POWER AND INDUSTRIAL ELECTRONICS

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Contents

Summary

Power electronics is intended as a solution for a better use of electrical energy, acting as an optimal "adaptor" between the various electrical production sources and the numerous electrical loads. Power electronics aim is to regulate and conditioning power flow under high efficiency levels, trying to minimize power consumption and trying to maximize power production. This chapter is intended to introduce what is power electronics, its operating principle, its construction and evolution, how it is implemented and where and when it is used. It gives a basic overview of related main topics, trying to give an overview of its wide and pluridisciplinary fields of interests. The first section is dedicated to the introduction of the basics and fundamentals, trying to give as much as possible the essentials of the discipline and the related techniques. The second section of the chapter addresses the control issues of power converters. The third section introduces the trends in power electronics with nowadays goals and expectations.

1. Power Electronics Principles and Specificities.

1.1. Introduction (Electrical Energy Conditioning at Highest Efficiency Levels)

Power Electronics aims are related to electrical power management and conditioning at the highest efficiency levels. Power management ranges from the Watt and the Volt up to few gigawatts and hundred of kilovolts. Low power, low voltage applications are related to microprocessor supplies, mobile phone recharge and power management, energy harvesting and low voltage lightning such as LED. As far as medium power is concerned, power electronics is widely used as switch mode power supplies to regulate voltages, or in association with motors and where it operates as drives in electrical mobility applications such as electric vehicles, trains and tramways, but also in the industry, anywhere torque or speed control is required. With the objective to optimize the power consumption, power electronics and motors are optimized to exhibit efficiencies in the range of 80% for medium power applications up to 95% in high power applications. In the upper power range, power electronics is found in HVDC or very high power system management where voltages and power are respectively in the range of hundreds of kV and MW.

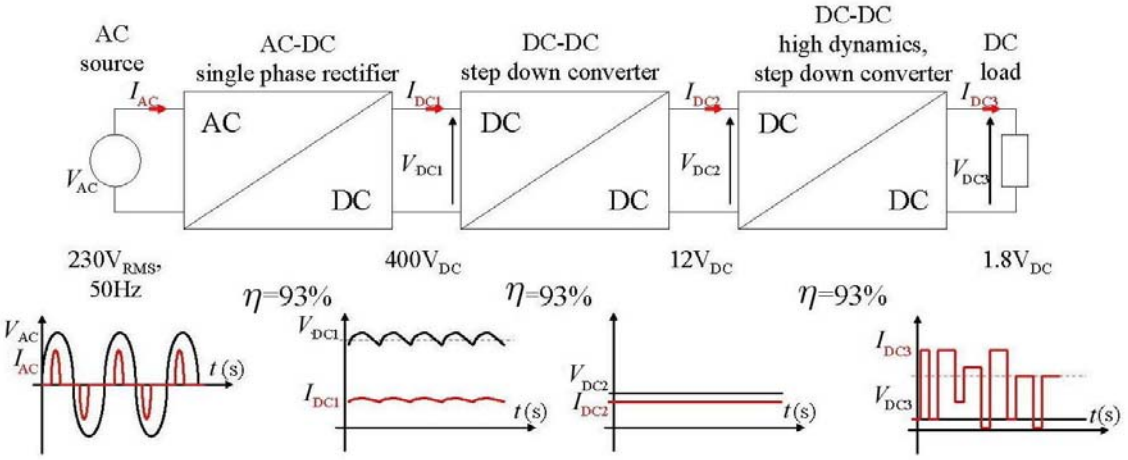

Figure 1. Block diagram of a micro processor power supply

If lots of energies have been wasted for a long time, it is today essential to manage power sources and loads in the best manner. Electricity is becoming the main energy vector and power electronics is becoming essential to adapt and optimize, in the best way, the electrical sources to the electrical loads. Indeed, sources can be DC, AC, 12, 24 or 48, 400… volt DC; 110, 240; 380AC single or three-phase and loads can be either AC, DC. Power electronics is providing an optimal coupling among them, each time adaptation is required. For example, to supply the microprocessor of a computer from the mains, the AC power is rectified and voltage supply reduced from 400V down to 12V before to being precisely regulated at about 5 or $3.3V_{DC}$. Three cascaded power electronics functions are necessary to adapt the $110/220V_{RMS}$, 60/50Hz AC voltages into a 3.3V DC with a global efficiency level, today above 70%. A block diagram is given as an example on Figure 1. Another example considers the connection of a solar plant to the mains. Considering a residential installation, three power electronics stages are required. The first one is implemented to optimize the photovoltaic production with a MPPT unit, the second one is used to boost the voltage up to 400V DC and the last one is necessary to convert the DC energy into a AC source thanks to a voltage source inverter. Power conversion can also be used in order to implement a high frequency galvanic isolation when needed. In this case, the power electronic isolated converter offers the opportunity to minimize the size of the magnetic transformer usually used to implement galvanic isolation.

In the first sections of this introduction chapter on power electronics, we are now going to focus on the operating principles and the basics of power electronics. Then, the power converter description will be addressed briefly in order to introduce the main elements required for the implementation of a power electronics converter. The last part of this section will provide a short overview of the main power electronics functions and associated converter topologies.

