

A novel pulsewidth modulation to operate a bidirectional two-stage dc-ac converter with high-frequency isolation in discontinuous conduction mode for photovoltaic applications

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Keywords

<<modulation strategy>>, <<matrix converter>>, <<insulation>>, <<transformer>>, <<battery charger>>, <<photovoltaic>>, <<pulse width modulation>>, <<soft switching>>.

Abstract

This paper presents a novel modulation for a two-stage dc-ac power converter with high-frequency isolation installed in a photovoltaic stand-alone system. The presented modulation, which is designed for the converter discontinuous conduction mode of operation, solves the problem of connection to a grid, and permits a bidirectional power flow. In this document is described the modulation strategy and some simulation and experimental results are presented.

Introduction

In photovoltaic stand-alone systems, a battery is needed in order to interconnect the generation and the demand. The system extracts the maximum energy at any given time. The energy that is not immediately delivered to the load is stored in the battery and will be delivered when the generated power is lower than the demanded power.

The dc-ac converter studied here is the one in charge of converting the dc electrical energy stored in the battery to ac to be injected at a local grid operating as a standard grid (50 Hz, 230 V). The second task that this converter must accomplish is to charge the battery from an electric source connected to the local grid. Therefore, the converter must be able to operate with a bidirectional power flow. Finally, the converter must present galvanic isolation between the input and the output for safety and operation requirements. It is usually solved introducing a transformer [1], [2].

With these specifications: galvanic isolation and ability to operate with a bidirectional power flow, together with specifications related to a low cost and low volume and weight, a converter is chosen and its operation is designed as it is possible to see in the following sections.

Converter topology

The selected converter is the two-stage dc-ac converter with high-frequency isolation presented in Fig. 1, designated as 2PP-V. It is considered an optimal converter for photovoltaic stand-alone systems from the point of view of compactness, low number of auxiliary systems and low transistor losses [3]. Fig. 2 deploys a converter prototype designed to test the performance of the modulation strategy proposed in the following sections.

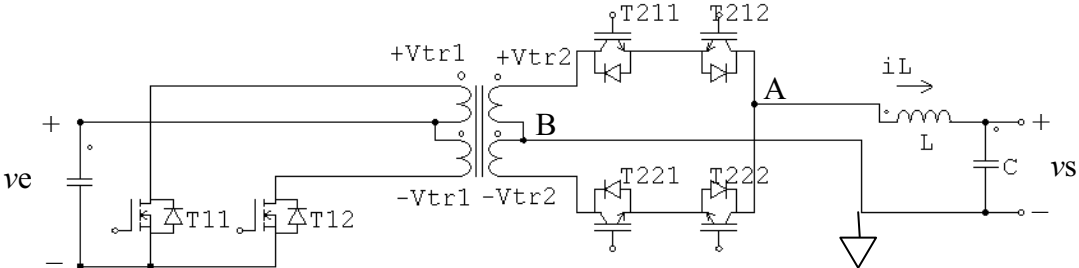


Fig. 1: Converter topology.

