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Hybrid Control of DC-DC Power Converters

Ilse Cervantes*, Francisco J. Perez-Pinal† and Angelica Mendoza-Torres*
*Applied Mathematics Division. Institute for Scientific and
Technological Research of San Luis Potosi (IPICYT)
†National Polytechnic Institute, IPN
Mexico

1. Introduction. Review of Renewable Energy

In recent years, there has been an increasing interest in applying renewable energy (RE) in **electricity generation and transportation.** In accordance to Enerdata, an independent energy consulting and information services company (Enerdata, 2008a), the global electricity needs in 2007 were closed to 19,900 TWh (almost 40 % of the overall energy consumption), where just 18 % of the total electricity production was coped by some source of RE. Additionally, it is estimated that the electricity demand will grow up to 60 % of the worldwide energy in 2040 (Enerdata, 2008b). This means that, in order to increase energy production almost 50 % in 30 years, some energy generation and distribution problems must be solved to obtain feasible and reliable applications. For example, the concept of distributed generation (DG) has to be revisited in view of the existence of multiple and highly disperse energy sources; as well as further investigation about High Voltage Direct Current (HVDC) energy transmission, Flexible AC Transmission Systems (FACTS) and Micro grids. Furthermore, power electronics can account for, as much as 30–40 % of a distributed generation facility cost (ECPE et al., 2007). This is due to the fact that most utility scale power electronics are custom designed, which generates an expensive installation. That is, there are also important concerns such as price reduction and system reliability that need further investigation.

On the other hand, *transportation* demands about 28 % of the worldwide energy and it is expected an increment up to 40% in 2040 (International Energy Outlook 2008). In order to reduce this tendency, during the past three decades, a rapid development of more efficient vehicles has been performed. Those efforts have been focused on two main areas: i) the development of high efficient and high-density power converters, and ii) the improvement of robust and flexible modern control techniques. However, in spite of some advances, there are still open questions regarding the achievement of three of the most important issues in RE applications: reliability, efficiency, and cost.

1.1 DC-DC Power converters in Renewable Energy

Power converters (PC) and in particular Direct Current to Direct Current (DC-DC) converters play an important role in RE since they serve as a link stage for energy conditioning (usually step-up); and they can be used in low and high power converters such as HVDC, FactS, Microgrids, Fuel cell generator, Fuel cell vehicles, Photo voltaic Panels (PVP) and hybrid generation systems[*].

The connection of renewable energy sources to power grids is not possible without power electronics, *i.e.* DC-DC converters optimize the efficiency of solar panels, rectifiers and inverters which are needed in wind generators. Automotive applications such as electric and hybrid drive trains are only possible with efficient and intelligent power electronics. X-by-wire concepts operated by power converters may lead to power saving of more than 20% (ECPE et al., 2007). Different topologies of PC are used in RE, the final decision to use one or another is based on the range of the final application, the kind of RE source, and if the system requires mandatory isolation or not (this specification varies upon country regulations). The most used topologies of DC-DC power converters are,

1. Simple buck and boost converters.
2. Interleaved and cascaded converters.
3. Synchronous converters.
4. High Frequency (HF) transformers using an isolated push-pull boost converters.
5. Full-bridge isolated converters.
6. Single-Inductor push-pull converters (SIC).
7. Double-Inductor push-pull converters (SIC).
8. Full-bridge converters.
9. Self-commutated inverters using thyristors.

On the other hand, at the present time, the new directions in the design of DC-DC in RE deals with the following topics (ECPE *et al*., 2007)

1. System cost reduction.
2. New interconnection technologies for ultra-high power density systems and high temperature electronics.
3. Advanced thermal management; high temperature magnetics, capacitors, sensors, control ICs.
4. In lighting smart and simple dimming concepts; smart control of street lighting; high efficient.
5. Light sources (LED/OLED) and their power electronic drivers.
6. Higher level of integration e.g. for more compact energy saving lamps.
7. New topologies for photo voltaic (PV) solar converters focused on more efficient PV solar cells.
8. Load management by power electronics in distributed energy generation networks.
9. Zero-defect design and improved system reliability including fault-tolerant systems.
10. Digital power conversion and smart power management.

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[*] Here the term *"hybrid"* refers to the use of two different energy sources.

It is in the solution of the problems related to these new tendencies in power electronics and renewable energy, that control plays a crucial role. Robust and flexible controllers are capable to guarantee efficient energy transmission and processing, are able compensate some design limitations and to reduce operation and maintenance cost. Furthermore, they can be used also for increasing reliability and safety of operation.

In the past, traditional control schemes as direct duty ratio control (Mohan *et al.,* 1989), (Rashid, 1988), (Erickson & Maksimovic, 2001), voltage and current programming control (Capel *et al.*, 1978), (Redl & Sokal, 1985), (Middlebrook R., 1985), have been applied in the solution of some of the main operation concerns. However they are based on averaged models (Middlebrook & Cuk, 1976), (Erickson *et al.*, 1982).

Basically, an averaged model assumes high switching frequency, giving as a result continuous time models and controllers. Nevertheless, it has been shown that this procedure has some limitations in the exact estimation of the DC output voltage and harmonics components; in addition, averaged models fail to predict sub-harmonic and chaotic oscillations under some control techniques (Deane, 1990). In order to analyze this erratic behavior, it is used sometimes discrete-time maps, which relate state variables at every switching period. The main limitation of digital techniques is that obtained models are nonlinear with respect to the duty cycle (Kassakian *et al.,* 1991); this fact makes more complicated the control design task.

The highly need of flexibility and more robust controllers in areas such as motor controllers, renewable energy, and power electronics; has opened the niche to apply and develop a new family of more active control methods that are able to work in operation regions rather than in a single operation point. Control methodologies such as: fuzzy, linear quadratic, passivity based and pulse adjustment among others, are good examples of complex controllers usually designed to fulfill strict standards of performance. However, in spite of the advantages in terms of robustness and good performance, their applicability is limited by the complexity of their design and implementation.

That is, in spite of the last efforts of research in the field, there is still a truly need to develop new families of controllers, due to the highly demand environments of modern power electronics applications and the advances in digital processors. Therefore, hybrid-time controller has received a lot of attention due to its practical feasibility to achieve a high performance and flexibility as well as, natural digital implementation in signal processors.

There are several types of hybrid controllers that has been applied to power converters; but perhaps the most commonly found in the literature, in view of the switching nature of the converters, are the piece-wise continuous controllers. In this type of control, system commute by virtue of a discrete event, that is product of the satisfaction of a prescribed set of conditions. Due to this fact, the control is also known as switched (Liberzon, 2003), (Li *et. al*, 2005), (Sun & Ge, 2005) or boundary control (Ting-Ting & Chung, 2008), (Leung & Chung, 2004), (Quaicoe & Iqbal, 2008).