1.2. Operating Principles (Switching and Filtering)

In order to perform power management and conditioning, power electronics is based on switched mode operation. Therefore switching and filtering of voltages and currents are the basics of power electronic converters. Thanks to this operational principle, power electronics is able to regulate power flow and electrical quantities at high efficiency levels. This is obtained thanks to a succession of states allowing power flow or not and presenting low loss operating points: when power flows, minimum ON state losses are produced and when power flow is stopped, only very small leakage currents are created. Additional losses are generated to change from one state to the other. Nevertheless, this regulation approach is greatly more efficient than linear regulation strategies. This can be obtained with the help of power devices, active and passive, with great electrical characteristics. As far as active devices are concerned, power transistors or diodes with reduced ON state voltage drop, fast switching characteristics and minimized leakage current are searched for the best operational behaviors. Considering passive filtering devices such as inductors or capacitors, their parasitic effects must be minimized whereas their frequency range of optimal operation must be maximized.

The high frequency patterning of electrical quantities is carried out thanks to the commutation cell which is presented on Figure 2. Its operation is based on the association of active switches implemented between one or several voltage sources and current loads or vice versa. If one of them is a voltage type of source or load, the other one must be the opposite and vice versa. If necessary, passive components are added to the basic structure in order to change either the source or the load type and to create a complementary structure. Therefore, the basic structure, also called the commutation cell switches voltages on one side and currents on the other side. The Figure 2 below presents the elementary switching cell composed by a current source acting as a load, a voltage source and a pair of switches implemented and controlled to perform high frequency switching of the electrical quantities. Acting on the power devices thanks to the control of their ON state duty cycle, power flow can be set and regulated, allowing to pattern or transfer electrical energy as desired. For this to be done, power devices are controllable components with variable duty cycles.

For the correct operation of the switching cell, two conditions must be always fulfilled:

- the voltage source must never be shorted by the commutation cell
- a path for the current load must always be provided by the commutation cell

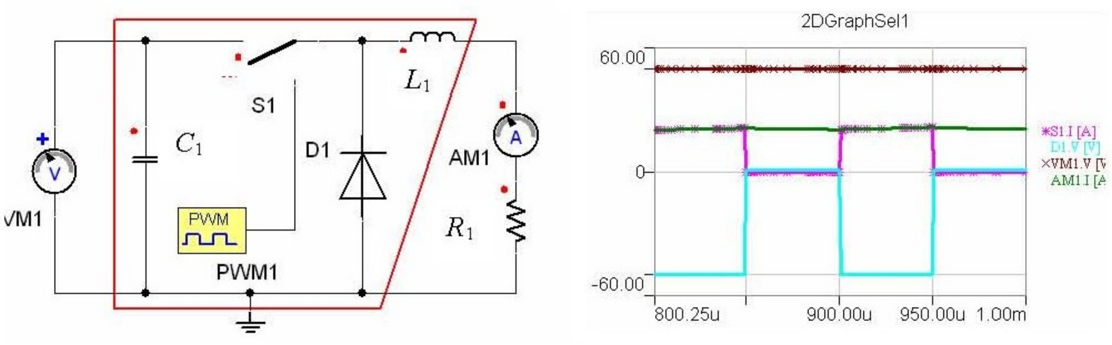

Figure 2. The basic switching cell made out and active switch, its corresponding free wheeling diode, with their filtering capacitor and inductor

As a result, control of the switching cell is carried out by controlling part of the active power devices and using self commutating devices to complement the operation of the controlled devices in the best manner. If not, voltage source short circuits will lead to undesirable current peaks and current load opening will lead to undesirable voltage spikes, both of them creating large electromagnetic disturbances and extra power losses and being able to bring the converter into failure mode or even destruction.

Once the electrical quantities are patterned thanks to high frequencies switching operation, they must be filtered. This is carried out thanks to passive devices. As it is well known, the higher will be the frequencies of the switched patterns, the smaller will have to be the passive filters. Nevertheless, high switching frequencies will introduce extra losses and one of the most important power electronics trade of will be to optimize size, weight and cost versus switching frequency and efficiency. Averaging and filtering electrical quantities are important in order to limit the propagation of electromagnetic disturbances through the cables and wires and spread undesired electromagnetic and electric fields anywhere in the environment of the converter. This is carried out with the help of passive filters which must be added at the entrance and at the output of the converters.

Basically, capacitors are located across DC voltage sources to filter current ripples and inductors are usually associated to account for the voltage filtering on current load side. The converter basic topology moves to the following one presented in Figure 3.

