Basic MOSFET Based vs Couple-Coils Boost Converters for Photovoltaic Generators

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ABSTRACT

Considering the optimization of a photovoltaic system, several studies show the advantage in the choice of a distributed structure. For such structures small power converters such as the boosts and buck converters appear as most appropriate. We have analysed the efficiency of small power boost-converters especially dedicated for photovoltaic energy conversion systems working in the middle and high voltage ranges. The setup studied is a photovoltaic generator connected to an AC grid working in 230 Volts via an inverter. Moreover, we considered the possibility of multiple electrical energy sources as photovoltaic, wind systems in the same energy production system, which obliged an adaptive converter structure. We evaluated the losses in the various stages of a boost converter and point out the importance of the power MOSFET used as the commutation element. New transistors databases obtained from manufacturers show the nonlinear dependency between the resistance drain-source when passing, R_{dson} and the maximum rating voltage when the transistor is off, V_{dsmax}, for all transistor families. Thus nonlinear dependency induces a huge increase of losses with the voltage in the MOSFET, and as a direct consequence in the converter the more as V_{dsmax} is higher. In order to minimize losses of the converter we have designed and realized a new high efficiency version of a Step-Up structure based on a commutation element integrating a low V_{dsmax} voltage MOSFET and very low R_{dson}.

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1. INTRODUCTION

The photovoltaic (PV) energy provided by solar panels fluctuates naturally and the permanent search of the maximum power point makes its use difficult. In view of optimizing the system, several studies show the advantage in the choice of a distributed structure [1, 2]. It is thus necessary to consider small power converters such as boosts and buck converters [3, 4]. In practice for structures comprising many inter-connected panels, the problem of energy extraction in an optimal way is acute and more study of the maximum adaptation in case of partial shadows, which are sources of unmatching is needed [5, 6]. New structures based on power conversion and swarm intelligence are currently developed in the voltage ranges (HVDC and HVAC micro grids) [7, 8]. In a general context, power conditioning delivered by a system, which can be composed by various generators as photovoltaic (mono-crystalline, poly-crystalline and/or amorphous) solar panels and/or wind turbines and/or fuel cells is a key point in terms of development for energy production applications. Because of their intrinsic characteristics, typically low voltage sources, the connection and power management of several generators in series and despite technical efforts is generally not easy to exploit for high output voltage. In this case, the used of parallel architecture with efficient converters connected by a high voltage DC bus could offer increased performance [4, 9].

On the other hand, the interface between a low voltage power source and a high voltage DC output is generally proposed by complex converter circuit as a cascaded structure composed of two or multiple sub-converters allowing a high voltage ratio [10, 11].

The powerful conversion of low DC voltage from photovoltaic panels and/or wind turbines into a HVDC grid [11, 12, 13] able to supply uninterruptible power [14], implicates simple, reliable and cheap high efficiency converters while supplying voltages higher than 100V. Therefore, power converters must also have new specifications in terms of efficiency, cost and environmental constraints to satisfy the quality criteria required in renewable energy production.

Basic boost converters currently integrate a coil inductor and a freewheeling diode in series, and a power switch system driving the output voltage. The principal causes of losses for converters working in middle and high voltage ranges are due to these discrete elements. To describe the behaviour of these elements, and to evaluate the losses and the overall efficiency, some standard models are largely used and presented in literature [10, 15, 16]. Nevertheless, new recent data available in literature and/or given by the manufacturers on power MOS transistors that can be integrated as commutation elements present new possibilities for direct high voltage converter systems. In this case, the DC/DC conversion law available for low voltage converters must be revised and suggests the redesign of new converter architecture. After the evaluation of the losses in the inductance and in the diode, we have simulated the behaviour of the most usual MOS transistors on Orcad and Proteus simulation software using manufacturer’s data. To determine the dependence between the R_{dson} and V_{dsmax} of the transistors, we have included the bonding resistance in the Gummel Poon model [16].

The presented methodology and conclusions of this study allow direct choices of performing converter structures, by an optimization of the main power components, especially while keeping in view the objective of the middle voltages, i.e. about the 150V to 500V usually implemented in usual PV systems. This approach implicitly suggests a minimization of losses in cables used for interconnection by increasing the output voltage on the HVDC bus, and consequently, allows a drastically decrease of currents in the power bus. It results a decrease of the wires bus sections and of the generator cost.

Note that, even so this study is developed in view of a global search of the optimization of the overall process in photovoltaic generator efficiency, we will not discuss the optimization of electric power delivered by photovoltaic generators such as methods used for the MPPT (maximum power point tracking) which are issues out of the scope of this paper.

