRef]
92. Buticchi, G.; Bozhko, S.; Liserre, M.; Wheeler, P.; Al-Haddad, K. On-Board Microgrids for the More Electric Aircraft—Technology Review. *IEEE Trans. Ind. Electron.* **2019**, *66*, 5588–5599. [CrossRef]
93. Buticchi, G.; Costa, L.; Liserre, M. Improving System Efficiency for the More Electric Aircraft: A Look at dc\/dc Converters for the Avionic Onboard dc Microgrid. *IEEE Ind. Electron. Mag.* **2017**, *11*, 26–36. [CrossRef]
94. Rojas-Duenas, G.; Riba, J.-R.; Moreno-Eguilaz, M. A Deep Learning-Based Modeling of a 270 V-to-28 V DC–DC Converter Used in More Electric Aircrafts. *IEEE Trans. Power Electron.* **2021**, *37*, 509–518. [CrossRef]
95. Gu, C.; Yan, H.; Yang, J.; Sala, G.; De Gaetano, D.; Wang, X.; Galassini, A.; Degano, M.; Zhang, X.; Buticchi, G. A Multiport Power Conversion System for the More Electric Aircraft. *IEEE Trans. Transp. Electrif.* **2020**, *6*, 1707–1720. [CrossRef]

96. Yang, J.; Buticchi, G.; Gu, C.; Gunter, S.; Zhang, H.; Wheeler, P. A Generalized Input Impedance Model of Multiple Active Bridge Converter. *IEEE Trans. Transp. Electrif.* **2020**, *6*, 1695–1706. [CrossRef]
97. Buticchi, G.; Costa, L.F.; Liserre, M. Multi-port DC/DC converter for the electrical power distribution system of the more electric aircraft. *Math. Comput. Simul.* **2018**, *158*, 387–402. [CrossRef]
98. Khersonsky, Y.; Hingorani, N.; Peterson, K.L. IEEE Electric Ship Technologies initiative. In Proceedings of the 2009 Record of Conference Papers-Industry Applications Society 56th Annual Petruleum and Chemical Industry Conference, Anaheim, CA, USA, 14–16 September 2009; pp. 1–10. [CrossRef]
99. Mukund, R.P. *Shipboard Electrical Power Systems*; CRC Press: Boca Raton, FL, USA, 2012.
100. Kim, K.; Park, K.; Roh, G.; Chun, K. DC-grid system for ships: A study of benefits and technical considerations. *J. Int. Marit. Saf. Environ. Aff. Shipp.* **2018**, *2*, 1–12. [CrossRef]
101. Thongam, J.S.; Tarbouchi, M.; Okou, A.F.; Bouchard, D.; Beguenane, R. Trends in naval ship propulsion drive motor technology. In Proceedings of the 2013 IEEE Electrical Power & Energy Conference, Halifax, NS, Canada, 21–23 August 2013; pp. 1–5. [CrossRef]
102. Su, C.-L.; Lin, K.-L.; Chen, C.-J. Power Flow and Generator-Converter Schemes Studies in Ship MVDC Distribution Systems. *IEEE Trans. Ind. Appl.* **2015**, *52*, 50–59. [CrossRef]
103. Skjong, E.; Volden, R.; Rodskar, E.; Molinas, M.; Johansen, T.A.; Cunningham, J. Past, Present, and Future Challenges of the Marine Vessel's Electrical Power System. *IEEE Trans. Transp. Electrif.* **2016**, *2*, 522–537. [CrossRef]
104. Dai, J.; Nam, S.W.; Pande, M.; Esmaeili, G. Medium-Voltage Current-Source Converter Drives for Marine Propulsion System Using a Dual-Winding Synchronous Machine. *IEEE Trans. Ind. Appl.* **2014**, *50*, 3971–3976. [CrossRef]
105. Moradisizkoohi, H.; Elsayad, N.; Mohammed, O.A. A Bipolar DC–DC Converter with Wide Voltage-Gain Range for Energy Storage Integration in Ship Power Systems. In Proceedings of the 2019 IEEE Electric Ship Technologies Symposium (ESTS), Washington, DC, USA, 14–16 August 2019; pp. 511–517.
106. Steinsland, V.; Kristensen, L.M.; Arghandeh, R.; Zhang, S. Design of Modular Multilevel Converters for the Shipnet in Medium Voltage DC All-Electric Ships. In Proceedings of the 2020 IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL), Aalborg, Denmark, 9–12 November 2020; pp. 1–8.
