A More Efficient Current Source Inverter with Series Connected AC Capacitors for Photovoltaic and Fuel Cell Applications

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Abstract

Renewable energy sources such as photovoltaics (PVs) or fuel cells (FCs) are not fitted for direct power grid connection because they deliver DC voltage and current. In addition, they also have a high internal resistance/nonlinear V/I dependence, which is why a power electronic interface is always needed. This paper presents the implementation of a three-phase power electronic interface for PV/FCs that uses a single conversion stage approach based on a current source inverter (CSI) topology with series connected capacitors, that would need only six reverse blocking IGBTs and due to the possibility to reduce the AC voltage at high load, would reduce the size of magnetics and the losses compared to a standard CSI.

1. Introduction

In order to increase the utilization of renewable energy sources such as wind, photovoltaics (PV) or fuel cells (FC) that use hydrogen generated from renewable energy, more research is needed to constantly decrease their specific costs ($/kW installed), an important part being not only the capturing of the renewable energy cheaply, but also interfacing it to the power grid in an efficiently and cost effective way.

There are a few alternative power converter topologies available to connect a PV/FC to the AC power grid [1]-[3]. It could use a two-stage arrangement by using a DC/DC converter (with or without isolation to boost the low voltage typically delivered by the PV/FC to a higher level suitable for a typical DC/AC PWM inverter. If the DC/DC converter is not galvanically isolated, additional precaution when designing the DC/DC inverter should be considered in order to comply with the safety regulations and to contain any potential EMI [3]. In case the DC/DC converter provides galvanic isolation by means of a high frequency transformer, all the latter issues are automatically solved. In addition, the high frequency transformer is small and operates typically with very high efficiency (99%) and because it allows the adaptation of the semiconductor voltage/current levels, it will require an installed power in semiconductors close to the power processed which means it will not be very expensive. A more advanced DC/AC inverter technology may involve the modulation of the high frequency voltage, requiring a more efficient unfolding inverter.

Another solution is to use a DC/AC inverter that converts the DC power delivered by the PV/FC into AC voltage at the supply frequency which is stepped up at the grid level by a low frequency transformer, making this solution the simplest technologically, but due to the large size of a 50/60 Hz transformer, the bulkiest/heaviest.

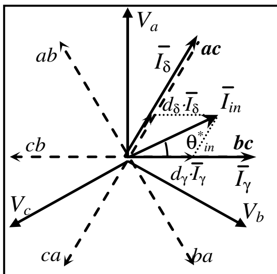
The last solution consists of using a single stage DC/AC converter, which seems the simplest but has several drawbacks: if a Voltage Source Inverter (VSI) which is the most popular grid side interface [3]-[4], is used, a higher voltage level exceeding the peak line-to-line grid voltage level will be necessary on the DC-side (PV/FC) to provide proper operation. In case of a 415 Vrms line voltage, this means that the PV/FCs have to be connected in series to deliver voltage in excess of 585V, which raises serious safety issues [3]. On the other hand, an important requirement is that the current drawn from the PV/FC terminals to have a low ripple, which would require additional DC-side filtering. But these two restrictions make the current source inverter (CSI) [5]-[9] the ideal choice. In addition, the CSI has the capability to boost the voltage from the DC side to the AC side which means that a lower DC-voltage would be needed, solving partly the safety issues. However, this option to reduce too much the DC-side voltage is not economical as the higher the DC/AC voltage transfer ratio is, the higher the installed power in the semiconductors would be and so the cost. Actually, the smallest voltage transfer ratio that a current source inverter can achieve whilst still providing sinusoidal grid currents is 1.154.

In [9], the use of a Current Source Inverter as a PV/FC interface has been explored, and additional new features have been proposed such as the possibility to use efficiently reverse blocking IGBTs, a mixed devices topology to optimize the efficiency and to construct cost-effective multiport configurations. In this paper, the use of a CSI with series connected capacitors to interface PV/FC sources with improved efficiency compared to the standard CSI, will be explored. This solution was used in [10]-[11] in a hybrid active filter application due to the advantage of having reduced voltage rating of the switches compared to the main circuit.

2. Modulation and Control

2.1. Space Vector Modulation for Current Source Inverters

A method often used in modern PWM converter control is the Space Vector Modulation (SVM) [5]. This technique uses a combination of two adjacent vectors and a zero-vector to synthesize a reference vector of variable amplitude and angle. The proportion between the two adjacent active vectors gives the direction, and the zero-vector duty-cycle determines the magnitude of the reference vector. The reference vector for a CSI is the input (AC side) current vector I_{in} (Fig. 1). Similar to VSIs, there are six active current vectors (connection of any given input line-to line voltage with the desired polarity to the DC-link) and three zero current vectors (shorcircuit of the DC link via the two switches in a leg).