2. BASIC BOOST PV CONVERTER

For PV applications, a number of interconnected grid inverters have been developed and used over the last thirty years with various technological approaches [1, 2]. The general architecture of such distributed PV system is represented in Figure 1 in case of a structure of eight panels associated with individual DC-DC boost converters which are linked to a common DC-AC converter to the electrical grid.

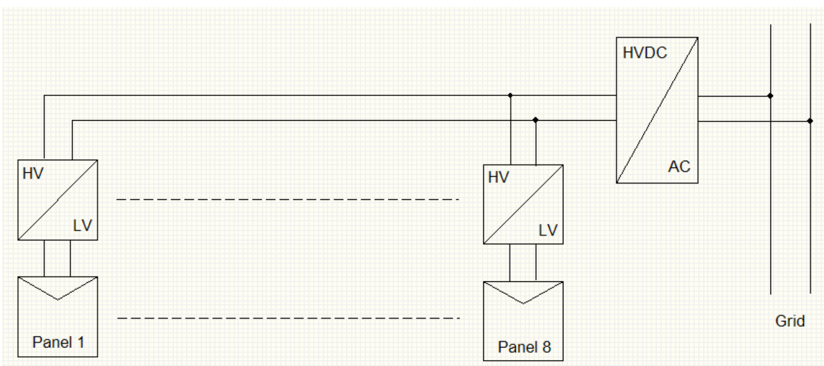

Figure 1. Schematic representation of a distributed photovoltaic generator built with 8 PV panels associated with dc/dc convertors connected via an inverter to the grid.

A basic boost DC/DC converter for DC load is shown in Figure 2. It includes DC voltage sources represented as the photovoltaic generator, the input inductor L_1 with series, R_s and parallel R_p resistors and the input and output transfer capacitors, C_1 and C_2, respectively. In this diagram, D_1 is the freewheeling diode, M_1 the power switch driven by a pulse width modulator (PWM).

The various components constituting the converter, as shown in Figure 2 must be adapted according to the modulator working frequency, the converter input and output voltages, and the electrical power to be converted. As we will see in the following, for high-level performance converter, the freewheeling diode, which insures a passive operation, is replaced by an active switch in which the commutation is generally provided by a MOSFET transistor.

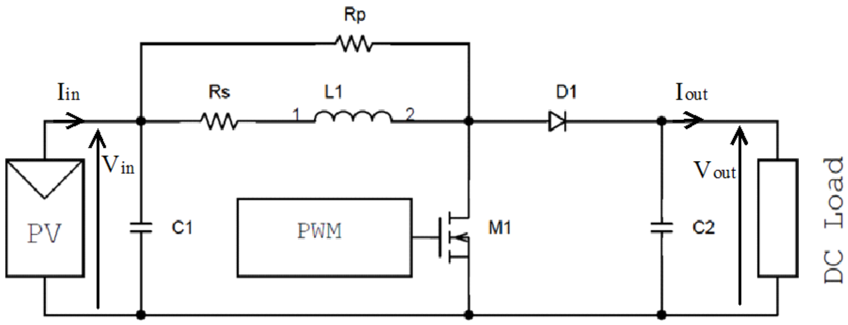

Figure 2. Schematic diagram of a basic Step-Up converter integrated in a photovoltaic generator. PV is a photovoltaic panel, PWM is the Pulse Width Modulator. C1, C2, Rp, Rs, L1, D1 and M1 are the discrete elements constituting the electronic circuit (see the text).

On the basis of a photovoltaic system, the DC input voltage, which can be considered as generated by a battery, is currently produced by photovoltaic interconnected panels in series, in parallel, or in a joint series-parallel configurations but a single photovoltaic panel can also constitute it. Voltage at the input of the converter is in the range of few tens of volts. The converter is sized as function of the required power output, dependent on the input parameters, which are the irradiation level, the effective active surface, the orientation and the efficiency of the panels, and the converter itself. Performances of the Maximum Power Point Tracking driver, allowing the maximum power conversion, play also a non-negligible role in the overall efficiency of the system.

For an interconnected photovoltaic system to the electrical network, the inverter is generally sized up to a nominal power and to the output AC voltage of the network. Thus, the Step-Up is considered as an interface, designed for a given output voltage, between the photovoltaic generator and the inverter.

Figure 3 shows the distribution of the currents in a classical Step Up converter. Figure 3.a in case of passive energy transfer mode using a free-wheeling diode working in natural commutation and Figure 3.b, in case of active energy transfer mode using a switch which can be MOSFET transistor. Figure 3.c shows the current variation in the inductor. In this figure, a is defined as the duty cycle of the pulse width modulator.