107. Bazzi, A.M.; Liu, Y.; Fay, D.S. Electric Machines and Energy Storage: Over a Century of Technologies in Electric and Hybrid Electric Vehicles. *IEEE Electrif. Mag.* **2018**, *6*, 49–53. [CrossRef]
108. Ehsani, M.; Singh, K.V.; Bansal, H.O.; Mehrjardi, R.T. State of the Art and Trends in Electric and Hybrid Electric Vehicles. *Proc. IEEE* **2021**, *109*, 967–984. [CrossRef]
109. Saponara, S.; Lee, C.H.; Wang, N.X.; Kirtley, J.L. Electric Drives and Power Chargers: Recent Solutions to Improve Performance and Energy Efficiency for Hybrid and Fully Electric Vehicles. *IEEE Veh. Technol. Mag.* **2020**, *15*, 73–83. [CrossRef]
110. Zhou, X.; Sheng, B.; Liu, W.; Chen, Y.; Wang, L.; Liu, Y.-F.; Sen, P.C. A High-Efficiency High-Power-Density On-Board Low-Voltage DC–DC Converter for Electric Vehicles Application. *IEEE Trans. Power Electron.* **2021**, *36*, 12781–12794. [CrossRef]
111. Elsayad, N.; Moradisizkoohi, H.; Mohammed, O.A. A Single-Switch Transformerless DC–DC Converter with Universal Input Voltage for Fuel Cell Vehicles: Analysis and Design. *IEEE Trans. Veh. Technol.* **2019**, *68*, 4537–4549. [CrossRef]
112. Janabi, A.; Wang, B. Switched-Capacitor Voltage Boost Converter for Electric and Hybrid Electric Vehicle Drives. *IEEE Trans. Power Electron.* **2019**, *35*, 5615–5624. [CrossRef]
113. Elsayad, N.; Moradisizkoohi, H.; Mohammed, O.A. A New Hybrid Structure of a Bidirectional DC–DC Converter with High Conversion Ratios for Electric Vehicles. *IEEE Trans. Veh. Technol.* **2019**, *69*, 194–206. [CrossRef]
114. Zhang, Y.; Gao, Y.; Zhou, L.; Sumner, M. A Switched-Capacitor Bidirectional DC–DC Converter with Wide Voltage Gain Range for Electric Vehicles With Hybrid Energy Sources. *IEEE Trans. Power Electron.* **2018**, *33*, 9459–9469. [CrossRef]
115. Gu, C.; Zheng, Z.; Xu, L.; Wang, K.; Li, Y. Modeling and Control of a Multiport Power Electronic Transformer (PET) for Electric Traction Applications. *IEEE Trans. Power Electron.* **2016**, *31*, 915–927. [CrossRef]
116. Ahrabi, R.R.; Ardi, H.; Elmi, M.; Ajami, A. A Novel Step-Up Multiinput DC–DC Converter for Hybrid Electric Vehicles Application. *IEEE Trans. Power Electron.* **2017**, *32*, 3549–3561. [CrossRef]
117. Saponara, S.; Tisserand, P.; Chassard, P.; My-Ton, D. DC/DC converter integrated architecture for 48V supplies in micro/mild hybrid vehicle electrical engine control module. In Proceedings of the 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), Florence, Italy, 7–10 June 2016; pp. 1–5.
118. Rivera, S.; Kouro, S.; Vazquez, S.; Goetz, S.M.; Lizana, R.; Romero-Cadaval, E. Electric Vehicle Charging Infrastructure: From Grid to Battery. *IEEE Ind. Electron. Mag.* **2021**, *15*, 37–51. [CrossRef]
119. Khaligh, A.; D'Antonio, M. Global Trends in High-Power On-Board Chargers for Electric Vehicles. *IEEE Trans. Veh. Technol.* **2019**, *68*, 3306–3324. [CrossRef]
120. Mehta, R.; Srinivasan, D.; Khambadkone, A.M.; Yang, J.; Trivedi, A. Smart Charging Strategies for Optimal Integration of Plug-In Electric Vehicles Within Existing Distribution System Infrastructure. *IEEE Trans. Smart Grid* **2018**, *9*, 299–312. [CrossRef]
121. Shahidehpour, M. Role of smart microgrid in a perfect power system. In Proceedings of the IEEE PES General Meeting, Minneapolis, MN, USA, 25–29 July 2010; p. 1.
