A DC/DC converter for clean-energy applications

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1. Introduction

Fossil fuels are depleting day by day, therefore it is imperative to find out alternative methods in order to fulfill the energy demand of the world. Renewable energy is becoming more important nowadays. There exist applications of renewable energy which employ hundred of MW (high power) and there are also those which uses hundred of W (low power). Applications can also be classified depending if they are connected to the grid or not, as well known as cogeneration and stand alone systems. This last one is a low power application, specially employed in remote places, where electricity is not available.
Usually photovoltaic and wind systems are the source of energy in stand alone systems. Efficient use of energy is very important, since there is no utility line; a battery set becomes essential because energy power is provided in an irregular way from the renewable source; leaving aside this issue a power conversion stage is required in order to make sure a good output power quality.
The operation of a dc/dc converter applicable in stand alone systems is discussed in this chapter, which is for using clean energy as it could be a photovoltaic panel or a wind turbine. The system optimizes delivered energy in a smart way, but assuring its availability in the best possible way.
Chapter is organized as follows: stand alone systems are described first, later on some converters reported in literature are discussed, and finally operation, energy administration and results of a dc/dc converter for clean-energy applications are presented.

2. Stand alone systems and renewable sources

Energy is not provided from the utility line for the stand alone systems but from renewable source, which depends on weather conditions. So that, in order to make sure there will exist availability of energy, when load required it, a battery set is traditionally considered. Power consumption is restricted to a maximum limit and it also is a finite measurable quantity, to deliver the more amount of energy its use has to be optimized.
A block diagram for stand alone systems is shown in Figure 1. Photovoltaic panel, wind turbine system or both can be used as renewable source of energy; reliable energy is provided by a power converter, which is fed from the renewable source and the battery set, it focus mainly to deliver a regulated voltage to the load.

Certainly weather conditions restrict the renewable sources, but output power not only depends on wind speed or solar irradiance when it is employed a turbine system or a photovoltaic panel, also depend on the load. System behaviour for constant weather conditions is shown in Figure 2; traditionally the output power is plotted against its output voltage, but particularly for this graph the load is been changed, because the system depends on it. For different weather conditions similar graph can be obtained but the power varies according it.

When a renewable source is connected to a load not necessarily the maximum output power is consumed, as it is shown between A and B points in Figure 2. A maximum power point tracker (MPPT, point B) is employed in order to optimize the obtained energy; however this is not completely required in stand alone application, due to the load is fixed or bounded and the power system requirements could be lower than the maximum obtainable from the renewable source.

When considering a photovoltaic system and a specific load connected to the stand alone system, there exist two different possibilities: first one occurs if the maximum energy obtained from the panel is lower than the output power (point C) then it is necessary to use a battery in order to deliver the required amount of energy to the load; secondly, it may happen that the maximum energy obtained from the panel is higher or equal than the output power (a point between A and B) then no battery is needed.

A power converter must take into account these two scenarios in its operation form in order to provide a constant regulated output voltage no matter weather conditions. Obviously the amount of energy is finite and depends on the battery set and the climatic conditions.

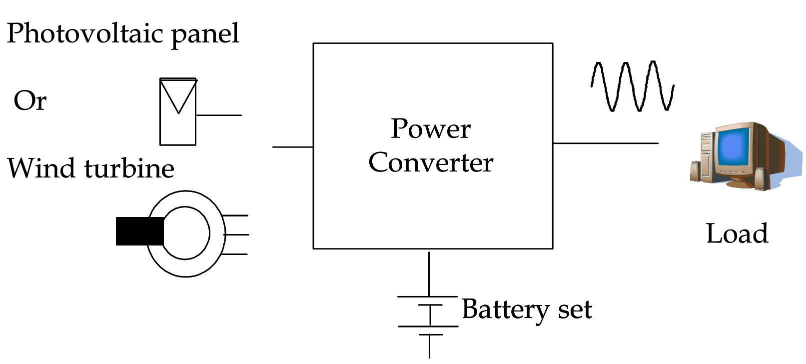


Fig. 1. Block diagram for stand-alone systems

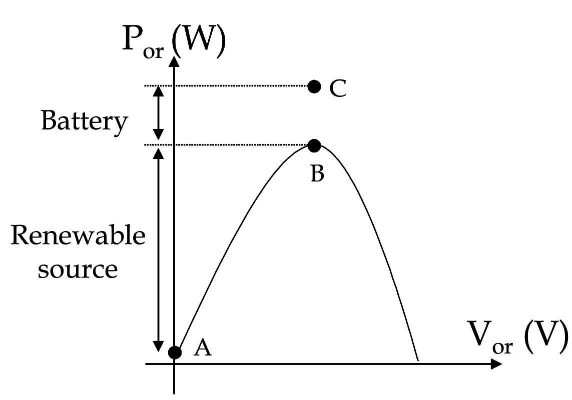


Fig. 2. Characteristic waveforms of renewable sources

3. State of the art in power conversion for renewable systems

Power converters normally reported in literature (Carrasco et al., 2006) consider not only different power stages, but also different ways of operation. Some of them are connected to the grid but some others are stand alone systems. Fortunately, two types of converters are typically used no matter configuration: a dc/dc converter and a dc/ac converter. This section describes some topologies reported in literature for renewable systems dealing with photovoltaic and wind systems.