With the help of the observed curves, we analyse further down the individual contribution of each element in the global efficiency of the DC-DC converter. This study is essential before making any choice of architecture for converters and PV systems as suggested in an example shown in Figure1. Conclusions of the study of the existing architectures of converters also show the limitation of the actual systems and allowed us to propose a high efficiency version of Step-Up structures, based on a commutation element integrating a MOSFET.

2.1. The Coil Inductor Input Stage

Losses in the inductor have been studied in the past [18, 19]. Various origins for the inductor losses can be listed. The three main losses are i) the magnetic losses and Foucault currents in the magnetic material which influence on the R_p value, ii) the Joule effects in the coil, and iii) the Skin effect on the wire of the coil, due to high frequencies and harmonics, which increases the R_s value. As we can observed in Figure 3c., the shape of the current in the inductor presents variations amplitude referred as ΔI. The minimization of the dissipated power in the inductor will only happen if ΔI is reduced to a minimum value. Thus, the level of losses directly depends on physical parameters fixed during the inductor conception and fabrication, i.e. the global dimensions and the constituting material of the magnetic circuit, the air-gap size, which is responsible of the storage of about 50% of the magnetic energy, the wire section, and the configuration of the various coils. As these parameters depend on the frequency of the currents circulating in the coils, the losses too.

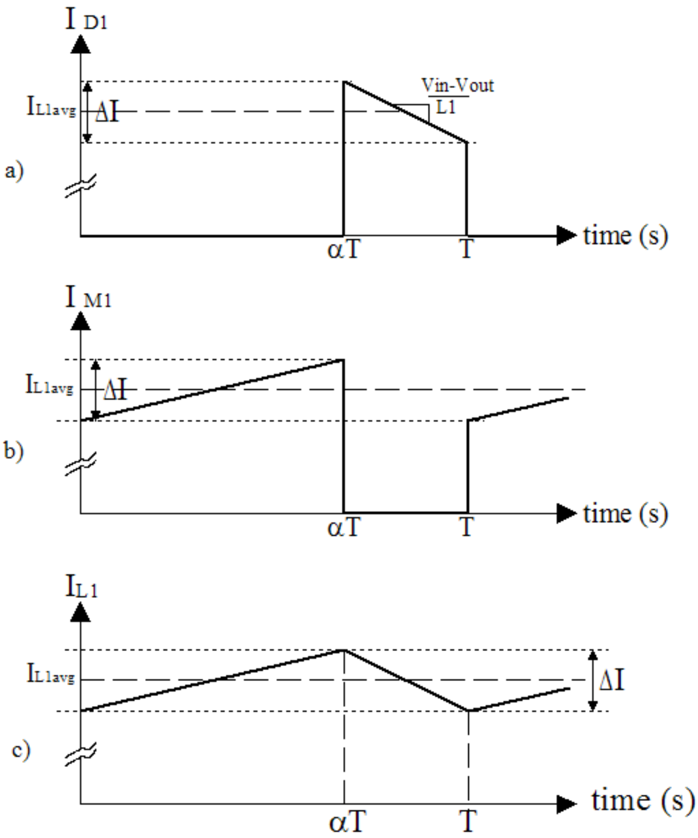

Figure 3. Intensity shape in a) a passive the free-wheeling diode switch stage, b) in the active MOSFET switch stage, and c) in the inductor.

We can see that the performance improvement of a converter must include the lowering of losses in the inductor, thus an optimization of its physical and electrical parameters. Nevertheless, this stage is not the main key point of the converter efficiency because the charge is not directly connected to the inductor but to the energy transfer output stage assuming the switch function. A discussion about losses in the output stage is done further down.

2.2. Energy Transfer via a Passive Output Stage

The recovery energy transferred in a passive mode via a freewheeling diode is the simplest system used from the beginning of energy conversion. The diode conducts current during the recovery phase and automatically switches off during the next phase. The current, I_{D1} in the freewheeling diode is well described in the literature [15, 16] and takes the form shown in Figure 3.a.

The main advantage of this solution is its simplicity due to the fact that the commutation operates naturally at zero current, i.e. in a passive mode so it does not need any specific circuit or tracking strategy for driving the output voltage. In view of a further minimization of losses, it is possible to use a low voltage diode such as Schottky diode well adapted for this application due to its low voltage drop of about 0.2 volts. Until recently, the main drawback of this solution was the too low reverse voltage supported by the diode. Some new Schottky diodes in silicon carbide or silicon nitrite are, by now, available; these diodes support a reverse voltage up to 600 volts, which makes it worth considering for medium voltage range converters [4,18].