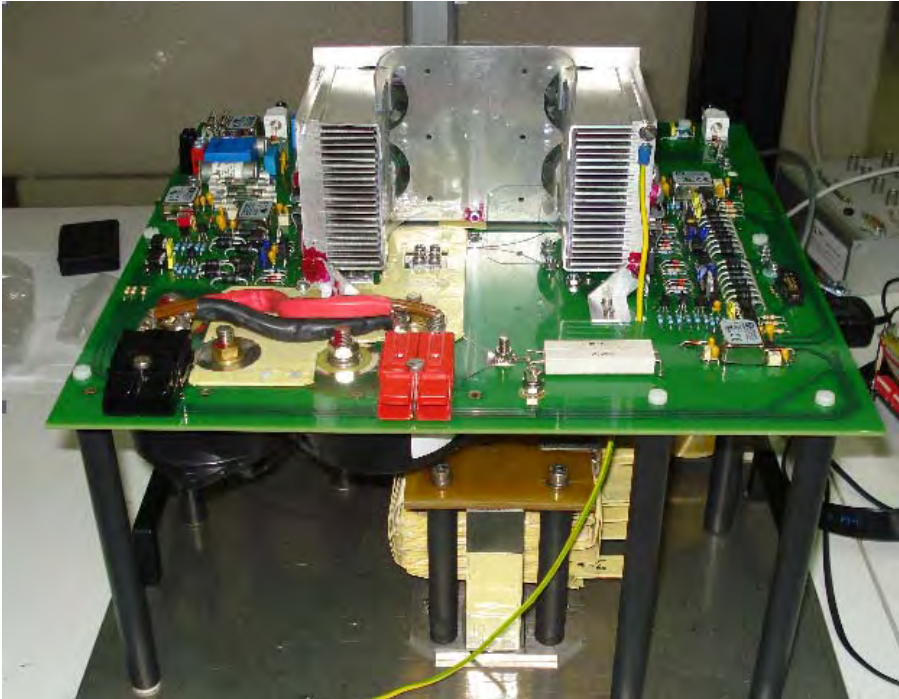


Fig. 2: Converter prototype. $P_n= 3 \text{ kW}$, $L=400 \text{ uH}$, $C= 20 \text{ uF}$, $r_t= 9$, $V_e = 20\text{-}50 \text{ V}$

The first stage of the converter operates as an inverter in order to inject energy to the transformer. The second stage operates as a cycloconverter: it must transform a high frequency square waveform to a pulsewidth modulated waveform with a low-frequency fundamental component [3], [4], and [5].

Operation as a power source

The converter will be operated in discontinuous conduction mode (DCM); i.e., the inductor current i_L will be zero in certain portions of the switching cycle. In this mode of operation the converter allows a good control of short-circuits since the current i_L is forced to zero in every switching cycle. Fig. 3 presents the output-current vs. output-voltage characteristic of a buck converter operating in DCM. It is seen that a converter operating in DCM can be assimilated to a power source. A power source can be connected to a voltage source or to a current source without large current or voltage problems. This is one method to allow the connectivity of the converter to a local grid with other electric sources like a generating set [6], [7], and [8].

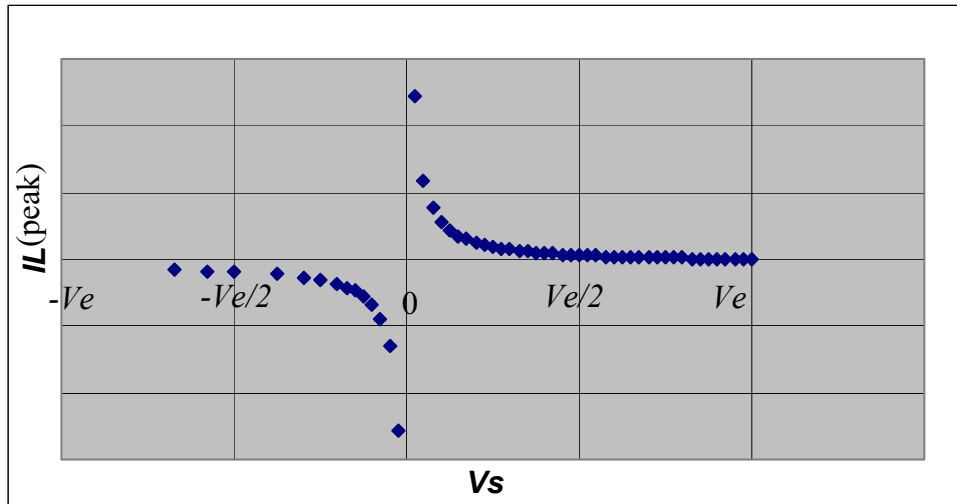


Fig. 3: Output current vs. output voltage in a buck converter operating in DCM.

Proposed pulsewidth modulation in DCM

Fig. 4 shows the 12 different operation stages for which the modulation strategy has to be defined. Each stage corresponds to a particular combination of the polarity of the high-frequency voltage across the transformer, the polarity of the inductor current i_L and the polarity of its slope: positive (Ton), negative (Toff), or zero (Toff⁰).