Most switched control algorithms are easy to implement with respect to other nonlinear methodologies and they have advantage that the switching criteria can be expressed by very intuitive (design) restrictions, *i.e.* maximum current switching criterion, maximum ripple switching criterion, etc. Moreover, some of these controllers have high flexibility and adaptability in a large set of operating conditions, including changes on power load and voltage source or under continuous and discontinuous operation mode. Furthermore, since their design is not based on an averaged behaviour of the converter they are suitable to compensate a wide range of nonlinear phenomena.

Following this trend in the development of flexible controllers, the main purpose of this chapter is to describe some of the most significant results regarding hybrid controllers used in DC-DC converters; to discuss their stability properties and their limitations, as well as their applicability and relevance.

The chapter begins (Section 2) with an introduction to hybrid systems (HS). Different definitions found in the literature are discussed and special attention is paid to switched and impulsive systems. Moreover, a detailed description of the switched characteristics is given. In Section 3, a description of the tools used to analyse stability of HS is performed, emphasis is made about the class of stability result obtained from each methodology. A general description of most relevant hybrid controllers proposed in the literature is given in Section 4; it is stated that the proposed methodologies can be classified in two different kinds and particularities of each one are discussed. General aspects as robustness and implementing advantages and drawbacks are discussed. Finally some concluding remarks are given (Section 5).

2. Hybrid Systems Description

The term hybrid denotes a mixed origin. In physics a hybrid electromagnetic wave is one having components of both electric and magnetic field vectors in the direction of propagation. A hybrid vehicle is one having two or more energy sources; for example electric and chemical (combustion).

Regarding dynamic systems, there is not a universal definition of hybrid systems, but most authors coincide that ***in such systems, it exists interaction and coexistence of two kinds of dynamics: continuous and discrete*** (Liberzon, 2003), (Li *et al.*, 2005) (Goebel *et al.*, 2009). In view of this idea, most real-time controlled systems can be called hybrid; for example, an electric motor or a generator controlled by a Digital Signal Processor (DSP). In this case, the continuous dynamics is given by the machine, which by the process of sampling and data processing is controlled at discrete times. Moreover, notice that the definition above can describe interaction between finite or infinite dimensional dynamic systems with discrete events or dynamics. It can be considered as hybrid, continuous systems manipulated by piece continuous controls as supervisory control, sliding mode control and gain scheduling control for example. On the other hand, controllers as current peak control (CPC) are also a good example of hybrid controllers.

Deriving a general model for hybrid systems (HS) may be quite complicated, since various types of interactions between discrete and continuous dynamics may exist. Models found in the literature vary mainly depending upon the type of HS studied and the way the author conceives such interaction. Among hybrid systems, **switched and impulsive systems** are probably the most studied and since the discrete interaction is well defined, general models can be defined.

At this point, it is worthy noticing that some authors (Sun & Ge, 2005) consider also as impulsive and switched, classes of systems that commute between discrete dynamics. That is, no continuous dynamics exists and the overall system is constituted only by different discrete behaviours. Such systems are not hybrid in the sense discussed here, even if they are truly switching or impulsive. In this way, the terms switched and impulsive cannot be taken as synonymous of hybrid.

In **Impulsive systems (IS)** the members of a family of continuous systems (**subsystems or modes**) interact between them by virtue of a discrete event or condition. Such discrete interaction changes the dynamics in such a way that the system trajectories are discontinuous. In Fig. 1 it is possible to observe the time evolution of a second order impulsive system (i.e. $x = [x_1,x_2]^T$) as well as the system trajectories in the phase plane. Observe that in a given time, the trajectories reset to a given new value. This is, the discrete interaction induces a jump on systems trajectories making the initial condition at the $k+1$ subsystem be different from the final condition of the k subsystem. In this way, the trajectories of an impulsive system are only piecewise continuous.

Examples of impulsive systems are those describing the population of insects and other living species in which, grow rate varies impulsively *(i.e.* birth rate may lead to instantaneously population differences). Some chemical reactors with fast continuous dynamics behave as IS if the reactive is fed impulsively. Some financial systems behave also impulsively. Some other examples can be found in (Yang, 2001 a,b), (Li *et al.*, 2005), (Sun & Ge, 2005).

Impulsive systems are almost inexistent in DC-DC power electronics, even if perturbations are usually modelled as impulsive. The reason resides in the fact that in most cases, there exist continuous dynamics in such applications that serve as a filter (slow dynamics), making continuous every trajectory subjected to impulsive phenomena. For example, the RC tank in DC-DC converters serves as a low pass filter to reduce voltage ripple originated by the (impulsive) transition of the switch. Models of impulsive systems can be found in (Yang, 2001a) and (Yang, 2001b).

2.1 Switching Systems

Since switching systems are of special interest in power electronics, this subsection will be devoted to gain insight in the most common description used to describe such systems. We begin by saying that switching systems are constituted mainly of two parts: i) The family of continuous subsystems or modes and, ii) the switching law. As in the case of hybrid impulsive systems; in switched systems, the members of a family of continuous systems (**subsystems or modes**) interact between them by virtue of a discrete event or condition.

Such discrete interaction changes the dynamics in such a way that the system trajectories **remain continuous** (see Fig 2). Good examples of switched systems are the piecewise linear systems as the following:

$$\dot{x} = A_m x + B_m u_m \quad m \in \{1,\dots p\} \tag{1}$$

where $\boldsymbol{x} \in \Re^n$ is the state variable vector, $\boldsymbol{u_i}$ is the input vector (possible controlled) and matrices $\boldsymbol{A_m}$ and $\boldsymbol{B_m}$ have suitable dimensions. The family of continuous time systems (1) is subjected to a **discrete time event *m*** that defines the current election of the active subsystem ***i***, that is, *m* is an index that stands for the switch between stages. Such an index can be described by algebraic equations, difference equations or by a set of restrictions or conditions depending possible on systems states and/ or time. The expression that defines *m* at every instant is called **switching law**. In most cases, such an expression is a single valued function at every time (i.e. uniquely defined at every time).