The power losses, P_d, in the diode follow the equation:

$$P_d = V_d(1-\alpha)I_{inAvg} \tag{1}$$

where V_d is the direct voltage of the diode, α, is the duty cycle of the pulse width modulator, and I_{inAvg} is the mean current transmitted during the passing part of the cycle. L_1 is the inductor as shown Figure 2. In those systems the duty cycle, α is in direct dependence on the input and output voltages V_{in} and V_{out}, respectively.

As an example of a photovoltaic high power converter specifications V_{in} =18V_{DC} and V_{out} =500V_{DC}, I_{inAvg} = 5A, gives after simulation of the losses in the diode, a power equal to P_d = 54mW. This power loss corresponds to about 0.6% of the total power delivered by the converter.

2.3. Energy Transfer via an Active Output Stage

To increase the efficiency of the transfer output stage, the substitution of the freewheeling diode by a transistor allowing an active control of the rectifying current is proposed as a solution [19]. This solution is labelled a synchronous rectifier. It uses the inverse characteristics of a MOS transistor in direct mode with a very low resistance R_{dson}. As an example, the R_{dson} of IRF2807, which can be used for this kind of application, is equal to about 13mΩ. This resistance induces a voltage drop three times lower than with an usual Schottky diode. The current, I_{M1}, passing through the transistor takes the form shown in Figure 3.b. with the duty cycle, α, expressed as

$$\alpha \approx 1 - \frac{V_{in}}{V_{out}} \tag{2}$$

with V_{in} and V_{out} the input voltage and output voltages, respectively. In practice, V_{out} is lower than or equal to V_{dsmax}. It should be noted that the holding voltage of this component must be carefully chosen to withstand the value of the output voltage of the converter. The dependency of the duty cycle α with the ratio V_{in}/V_{out} implies that for high output voltages, α can reach an important dissymmetry that also implicates high voltage pulses in the output rectifying stage. Thus, for high output voltage values the gain in the efficiency that can be expected with an active output stage becomes negligible. Nevertheless, in terms of commutation speed, this solution is particularly advantageous because of the short recovery time, and thus overcomes the drawbacks of the usual conventional diodes [17].

The energy losses in the active output stage are reduced almost to the Joule losses in the MOSFET added by the losses in its control driver. In addition, two contra-effects complicate the system: the Miller's effect and the particular link to the control driver system, i.e. the need of a control for the switch of the transistor in a perfectly synchronous mode. Within the input and output voltages and the power in a defined range, the losses provided by an active switch is minimal compared to the solution based on a freewheeling Schottky diode. On the other hand, the complexity of its implementation makes the system less reliable [10, 18].

In this architecture, the active output stage is the main key point of the converter because the output charge is directly applied to the transistor assuming the switch function. For direct high voltage conversion, the choice of the output electronic component of the output stage is quite difficult due to the increase of the Joule losses and a judicious choice of this component constitutes an important issue for the increase of the converter efficiency. The losses in this stage are mainly due to the R_{dson} resistance, active in direct mode. The RMS value of the current I_{M1} through the switch is in the form shown in Fig. 3b. The RMS current in the MOSFET with a duty cycle α appears in Equation 3.

$$\mathrm{I_{RMS}} = \left[\alpha \left(\mathrm{I_{inAvg}^2} + \frac{(\Delta \mathrm{I})^2}{3} \right) \right]^{-1} \tag{3}$$

To evaluate the losses in the MOSFET during the active switch stage, we have analysed the particular role of R_{dson} as function of the voltage V_{dsmax} applied to the transistor for various MOSFET families. After identifying several transistors families compatible with high voltage converter applications, above 200V, we have simulated the behaviour of many transistors with the Orcad and Proteus software to find the relation between the parameter couples formed by R_{dson} and V_{dsmax}. The details of the analysis are published elsewhere [20]. Nevertheless, for a self-consistent reading of the present work, we summarize the main results. We have demonstrated by simulation that for any transistor likely to be the active element of a switch of a boost converter, it exists a linear relation, Equation 4, between R_{dson} and V_{dsmax}.

$$R_{dson} = R_0 + K_g V_{ds\max} \tag{4}$$

where R_0 is the resistance approximating of the bonding contacts resistor ad K_g a proportionality constant. Nevertheless, when the problem is the optimization of the switch stage for photovoltaic system, as function of the input or output power of the converter, the choice of a transistor is quite delicate and the knowledge of K_g for a particular transistor cannot give any information for other transistors belonging to the same component family. In this case, we have shown [19] that this problem can be solved by the introduction of a new proportional factor K_f and an exponent γ specific for a transistor family, yielding the transformation of Equation 3 to a nonlinear relation.

$$R_{dson} = R_0 + K_f \left(V_{dsmax}\right)^{\gamma} \quad (5)$$

We notice that the linear model for one transistor is a particular case of the general one for a given family with $K_f = K_g$ and with $\gamma = 1$. The simulation of around thirty transistor families shows that γ is always above one and often reaches two.