3.1 Grid connected systems

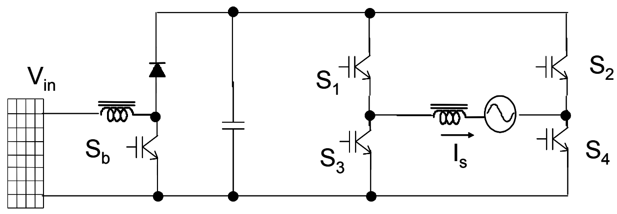
Grid connected systems deliver the maximum obtainable power to the ac mains from the photovoltaic (PV) and/or wind system (Carrasco et al., 2006); since the provided energy is variable and dependent on weather conditions, the possible released energy is also variable. Algorithms like improved perturbation and observation method (Femia et al., 2009), sliding mode observer technique (Kim et al., 2006), or some others (Park et al., 2006; Kwon et al., 2006) are used to track the maximum power point (MPP).

In order to increase the system efficiency is preferred to have low voltage with the solar cell array (Ertl et al., 2002), and also some wind systems generate relatively low voltage. Therefore, converter in these application require boosting type converters, Figure 3 shows different topologies which provide current to the ac-mains.

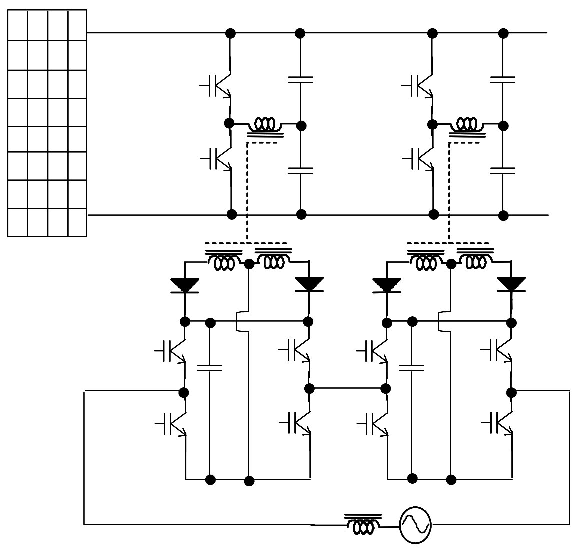
Figure 3(a) shows a topology which considers two stages: a dc/dc boost converter and a dc/ac converter (Kwon et al., 2006). Dc/dc is used for increasing the output voltage at a constant level allowing interaction to ac mains on the inverter stage, which is employed in order to perform the MPPT and deliver a sinusoidal current to the utility line. Converter illustrated in Figure 3(b) has also two stages: multiple isolated dc/dc converters and a multilevel inverter (Ertl et al., 2002); first stage is mainly used for isolation purposes and the next one to provide sinusoidal current to the ac mains.

It is normally found in literature systems which combine the power from two or more sources. Kobayashi et al. (2006) suggested a converter which is able to obtain energy from a PV array and the utility mains for telecommunication applications. Particularly for this case there are not energy injected to the ac mains. Walker & Sernia (2004) proposed a cascade connection of dc/dc converter when multiple photovoltaic panels are employed, a single converter for each panel, also different dc/dc converters can be taken into account. Chen at al. (2007) presented a system which uses photovoltaic panels and a wind turbine as main inputs, the photovoltaic voltage is higher than the output voltage and the wind turbine voltage is lower than the output voltage.

Figure 4 shows converters which are able to handle photovoltaic arrays and/or wind systems. They are multiple input dc/dc converters, they have the purpose to increase the output power or deliver energy from different renewable sources. Figure 4(a) shows how buck and buck-boost dc/dc converters are integrated to produce a single output voltage (Chen et al., 2006). Specially for this topology one input has to have high voltage (or at least higher than the desired output voltage) and the other one could have a low voltage; the energy can be delivered independently from both inputs.

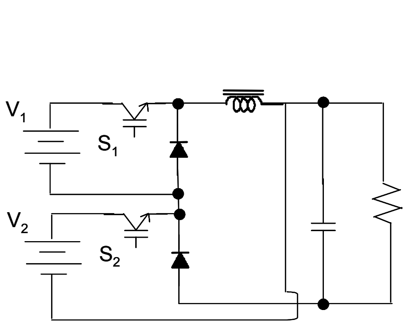


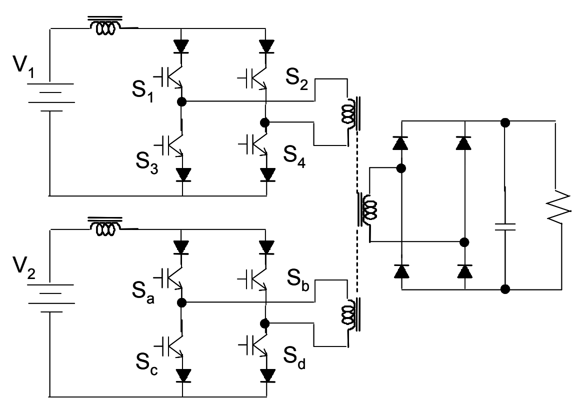
(a) Dc/dc converter and inverter



(b) Multiple dc/dc converters and multilevel inverter

Fig. 3. Topologies to inject current to the ac mains





(a) Buck converter and buck-boost converter

(b) Isolated converter

Fig. 4. Multi-input converters

Figure 4(b) illustrates an isolated converter (Chen et al., 2002), two inputs are magnetically coupled by a current fed transformer, for this case the two inputs may have different input voltage range, this is due to the transformer ratio which can be used to increase or decrease the voltage, however semiconductor counts is its major disadvantage.

