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Single-Phase AC/DC PWM Converter with Output Voltage Cell Performance Characteristic for Four-Quadrant AC Traction Systems

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Abstract: - This paper presents a new and original ac/dc single-phase converter topology suitable to be applied in alternating-current traction systems. This topology uses eight power switches (two legs) and an inductor--capacitor dc-bus. This converter provides bi-directional power flow with constant output voltage, by means bi--directional current, and can be used for supplying DC systems, including DC/AC converters for variable speed drives. The overall control strategy for providing DC-bus voltage, PWM signal generation, and simulated results are presented.

Key-Words: - Traction systems, PWM, drives, bi-directional power converter.

1 Introduction

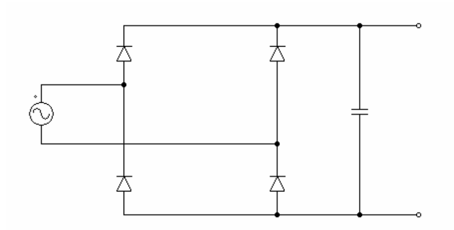
Single-phase to three-phase power conversion systems for supplying three-phase loads, for example induction traction motors, usually employs a full bridge topology, where the ac/dc conversion is usually made by means diode rectifiers, as presented in Fig.1(a). This solution presents a low price and no needs control circuitry, however regenerative braking operation is not available.

In industrial applications where the regenerative braking is fundamental, two ac/dc thyristor anti--parallel bridge rectifiers are used, as can be seen in Fig.1(b), where eight power semiconductors are necessary. The bridge with T_{i1} switches is employed for first and second quadrants, whereas T_{i2}-switch bridge is used for third and four [1].

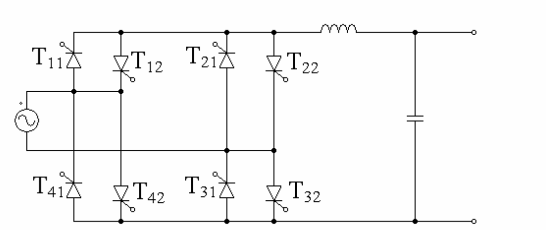
A low power factor (PF) as well as a high supply--side current total harmonic distortion (THD) are presented with this solution. Thus, a major drawback to this converter is the need of a supply-side active compensator for the reactive power and harmonic distortion created [1].

More recently hard-switched bridge converters have been proposed, one of which is shown in Fig.1(c). These converters are capable of a bi--directional conversion, however high supply-side inductive filters must be used. In addition the supply--side currents are also high [1,2,3,4].

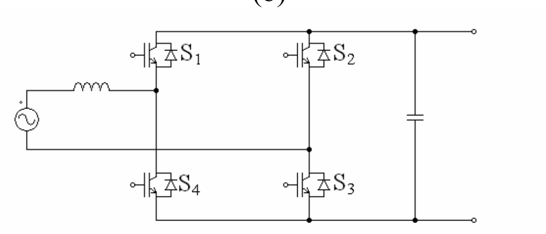
A new and original 8-switch, four-quadrant, hard-switched, ac/dc single-phase converter, giving the advantages of a good PF, a low THD, and smaller filters, is proposed in this paper.



(a)



(b)



(c)

Fig.1 Conventional single-phase AC/DC converter topologies.

2 Converter topology

The configuration of the proposed single-phase ac/dc converter is shown in Fig.2. This converter comprises eight switches, an intermediate inductive link and a capacitor bank (note that batteries can be used for uninterrupted power supply) at the DC-bus.

The proposed converter results of an association between two hard-switched bridges, where the bridge with S_{i1} switches is employed for first and second quadrants, whereas third and four quadrant conversion is provided by S_{i2}-switch bridge.

The major difference between the proposed topology and that shown in Fig1(c) consists in the current smooth reactor location, allowing a reactor and a supply optimized design (best relationship between rated voltage and current). On the other hand, because commutation strategies avoid supply-side short-circuit situations, the converter duty cycles became more stable.

3 Control strategy

Any ac/dc switched converter has its control strategy related with the input voltage. Thus, the switching times must be synchronized with the supply voltage. Due to the configuration of each converter leg (two n-type IGBTs assembled in series and opposition), there is no freewheel natural way to reactor current discharge. Then, this circuit difficulty must be present in the definition of the control strategy.

The implemented commutation strategy is a PWM, Pulse-Width Modulation, determined directly from the source voltage, for synchronization reasons. The PWM gating signal will be generated by comparing a modulated reference signal with a high frequency triangular carrier signal.