Considering a converter working in specific voltage and power ranges, the choice of a MOSFET in a transistor family to optimize the efficiency of the active output stage, Equation 5 clearly shows that one can expect an increase of R_{dson} as function of V_{dsmax} that implies a huge increase of losses in the MOSFET and, as a consequence in the converter. To illustrate the losses in the switch stage, we have to evaluate the mean power P_0, that dissipates in the transistor. For the nonlinear model, Equation 5, with the expression of I_{RMS}, Equation 3, we obtain

$$P_0 = \left(1 - \frac{V_{in}}{V_{dsmax}}\right)\left[R_0 + K_f \left(V_{dsmax}\right)^{\gamma}\right]\left(I_0^2 + \frac{\Delta I^2}{3}\right) \quad (6)$$

In a Step-Up converter, the inductor was generally chosen with a sufficient size to obtain a good smoothing of the current and, for P_0 evaluation, we can assume that the system works near its nominal point and neglect the term ΔI in Equation 6. To illustrate the behaviour of a MOSFET used as an active switch element in a PV converter, we have chosen the IRF2807 transistor family, which presents a good speed commutation and R_{dson} compromise. Calculations were done for V_{dsmax} varying between 0 to 500 Volt and for a current varying from 0 to 5A. The computation gives $\gamma = 1.7$, $R_0 = 1.10^{-3}\Omega$ and $K_f = 7.7\ 10^{-6}$. Results of simulations are illustrated in the Figures 4.a and 4.b, for full voltage and low voltage ranges, respectively.

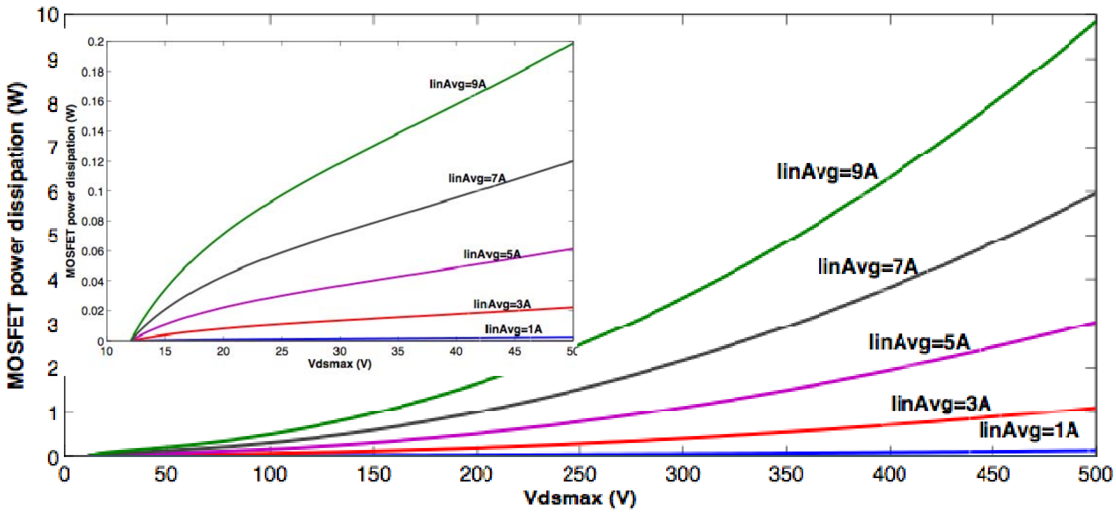

Figure 4. Power losses in the switch (MOSFET) as function of I_{inAvg} and V_{dsmax} in the full operating voltage range. Insert: a zoom in the low voltage range.

The plots in Figure 4 clearly show the very rapid rise of losses when the voltage V_{dsmax} exceeds one hundred volts, which is the case in PV applications as described above. The power losses increase very rapidly and reach a maximum of 12.24W for high voltage, which gives a percentage of losses in the converter around 12.7%. These losses are not compatible with the performance goals of a PV converter fixed lower than 1.5% for the entire system. As we can see in the zoom reported Figure 4.b, obtained for V_{dsmax} below 50V, the power in the transistor does not exceed 133mW, corresponding to losses equal to approximately 0.1% of the total transmitted power, consistent with the performance goal of a PV converter.