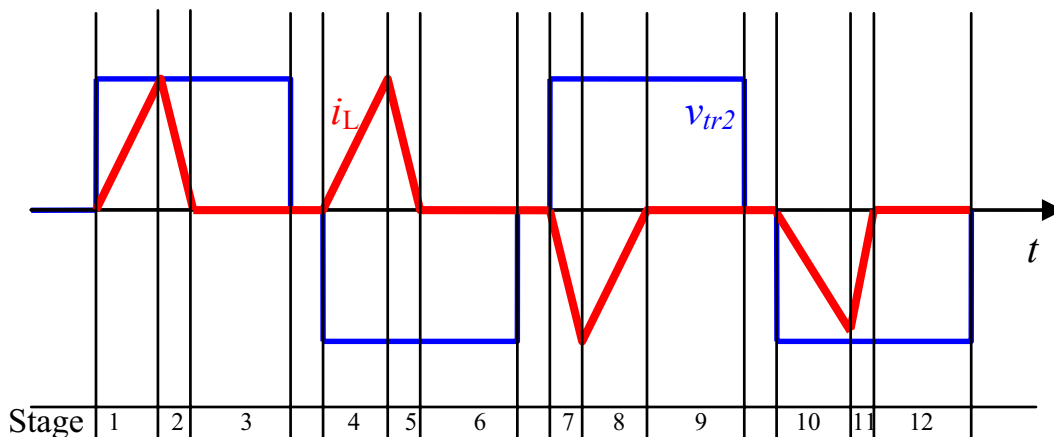


Fig. 4: Operation stages for the 2PP-V converter in DCM.

To achieve the desired operation sequence outlined in Fig. 4, the first step is to define appropriate converter switching states for each converter stage and operation stage. Then, a proper transition among converter switching states has to be defined in order to avoid the short-circuiting of any voltage source, avoid the opening of any current source, and produce minimum switching losses [9],[10], and [11].

For the first converter stage, a square modulation is chosen. For the second converter stage, a modulation defined from a peak inductor current command is employed. For the first converter stage two switching states are defined: T11 off and T12 on (state +); and T11 on and T12 off (state -). The switching states defined for the second converter stage are four. They correspond to the conduction of one and only one of the second stage converter switches, as it is shown in Table I, where the output voltage before the filter (V_{AB}) for each state depending on the inductor current direction is specified. This voltage can be the battery voltage times the transformer turns-ratio (rt) with positive or negative polarity. When there is no current through the inductor, V_{AB} is equal to the output capacitor voltage, V_s , because the inductor voltage is zero. Therefore, its value depends on the operating point.

Table I Switching states for the second converter stage and the corresponding voltage before the filter for different inductor current directions.

Switch positions				Switching state name	V_{AB} with $i_L > 0$	V_{AB} with $i_L < 0$	V_{AB} with $i_L = 0$
T211	T212	T221	T222				
1	0	0	0	EC1	V_{tr2}	-----	V_s
0	1	0	0	EC2	-----	V_{tr2}	V_s
0	0	1	0	EC3	$-V_{tr2}$	-----	V_s
0	0	0	1	EC4	-----	$-V_{tr2}$	V_s

(1: Switch on; 0: Switch off)

The relation between switching states and operation stages is shown in Table II. This table presents the output voltage before the filter and the conducting device in each stage. Since we know the current direction, we can control the voltage before the output filter.