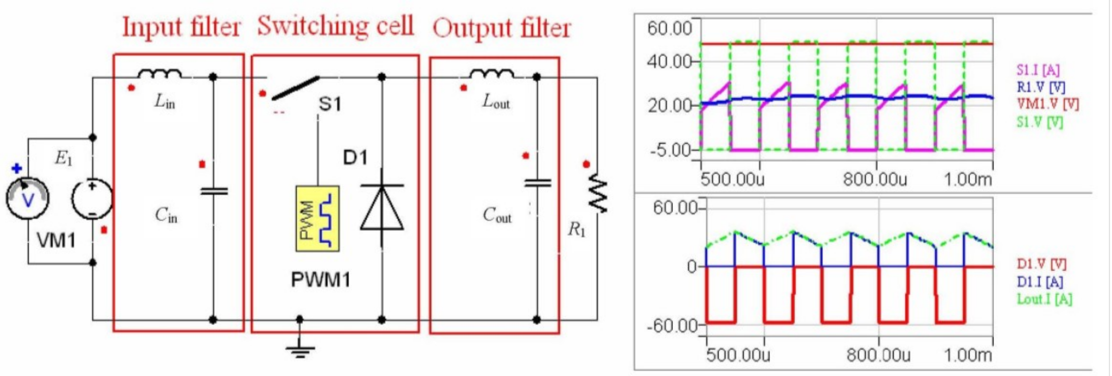

Figure 3. Basic DC to DC converter including switching cell input and output filter and general time domain waveforms.

Switching and filtering efficiently electrical quantities is not a simple task. It requires good components and adapted physical and electrical environments. After the introduction of the different families of converters and related operational principles, their main elements and physical environments are going to be shortly introduced. First of all, we will briefly present its physical environment, electrical and physical and then, a section of the chapter will be dedicated to the control of the converter, a part which is important since the main tasks of power converters are the regulation of power flow, voltage levels or even active current shaping.

1.3. Main Conversion Techniques and Topologies (DC/DC, AC/DC…)

They are many power conversion techniques and topologies and it is out of the scope of this chapter to present all of them, even most of them. Basically, it is important to keep in mind that power electronics is suited to adapt the source to the load. Since some sources are AC, others DC, and since it is the same for the loads, there are four basic conversion families: AC to AC, AC to DC, DC to DC and DC to AC. Functional analysis is carried out with the help of specialized time domain simulators such as Saber, Simplorer, Psim, Matlab-Simulink, Portunus or even Pspice. In this chapter, Simplorer softwave suite is used to compute time domain simulation results.

1.3.1. AC to DC rectification.

Natural rectification.

The simplest technique and one of the mostly used, is the AC to DC diode rectification. It is usually based on diodes power devices which are direct conducting current and reverse voltage blocking components. Since diodes are self commutated devices, the AC voltage is rectified thanks to the operational characteristics of the PN junction. The single phase, full bridge, diode rectifier is presented in Figure 4. As presented above, capacitors and inductors must be added to the rectifier to filter highly discontinuous voltage and current waveforms. Considering inductive output, the voltage and current patterns of the rectifier are presented Figure 4 on the right. When three phase or multiphase AC power supplies are considered, the single phase diode rectifier can be adapted for the three or more phase rectification.

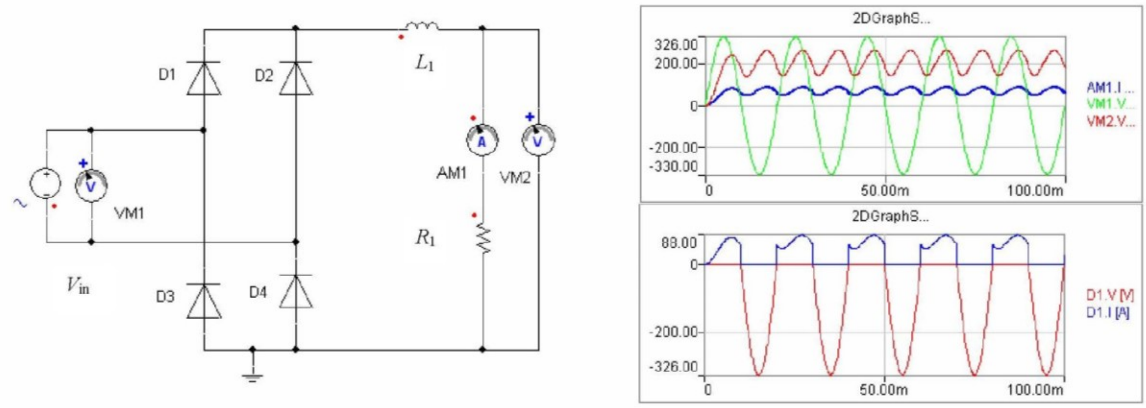

Figure 4. AC to DC single phase full diode rectifier operated in continuous mode and its corresponding time domain waveforms ($V_{\text{in}} = 240V_{\text{RMS}}, L_1 = 10\text{mH}, R_1 = 3\Omega$) .

Controlled rectification

The main limitations of diode rectifiers are at first the absence of control and second of all, the large low frequency harmonic disturbance generation. This can be seen on Figure 4 with the current waveform in diode D1, highly discontinuous. In order to overcome the first limitation, thyristor rectifiers can be implemented. Thyristors are controllable turn ON power semiconductors which means that their firing can be delayed but their blocking can not be controlled and occurs only once the current inside the power switch goes naturally to zero or when negative voltage is applied between its power terminals. Delaying thyristor firing gives the opportunity to chop part of the AC signal and to apply to the DC bus only a fraction of the rectified AC signal. This modifies the average voltage applied to the output filter and allows regulating the average value of the output DC voltage. Since input voltages are AC signals, thyristors can be periodically fired and then they naturally turn OFF as the AC voltage periodically passes from positive to negative levels.