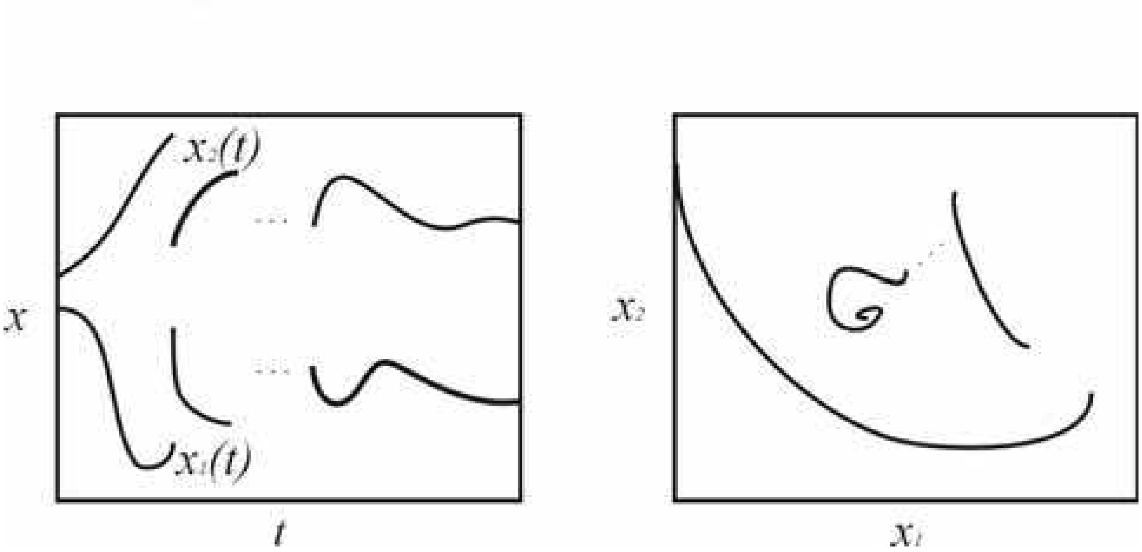

Fig. 1. Typical evolution of a impulsive system (left) time evolution, (right) phase portrait.

The switching law can be state dependent and/or time dependent (Liberzon, 2003). Usually, the switching law is given by a set of prescribed conditions leading to a division of the state space. As time evolves, the switching law generates a sequence of subsystems active for a certain time, that is

$$\sigma = \{(\theta_0, i_0), (\theta_1, i_1) \dots (\theta_k, i_k)\} \tag{2}$$

where θ_k stands for the residence time in mode or subsystem i_k for $i_k = 1,2 \dots p$ and $k = 1,2,3\dots$ Such a sequence is called **switching sequence** and it is used some times instead of the switching law to study the stability of the overall hybrid system (Xu, 2004), (Xu *et al.*, 2007).

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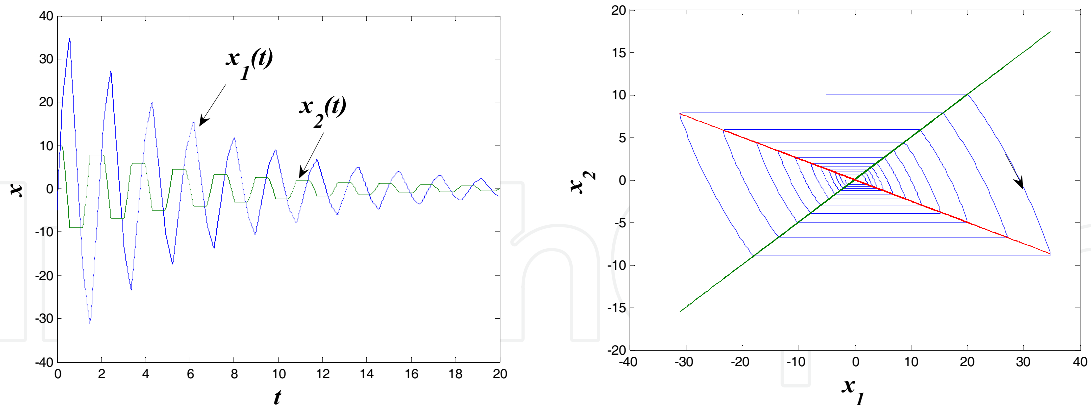

Fig. 2. Typical evolution of a switched system (left) time evolution, (right) phase portrait.

In general, switching systems can be described as:

$$\dot{x} = f_i(x,t,u) \quad i \in \{1,\dots p\} \tag{3}$$

where $\boldsymbol{x} \in \Re^n$ is the state variable vector and $\boldsymbol{u}$ is the input vector (possible controlled). On the other hand, the switching law is sometimes described as a piece-wise continuous function that in a general case depends on system states, time and the input vector as follows:

$$i(l+) = g(x(t), i(l), u(t), t) \tag{4}$$

where $i(l+) = i(l+1)$. Eq. (4) is not the only way of representing a switching law; a combination of a **switching criterion** and **mode assignment criterion** is also used. The switching criterion or **switching conditions** are usually formulated only upon a part of the state space (output) in the form of hyper-surfaces that are called **switching surfaces**. It is required that every region in the entire state space has assigned an active subsystem in order to have a well defined system (Liberzon, 2003). Once the system hits a pre-defined surface (Eq. (5)), the *mode assignment criterion* (Eq. (6)), decides based on the function ψ, which system is the next to be active in view of the current subsystem (Li *et al.*, 2005). In such a case, the switching law can be described as follows:

$$S = S(x(t), i(t), t) = 0 \tag{5}$$

$$i(l+) = \psi(i(l)) \tag{6}$$

Notice that in general, **a finite set of surfaces instead a single surface may be used to describe the switching criterion**. In this case, the state space is divided in a finite number of regions and the possible combinations of active subsystems can increase dramatically. It is worthy to notice that hybrid switched control can be seen as a generalization of sliding mode control. This last is a switching control that uses a single switching surface along with a mode assignment criterion that chooses only between two options (Barnejee & Vergese, 2001).

Notice that in Eqs. (3)-(4), there exists the possibility of using different *control* inputs in a switching system. That is, a control problem in a general switched system can be formulated as one of stabilization or tracking, using three kinds of control inputs: The switching criterion, the mode assignment criterion and the continuous control input u. To be precise, using hybrid control one can increase the number of degrees of freedom that can be used to accomplish a control objective.