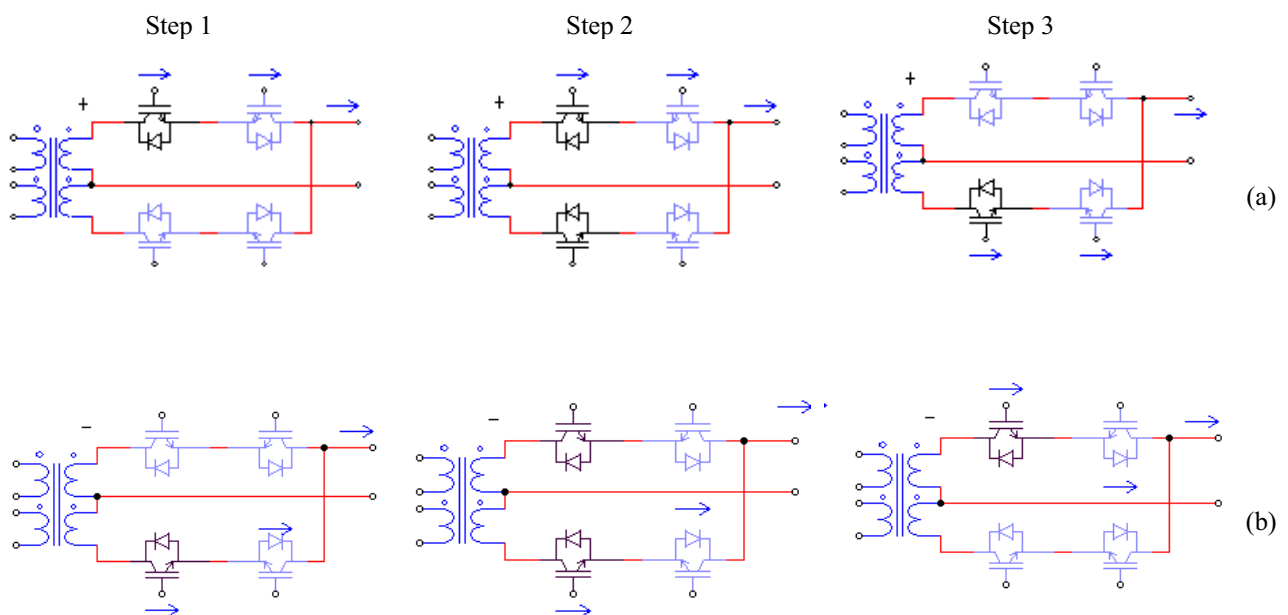
Table II. Operation stages and their conditions

	Operation stage of the converter	1 st stage converter state	2 nd stage converter state	V_{AB}	Conducting device					
					T11	T12	T211	T212	T221	T222
$i_L > 0$	(1)-Ton	+	EC1	$+V_e \cdot rt$	--	T	T	D	--	--
	(2)-Toff	+	EC3	$-V_e \cdot rt$	--	D	--	--	T	D
	(3)-Toff'	+	EC3	V_s	--	--	--	--	--	--

	(4)-Ton	-	EC3	$-V_e \cdot r_t$	T	--	--	--	T	D
	(5)-Toff	-	EC1	$+V_e \cdot r_t$	D	--	T	D	--	--
	(6)-Toff'	-	EC1	V_s	--	--	--	--	--	--
$i_L < 0$	(7)-Ton	+	EC4	$-V_e \cdot r_t$	--	D	D	T	--	--
	(8)-Toff	+	EC2	$+V_e \cdot r_t$	--	T	--	--	D	T
	(9)-Toff'	+	EC2	V_s	--	--	--	--	--	--
	(10)-Ton	-	EC2	$-V_e \cdot r_t$	T	--	--	--	D	T
	(11)-Toff	-	EC4	$+V_e \cdot r_t$	D	--	D	T	--	--
	(12)-Toff'	-	EC4	V_s	--	--	--	--	--	--

(T: Transistor; D: Diode)

Fig. 5 defines how the transitions between the operating states occur. The transformer output is never shorted and the inductor is never opened. Each transition starts with the charging of the inductor (Ton), where the voltage polarity across the inductor is positive. Then, the inductor voltage polarity changes to negative in order to discharge the inductor (Toff). This change is forced when the instantaneous current reaches the peak command value. The output inductor is discharged until its current reaches 0 A. Then, without changing the switching state, the inductor remains discharged (Toff') waiting for a new period of conduction. It is not necessary to define a new switching state for Toff' stages and it is not necessary to detect the zero current condition of the inductor. This is thanks to the fact that the opposite current direction is forbidden by the diode in opposite polarity.