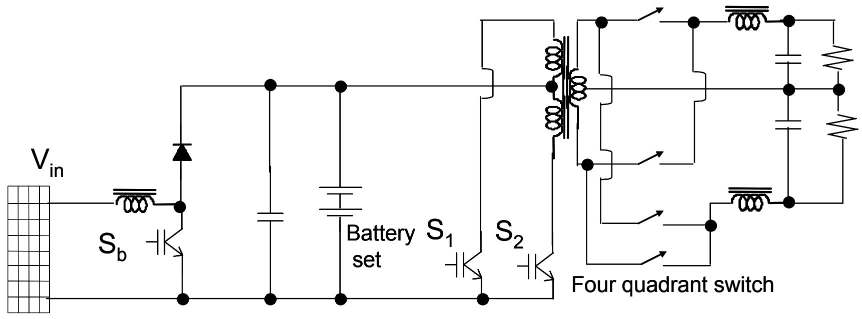
3.2 Stand alone systems

Stand alone systems are not connected to utility line, for this type of systems is compulsory to use a battery set in order to provide energy due to weather conditions. Energy is stored in the battery set and when it is completely charged then is ready to feed the load. Traditionally at this time the energy available from PV system is not used until the battery set is charged again.

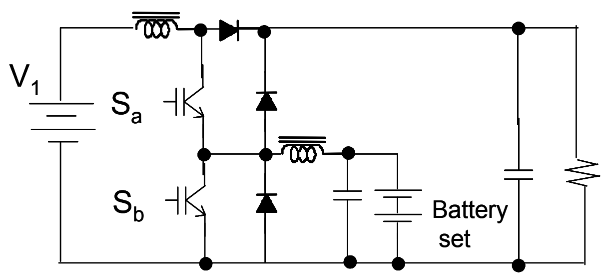
Figure 5(a) shows a converter, which consist of two stages, proposed by Song and Enjeti (2004). The first stage is a dc/dc boost converter that increases the input voltage, but also charges the battery set. The second stage is a dc/ac converter based on an inverter plus an ac/ac converter, which is fed in straight way by the battery set, this feature turns out to be its major disadvantage because the battery is charged continuously and deteriorates its useful life.

Figure 5(b) illustrates a dc/dc converter for stand alone applications based on the integration of different dc/dc converters. Energy, which can be administrated by having control on the switches, is delivered in three modes: the first one feeds the load and charge the battery set simultaneously from the renewable source, the second one delivers energy from the sources to the load, and finally, the last one when the battery set provides all the energy to the load. However, it is not possible to deliver energy only from the renewable source for this topology, so that the battery set is always involved, which deteriorate its useful life.

A converter, which is able to deliver energy from the renewable source without the use of the battery set, is suggested in next sections. Not only an optimum use of the renewable source and the battery set is achieved with the proposed topology but also similar operating modes are allowed as those proposed by Pacheco et al. (2002). Energy may be delivered by the battery set or the renewable source independently and also simultaneously from both sources with the aid of a smart use of the energy available from the renewable source.



(a) Isolated converter



(b) Integrated converter

Fig. 5. Converters for stand alone systems

4. A dc/dc converter applicable in renewable systems

It is analyzed a topology based on a step-up converter, which also accepts two input voltages (as shown in Figure 6(a)). Output for this converter can be connected to DC loads or an inverter for AC loads. The system is composed by a dc/dc boost converter and two input sources are located with the aid of some extra components, as it is shown in same figure. An input could be a photovoltaic or wind system, and the other one is a battery set.
Converter is capable of being operated in four modes, first and second modes occur when the power becomes just from one input, the third one happens when no energy is available from both sources and finally the last one when energy is demanded from both inputs. These operating modes are employed to feed the load by having an optimization of the energy obtained from the renewable source.
Energy is provided completely from the renewable system, if is able to do it, depending on weather circumstances and without using the battery set. Also if there is not enough power, an energy complement may be delivered from the battery set, just in case it is required to do so, then energy is taken from both voltage sources in a complementary way. Finally if there is no available power from the wind system then energy is provided from the battery set only. Operating this way allows optimizing the use of the battery set and also obtainable energy from the photovoltaic/wind system.