The methodology to obtain the modulated signal is shown in the block diagram of Fig3. As can be seen a PI controller with voltage feedback to stabilize the output DC voltage is used to reduce the error between the V_{outDC} and its reference value V_{ref}.

Considering first quadrant conversion a positive output voltage associated with a positive output current must be applied to the load. Thus, the switching pattern concerning switches S_{ij}, being i the

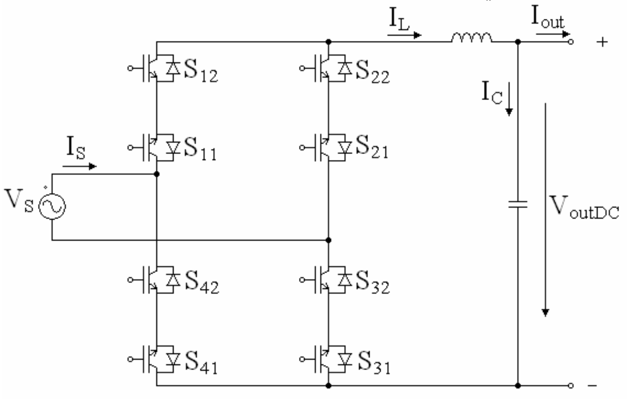


Fig.2 Proposed AC/DC converter topology.

switch number of bridge j, is as follows.

	S_{11}	S_{21}	S_{31}	S_{41}	S_{i2}
$V_S>0$	PWM	$\overline{PWM}$	1	0	0
$V_S<0$	$\overline{PWM}$	PWM	0	1	0

In the fourth quadrant conversion, the energy will be delivered from load to the supply, with positive voltage and negative current in the load-side, becoming the following switching pattern:

	S_{12}	S_{22}	S_{32}	S_{42}	S_{i1}
$V_S>0$	PWM	$\overline{PWM}$	1	0	0
$V_S<0$	$\overline{PWM}$	PWM	0	1	0

In the third quadrant conversion, a positive power will be delivered to the load with both negative voltage and current, having the following pattern:

	S_{12}	S_{22}	S_{32}	S_{42}	S_{i1}
$V_S>0$	$\overline{PWM}$	PWM	0	1	0
$V_S<0$	PWM	$\overline{PWM}$	1	0	0

In the second quadrant conversion, the energy will be delivered from load to the supply, with negative voltage and positive current. In this situation the pattern table becomes:

	S_{11}	S_{21}	S_{31}	S_{41}	S_{i2}
$V_S>0$	$\overline{PWM}$	PWM	0	1	0
$V_S<0$	PWM	$\overline{PWM}$	1	0	0

Taking into account that static dc generators (batteries) are two-quadrant (first and fourth) apparatus, the control strategy was designed to comprise only this item. Thus, the system must be able to maintain a given capacitor positive for any load.

Another important issue is referred to transition between the utilization of converter 1 and converter 2. In this case it is necessary to impose a zero value to the PWM signal, and wait that the reactor current becomes null to make the transition. This will prevent high voltage in the link reactor and consequently in the converter switches.

Fig.4 presents the control system block diagram of the converter, and the definition process of the binary state variables S_{ij} of the switches. Note that, with microprocessor control, the system performance and stability have a significant increase [5].

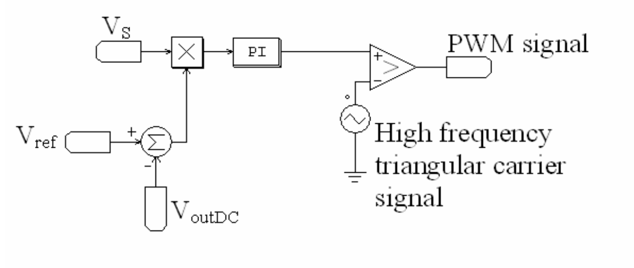


Fig.3 Block diagram for the PWM generation.