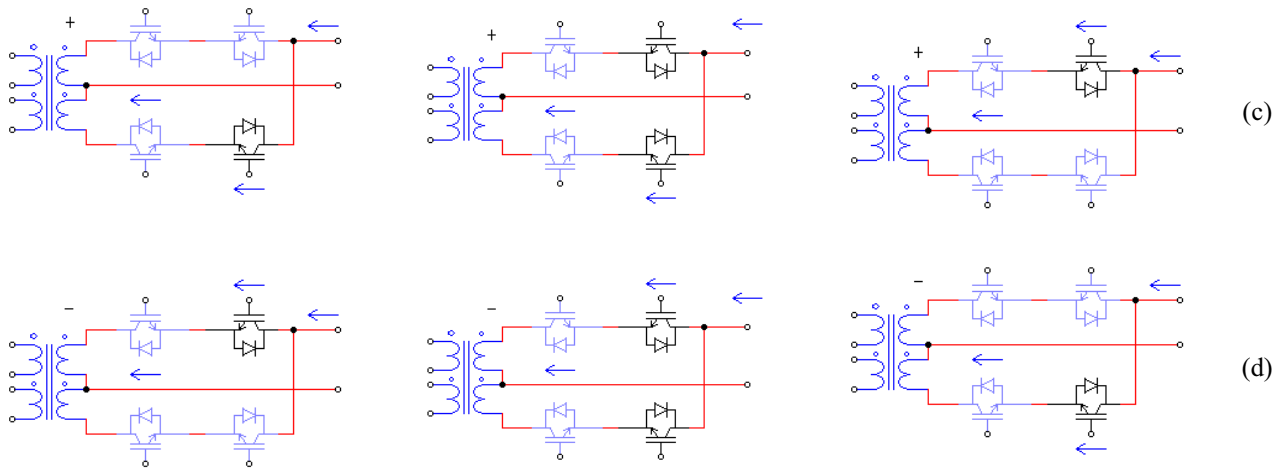


Fig. 5: Transitions among converter switching stages for 2PP-V operating in DCM. (a) Transition between 1 (Ton) and 2 (Toff) stages. (b) Transition between 4 (Ton) and 5 (Toff) stages. (c) Transition between 7 (Ton) and 8 (Toff) stages. (d) Transition between 10 (Ton) and 11 (Toff) stages. (Black devices: on; blue devices: off)

Simulation and experimental results

Fig. 6 and Fig. 7 show simulation and experimental results that prove the good performance of the proposed PWM strategy. A voltage closed-loop is used to define the reference peak value of the inductor current \hat{i}_L in order to have a sinusoidal voltage across the output capacitor and we can see the results in Fig. 6. In Fig 7 we can see some results in open-loop.