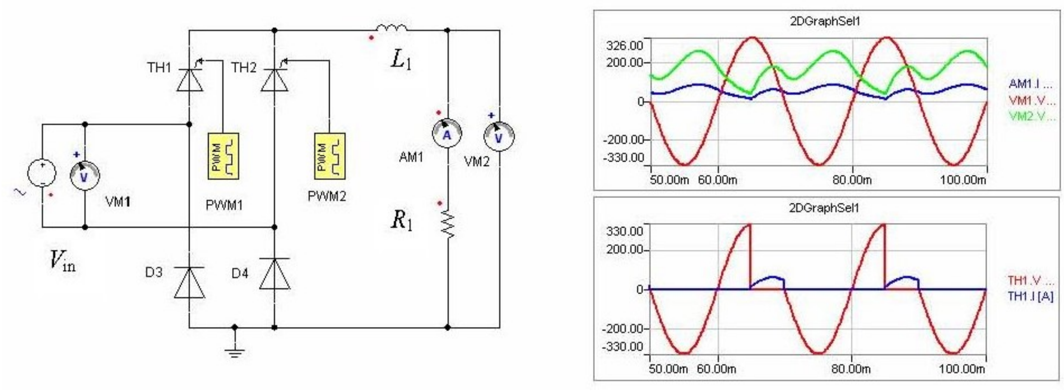

Figure 5. AC to DC single phase half bridge thyristor controlled rectifier operated in continuous mode (phase lag =90°, $L_1 = 10\text{mH}, R_1 = 3\Omega$) and its corresponding time domain waveforms.

If thyristors are able of output voltage regulation and power flow control, they are still great low frequency harmonic disturbance generators. Besides, they introduce consequent phase angle between input voltage and current which is responsible of undesired reactive power flow. Large filters must be added at the input side of the converter in order to limit the spread of low frequency harmonics. As a result improved topologies based on fully controllable power devices have been developed. These are able of input current shaping and output voltage regulation which in turns are very suitable for high quality rectification. Their main drawbacks are related to the increase of converter complexity, cost and the possible reduction of conversion efficiency.

1.3.2. DC to DC Chopper

DC to DC converters are usually simple structures called choppers. Their aim is to adapt the voltage level of the source with respect to the load requirements and to regulate the output voltage. The most basic converters can either increase or reduce the output voltage level or both and some topologies include a transformer in order to offer galvanic isolation or large step up and down conversion ratios.

Step down DC to DC converter also called buck chopper.

The topology of the step down DC to DC converter is given Figure 6. At the input, the commutation cell chops the input voltage at the switching frequency. This voltage pattern is then applied to the output inductor for filtering. In steady state, the average value of the chopped input voltage corresponds to the output voltage level once it is filtered thanks to the output inductor and capacitor. The converter can operate in continuous or discontinuous mode as a function of average and ripple current levels in the inductor. Continuous mode operation means that the current inside the filtering inductor never reaches zero over a switching period or it means that ripple current is smaller than half the value of the average current. In discontinuous mode, each switching period, the inductor current reaches zero for a fraction of the period. Bottom part of Figure 6 gives switching cell input and output voltage and current waveforms for continuous operation on the left and discontinuous operation on the right. .