4.1 Operation modes of the converter

Converter is operated in different established modes by switching states of semiconductors involved (S_1, S_2 and S_m), as described next:

- *Power delivered from one of the voltage source.*

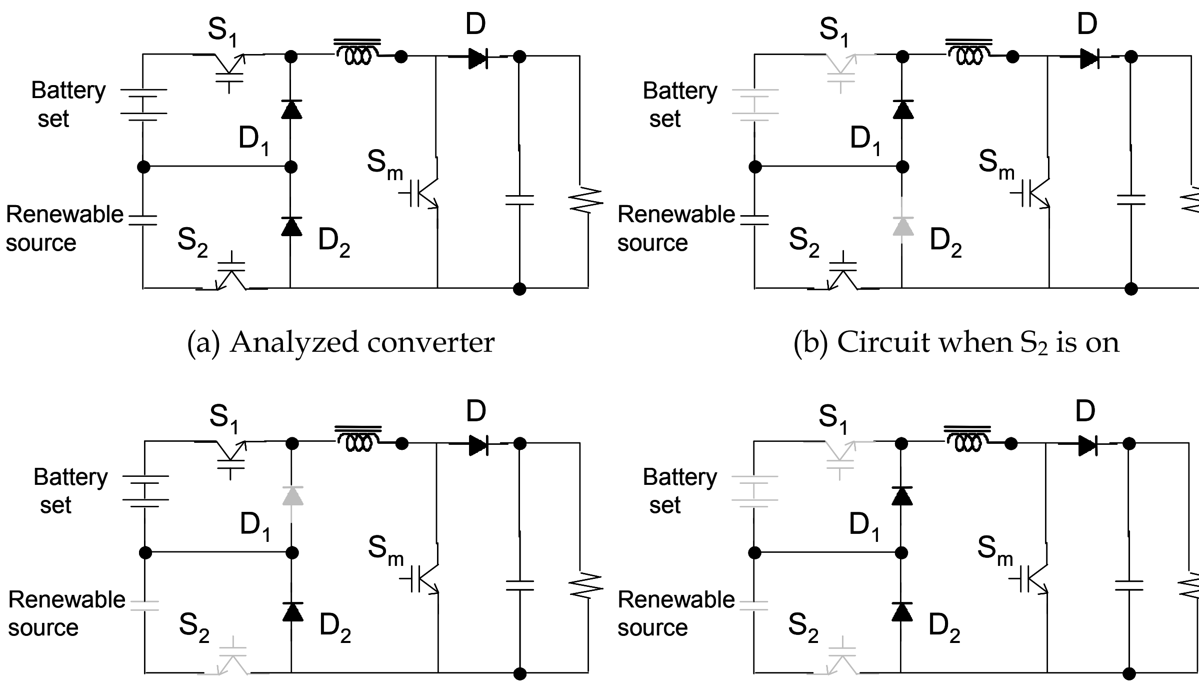
There exist two possibilities for this operating form. Figure 6(b) and (c) shows the equivalent circuits. If energy is just delivered by wind system, then the auxiliary switch S_1 is turned off and the switch S_2 is on, as illustrate in Figure 6(b). When the wind system cannot provide the required energy to the load, then the auxiliary switch S_2 is turned off and the switch S_1 is turned on, in this case the energy is delivered only by the battery set as shown in Figure 6(c). Semiconductor S_m is switching to regulate the output voltage independently of the source used.

- *Not energy available from the voltage sources*

It is possible not to have energy due to weather conditions and the battery set may be discharged. The two auxiliary switches (S_1 and S_2) are turned off as shown in Figure 6(d). As a consequence there is not energy available to regulate the output voltage so that the remaining energy is delivered by the free wheeling diodes.

- *Power delivered from both voltages sources*

When wind/photovoltaic system cannot provide all required energy by the load, but still there is available energy, then the system could be operated to demand energy from both sources: the wind/photovoltaic system and the battery set. This mode occurs if S_1 and S_2 are turned on simultaneously or if they are alternated at different times. This last switching state was used in the converter as illustrated in Figure 7.



(a) Analyzed converter (b) Circuit when S_2 is on

(c) Circuit when S_1 is on (d) Circuit when S_1 and S_2 are off

Fig. 6. The dc/dc converter and its different stages

Figure 7 shows control signals of the semiconductors in order to deliver energy from both voltage sources, a low constant switching frequency is considered; control signals S_1 and S_2 are complementary, the duty cycle is used for controlling the amount of energy given by each source. A constant output power to the load is provided by switching the main semiconductor S_m, which guarantied the appropriate output voltage, however in order to be able to increase the efficiency the auxiliary switches are turned on and off in a complementary way at low switching frequency.

4.2 Energy administration

Since the converter is designed for stand alone applications, the load is only fed by the renewable source and the stored energy in the battery set. System gives priority to the power obtained from the renewable source for optimizing the energy use, this means: energy from the battery is taken into account just when is really needed due to weather conditions and/or output power.

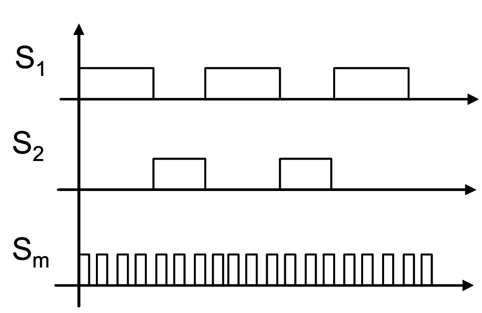


Fig. 7. Control signals.