122. Kroposki, B.; Lasseter, R.; Ise, T.; Morozumi, S.; Papathanassiou, S.; Hatziargyriou, N. Making microgrids work. *IEEE Power Energy Mag.* **2008**, *6*, 40–53. [CrossRef]
123. Wang, H.; Li, W.; Yue, Y.; Zhao, H. Distributed Economic Control for AC/DC Hybrid Microgrid. *Electronics* **2021**, *11*, 13. [CrossRef]

124. Eghtedarpour, N.; Farjah, E. Power Control and Management in a Hybrid AC/DC Microgrid. *IEEE Trans. Smart Grid* **2014**, *5*, 1494–1505. [CrossRef]
125. Patterson, B.T. DC, Come Home: DC Microgrids and the Birth of the "Enernet". *IEEE Power Energy Mag.* **2012**, *10*, 60–69. [CrossRef]
126. Lotfi, H.; Khodaei, A. AC versus DC Microgrid Planning. *IEEE Trans. Smart Grid* **2017**, *8*, 296–304. [CrossRef]
127. Salonen, P.; Kaipia, T.; Nuutinen, P.; Peltoniemi, P.; Partanen, J. An LVDC Distribution System Concept. In Proceedings of the Nordic Workshop on Power and Industrial Electronics, Espoo, Finland, 9–11 June 2008.
128. Lv, J.; Wang, X.; Wang, G.; Song, Y. Research on Control Strategy of Isolated DC Microgrid Based on SOC of Energy Storage System. *Electronics* **2021**, *10*, 834. [CrossRef]
129. Prabhakaran, P.; Agarwal, V. Novel Four-Port DC–DC Converter for Interfacing Solar PV–Fuel Cell Hybrid Sources With Low-Voltage Bipolar DC Microgrids. *IEEE J. Emerg. Sel. Top. Power Electron.* **2020**, *8*, 1330–1340. [CrossRef]
130. Tian, Q.; Zhou, G.; Leng, M.; Xu, G.; Fan, X. A Nonisolated Symmetric Bipolar Output Four-Port Converter Interfacing PV-Battery System. *IEEE Trans. Power Electron.* **2020**, *35*, 11731–11744. [CrossRef]
131. Kolahian, P.; Tarzamni, H.; Nikafrooz, A.; Hamzeh, M. Multi-port DC–DC converter for bipolar medium voltage DC micro-grid applications. *IET Power Electron.* **2019**, *12*, 1841–1849. [CrossRef]
132. Lee, J.-O.; Kim, Y.-S.; Moon, S.-I. Current Injection Power Flow Analysis and Optimal Generation Dispatch for Bipolar DC Microgrids. *IEEE Trans. Smart Grid* **2021**, *12*, 1918–1928. [CrossRef]
133. Alonso, J.M. *LED Lighting and Drivers*; Amazon KDP: Seattle, WA, USA, 2019.
134. Wang, Y.; Alonso, J.M.; Ruan, X. A Review of LED Drivers and Related Technologies. *IEEE Trans. Ind. Electron.* **2017**, *64*, 5754–5765. [CrossRef]
135. Almeida, P.; Camponogara, D.; Costa, M.D.; Braga, H.A.C.; Alonso, J.M. Matching LED and Driver Life Spans: A Review of Different Techniques. *IEEE Ind. Electron. Mag.* **2015**, *9*, 36–47. [CrossRef]
136. Cheng, C.-A.; Chang, C.-H.; Chung, T.-Y.; Yang, F.-L. Design and Implementation of a Single-Stage Driver for Supplying an LED Street-Lighting Module with Power Factor Corrections. *IEEE Trans. Power Electron.* **2014**, *30*, 956–966. [CrossRef]
137. Poorali, B.; Adib, E. Analysis of the Integrated SEPIC-Flyback Converter as a Single-Stage Single-Switch Power-Factor-Correction LED Driver. *IEEE Trans. Ind. Electron.* **2016**, *63*, 3562–3570. [CrossRef]
138. Zhang, F.; Ni, J.; Yu, Y. High Power Factor AC–DC LED Driver with Film Capacitors. *IEEE Trans. Power Electron.* **2012**, *28*, 4831–4840. [CrossRef]
139. Wang, Y.; Guan, Y.; Xu, D.; Wang, W. A CLCL Resonant DC/DC Converter for Two-Stage LED Driver System. *IEEE Trans. Ind. Electron.* **2016**, *63*, 2883–2891. [CrossRef]
140. Camponogara, D.; Vargas, D.R.; Costa, M.D.; Alonso, J.M.; Garcia, J.; Marchesan, T. Capacitance Reduction With An Optimized Converter Connection Applied to LED Drivers. *IEEE Trans. Ind. Electron.* **2014**, *62*, 184–192. [CrossRef]