In this first part of the presentation, we have analysed the efficiency of power converters specially dedicated for photovoltaic energy conversion systems and working in the middle and high voltage ranges. The losses in the coil inductor, the output transfer stage and in the switch of a boost converter were considered. It will be noted that the aspects related to losses in the filter elements, capacitors and parasitic capacitances were not taken into account. These elements involve low losses, but are sources of failures, due to overheating.

The analysis and software simulations point out the importance of the power MOSFET used as the commutation element in the entire efficiency of the system. With the actual MOSFET transistor families, even the more recent ones, for high voltage conversion ratios and with output voltages above 100V, there is no possibility to reach high conversion efficiencies. This is mainly due to high losses occurring in the switching MOSFET, which presents a too high R_{dson}. These results exclude the direct conversion of photovoltaic energy for high reliability voltages close to 300V. Within the actual performances of transistors available in the market, for proper power conversion, it is essential to use low-voltage MOSFETs working in the 50V to 100V range. For direct high voltage DC/DC converter, it will therefore be necessary to change the structure of the converter, to operate at reduced voltage for the switching transistor, while producing a high output voltage. Among the several possible structures, we suggest converter architecture based on a coupled-coils arrangement. Hereafter, we present and analyse the performance of such a system.

3. COUPLED-COILS BASED BOOST PV CONVERTER

In order to conciliate the low voltage require insuring a high efficiency of the MOSFET switch transistor and the high output voltage, we propose to add a second coil L_2 strongly magnetically coupled to the first one L_1. This structure, named Couple-Coils Boost Converter, CC-BC is very well known and is used for example, to generate the TV high voltages supplying cathode ray tube and the originality consists in the implantation of such a structure in boost converters for photovoltaic applications with their specific constraints.

The principle of a CC-BC is based on the electrical load of the first inductor L_1 with the input energy when S_1 is closed, followed by the restitution in the second inductor L_2 when S_1 is opened. The introduction of the second inductor L_2 in the output stage increases the overvoltage effect. The schema associated to this solution is reported in Figure 5 where R_1 and R_2 are the resistors of the two inductances L_1 and L_2, respectively. In a first approach, we describe the system and point out the method to optimize the duty cycle by considering an ideal electronic system without losses due to the parallel equivalent resistors or parasitic discrete elements. The real operation of the converter will be presented in the second part.

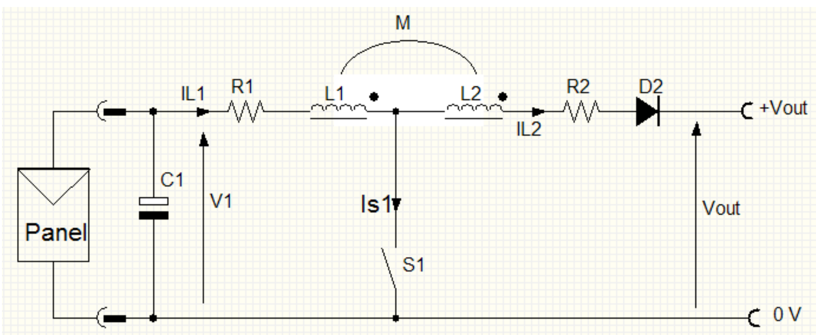

Figure 5. Electronic diagram of the ideal CC-BC. The MOSFET transistor, S1, is connected at the middle of two magnetically coupled inductors.

The energy stored in the inductors, W_L is calculated by the classical equation

$$W_{L1} = \frac{1}{2} L_1 I_1^2 \quad (7)$$

where

$$L_1 = \frac{N_1^2}{R} \quad (8)$$

where, considering the system based on an autotransformer with a coupling coefficient equal to 1, i=1, 2, 1+2 linked to the active inductors considered, R is the reluctance of the magnetic circuit and N the number of turns of the inductors.

Considering the case of CC-BC adjusted to a well-balanced duty cycle α = 50%, we report in Figure 6, the repartition of the currents in the two inductors and in the active switch.