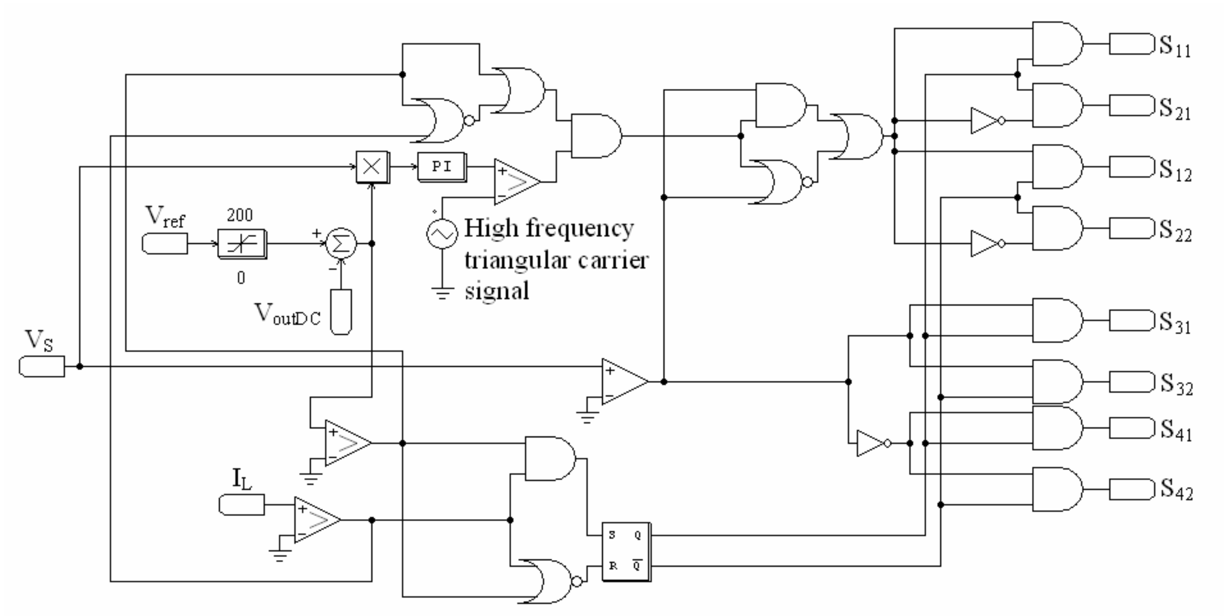


Fig.4 Control block diagram.

4 Converter voltages

Consider the collector to emitter voltage drop of the IGBT as V_{Sij}, being V_{Dij} the corresponding anti-parallel diode anode-cathode voltage. These voltages, as well as the output DC voltage V_{outDC} and the reactor link voltage V_L, depend of the conduction state functions of the switches defined in terms of binary variables S_{ij}, the source voltage V_S and the load level. Thus, the following expression can be determined to achieve de output DC voltage:

$$V_{outDC} = V_S \cdot (S_{11} \cdot S_{31} - (1 - S_{11}) \cdot (S_{41}) + S_{12} \cdot S_{32} - (1 - S_{12}) \cdot (S_{42})) - V_L \quad (1)$$

where V_{outDC} and V_L are both functions of the current, as expressed in (2) and (3):

$$V_{outDC}(T) = \frac{1}{C}\int_0^T I_C(t)\partial t \quad (2)$$

$$V_L = L\frac{\partial I_L(t)}{\partial t} \quad (3)$$

$$I_L = I_{out} + I_C \quad (4)$$

Eq. (3) emphasizes the need of waiting that the reactor current equals to zero, during the changing of operating quadrant. This proceeding avoids high gradients in reactor current, and consequently semiconductors high peak voltages.

5 Simulation results

In this work the model was implemented in the PSIM program of Powersim Inc. and a generic RLE load was defined. Thus, the power circuit becomes as represented in Fig.5. In this model the reactor link inductance is 200mH and the capacitor bank value of the DC-bus is 8.8mF.

An important aspect to analyze is the output error, expected to be dependent of the both delivered current and input voltage. A two seconds time was defined as maximum stabilization time admitted. An simulation example is represented in Fig.6, where a 0.5Ω and 0.1H load was used. The e.m.f. E was regulated in steps of 40V to experiment several load current levels. The supply voltage is the 230V 50Hz grid voltage and the frequency of the triangular carrier signal is 1kHz.

As can be seen the error is nearly independent from the load and is approximately 10% of the reference value fixed in 230V (the same of the root mean square of the input voltage).

The system presents high errors for high references, and for references lower than 207V (maximum rectifier average value) the error is null.

Finally, Figs.7 to 10 show steady-state simulations concerning first and fourth quadrant. As can be seen good achievements have been obtained in harmonic distortion and power factor in the supply-side.