141. Wang, Y.; Huang, J.; Wang, W.; Xu, D. A Single-Stage Single-Switch LED Driver Based on Class-E Converter. *IEEE Trans. Ind. Appl.* **2016**, *52*, 2618–2626. [CrossRef]
142. Pouladi, F.; Farzanehfard, H.; Adib, E. Battery operated soft switching resonant buck–boost LED driver with single magnetic element. *IEEE Trans. Power Electron* **2019**, *34*, 2704–2711. [CrossRef]
143. Mukherjee, S.; Yousefzadeh, V.; Sepahvand, A.; Doshi, M.; Maksimovic, D. A Two-Stage Automotive LED Driver with Multiple Outputs. *IEEE Trans. Power Electron.* **2021**, *36*, 14175–14186. [CrossRef]
144. Pinto, R.A.; Alonso, J.M.; Perdigao, M.S.; Da Silva, M.F.; Prado, R.N.D. A New Technique to Equalize Branch Currents in Multiarray LED Lamps Based on Variable Inductors. *IEEE Trans. Ind. Appl.* **2015**, *52*, 521–530. [CrossRef]
145. He, Q.; Luo, Q.; Huang, J.; Cao, C.; Sun, P. Analysis and design of modular open-loop LED driver with multi-channel output currents. *IET Power Electron.* **2019**, *12*, 1721–1729. [CrossRef]
146. He, Q.; Luo, Q.; Wei, Y.; Sun, P. A Variable Inductor Controlled Single-Stage AC/DC Converter for Modular Multi-Channel LED Driver. *IEEE Trans. Energy Convers.* **2021**, *36*, 2912–2923. [CrossRef]
147. Zhang, Y.; Rong, G.; Qu, S.; Song, Q.; Tang, X.; Zhang, Y. A High-Power LED Driver Based on Single Inductor-Multiple Output DC–DC Converter With High Dimming Frequency and Wide Dimming Range. *IEEE Trans. Power Electron.* **2020**, *35*, 8501–8511. [CrossRef]
148. Lee, J.; Kim, E.; Shin, K.G. Design and Management of Satellite Power Systems. In Proceedings of the 2013 IEEE 34th Real-Time Systems Symposium, Vancouver, BC, Canada, 3–6 December 2013; pp. 97–106.
149. Ali, A.; Mughal, M.R.; Ali, H.; Reyneri, L. Innovative power management, attitude determination and control tile for CubeSat standard NanoSatellites. *Acta Astronaut.* **2014**, *96*, 116–127. [CrossRef]
150. SMPS POWER SUPPLY for ATX COMPUTERS. Available online: https://www.smpspowersupply.com/power-supply.html (accessed on 1 April 2022).
151. Liu, C. Gain Top-Notch Efficiency for Your Desktop PSU. Industrial-Technical Articles-TI E2E Support Forums. 30 October 2017. Available online: https://e2e.ti.com/blogs_/b/industrial_strength/posts/gain-top-notch-efficiency-for-your-desktop-psu (accessed on 1 April 2022).
152. Dasgupta, A.; Potta, M.; Vaishaka, N.R.; Meghana, D.R.; Kendaganna, S.S. SoC Power Management Unit for IoI Applications. *Sci. Technol. Dev.* **2021**, *10*, 169.

153. Semiao, J.; Duran, E.; Litrán, S.P.; Ferrera, M.B. Multiple-Output Switched-Capacitor DC-DC Combination Converters for IoT Applications. In Proceedings of the 2020 IEEE 14th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Setúbal, Portugal, 8–10 July 2020; Volume 1, pp. 143–148.
154. Semião, J.; Cabral, R.; Santos, M.B.; Teixeira, I.C.; Teixeira, J.P. Performance Sensor for Reliable Operation. In Proceedings of the UAHCI: 12th International Conference on Universal Access in Human-Computer Interaction, Integrated in the 20th HCII, Las Vegas, NV, USA, 15–20 July 2018; pp. 347–365.
155. Semião, R.J.; Cabral, H.; Cavalaria, M.; Santos, I.C.; Teixeira, J.; Teixeira, P. Ultra-Low-Power Strategy for Reliable IoE Na-noscale Integrated Circuits. In *Harnessing the Internet of Everything (IoE) for Accelerated Innovation Opportunities*; IGI Global: Hershey, PA, USA, 2019.