DC voltage & input currents vs switching state

Sw.state	γ	δ	0
Ref.vector	"bc"	"ac"	"cc"
V_P=	Vb	Va	Vc
V_N=	Vc	Vc	Vc
V_{PN}	Vbc	Vac	0
Ia=	0	+Idc	0
Ib=	+Idc	0	0
Ic=	-Idc	-Idc	0

Fig. 1. Generation of the reference current vector in a CSI using SVM and I/O voltage and current correspondence for sector 1

A legal switching state of the CSI is produced by turning on one switch in each group of three switches, where a group is defined by the switches that connect every AC input to a particular DC output. As there are two groups (one connecting the AC to the positive DC-link rail, one to the negative), it means that only two switches are on at any time, which also means that if the DC-link current remains constant, the conduction losses of a CSI will remain constant independent on the CSI modulation index.

The switching state of the CSI can be represented by a group of two letters, that designate which of the AC lines are connected to the positive and negative DC-link terminals respectively ("*bc*" means input phase *b* is connected to *P* and *c* is connected to *N*). A zero current vector is normally produced when only two switches in the CSI leg are on, which cause a shortcircuit of the two DC-side terminals that will now be connected also to the input line that corresponds to the ON leg. An interruption in the input currents will appear, as the inductor current freewheels through a single inverter leg switches.

The calculation of the active switching vectors I_γ, I_δ duty-cycles by using SVM, is using (1). The zero-vector completes the switching sequence.

$$d_\gamma = m \cdot \sin\left(\pi/3 - \theta^*_{in}\right) \quad d_\delta = m \cdot \sin\theta^*_{in} \quad d_0 = 1 - d_\delta - d_\gamma \quad (1)$$

where m is the rectifier modulation index and θ^*_{in} the angle within the sector of the input current reference vector. These duty-cycles are multiplied with the switching period in order to determine the on-times of the switches.

Since the input current is synthesized straightforward by the CSI, it means that in applications that would require accurate control of the AC currents (active filters [11]), no additional control is necessary, which is not the case of Voltage source rectifiers/active filters, where even a small presence of low order harmonics can damage the quality of the AC currents unless additional compensation techniques are used.

2.2. Control of the Current Source Inverter with Series Capacitors

The control of the CSI with series connected capacitor can be done in order to achieve low voltage ratings of the switches, similar to [11]. The situation is illustrated in Fig. 2b. It is seen that in order to cause large voltage drops across the series connected capacitor, the CSI needs to draw pure inductive currents. This would not be acceptable in the case of an inverter for PV/FC because of the large conduction losses since in order to produce with the CSI large reactive currents on the AC side, a large DC-link current is needed. Moreover, it is clear that if the CSI injects only reactive current into the AC grid, the active power will be zero, requiring the average DC-link voltage which is also the voltage generated by the PV/FC, to become zero (shortcircuit of PV/FC), leading to an inefficient extraction of the energy from a renewable source. This again leads to the conclusion that lowering the voltage rating by injecting reactive current solely with the CSI is not possible, and therefore, another way of lowering the voltage rating is proposed.

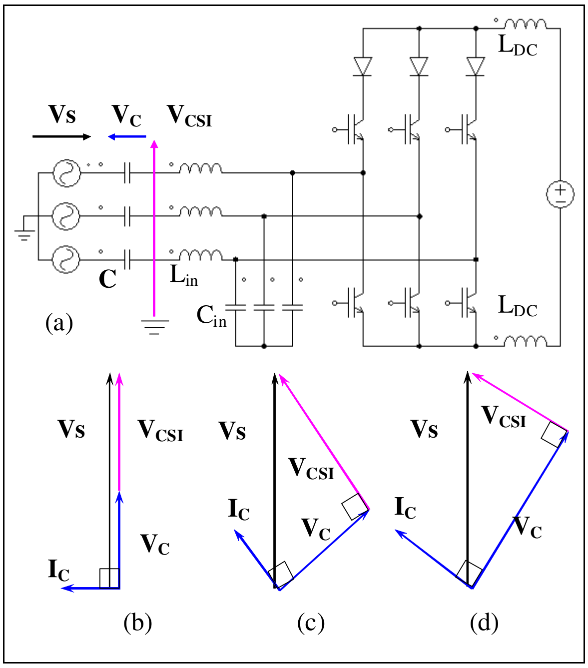


Fig. 2. CSI with series capacitors: a) topology and the phasorial diagram when it operates: b) at no load or with c) low power level; d) higher power level into the grid.