Output power, which depends on the load, is not only constant for certain specific conditions but also is bounded, so that the boost converter must be controlled in order to regulate the output voltage and makes sure to maintain the required output voltage at the load. All this is made by using a sliding mode controller in order to introduce a good dynamic response to the system (Sira-Ramirez & Rios-Bolivar, 1994). The sliding surface considered allows avoiding the use of current sensors (Vazquez et al., 2003).
In spite of weather conditions, output power must be maintained, so that the system takes in consideration the battery set in order to supply the required energy which allows feed the load properly. Auxiliary switches are turned on and off depending on the availability of the renewable source, in order to be able to do this a modified MPPT algorithm, which is performed with a microcontroller, is considered.
Modified MPPT not only defines the maximum power point (MPP) for the renewable source but also established when the energy must be taken either from the two voltage sources or just from a single one. Algorithm determines when the renewable source delivers the possible maximum power in order to optimise its use and the battery set provides the complement. Sometimes when the required load power is lower than the maximum and the demanded energy can be obtained from the renewable source, the maximum point is not tracked.
The system is turned off for safety purposes when energy is not enough to maintain the system operation because the battery set is discharged.

(a) Modified MPPT algorithm
Figure 2 shows the renewable source behaviour for certain weather conditions, the output power may be different depending on the load. The figure illustrates three points, where each point represents a specific load power. If load requires power between points A and B, then the photovoltaic/wind system is able to provide the total load power, this leads that the system must be inside the curve behaviour of the renewable system and the maximum point is not tracked. However, if load demands a power higher than the possible provided from point B, as well it could be point C, then the battery provides the rest of power in order to reach the total load power, especially at this point the renewable system must be operated to track the MPP.
Operation mentioned before is achieved with aid of a modified MPPT algorithm; Figure 8 shows the flow chart. The method is based on the perturbation and observation technique, voltage and power of the renewable source are used as inputs. Depending on system conditions the duty cycle of auxiliary switch S_2 must be increased or decreased, it should be notice that the other auxiliary switch (S_1) has a complement operation in order to demand the complement power from the battery set.

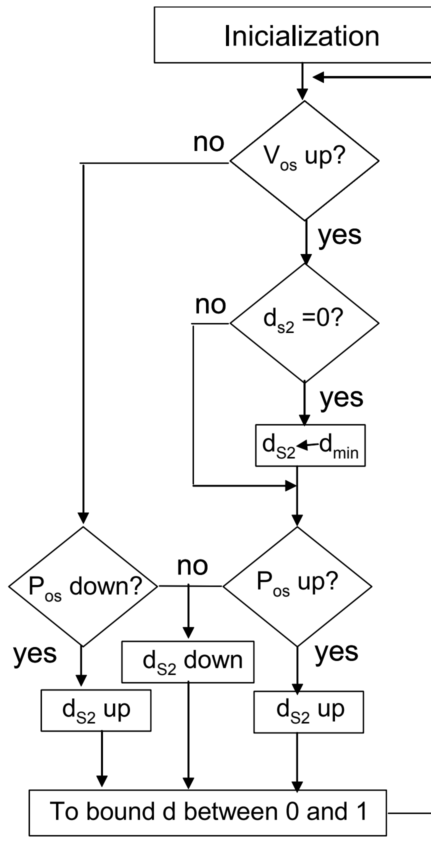


Fig. 8. Flow diagram of the modified MPPT algorithm.

It is an important part of algorithm that duty cycle, due to its natural values, must be bounded to a maximum and minimum value (1 and 0). Particularly when the duty cycle is limited to a unity, the system is not tracking the MPP, then it operates inside the curve behaviour (between points A and B). While algorithm is continuously sensing the voltage and power, the duty cycle is set to the working condition.

For the case when the duty cycle is zero and a voltage variation is detected at the renewable system, the duty cycle of S_2 is set to minimum value, to permit the operation of the system.

4.3 Controlling the dc/dc boost converter

A sliding mode controller is employed for controlling the dc/dc boost converter, the main switch (S_m) is used for this purpose and the output voltage is tighly regulated. The sliding mode control offers good characteristics to the system: fast regulation and robustness under input voltage and load variations (Sira-Ramirez and Rios-Bolivar ,1994). The following sliding surface and control law are used:

$$\sigma = s_1 e_x + k_p e_y + k_i e_z = 0 \tag{1}$$

$$u = \begin{cases} 1 & If\ \sigma < 0 \\ 0 & If\ \sigma > 0 \end{cases} \tag{2}$$

Where: $\dot{e}_x = f(t) - k_i e_x$,
$e_y = x_2 - x_{2r}$,
$\dot{e}_z = x_2 - x_{2r}$,
$f(t) = a - w_o x_2 (1-u)$,
s_1, k_c and k_i are the controller parameters

The dc/dc boost converter model is:

$$\begin{aligned} \dot{x}_1 &= a - w_0 x_2 (1-u) \\ \dot{x}_2 &= -b + w_0 x_1 (1-u) \end{aligned} \tag{3}$$

Where: $u = \begin{cases} 1 & S_m \ turn \ on \\ 0 & S_m \ turn \ off \end{cases}$
$x_1 = i_L \sqrt{L}$, $x_2 = v_o \sqrt{C}$,
$w_o = 1/\sqrt{LC}$, $a = V_{in}/\sqrt{L}$, $b = i_o/\sqrt{C}$
$V_{in} = u_2 * V_{wind} + u_1 * V_{bat}$,

u_2 and u_1 are the control signals of the auxiliary switches

In order to make sure that operation of the sliding mode controller, an existance of the sliding mode and an stability analysis must be done.