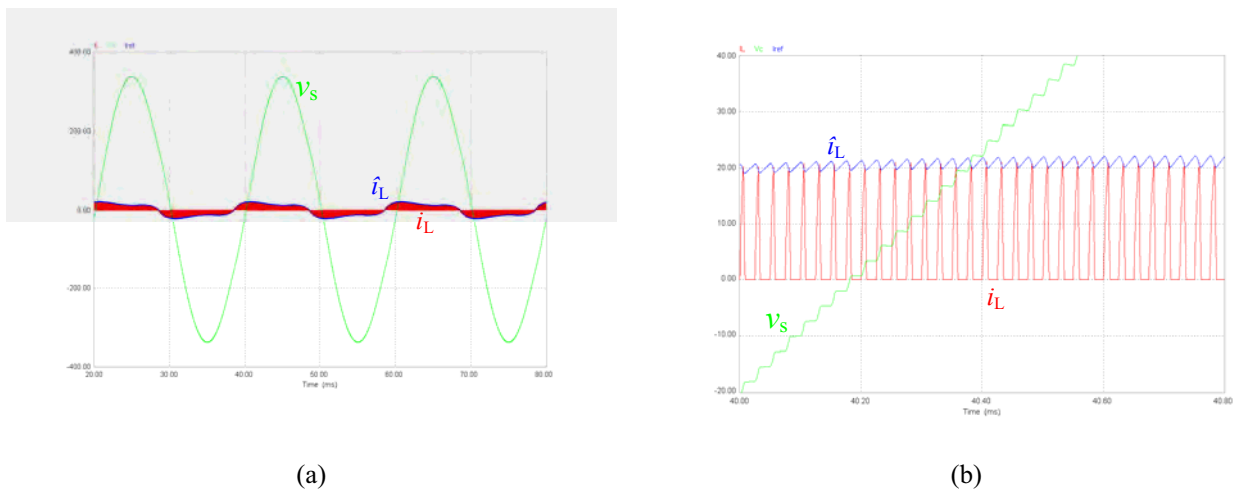


Fig. 6: Simulation results for the converter output voltage v_s , inductor current i_L , and reference peak inductor current \hat{i}_L in the following conditions: $V_e = 48$ V, transformer turns ratio $rt = 12.5$, $L = 100$ μH , $C = 40$ μF , $f_s = 20$ kHz and load resistance $R_{\text{Load}} = 50$ Ω . With a voltage closed-loop (a) Three output line-cycle view. (b) Zoom of Fig. 6(a).