Assuming that it is desired that the CSI injects only active power (reference current to be always in phase or 180 degrees displaced with the phase voltage seen across its input filter capacitor), then a restriction that would make possible the operation of the CSI with series connected capacitor can be formulated. Since the current through the series connected capacitor is always leading by 90 degrees the voltage across this capacitor, and since the vectorial summation of the voltage drop across the series connected capacitor and the CSI input voltage should result in the supply voltage, with the capacitor current and the CSI voltage in phase, it means that the phasor diagram will always consist of a rectangular triangle, with the series connected capacitor voltage and the CSI input voltage 90 degrees displaced. Fig. 2c and 2d illustrate this situation for two different power levels processed by the CSI. It can be noted that the reduction in the voltage seen at the input of the CSI takes place with the increase of the power processed, because more power means higher supply current which when passing through the series connected capacitor would cause a larger voltage drop. If the series connected capacitor is designed to match the external characteristic of the PV/FC, it will be possible to run the CSI in the whole operating range of the PV/FC with little variation of the CSI modulation index and achieve minimum switching losses, as they depend not only on the DC-link current (which is set anyway by the maximum power point tracker: high value of the no-load voltage when the circuit is energized and lower voltage at full load), but also by the amount of AC voltage that is switched during each commutation. Furthermore, by reducing the DC-link voltage ripple at full load, will allow for a smaller CSI DC-link inductance.

Due to this paper page limitation, the full development of the analytical model for designing the series connected capacitors is not included.

3. Evaluation of the Series Capacitor CSI Performance

Simulation models of the standard and the series capacitor CSI controlled by using SVM was implanted in Saber in order to compare their performance. The parameters of the circuit are presented in Appendix A.

3.1. Simulation Results

Fig. 3 shows the simulation results comparing the performance of the standard CSI (left side) with the CSI with series capacitors (right side) at two different DC-link current and voltage levels that correspond to a lighter load situation (Fig. 3a-b) and a heavier load (Fig. 3c-d), in order to accommodate the restrictions imposed by the phasorial diagram as shown in Fig. 2c-d.

Fig. 3a-b shows the supply current, phase voltage of the supply and the phase voltage seen at the input of the CSI bridge at light load (Idc=1.35A). Since the DC-link current is low, the level of the supply current is also low which will cause insignificant voltage drop across the series capacitors denoted by the similar peak levels of the supply voltage and of the voltage at the CSI bridge input (approx 300peak). This also allows for a negligible degradation of the displacement power factor. Fig. 3c-d shows the same set of data in the situation when the DC-link current doubles, which in case of a PV type of DC source, will correspond to a decrease in voltage by a third (221V) from the previous situation (328V). The larger DC-link current level (2.74A) will lead to the necessity to accommodate a larger phase shift of the supply current to comply with the phasor diagram in Fig. 2d and in consequence, the decrease of the displacement power factor reflected by a supply current of 2.2A peak for the CSI with series caps compared to only 1.5Apeak for the standard CSI.