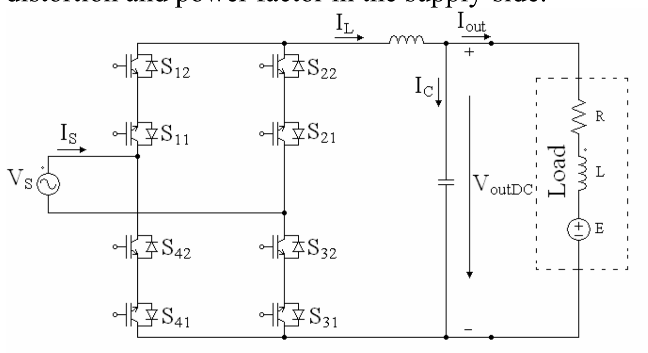


Fig.5 Simulated circuit topology.

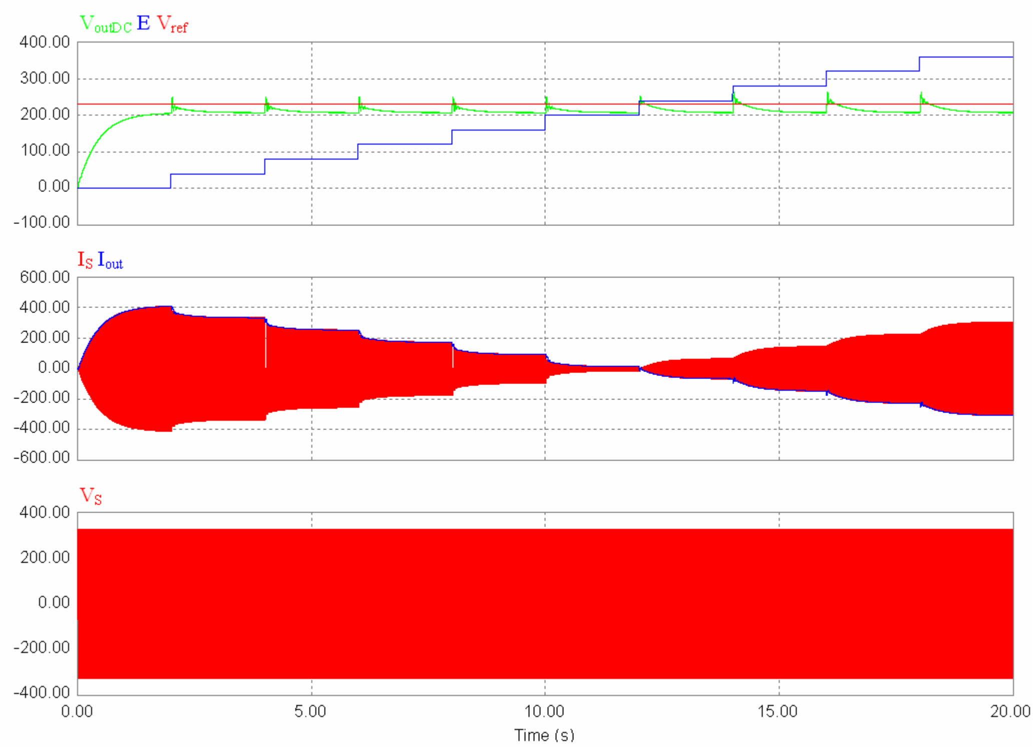


Fig.6 System response to load variation.

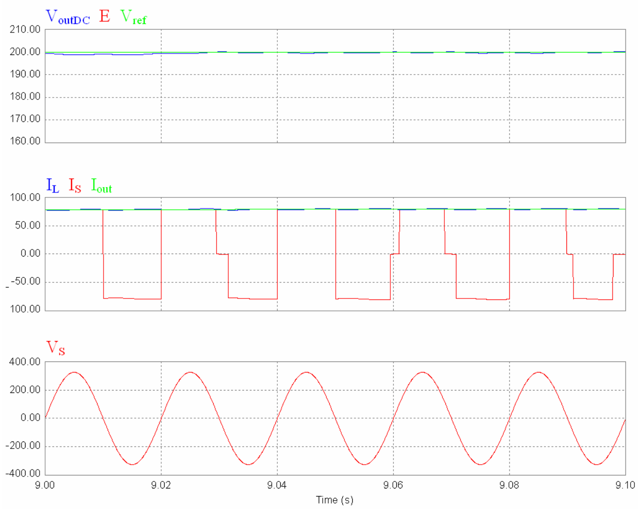


Fig.7 System performance in first quadrant.