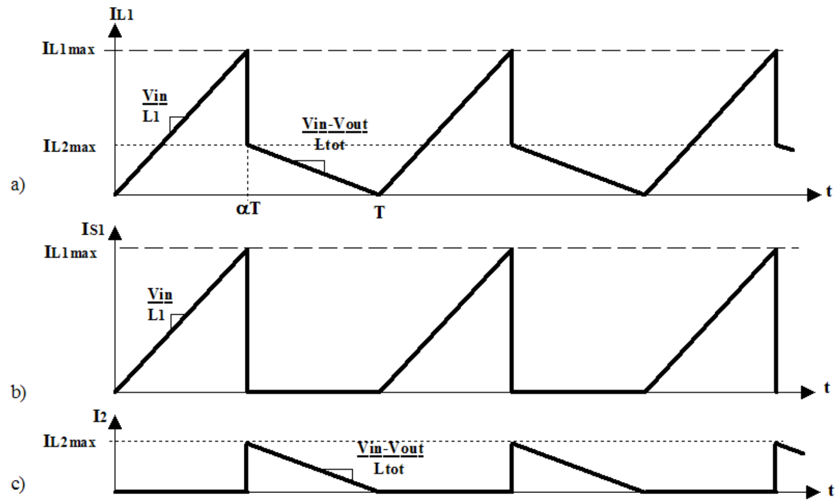

Figure 6. Typical currents in the CC-BC: (a) current in the input inductor L_1, (b) current in the MOSFET used as a switch, (c) current in the second inductor L_2

We can explain and comment the operation principle as follow. At first, when S_1 is closed and taking into account the coupling sign of the coils, only L_1 is crossed over by the input current. The index i is equal to 1 in Equations 7 and 8. The current frame in the inductor is the same as the one provided in a basic boost converter, following a linear increase, as shown in Figure 6a as long as the inductor L_1 is not on saturation. In case of saturation of L_1, the decrease of the inductor will induce a non-linear evolution of the current in the coil. At second, when S_1 opens, both coupled inductors are implicated in the restitution current and the index i is equal to 1+2 in Equations 7 and 8, which indicate that as the recovered energy is done in a higher self-inductance, the decrease rate is different according to the basic boost converter. The abrupt variation of the current I_{L1} in the inductor L_1 during this phase is explained by the instantaneous transfer of the initial energy from L_1 to $L_1 + L_2$ adding a large number of turns in the system. The efficiency of the CC-BC is improved by an adjustment of the duty cycle at about 50%, as shown in Figure 6. This symmetry suggests the equilibrium between the loading phase and the recovered energy phase. This can be done by an adjustment of the transformation ratio by a judicious choice of the number of turns. From Equation 7 and considering the conservation of the energy in the inductors during the two phases of a cycle, we can write

$$\left(\frac{I_{e\max}}{I_{L2\max}}\right) = \frac{N_1 + N_2}{N_1} = (1+m) \quad (9)$$

where m, the transformation ratio of the transformer equals to N_1/N_2. The currents IL_{1max} and IL_{2max} are defined during the two phases and they are linked to the duty cycle by respectively.

$$I_{L1\max} = \alpha T \frac{V_1}{L_1} \text{ and } I_{L2\max} = I_{L2max} = (1-\alpha)T\frac{(V_2 - V_1)}{L_{tot}} \quad (10)$$

Finally, according to the Eqs. 9 and 10, we can write

$$(1+m)\frac{\alpha}{1-\alpha} = \frac{V_2 - V_1}{L_{tot}} \quad (11)$$

Thus, Equation 11 shows that when considering the voltage in the inductors, we can choose the transformation ratio allowing an adjustment of the duty cycle to about 50% of the total cycle duration.

We have simulated with Orcad such a CC-BC in a real situation, i.e. with all parasitic elements neglected in the first theoretical approach presented above, with the practical values of the discrete elements reported in the schema of Figure 7.

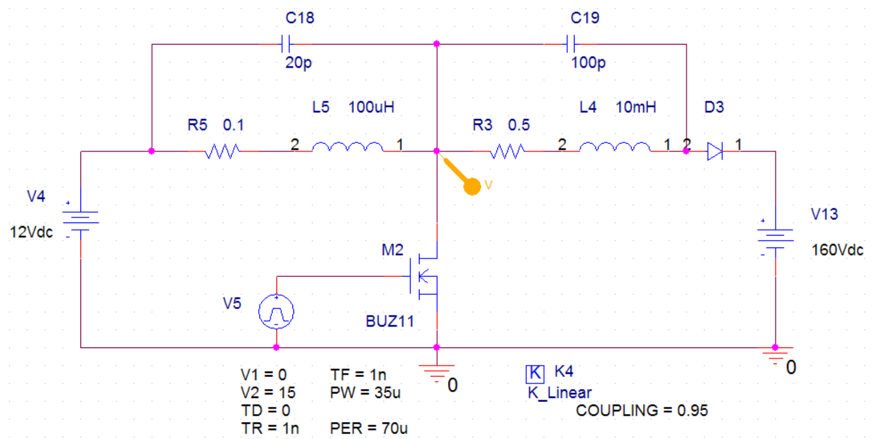

Figure 7. Electronic diagram of the ideal CC-BC including all parasitic elements.