(a) The sliding mode existance
In order to verify the existance condition the following condition must be fulfilled (Sira-Ramirez & Rios-Bolivar ,1994):

$$\sigma\dot{\sigma} < 0 \tag{4}$$

This last expression must be fulfilled, therefore control law values of (2) are taken into account together with (3), and it is obtained next:

$$\begin{aligned} &If \quad u = +1 \rightarrow \sigma < 0; then \quad \dot{\sigma} > 0 \\ &If \quad u = -1 \rightarrow \sigma > 0; then \quad \dot{\sigma} < 0 \end{aligned} \tag{5}$$

Using equations (1), (3) and (5) is obtained:

$$\dot{\sigma} = -\frac{w_0}{2}\{s_1 x_2 - x_1\}(1-u) + s_1 a - b + k_i (x_2 - x_{2r}) = 0 \tag{6}$$

With expressions (5) and (6) existence conditions are:

$$\begin{aligned} r > 0 \\ -w_0\{s_1 x_2 - x_1\} + r < 0 \end{aligned} \tag{7}$$

Where: $r = s_1 a - b + k_i e x_2 - \dot{x}_{2r}$

(b) The stability analysis

The analysis of stability for the controller is made with the equivalent control; which is substituted into the system model, and is verified under that condition.

The equivalent control is the control law when the system is into the sliding surface, and it is obtained from $\sigma = 0$, however changing the control law (u) for the equivalent control u_{eq} is obtained:

$$u_{eq} = 1 - \frac{s_1 a - b + k_i (x_2 - x_{2r})}{\frac{w_0}{2}\{s_1 x_2 - x_1\}} \tag{8}$$

This analysis is beyond purposes for this communication, so it is not included, but the result has to fulfill the following inequality:

$$0 < k_i < s_1 \omega_1 \tag{9}$$

The inequality (9) is an approximation, but establishes a region where system is stable.

(c) The implemented circuit

Figure 9 shows the circuit for implementing expressions (1) and (2). There are four important parts represented in blocks. Block A is used to obtain the funtion *f(t)* which emulates the inductor current, block B determines the variable e_x, the circuit for implementing equations (1) and (2) is shown in the block C; an operational amplifier and a comparator are used. The operational amplifier is employed for proportional and integral operation of voltage error and comparator in order to obtain the control law. A soft start was performed with a capacitor, this allows to the reference initiate in zero voltage condition at the start up.

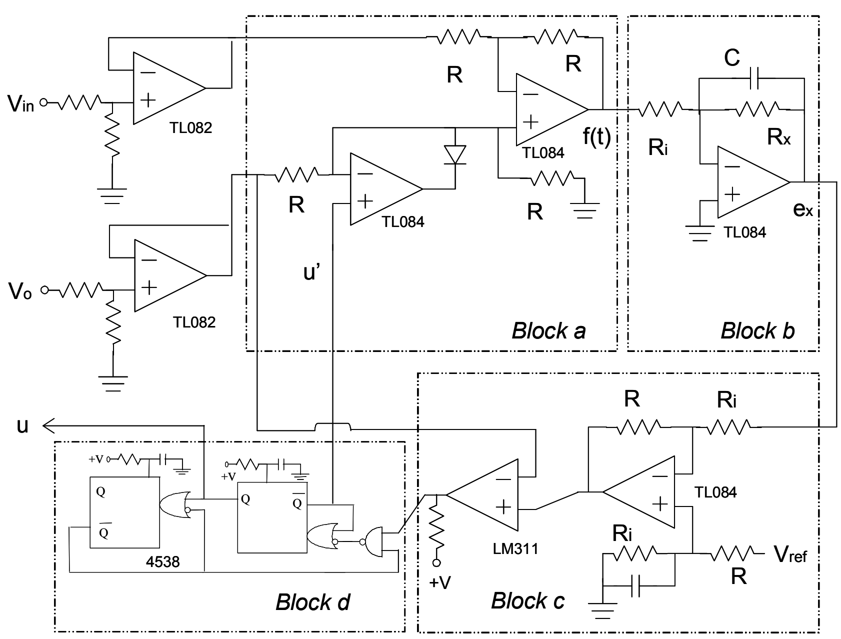


Fig. 9. Implemented controller for the dc/dc boost converter.

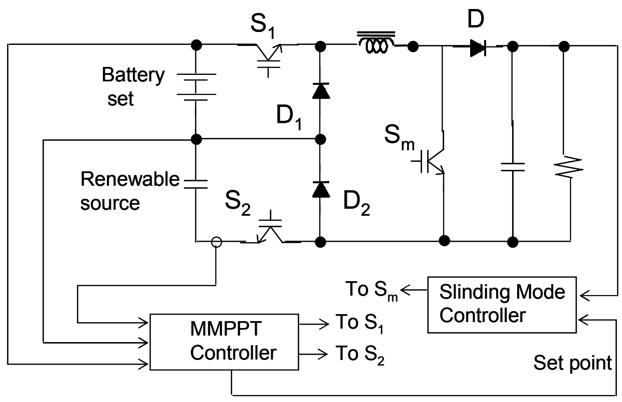


Fig. 10. Block diagram of the implemented system.

Since the ideal sliding mode controller has an infinite switching frequency, a circuit to limit is employed. For this purpose the block D is employed. Two CMOS logic circuits are used, the timer 4538 and the NAND gate 4011.