There exist in the control literature, various authors leading with these control problems (Lin, 2008), (Lazar, *et al.*, 2006), (Tsinias, (2007), (Zhai & Michel, 2002), (Zhai & Michel, 2003), (Rodrigues & How, 2003). However much of this literature cannot be applied directly to power electronics due that the input u cannot be manipulated (consider converter description as in (3), (4)). In other words, the vector fields among which the converter is evolving between switches cannot be manipulated; hence, properties as stability and equilibrium points can not be modified. In view to this fact, a relevant problem in switching control applied to power electronics is how to choose the switching surfaces (possible moving surfaces) in order to stabilize the overall system. Observe that, given a mode assignment criterion, the manipulation of surfaces can be seen as equivalent to choose a set of switching times. Since in DC-DC Power electronics, the control actions are applied only at some instants (not necessarily synchronous), sometimes these systems are called ***partially open-loop systems***.

Another option of describing switched systems can be performed using **Hybrid Automata**. A hybrid automaton (HA) is a mathematical model, borrowed from computation theory, used to describe processes consisting in discrete state transition and continuous evolution. In this way, HA can be seen as a finite state machine that uses differential equations; in which the model is composed of a finite number of states, transitions between states and actions (differential equations) (Henzinger, 1995), (Henzinger, 1996), (Rajeev *et al.*, 1996).

A hybrid automaton H is composed by a finite set of variables ($X = \{x_1, x_{2 \ldots} x_n\}$), that describe the system during continuous evolution ($X = \{x_1, x_{2 \ldots} x_n\}$) and during discrete transitions ($X' = \{x'_1, x'_{2 \ldots} x'_n\}$). The system dynamics is represented by a multi-directed graph called a control graph (V,E). The vertices V are called **control modes**. The edges E are called **control switches or guards**. By virtue of a **jump or switch condition** it is assigned to each control switch $e \in E$ a given consequence which is detonated by an event.

In mathematics literature, the description of switched system by means of differential inclusions is common; however, in power electronics literature is rarely found. The interested reader is referred to (Filipov, 1998) for detailed description of this modelling tool.

2.2 Examples in DC_DC Power converters

In order to illustrate the modelling techniques mentioned above, the case of a conventional boost converter is used as a benchmark. In this way, the piece-wise continuous equations describing the converter dynamics are given by Eq (1) where $x = [i_L, v_c] \in \Re^2$ is the state vector constituted by the inductor current and the output voltage, $u \in \Re^2$ is the input vector that account for the translation due to the input voltage source. If the converter is working under continuous conduction mode (CCM) the number of modes or subsystems is $p = 2$ with

$$A_1 = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix} \quad and \quad B_1 = \begin{bmatrix} \frac{E}{L} \\ 0 \end{bmatrix} \quad for\ m{=}1 \tag{7}$$

$$A_2 = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \quad and \quad B_2 = \begin{bmatrix} \frac{E}{L} \\ 0 \end{bmatrix} \quad for\ m{=}2$$

where E is the voltage input, L is the inductance, C the capacitance and R the load resistance. If the converter is working under discontinuous conduction mode (DCM) the number of modes or subsystems is $p = 3$ with $m = 1$ and $m = 2$ given as in Eq. (7) and

$$A_3 = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix} \quad and \quad B_3 = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad for\ m{=}3 \tag{8}$$

The description of the switching law will depend if the converter is open or closed loop and on the switching regime used. If a driven signal of frequency $f = 1/T$ is used, the switching law can be described as follows for a converter operating in CCM:

$$i(t+) = \begin{cases} 1 & if \quad 0 \le \mathrm{mod}(t,T) < \delta T \\ 2 & if \quad \delta T \le \mathrm{mod}(t,T) < T \end{cases} \tag{9}$$

where the function $mod(a,b)$ stands for the remainder of the division of a/b, and δ is the duty cycle. For the converter in DCM the switching law is given by

$$i(t+) = \begin{cases} 1 & if \quad 0 \le \mathrm{mod}(t,T) < \delta T \\ 2 & if \quad \delta T \le \mathrm{mod}(t,T) < T_2 \ \ and \ \ \mathrm{mod}(t,T) > \delta T \\ 3 & if \quad T_2 \le \mathrm{mod}(t,T) < T \ \ and \ \ \mathrm{mod}(t,T) > \delta T \end{cases} \tag{10}$$

where T-T_2 stands for the time length that the inductor has zero current.

On the other hand, the description of the converter in both CCM and DCM using hybrid automaton can be observed in the control graph shown in Fig. 3, which is a reproduction of Figure 3 in (Sreekumar & Agarwal, 2008), where the inductor currents rising phase is defined with σ_1†, the falling phase with σ_2 and zero phase with σ_3. The transition between stages (σ) is defined by the guards in Table 1. In Fig. 3, q are the discrete states, x are the continuous states, $I_{1,2,3}$ are invariant sets and G are the guards.

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† $m = 1$ in Eq. (7)

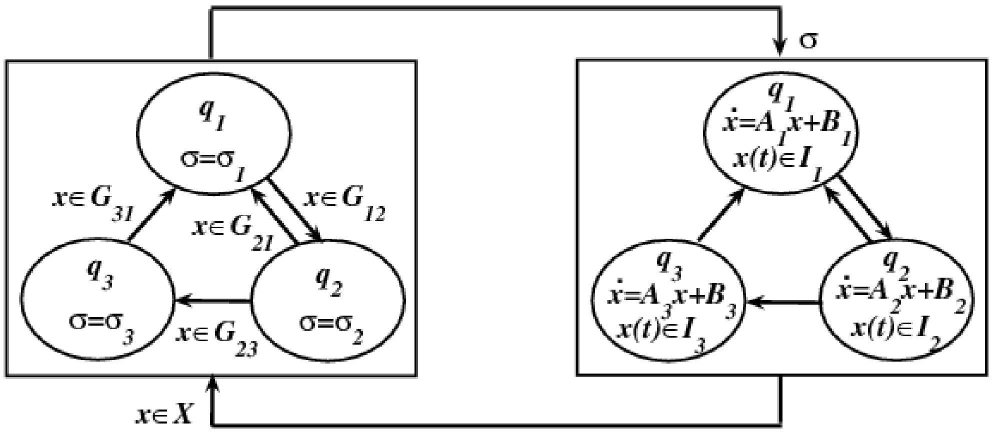

Fig. 3. Hybrid description of a conventional boost converter under CCM and DCM (Sreekumar & Agarwal, 2008).

where:

G_{12}	$0<mod(T,t)\leq\delta T$	G_{23}	$\delta T <mod(T,t) \leq T_2$ and $t>\delta T$
G_{21}	$\delta T <mod(T,t) \leq T$	G_{31}	$T_2<mod(T,t) \leq T$ and $t>\delta T$

Table 1. Guard description of Fig. 3.