We have considered in the simulation the connection of a converter to a load with an output voltage equal to $150V_{DC}$. The results of the simulations of the current in the MOSFET and the voltage V_{ds}, recorded at the middle point of the set-up, i.e. between the two coils, are shown in Figure 8.

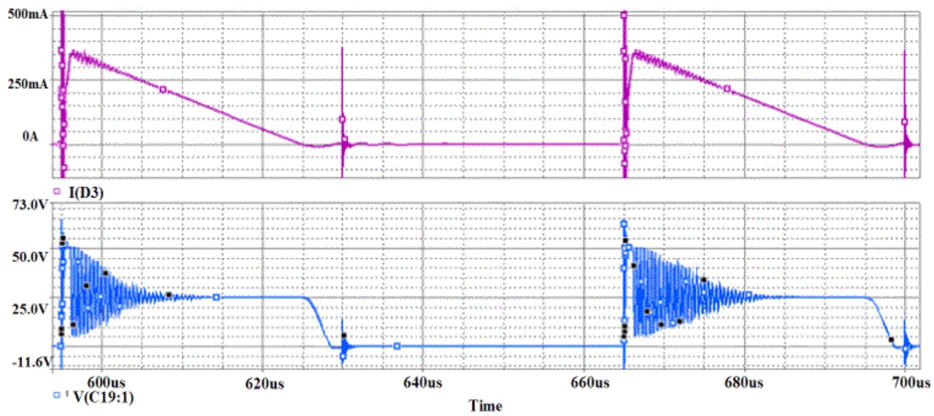

Figure 8. Chronograms of current and voltage in the CC-BC

We clearly observe some resonance phenomena in the two coils witch perturb the current and which appear during the all cycle. In the first phase of the switching cycle, we can observe a low frequency pseudo-oscillation of the current originate from the diode capacity D_3 and C. This transient phenomenon is superposed by a second oscillation caused by the interruption of the current in the MOSFET, the capacity of which coupled with the leakage inductor of the autotransformer generates resonances. In the second part of the cycle, when the switch opens, we observe a high frequency pseudo-oscillation for the recovery current and for the voltage V_{ds}. The peak of the over-voltage, $V_{ds\text{-}peak}$ induced by these resonances can reach the same level as the output voltage used for the boost, e.g. it can reach 75V in the present set-up, as shown in Fig. 8. This oscillating phenomena in real system yields to use a high voltage MOSFET, which thus raises, as sawn before, the problem of the presence of a transistor with a high R_{dson}, causing a drastic losses increase and performance deterioration of the converter.

As we have shown in this study based on simulation and measurements done on a real prototype dedicated for photovoltaic applications, the first innovation of the CC-BC architecture, comparing to the basic step-up converter is the possibility of this system to adjust the duty cycle to 50% in spite of imposed external input and output voltages. The second advantage of this structure is the use of a low voltage MOSFET to insure the switching function even for high output voltage assuming high efficiency conversions.

4. CONCLUSION

The powerful conversion of low DC voltage from photovoltaic panels or wind turbine into a HVDC grid able to supply uninterruptible power, implicates simple, reliable and cheap high efficiency converters while supplying voltages higher than 100V. Such high voltage architectures have been considered until recently, as a technologic lock in classical Boosts. In the present study, we have shown, thanks to simulations and measurements on electronic prototypes, that the use of an autotransformer coupled driven by a smart PWM control with a nominal duty cycle near 50% presents a real progress in term of efficiency compared to the basic boost converter dedicated to low and medium power conversion. The consideration of the non-linear relation between V_{dsmax} and R_{dson} of the MOSFET used as the switch in the converter allows modelling of the behaviour of such a boost converter. In this study, some experimental parameters slightly affect the obtained results, such as the coupling coefficient in the autotransformer, which is supposed equal to one and the current-voltage converter, which introduces joules losses. An additional study must be performed to recover the parasitic energy stored in the leakage inductor especially when the coupling coefficient of the coupled coils differs from 1 as in the low-coupled coils.

Different versions of the two improved Step-Up boost converters will be successfully tested with the individual connection of 12V and 40V PV panels to a grid able to supply a standard inverter.

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