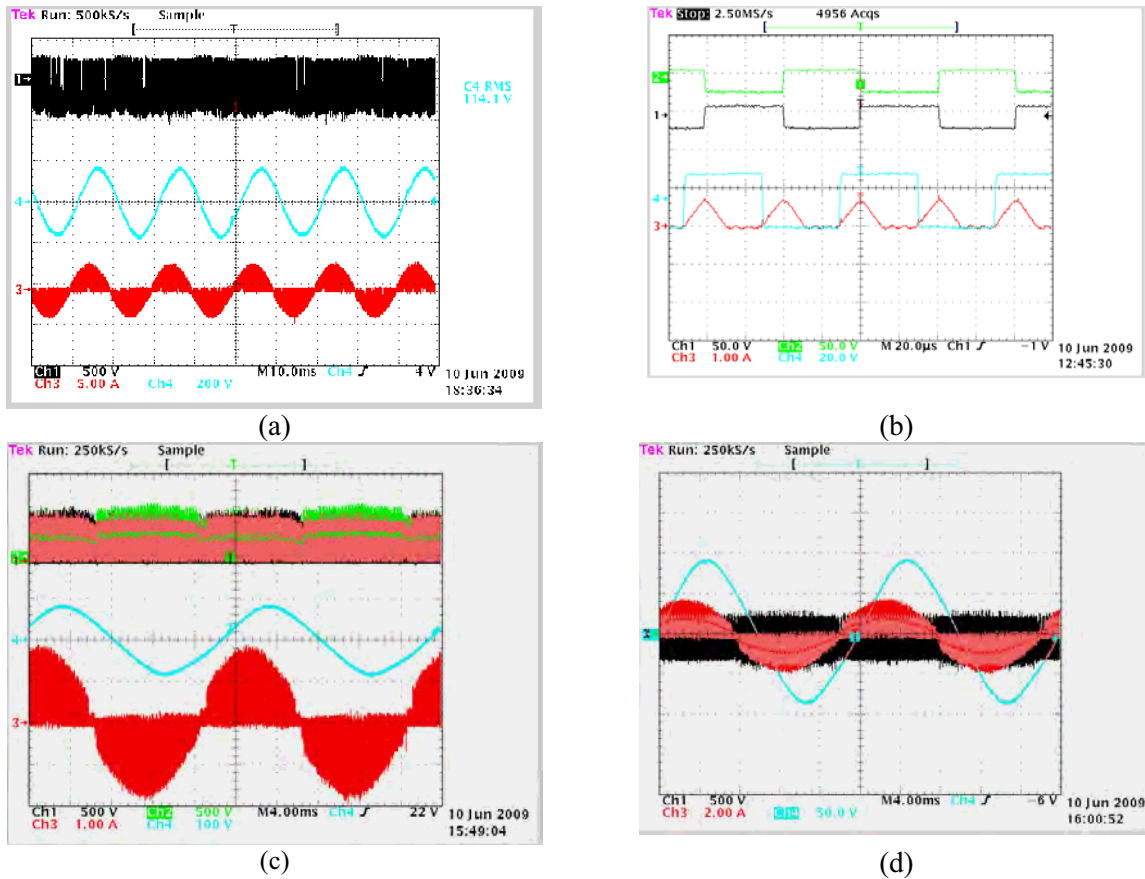


Fig. 7: Experimental results of 2PP-V operating with the designed modulation.. :The converter output voltage v_s , inductor current i_L , and some transistor voltage and transistor control signals in the following conditions: $V_e = 25$ V, transformer turns ratio $rt = 9$, $L = 400$ μ H, $C = 20$ μ F, $f_s = 12$ kHz and load resistance $R_{Load} = 120$ Ω . In open-loop operation for different reference current: (a) Output voltage before filter (black), output voltage after filter (blue) and inductor current (red) (b) Detail of inductor current (red) with gate signals of T12 (blue), T211 (green) and T221 (black), (c) Output voltage after filter (blue), inductor current (red), voltage in T221 and T222 (green and black) (d) Output voltage before filter (black), output voltage after filter (blue) and inductor current (red).

Conclusion

In this paper, the operation of the 2PP-V converter in DCM is tested. This converter is one of the most compact bidirectional two-stage dc-ac converters with high-frequency isolation, optimum from the point of view of cost and volume. The operation in DCM allows the connection of the converter to a voltage or current source without problems, which is a good feature when a connection to a local grid is desired.

The proposed PWM is optimum from the point of view of losses and minimum sensing requirements. It has been designed taking advantage of natural commutations and with no zero current detection. These are good properties for reliability and efficiency, which are important in remote places where there is no electrical utility.

References

- [1] M. Mata Dumenjó: "Sistemes d'aprofitament d'energia solar fotovoltaica aïllats de la xarxa de distribució" Jornades d'Electrònica de Terrassa, Dec. 20, 2000.

- [2] G. Venkataramanan and G. and M. Illindala: "Small Signal Dynamics of Inverter Interfaced Distributed Generation in a Chain-Microgrid." IEEE Power Engineering Society General Meeting, 2007, pp. 1-6.
- [3] M. Mata Dumenjó: "Ondulador reversible amb aïllament a alta freqüència per aplicacions fotovoltaïques" Phd . Departament d'Enginyeria Electrònica, Universitat Politècnica de Catalunya, June 2002- April 2009.
- [4] R. L. Cardoso and I. Barbi,: "New bi-directional DC-AC converters with high frequency isolation." International Symposium on Signals, Circuits and Systems, 2005, pp. 593-596.
- [5] Y. Xue, L. Chang, S. B. Kjaer, J. Bordonau, and T. Shimizu: "Topologies of Single-Phase Inverter for Small Distributed Power Generator and Overview" IEEE Trans. Power Electronics, vol. 19, pp.1305-1314, Sept. 2004.
- [6] R.D. Middlebrook and Slodoban Cuk: "Advances in Switched-Mode power Conversion" Telaco 1983.
- [7] D. Maksimovic and R. Erikson: " Advances in Averaged Switch Modeling and Simulation ", Power Electronics Specialists Conference, Tutorial, 1999.
- [8] H. Valderrama-Blavi,: "Gestión Inteligente de un ondulator Modular para Aplicaciones Fotovoltaicas" Ph.D. thesis dissertation, Universitat Politècnica de Catalunya, 2001.
- [9] M. Barenys Espadaler, "Ondulador bidireccional monofàsic en MCD"." Final Degree Thesis, Universitat Politècnica de Catalunya, Juny 2005.
- [10] S. Xiangdong, S. Xiangdong, Z. Yanru, R. Biying, and Z. Bing: "Research on the control of phase-shift controlled high-frequency link cycloconverter." Power Electronics and Motion Control Conference, 2004. pp. 468-472.
- [11] C:Zimmermann, A.Rufer, and C. Chabert: "Non-linear properties and efficiency improvements of a bi-directional isolated DC-AC converter with soft commutation." Industry Applications Society Annual Meeting, 2005, pp. 1985-1991.