Notice that under CCM the active guards are G_{12} and G_{21}. Moreover, under DCM the switching can only be performed unidirectionally; that is $G_{12} \rightarrow G_{23} \rightarrow G_{31} \rightarrow G_{12} \rightarrow\ldots$ (Senesky *et al.*, 2003).

2.3 Control Problems in DC-DC Power Converters. Hybrid Control Solution

This subsection is devoted to describe the control problems in DC-DC power converters that are best suitable to be addressed with hybrid control, as well as describe some advantages of this tool.

From conceiving the system as piecewise continuous one or by using a combination of classical averaged models with discrete transitions or discrete controllers is that hybrid control arises in power electronics. That is, the system under study has open and/or closed loop hybrid description and, as stated before, its mathematical description can be very vast due to the variety of the possible interactions.

In order to describe the control problems in DC-DC power converters, it is worthy noticing that the main performance concerns in these applications are:

a. **Voltage regulation.** Voltage regulation of a constant desired reference is the primary objective of control and a basic performance requirement that has to be fulfilled in every real life application.
b. **Current limitation**. For safety reasons and to endure converter components life, it is required a current limitation in the circuit.

c. **Maximum current and voltage ripple**. Between 10-20% of the reference current(s) signal(s) and about 1-2% of the desired voltage.

Furthermore, it is highly desirable that the control is designed to fulfil the following requirements:

- **Adaptability or Applicability to CCM or DCM regimes**. Flexibility to operate in both modes, mainly due to possible perturbations in the parameters and to face near- to- cero load resistance conditions.
- **Robustness against model uncertainty and disturbances**. For example, disturbances in load resistance, input voltage and voltage reference. That is, it is desirable that the converter operates in regions of the state space, rather than in a small neighborhood about the nominal point.
- **Output feedback**. It is desirable that the control uses only a subset of the state vector for feedback purposes (output feedback). This is of particular interest in high order converters, where measuring all signals becomes prohibitive due to the high costs.
- **Fixed Switched Frequency.** Among the main reasons to operate at fixed frequency conditions are: i) the possibility that harmonic content arise in varying frequency operation, which in turn may induce a poor steady-state performance and ii) It is easiest to implement fixed frequency controllers.

An advantage of hybrid control and in particular, of switched control is that some performance requirements can be formulated explicitly by defining suitable switching surfaces or control guards. For example, effective current limitation can be performed with a time varying current-dependent switching surface *i.e.* peak current control with stabilizing ramp; voltage or current ripple can be limited for a suitable hysteresis-like controller , which can be seen as a switching control with two voltage and/or current dependent switching surfaces (Cervantes *et al*., 2009a), (Perez-Pinal & Cervantes, 2009a). Furthermore, due to the fact that the converters can be seen as switched systems, the switching criterion and the mode assignment criterion can be manipulated independently to obtain **multiple control objective**, for example, current limitation at the same time that voltage regulation (Austria-Gonzalez *et al.*, 2008) (Perez-Pinal & Cervantes, 2009b), or maximum voltage and current rippling as well as voltage regulation (Cervantes *et al*., 2009b).

On the other hand, hybrid controllers represent an option to solve **optimal operation problems**. For example in (Almer *et al.*, 2007) a predictive control with load estimation is proposed, in which a performance index is minimized to obtain a prescribed performance (see also, Geyer *et al*., 2008). In (Chen *et al*., 2006) a control strategy is proposed that is able to compute optimal switching instances that delivered over one switching period allow to a series parallel resonant converter to achieve its required steady state in minimum time.

Hybrid controllers can also be designed to solve voltage regulation problems even if the converter changes from **CCM** to **DCM** regime and vice versa (Sreekumar &, Agarwal, 2006), (Sreekumar &, Agarwal, 2007), (Sreekumar &, Agarwal, 2008), (Senesky *et al.*, 2003). Furthermore, many of the hybrid control strategies proposed can be implemented using **fixed frequency switching** (Geyer *et al.*, 2008).

Moreover, an additional advantage of describing the converter dynamics using a piece-wise model allows a confident description of the system for the whole operating regime. This fact opens the possibility of designing control laws valid in every operation point.

3. Some Stability Issues

A main concern when dealing with converter control is the closed-loop stability of the system. Regarding stability of hybrid systems, it is possible to find various approximations in the literature (Aeyels & Peuteman, 1998), (Branicky, 1998), (Filipov, 1998), (Liberzon, 2003) among many others. However, a great percentage of those results cannot be used directly in power electronics due to the fact that the HS considered in such works, do not fit in a possible description of a converter. That is, it is considered one or more of the following assumptions,

- Vector fields of the continuous part of the HS can be modified.
- In switched systems,
    - Subsystems have a common equilibrium point
    - All subsystems have equilibrium points
    - Subsystems have a given stability property

The reasons of the applicability limitation are clear when one looks into the converter structure. Consider for example the boost converter in Eqs. (7)-(8) subsystems 1 and 3 do not have any equilibrium point. Theoretically, the current is able to grow unlimited, while subsystem 2 has an stable equilibrium point in $x = (E/R\ ,E)^T$. Therefore, common equilibrium point approaches cannot be applied. Furthermore, as discussed before, the vector fields among which, the converter is evolving (subsystems 1-3) cannot be manipulated, since an extra control input u in Eq. (3) is not available. That is, neither equilibrium points nor stability properties of the subsystems can be modified. In view of this fact and as stated before, admissible control inputs are the residence time in each subsystem and mode assignment criterion.

3.1 Asymptotic Stability vs. Practical Stability

It is possible to find various definitions of stability in the literature; each one describing different behaviour of the system. Boundedness, input-output stability, output-state stability, asymptotic stability, exponential stability, practical stability and absolute stability are examples of these concepts. Although the objective of this subsection is not giving an exhaust description of such notions (the interested reader is referred to (Sontag, 1998) and (Khalil, 2002), it is relevant to notice that the inexistence or existence of equilibrium points is crucial to determine the type of stability that can be achieved by the system.

For example, asymptotic stability, exponential stability and absolute stability can only be achieved by systems with equilibrium points. In fact, these concepts are related to the ability of system trajectories to approach and stay at the equilibrium point (EP). In this way, it is said that trajectories are attracted by the EP and the set of all initial conditions such that this happens is called **attractive domain** or **region of attraction**. Having a large region of attraction is of great interest to controller designers mainly because it guarantees the existence of a set about the equilibrium point such that system trajectories are confined. This fact gives to the system, natural robustness against some perturbations.