An important part for the implementation is block A, for the *f(t)* term. A multiplying factor is involved in the expression, however it is also easy to implement. Actually the control law operates as if it was an analogue gate, which allows voltage appears or disappears with control law. For implementing this part, two operational amplifiers and a diode are employed; the diode with an operational amplifier makes same function as an analogue gate.

Summarizing, five integrated circuits are used; six operational amplifiers build it up into the TL084 and TL082, a comparator (LM311), and two CMOS logic circuits 4538 and 4011.

4.4 The complete system

A block diagram for the implemented control system and the dc/dc converter analyzed is shown in Figure 10. A microcontrolloer is used for performing the modified MPPT algorithm, voltage and current of the renewable source are measured; additionally a sliding mode controller is considered for regulating the output voltage of the dc/dc boost converter.

4.5 Simulation and experimental evaluation

System functionality was not only mathematically simulated but also an experimental prototype was built, so that converter operation was validated. Battery set voltage was 48V, and a low power wind system is considered, the dc/dc converter output voltage was 250V, the output power was 300V. Figures 11 through 15 shows some simulation and experimental results.

Figure 11 illustrates operation when wind system proportionate all the energy. Inductor current, output voltage and also control signal for the main switch are shown.

Figure 12 shows opertation when energy is provided from both input voltages. Inductor current, output voltage, control signal for the main switch and control signal of the auxiliary switches are also shown. It should be noticed that the auxiliary switches are operating at low frequency and the main switch at high frequency.

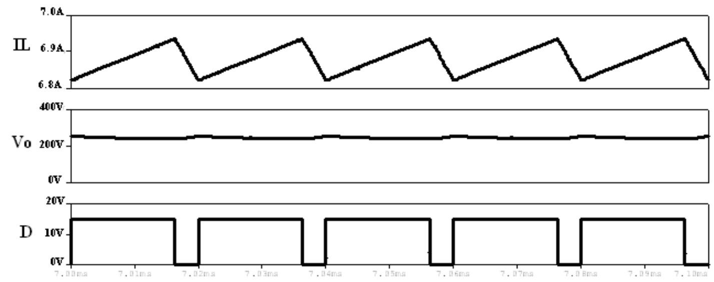


Fig. 11. Simulated waveforms when only one input voltage is available: the inductor current (I_L), output voltage (V_o) and duty cycle (D). (From top to bottom).

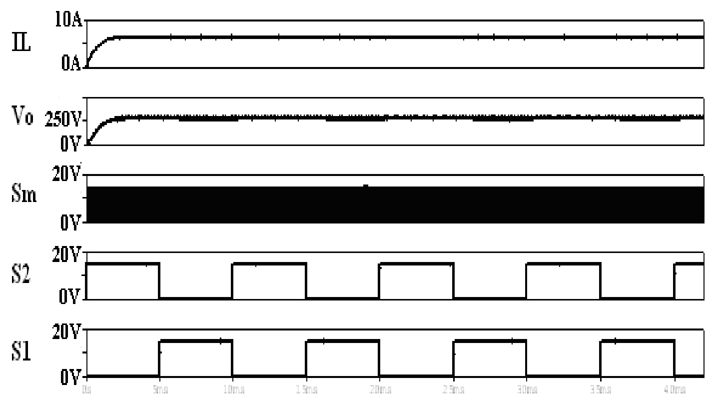


Fig. 12. Simulated waveforms when two inputs are in use: inductor current (I_L), output voltage (V_o), control signal of the main switch (S_m) and control signals of the auxiliary switches (S_2, S_1). (From top to bottom).

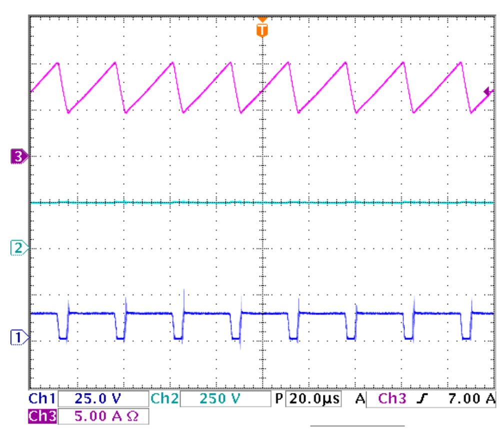


Fig. 13. Experimental waveforms when the wind system is only operating: the inductor current (I_L), output voltage (V_o) and duty cycle (D). (From top to bottom).

Figure 13 shows experimental results when wind system deliver all the energy to the load. The inductor current, output voltage and also control signal for the main switch are shown. Figure 14 illustrates operation when energy is taken from both voltage sources. Output voltage, inductor current, and also auxiliary swithces are shown.
Figure 15 shows a test when wind turbine changes its MPP due to a variation on weather conditions, it is easily seen how the system is being automatically adapted. Energy delivered

to the load from the emulated renewable source is higher than energy available before variation, particularly for this case the battery set is providing energy too.