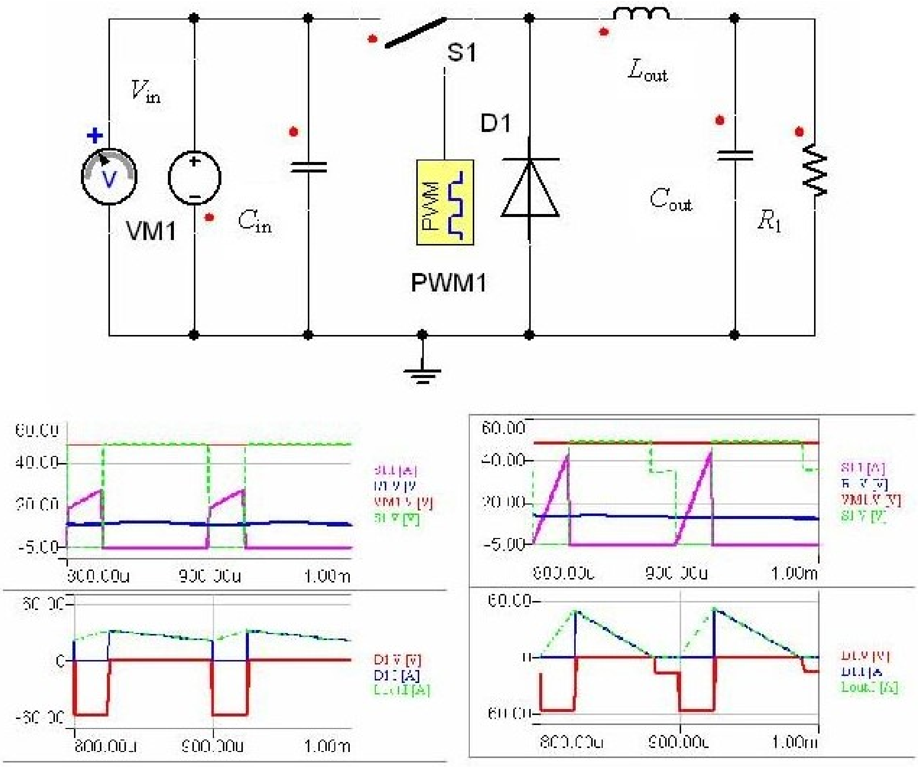

Figure 6. DC to DC Buck converter ($V_{\text{in}} = 48\text{V}, L_{\text{out}} = 20\mu\text{H}, C_{\text{out}} = 1\text{mF}, R_1 = 0.5\Omega, F_s = 10\text{kHz}$) operated in continuous ($\alpha = 0.5$) and discontinuous ($\alpha = 0.25$) modes and its corresponding time domain waveforms.

Eq. (1) gives the relation between V_{in} and V_{out} as a function of the duty cycle in continuous mode operation while Eq. (2) gives the relation in discontinuous mode operation. For the determination of all these equations, the basic principle is to consider that in steady state, average voltage across the inductor must be zero. Then, simple Kirchhoff relations can be derived to form the set of these general equations.

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \alpha \tag{1}$$

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{\alpha^2}{\alpha^2 + {2.I_{\text{o}}.L_{\text{out}}.F_{\text{s}}}\big/{V_{\text{in}}}} \tag{2}$$

This topology is non reversible since the current can only flow from the source to the load. It is also called unidirectional.

Step up converter also called boost chopper.

The topology of a step up DC to DC converter is given Figure 7. At the input, the commutation cell chops at the switching frequency the input current coming from the inductor, which is applied to the output capacitor for filtering. In a similar manner, the chopped output voltage is applied to the inductor. Since, in steady state operation, the average voltage across the inductor is zero, a simple relation can be derived between average V_{in} and V_{out} (see Eq. (3)). The converter can operate in continuous or discontinuous mode as a function of average and ripple current levels in the inductor. Bottom of Figure 7 gives switching cell input and output voltage and current waveforms for continuous operation on the left and discontinuous operation on the right. This topology is non reversible since the current can only flow from the source to the load.

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{1}{1-\alpha} \tag{3}$$

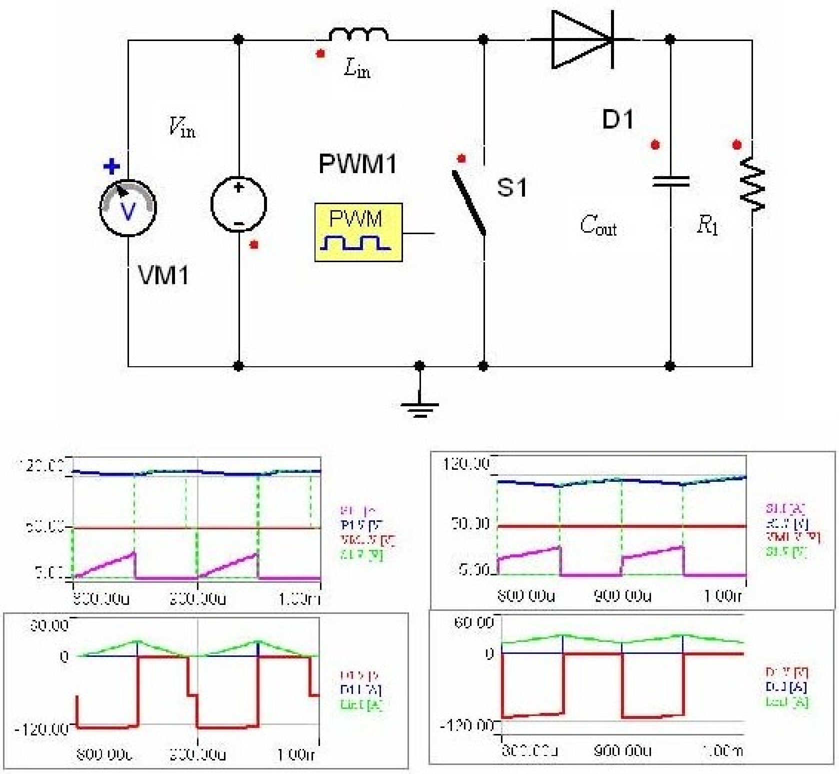

Figure 7. DC to DC boost converter ($V_{\text{in}} = 48\text{V}, C_{\text{out}} = 100\mu\text{F}, R_1 = 10\Omega, F_{\text{s}} = 10\text{kHz}$) operated in continuous ($L_{\text{in}} = 200\mu\text{H}$) and discontinuous ($L_{\text{in}} = 100\mu\text{H}$) modes and its corresponding time domain waveforms.

Bidirectionnal chopper.