Although it would be desirable to obtain asymptotic (or exponential) stability in power converts, in most cases this cannot be achieved using a hybrid description. The reason resides in the fact that in most cases, a common equilibrium point can not be found, e.g. the hybrid system (3)-(4). At this point, it is interesting to notice that when an average converter model is used along linear or nonlinear continuous controllers, a common average equilibrium point can be obtained. From the continuous point of view, we may be able to achieve both asymptotic and exponential stability to this "**fictitious**" equilibrium point; however in the converter, attractivity to a neighbourhood of this averaged equilibrium can only be obtained (practical stability).

Due to this fact, many of the results in switched and hybrid systems deal with the concept of practical stability, rather than with asymptotic stability. Since these two concepts will appear frequently in this chapter, the definitions are stated below:

Definition 1. (Khalil, 2002). The equilibrium point $x = 0$ is of the system $\dot{x} = F(x,t)$ is

- stable if, for each $\varepsilon > 0$, there is $\delta = (\varepsilon, t_0) > 0$ such that $\|x(t_0)\| < \delta \Rightarrow \|x(t)\| < \varepsilon, \quad \forall t \geq t_0 \geq 0$
- asymptotically stable if it stable and there is a positive constant $c = c(t_0)$ such that $x(t) \to 0$ as $t \to \infty$ for all $\|x(t_0)\| < c$

Definition 2. (Xu *et al.*, 2007). Given $\varepsilon > 0$, system (3) with $u=0$,

- is ε-practically uniformly stable (ε-PUS) about the origin under (4), if there is a $\delta = \delta(\varepsilon)$ >0, independent of t_0 such that $x(t_0) \in B(0,\delta) \Rightarrow x(t) \in B(0,\varepsilon) \quad \forall t \geq t_0 \geq 0$
- is ε-practically uniformly asymptotically stable (ε-PUAS) about the origin under (4), if is ε-practically uniformly stable and there is a $T = T(c) > 0$ independent of t_0 such that $x(t_0) \in B(0,c) \cap D \Rightarrow x(t) \in B(0,\varepsilon), \quad \forall t \geq t_0 + T$

Notice that the stability definition 1 differs from the concept of ε-PUS in the fact that in Definition 1 the condition over ε is assumed for all $\varepsilon > 0$, while in Definition 2, is enough the existence of some value (usually design-fixed). Furthermore, notice that Definition 1 requires the existence of an equilibrium point and the stability property is attributed to it. In contrast, in Definition 2, is the system the one which is stable and the result basically establishes confinement of system trajectories about the origin and in ε-PUAS, also attractiveness. On the other hand, when dealing with switched control, the concept of practical stability is also related with the *controlled invariant* one (Senesky *et al.*, 2003).

Notice that Definition 1 concerns about continuous nonlinear, time varying systems. If the hybrid system can be described as in this definition, necessary and/or sufficient conditions can be found to deduce stability (Sontag, 1998), (Khalil, 2002) . On the other hand, conditions that lead us to conclude asymptotic stability of a general HS may be hard to find. However, for switched systems such a task is easier in some cases.[‡]

In the following subsection we will describe some contributions in the area of hybrid control applied to DC-DC power converter. The discussion about their stability properties will be explained in view of the concepts and ideas stated here.

4. Types of HC in Power Electronics

The types of HC found in the literature can be classified in two groups mainly; a first one uses either a switched description or a switching control action in the converter; in these papers, the control objective is to find a switching law such that voltage is tracked. A second group, which description of the converter may be continuous or piece wise continuous, in these strategies the control objective is aimed to solve optimally (time or using and index performance) the voltage regulation problem. We will refer to the first group as **Hybrid Switched Control** (HSC) and to the second as, **Hybrid Optimal Contr**ol (HOBC).

4.1 Hybrid Switched Control

In this category we can find variable structure controllers such as: hysteresis, sliding and current peak mode controllers among the most common. **Sliding mode controllers** (SMC) are usually designed based on an averaged continuous model of the converter. In general, the converter is described by non-linear differential equations evolving in a *fictitious* averaged state space. Under this situation the control input is also continuous but restricted to $u \in [0,1]$. Once a continuous model is obtained, the next step is to define a suitable surface that resembles the desired steady state, usually such surface is a plane of the form:

$$S = \sum_{i=1}^{n} a_i \tilde{x}_i \tag{11}$$

where $\tilde{x} = x - x_{ref}$. and x_{ref} the desired state. However, the sliding surface can be also non-linear (Sira-Ramirez & Ríos-Bolivar, 1994), (Tokat *et al.*, 2002). Sliding mode control action can be divided in two operation modes: the **reaching mode** and the **sliding mode**. The reaching mode is related with the operation phase in which from an arbitrary initial condition the trajectories goes toward the surface S. The control input of SMC can be seen also as divided in two, u_{eq} that acts mostly on the reaching mode and u_d for the sliding. The input u_{eq} is usually continuous and parameter dependent, while u_d is a discontinuous input usually depending on the sign of the desired surface therefore, is parameter insensitive. There exist various papers in the literature dealing with the robust design of controllers for the reaching mode. For example in (Sira-Ramirez & Ríos-Bolivar, 1994) a passivity based controller is proposed to enhance the robustness properties of SMC. The controller make use of the passive relation between input voltage and inductor current of the converter, along with

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[‡] There exist trivial cases regarding stability of switched systems that are not of our interest. For example, if there is a stable mode in the subsystems family, we can guarantee stability of the switched system just by staying indefinitely on it, among others cases.

Lyapunov based arguments to show that the desired tracking dynamics approaches the origin asymptotically (*i.e.* the equilibrium point is asymptotically stable). The use of non-linear and time-varying sliding surfaces has also been proposed to enhance the robustness of SMC (Sira-Ramirez & Ríos-Bolivar, 1994), (Sira-Ramirez et al., 1995), (Tokat *et al.*, 2002). On the other hand, sensorless SMC has also been proposed, as well as some techniques for fixed frequency operation, the interested reader is refer to (Tan *et al.*, 2008) for a comprehensive review of sliding mode control in power electronics.

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Fig. 4. Types of hybrid controllers used in DC-DC power converters.