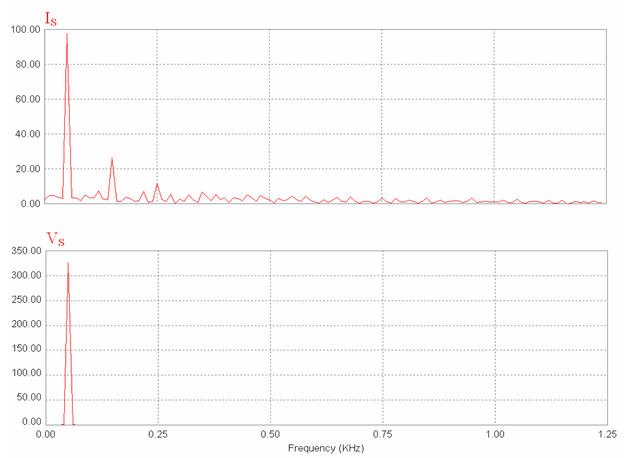


Fig.8 FFT of the supply current in first quadrant.

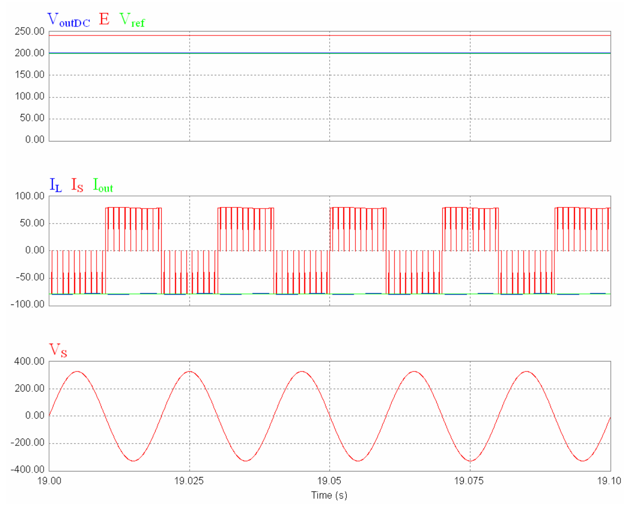


Fig.9 System performance in fourth quadrant.

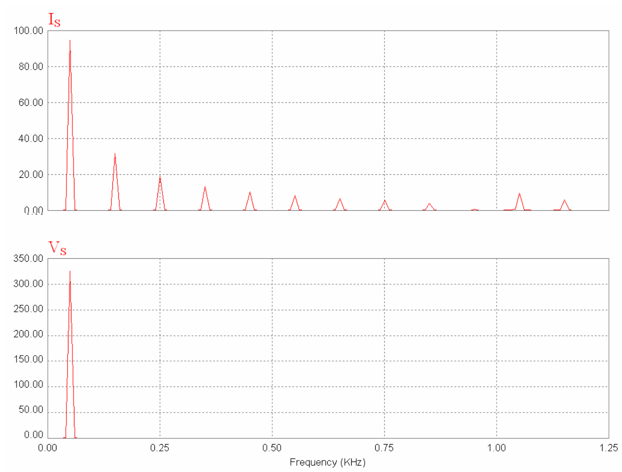


Fig.10 FFT of the supply current in fourth quadrant.

6 Conclusion

This paper has proposed a new single-phase, 8-switch, 2-leg, hard-switched ac/dc converter for supplying dc systems from a single-phase grid. This converter is particularly suitable for traction systems, more concretely motor rolling stock designed for low and medium speeds and equipped with any electric motor.

Converter control strategies for providing constant output voltage, independently from the load, have been proposed.

The main conclusions about the presented topology are as follows:

- good achievements have been obtained in harmonic distortion and power factor in the supply-side,
- good relationship between reactor rated voltage and rated current,
- good relationship between input and output voltages, specially in regenerative quadrants,
- ability to operate in four quadrants of speed(voltage)/torque(current) diagram, in electrical drives,
- the maximum output voltage to the rms supply--side voltage ratio is equal to the 0.9, i.e. equal to the converter factor.

Note that the literature on single-phase ac/dc converters is relatively sparse, due to the fact that traditionally ac/dc converters are based on three--phase supply-side, and are to be used in conventional industry, like as variable speed electric drives. However these converters are not suitable for electric traction systems, because the ac supply-side is single-phased. Thus, another important advantage of the proposed converter is its ability to be applied directly in electric traction.

This converter is part of a complete project concerning design, construction and testing of a people mover in development for the mountain city of Covilhã, powered by means a linear switched reluctance motor with an original topology, produced in first author's PhD works.

Acknowledgment

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