The combination of the two previous topologies gives birth to the bidirectional chopper which includes two commutation cells and the corresponding filters as it is represented in Figure 8. The operating modes and switching waveforms presented in the previous paragraph are fully applicable. If the two individuals boost and buck choppers are unidirectional converters, this topology allows bidirectional current flow and can be used in both directions. This can be seen on Figure 8 where the current flowing in the inductor is in average positive over a switching period. However, within the switching period, it is positive and then negative and inductor current flows into the two switches S1 and S2, which are unidirectional components at different time locations. This topology is one of the most generic topologies in power electronics and we will see it again later in this chapter.

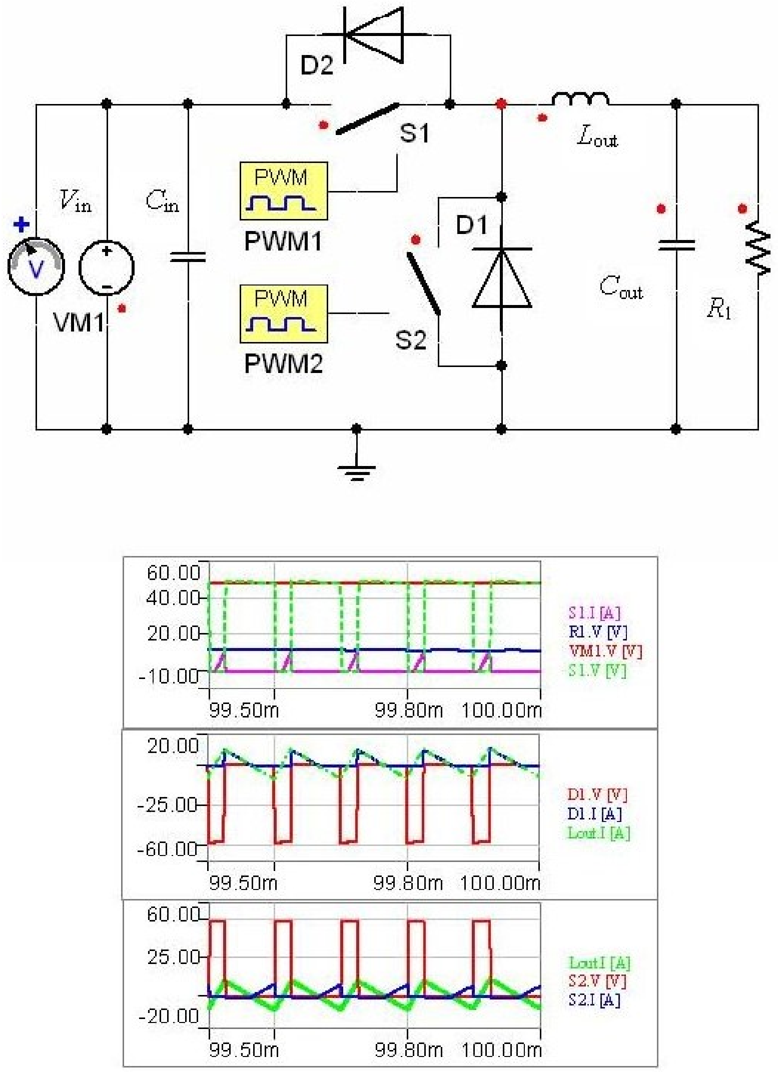

Figure 8. DC to DC buck-boost converter operated at α1=0.25 and its corresponding time domain waveforms ($V_{\text{in}} = 48\text{V}, L_{\text{out}} = 50\mu\text{H}, C\text{out} = 1\text{mF}, R_1 = 5\Omega, F_s = 10\text{kHz}$).

Particular DC to DC converters.

Apart from these basic and generic power converters, several particular but very well known topologies must be mentioned. The most popular is probably the Flyback converter that we are going to present in more details but other topologies such as the buck-boost converter, the forward topologies and others are also well known and they can be used preferably in some specific applications.

Considering the Flyback converter, it is interesting to notice that its topology is very simple with only one transistor, one diode and a coupled inductor as it can be seen on the Figure 9. While the converter includes a galvanic insulation with possibly a transformer ratio between primary and secondary sides, its operation is based only on one controllable power device making the converter friendly to use. As a matter of fact, specific ICs including the power switch and all surrounding components have been designed specifically for this topology. Limited in power range, the Flyback converter can nevertheless be used as a simple power factor correction converter when associated with a simple single phase diode rectifier. In a similar manner as for the buck and the boost chopper, the Flyback converter can operate in continuous or discontinuous mode. Basically, energy is stored periodically in the coupled inductor when the power switch is turned ON. Then, when the power switch is turned OFF, the energy is released on the secondary side through the free wheeling diode which naturally turns ON. The coupled inductor acts as a regular inductor with two windings and the energy is transferred from one to the other through the magnetic coupling and the energy stored and the magnetic loop. The absence of perfect coupling between the two winding introduces a leakage inductance which produces voltage spikes at primary switch turn OFF. This is visible on the time domain plots in Figure 9. This specific behavior becomes critical as the power transferred increases and it is one of the main limitations of this topology.