Hysteresis control can be interpreted as a switched control with two output-dependent switching surfaces: turn-on and turn-off surfaces (Babaa *et al.*, 1968). In this control methodology, the converter is described as a piece wise linear system (as in Eq. (1)) and the control objective is to maintain voltage confined within a pre-specified region, given two ad-doc surfaces. For example, in buck converters such surfaces will be:

$$\begin{aligned} S_{off} &= V_{ref} - \Delta v = 0 \\ S_{on} &= V_{ref} + \Delta v = 0 \end{aligned} \tag{12}$$

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For boost or fly-back converters (among others), current limitation has also be performed in order to avoid system instability. Some options to avoid such instability are the use of a current dependent switching surface or some kind of multi-loop control. On the other hand, since in this kind of controller the control input (switching surfaces and assign mode criterion) does not depend on system parameters, such control strategy results very robust (model free controller). However, a drawback of this controller is that it may lead to variable frequency operation. Since the first works about hysteresis control (Babaa *et al.*, 1968), various improvements have been performed. In (Leung & Chung, 2009), a time varying surface is proposed in order to reject large signal perturbation in two switching cycles. In (Schild *et al.*, 2009) a procedure that uses both clock-driven and event-driven switching criterion for controlling the stationary operation of a converter is proposed. The switching surfaces are planes that can be systematically computed using periodic control systems. Consequently, desired loop properties such as orbital stability of a limit cycle and a fast transient response are guaranteed at least in a local neighbourhood around a nominal set point. In (Tao *et al.*, 2006) variable hysteresis band control is proposed to achieve zero voltage switching for a multiple input converter.

On the other hand, in (Kimball, 2006) a sensorless hysteresis-type controller is proposed. Such strategy does not need current measurements and it can be implemented in converters operating under DCM conditions. In (Khaligh & Emadi, 2007) a hysteresis type controller that works under fixed frequency switching conditions is proposed. At this point, it is interesting to notice that although most hysteresis controllers have parameter insensitivity[§] and their stability and performance have been evaluated experimentally (see for example (Hwu & Yau, 2004); there exist a little formal theoretical support that explain their robust capabilities. Formal results involving robust practical stability of buck and boost converters under hysteresis-like controllers have been presented in (Cervantes *et al.*, 2009a), (Cervantes *et al.*, 2009b), (Perez-Pinal & Cervantes, 2009b); however, there are a lot of questions that remain open, specially for time varying and non-linear hysteresis (switching) surfaces.

Peak Current Mode Control (PCMC) is a class of switched control that has both time dependent and state dependent surfaces. This control strategy was conceived to limit inductor current while guaranteeing a fixed frequency switching operation. For a buck converter the PCMC is the following

$$\text{If } \; i > i_{max} \quad \text{then switch goes off} \tag{13}$$

$$\text{If } \quad 0 \le \operatorname{mod}(t,T) < \delta T \quad \text{then switch goes on} \tag{14}$$

For PMCM to be well defined it is necessary that the switching condition (12) be of higher priority than the one in (11). It is well known that, for duty cycles greater than 50%, PCMC leads to converter instability and strange behaviour such as bifurcation, chaos (Barnejee & Verghese, 2001) and breathing[**] (Cervantes & Femat, 2008). However, a stabilizing ramp is used to avoid such undesirable behaviour. Such a ramp makes a switching surface be both state and time dependent (the one that limits current). In spite of the well-known capabilities of PMCM, as in the case of hysteresis control, formal studies regarding stability are rare; hence issues regarding local or global stability capabilities are not yet completely known, as well as robustness properties of the controller.

There exist other expressions of switching control in the literature, for example the so-called "*boundary*" [††] control studied in (Leung & Cheun, 2004), (Song & Chung, 2008) and (Leung &

[§] Due to this fact, hysteresis control can be applied directly in many topologies without need of adjustment. This control is also called by some authors universal (Khaligh & Emadi, 2007).

[**] If a low frequency variable voltage input is used.

[††] This term is rarely used since confusion arise with the so-called boundary control in distributed system (infinite order systems) in which the frontier or boundary condition is

Cheun, 2007). Such controllers use a piece-wise linear description of the converter and switching surfaces which can be either planes or second order surfaces. It is shown that second order surfaces display better transient behaviour than planes, however the implementation of such surfaces may be quite involved. The design of the surfaces is based on one hand, on the regulation requirements of the converter; and on the other, on natural trajectories of the system, that reduce the transient response of the systems (ideally in two switching actions). The switching surfaces depend on system parameters and although a sensitivity study is performed in (Leung & Cheun, 2007) with respect to system inductance and capacitance, the surfaces depend dramatically on load resistance; such fact may limit the advantages of the controller if such parameters are uncertain.

Computation of switching instants based on an energy balance of the converter is shown in (Gupta & Patra, 2005). In this controller, the modes in which the converter gains and looses energy are identified. The switching instants are chosen so the total energy change is cero. Although this strategy has a physical motivation, the proposed strategy has the disadvantage of leading to variable current ripple and variable frequency operation.

Another expression of switching control can be found in (Senesky *et al.*, 2003). In such a reference, switched systems are described as hybrid automata. Based on this description the stabilization problem is stated in terms of the existence (and design) of suitable guards that guarantee that converter states remain in a safe set. In this excellent work, two regulation strategies are designed, the minimum ripple control and the minimum switching control that guarantee that a set of interest is controlled invariant (*i.e.* the system is practically stable). The proposed strategies have the advantage of having rigorous mathematical support and the effect of sample and perturbation is analysed. Although such techniques are probably easy to implement, unfortunately the authors do not show any experimental evidence of controller performance. On the other hand, other controllers based on the hybrid automata can be found (Sreekumar & Agarwal, 2007) (Sreekumar & Agarwal, 2008). In such works, a controller that is able to operate under both CCM and DCM is introduced. The authors give experimental evidence of the controller performance but unfortunately, the stability analysis presented do not take into account dynamic behaviour.

4.2 Hybrid Optimal Control

As pointed out before, in HOC the description of the converter is continuous or piece wise continuous and the control strategy is aimed to solve an optimal problem. Within this category we find predictive control of converters e.g. (Geyer *et al.*, 2008), (Morari *et al.*, 2006). In this case, the control is usually operated in fixed frequency and the optimization problem can be solved: i) once every switching cycle, ii) every fixed number of switching cycles or iii) offline. The optimization problem is usually stated, based on a performance index function that penalizes voltage error tracking, control deviation from nominal, among other common criteria. Major concerns when dealing with optimization problems are the solution existence and its computation time. Due to these facts, usually some simplifications to the optimal problem are performed and off-line computation of the control law is preferred.

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manipulated in order to control variables that are spatial dependent (You & Lee, 1989) (Morgul, 1992).