(a) Testing the modified MPPT algorithm
In spite of the waveform shown in Figure 15, system performance was evaluated with other circuit with a known MPP. Mainly the reason for doing this is explained because in a wind turbine or photovoltaic panel the MPP cannot be determined accurately under real performance.
System behaviour in a real situation is relatively difficult to verify because depends on weather conditions. In order to avoid this situation a simple laboratory emulator was implemented, as shown in Figure 16. Emulator circuits consists of a voltage source with an inductace and resistance in series with it, and a capacitor, where inductor and capacitor are included for filtering purpose. In steady state the output power is determined by:

$$P_{os} = \frac{-v_{os}^2 + v_{os}V_s}{R_s} \tag{10}$$

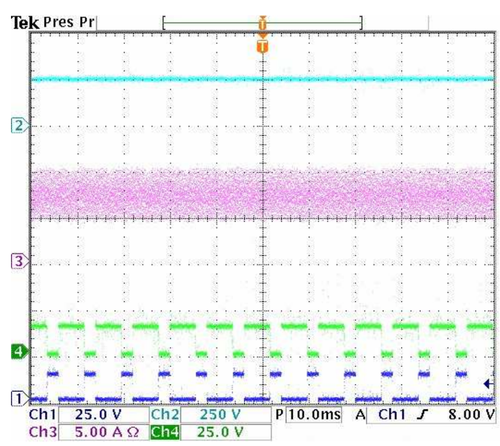


Fig. 14. Experimental waveforms when two inputs are in use: output voltage (V_o), inductor current (I_L), and control signal of the auxiliary switches. (From top to bottom).

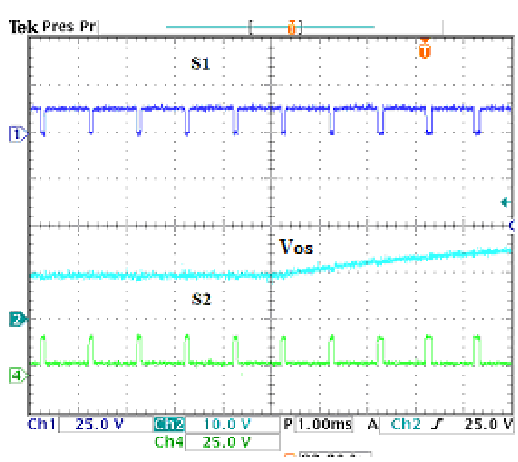


Fig. 15. Experimental waveforms under variation of climatic conditions: Auxiliary signal S_1, output of the renewable source, and auxiliary signal S_2. (From top to bottom).

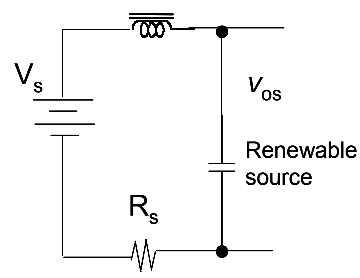


Fig. 16. Emulator as renewable source.

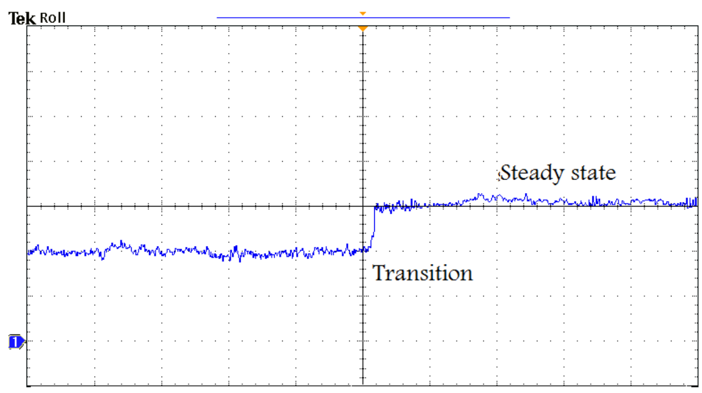


Fig. 17. Experimental waveforms under simulated variation of climatic conditions: output of the renewable source.

Where: v_{os} is the emulated output voltage,
V_s is the input voltage, R_s is the series resistance

Maximum power point occurs at the half of V_s, and the power is:

$$P_{MPP} = \frac{V_s^2}{4R_s} \tag{11}$$

When a different maximum power point is required to evaluate the performance, it is just necessary to change the series resistance or the input voltage (V_s). Then the system can be tested under controlled circumstances and with a known MPP.
Figure 17 shows converter operation when the emulated renewable source is not providing all the energy to the load and suddenly a variation is made. The system is adapted to the new condition, as the MPP are known in each case and the system reach them, then its reliability was verified.

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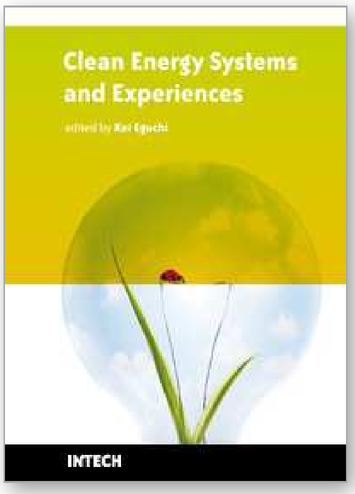

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This book reports the latest developments and trends in "clean energy systems and experiences". The contributors to each chapter are energy scientists and engineers with strong expertise in their respective fields. This book offers a forum for exchanging state of the art scientific information and knowledge. As a whole, the studies presented here reveal important new directions toward the realization of a sustainable society.

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