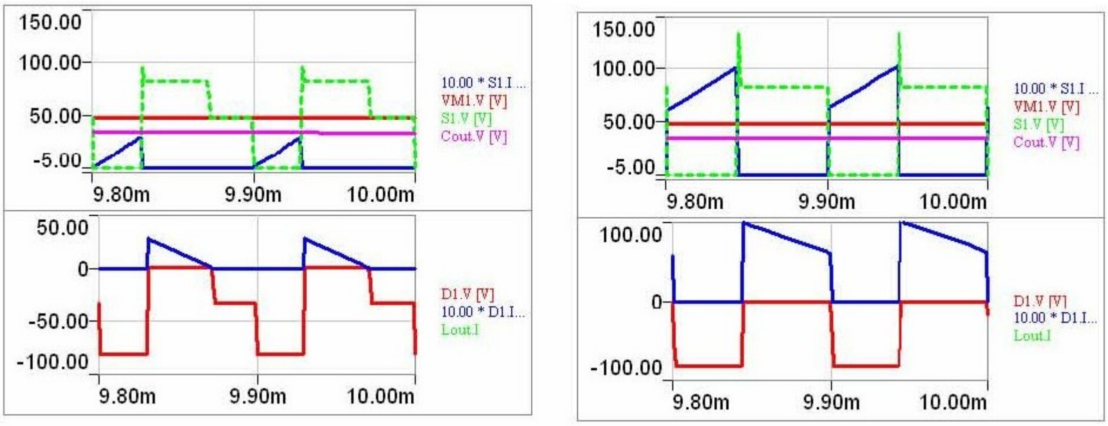

Figure 9. DC to DC Flyback converter ($V_{\text{in}} = 48\text{V}, L_1 = L_2 = 500\mu\text{H}, M = 0.995, C_{\text{out}} = 10\text{mF}, R = 5\Omega$) operated in discontinuous mode ($\alpha = 0.3$) and continuous mode ($\alpha = 0.44$) and its corresponding time domain waveforms.

1.3.3. DC to AC Inverters

Power electronics converters are widely used to convert the electrical energy from DC to AC. The converters are named inverters and they are used mainly in single and three applications for the creation of :

- HF AC signal applied to a HF transformer for step up or step down compact electrical transformation,
- low frequency 50 or 60Hz AC signal made from a HF chopping of the electrical quantities in order to connect a DC source to the power distribution network,

AC signal with variable low frequency fundamental made also from a HF chopping of the electrical quantities in order to drive an electrical motor (three phase brushless for example) for industry manufacture or electrical mobility (EV, trains, electrical scooters for example).

The inverters can single phase or three phases and can even be multiphase inverters. The AC signal is derived from the differential voltage created across the middle points of two inverter harms. Depending on the control command switching signals applied to the two harms, the DC chopped voltage can be applied positive or negative to the load allowing creating a HF AC signal. Figure 10 below presents the basic single phase inverter topology in which ideal switches are used to create a HF square wave AC signal. As it can be seen on the time domain plots, the resulting current is phase shifted as a function of the load (here it is a R-L circuit). Therefore and in this particular case, the switches must be able to withstand positive voltage and bidirectional current flow. Depending on the DC source and the load type, the inverter is called voltage inverter with bidirectional current switches or it is called current source inverter with bidirectional voltage switches. The former topology is rarely used in power electronics applications because most of power sources are voltage sources. In addition, bidirectional voltage switches are not generic devices and they require the use of several components in series connections making these types of topologies harder to design and to optimize from the efficiency point of view.

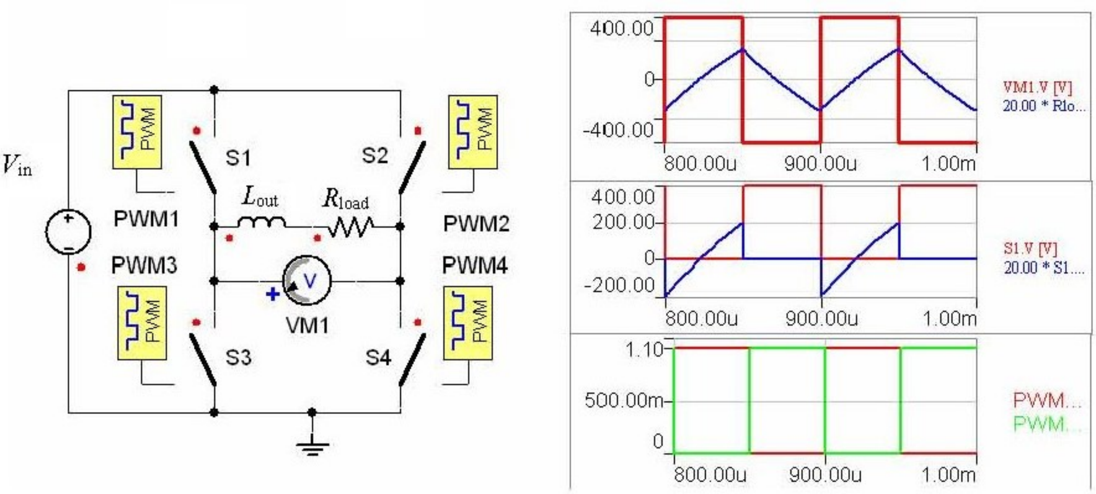

Figure 10. DC to AC single phase inverter operated fixed duty cycle for HF AC signal generation and its corresponding time domain waveforms ($V_{\mathrm{in}} = 400\mathrm{Vdc}, L_{\mathrm{out}} = 1\mathrm{mH}, R_{\mathrm{load}} = 10\Omega, F_{\mathrm{s}} = 10\mathrm{kHz}, \beta = 0.5$).