In (Geyer *et al.*, 2008) a predictive control of a step-down converter is proposed. The controller makes use of a piece-wise continuous model that is used to generate a discrete time approach of the system in order to simplify the solution of the constrained optimal control. The optimization problem is solved offline using dynamic programming and a Kalman filter is used to ensure voltage tracking and load estimation. The stability analysis is performed using piece-wise Lyapunov functions to show that a discrete equilibrium point is exponentially stable. Observe that in contrast to the discussed in Section 3, exponential stability in the discrete case can be guarantee since a discrete equilibrium point can be either i) a constant value or ii) a periodic orbit (which is the case in converters). A similar predictive control is also proposed in (Almer *et al.*, 2007) but in this case, a multi-loop robust controller that uses discrete integral actions to compensate uncertainty and track the reference voltage is used.

On the other hand, an optimum time controller has been proposed in (Chen *et al.*, 2006) for a series-parallel resonant converter. In this paper a piece-wise continuous model of the converter is used to analyze the state-state trajectories to compute optimal switching instants. The optimal control is able to compensate step voltage commands theoretically in one switching cycle. The controller makes use of voltage and current measurements as well as zero voltage crossing detection devices. Although the authors show the experimental performance of the controller, stability analysis is not complete and robustness of the proposed control has to be studied.

It can be observed that HOC can be much difficult to synthesize than switched controllers, such fact may affect adversely the complexity of actual implementations. Since these controllers are much complex, their application has to be well justified in terms of performance improvement or robust stability capabilities.

4.3 High Order Converter

Hybrid control and in particular, switched control has been gained more attention lately, among other things, due to its property of being easily implemented even in high order converters (interleaved or cascaded converters). These types of converters are mainly used in medium to high power applications in order to divide the converter power in cells, allowing managing lower currents and faster switching devices. In some topologies, there is a dramatic increasing in the number of switches. Incrementing the number of switches, increment also the number of degrees of freedom of the system, which in some cases may affect adversely the complexity of controller design. However, also open the possibility to solve more efficiently some operation problems. For example, in interleaved converters, the possibility of reducing substantially voltage rippling arises even at low switching frequencies. Moreover, perturbation rejection can be performed smoothly, since input actions and efforts can be divided among the branches (Batchvarov *et al.*, 2000).

In spite of these advantages, there exists in the literature very few works leading with voltage regulation and ripple limitation in higher order DC-DC power converters. In (Baja *et al.*, 2008) a stabilizing approach used to control capacitors voltage and current of a four-level three-cell DC-DC converter is proposed. The description of the converter is performed using bond graph formalism[‡‡]. Under the assumption that switching actions are performed in pairs, the notion of commutation cell is used to allow the converter description via bond graph formalism be topologic simple and with fixed causality in any mode. Three types of cells are detected: source, internal and load cells, for each one a static model is derived that relates inputs and outputs. The dynamic description of the converter takes also into account the dynamics of the Boolean control variables. The controller design is based on Lyapunov redesign technique and local atractivity of system trajectories is guarantee to a neighborhood of the origin.

On the other hand, a hysteresis like controller is proposed in (Cervantes *et al.*, 2009b) for the case of interleaved converters. The controlled derivation is based on an approximated switched description of the system. Closed-loop stability analysis of the converter is performed leading to a practical stability result. The proposed controller is able to regulate voltage, while warranting maximum current and voltage rippling, as well as current balancing. The performance of the controller is tested via both numerical simulations and experimental work; and it is shown that the controller can be readily implemented using integrated circuits.

In multi cell converters, the number of dynamic elements increases compared to traditional converters; therefore, it is convenient to use sensor-less control approaches, otherwise, the cost of the control implementation may increase dramatically. After a short review of the literature and in spite of the importance of developing such controllers, we could establish a truly need of investigation of this subject in the case of hybrid controllers. Furthermore, stability analysis of switching control in both parallel and cascaded topologies is also an open problem, as well as the development of a systematic procedure to design switching surfaces that lead to the solution of highly versatile control specifications.

5. Conclusions

In this work, a general description and classification of the most common hybrid controllers for DC-DC power converters is given. It is stated that in particular switched control has the advantage that some performance requirements can be formulated explicitly by defining suitable switching surfaces. Moreover, in some cases, the switching criterion and the mode assignment criterion can be manipulated independently to obtain multiple control input schemes. A main advantage of switched control is its inherent flexibility to operate in a wide operation region. Hybrid control also represents an option to solve **optimal operation problems,** for example, minimum switching control or predictive-type control. Furthermore, hybrid controllers have been designed to solve voltage regulation problems even if the converter changes from **CCM** to **DCM** regime and vice versa. Although some

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[‡‡] Bond graph modeling is a method for describing dynamic systems, which is based on the assumption that it is possible to define the characteristics of the subsystems and the connections between them without energy losses. Bond graph formalism may be perceived *some how close* to graph automata description, however there are substantial differences, see (Antic *et al.*, 1999) for more details.

HC methodologies are designed to operate at varying frequency (mostly transient response), there is an increasing tendency in the literature to investigate fixed frequency hybrid control schemes.

There are still a lot of open questions regarding stability and design of HC. We find a research opportunity in the formal stability study of some of the proposed control methodologies, in order to reveal advantages and limitations. We also find a research opportunity in the systematic design of switching laws based on time-varying nonlinear switching surfaces as well as on the design of sensor-less hybrid control of higher order converters.

Summarizing, hybrid controllers represent a versatile solution to guarantee energy quality in the renewable energy field, but the uncontroversial success of this control methodology will reside in the development of systematic approaches that guarantee both, simplicity in the implementation and robust stability properties.

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Renewable Energy is energy generated from natural resources-such as sunlight, wind, rain, tides and geothermal heat-which are naturally replenished. In 2008, about 18% of global final energy consumption came from renewables, with 13% coming from traditional biomass, such as wood burning. Hydroelectricity was the next largest renewable source, providing 3% (15% of global electricity generation), followed by solar hot water/heating, which contributed with 1.3%. Modern technologies, such as geothermal energy, wind power, solar power, and ocean energy together provided some 0.8% of final energy consumption. The book provides a forum for dissemination and exchange of up-to-date scientific information on theoretical, generic and applied areas of knowledge. The topics deal with new devices and circuits for energy systems, photovoltaic and solar thermal, wind energy systems, tidal and wave energy, fuel cell systems, bio energy and geo-energy, sustainable energy resources and systems, energy storage systems, energy market management and economics, off-grid isolated energy systems, energy in transportation systems, energy resources for portable electronics, intelligent energy power transmission, distribution and inter-connectors, energy efficient utilization, environmental issues, energy harvesting, nanotechnology in energy, policy issues on renewable energy, building design, power electronics in energy conversion, new materials for energy resources, and RF and magnetic field energy devices.

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Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
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Phone: +86-21-62489820
Fax: +86-21-62489821

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