Below Figure 11 is given an example in which a similar voltage source inverter is used to create a low frequency AC current from high frequency chopping of a DC source. In order to perform this operation, specific Pulse Width Modulation (PWM) must be applied to each of the power switches in order to pattern the electrical quantities. As mentioned earlier, this is used to connect DC sources to the power network trying to minimize the introduction of low frequency harmonics that could disturb other sources connected nearby on the power network.

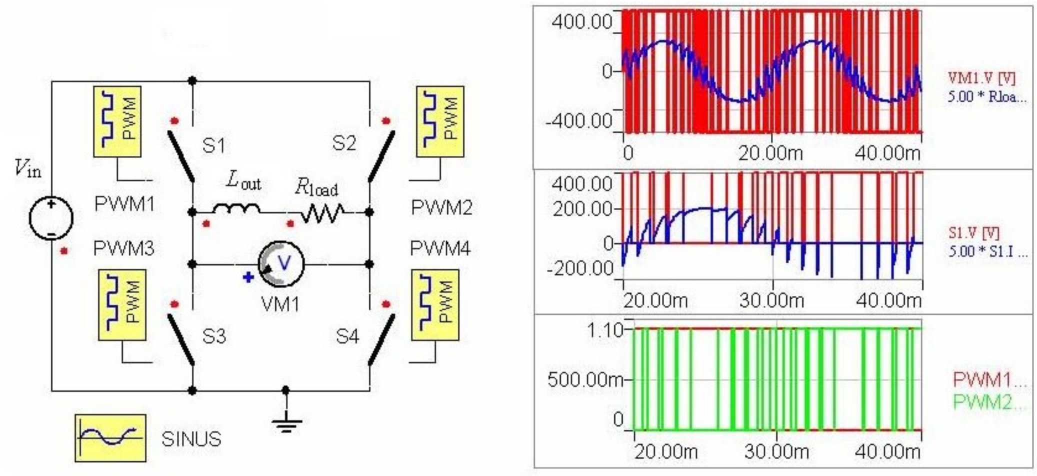

Figure 11. DC to AC single phase inverter operated under variable PWM for low frequency AC signal generation and its corresponding time domain waveforms ($V_{in} = 400\text{Vdc}, L_{out} = 1\text{mH}, R_{load} = 10\Omega, F_s = 10\text{kHz}, \alpha(t) = 0.5 + 0.5\sin(\omega.t)$ with $\omega = 2.\pi.50$).

In a similar manner, a third inverter harm can be added to this topology in order to create a three phase inverter able to drive the three phase motor into an Electric Vehicle for example. AC variable low frequencies are used to perform variable speed and torque as well as optimized converter plus motor efficiency. Indeed, if the three phase inverter is able to create sinusoidal waveforms, the machine torque is regular and besides the harmonics applied to the machine are reduced. This in turns limits harmonic losses and improves greatly global robustness and efficiency of the traction chain.

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Biographical Sketches

N. Rouger was born in Marseille, France, in 1981. He received the B.Eng. degree from Université Paris Sud, Orsay, and Ecole Normale Supérieure de Cachan, France in 2002. He received the M.Eng. degree (2005) and Ph.D. degree (2008) in electrical engineering from the Institut National Polytechnique de Grenoble, France. He was a post-doctoral researcher in the MiNa Group at the University of British Columbia (UBC, 2008-2009), where he worked on integrated optical systems. He is currently a research scientist at the French National Centre for Scientific Research (CNRS) and the Grenoble Electrical Engineering Lab. His main interests are integrated functions for power converters, novel optical functions and optoelectronics integration. Since 2006, he is author or coauthor for more than 30 peer reviewed international conference or journal papers.

Jean-Christophe Crebier earned his Bachelor degree in Electrical Engineering in 1995 from INP Grenoble, France. In 1999, he received his PhD in Power Electronics, EMC and power factor correction from LEG, INPG, France. In 1999 he was working as a Post-Doc student in CPES (Center for Power Electronics Systems), USA, doing research in system integration. In 2001, he is hired by CNRS (National Center for Scientific Research), France, as a full time researcher in power electronics. Today, he is at Grenoble Electrical Engineering Lab, his main research fields are system and functional, hybrid and monolithic integration and packaging for medium to high voltage power active devices. Applications of is work are related to the management of multicell systems such as PV, batteries and distributed systems. He as coauthored more than 80 peer reviewed international conference or journal papers