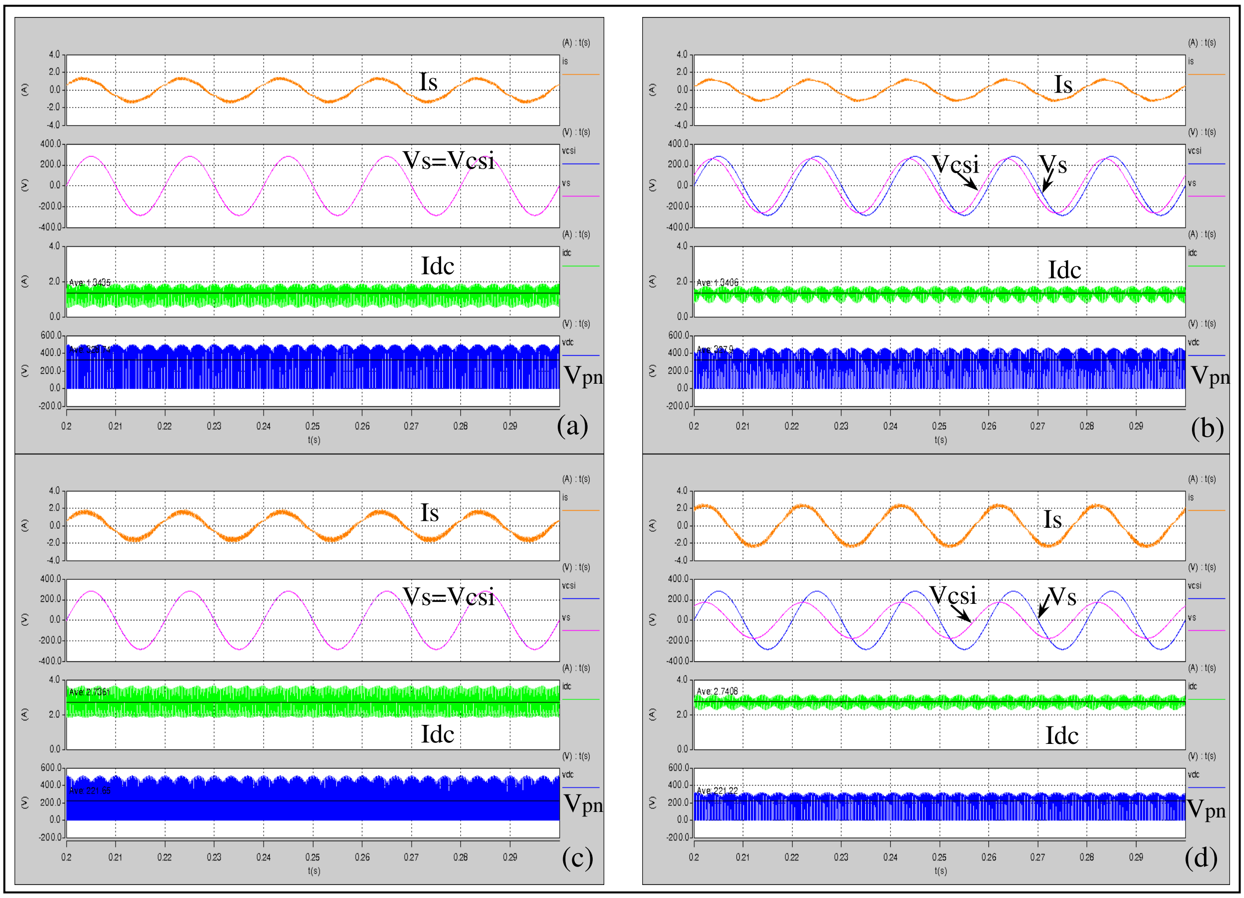


Fig. 3. Simulation results of the standard (left side) vs. the series capacitor (right side) CSI at: a-b) light load (R_L=245Ω);; and c)-d) high load (R_L=81Ω); Waveforms: is: supply current; Vs: phase-to-neutral voltage; Vcsi: input phase voltage CSI side (for series connected capacitors); Idc: dc-link current; Vpn: DC-link voltage on the DC CSI terminals.

This causes a larger voltage drop across the capacitors connected in series with the supply, leading to smaller voltage seen on the AC input of the CSI bridge (180V peak), which means smaller voltage stress and therefore smaller switching losses. The decrease of the AC voltage seen at the CSI input will also reflect in a much smaller DC-link voltage ripple whilst the average is the same with the standard CSI which switches full supply voltage but uses longer zero states. Since in both simulation models the same DC-link inductance is used, a smaller DC-link current ripple is achieved by the CSI with series caps (0.6$A_{pk\text{-}pk}$ compared to 1.6$A_{pk\text{-}pk}$ for the standard CSI). If the converter design aims at limiting the DC-link current ripple, smaller DC-link inductance is possible for the series caps CSI.

3.2. Experimental Results

A laboratory prototype (same circuit parameters as in Appendix A) of a CSI using six reverse blocking IGBTs previously reported in [9] is used to test the proposed topology in rectifier mode using a resistor as load to dissipate the power.

Fig. 4 shows by comparison the experimental evaluation of the standard vs the CSI with series capacitors operating in rectifier mode at two different power levels. Fig. 4a)-4d) shows the situation at light load, which for a PV/FC source would correspond to large voltages (emulated in this experiment by a mean value of 235-250V) and low DC-link currents (approx 1A), where the reduced power flow cause small supply current, therefore the voltage drop across the series connected capacitor (Fig. 4b) is small whish is reflected by the fact that both, the supply voltage Vs and the voltage seen at the CSI input, Vcsi are similar in magnitude.

Fig. 4e)-4h) shows the situation at higher power level. The DC-link currents have similar levels (2.3-2.5A) but the supply current for the standard CSI is only 1 Arms whilst for the CSI with series caps, is much larger (1.5Arms). Even though the supply current and the voltage at the input of the CSI bridge Vcsi remain in phase, the phase shift between Vcsi and the supply voltage necessary to reduce the CSI input voltage makes the supply current to lead the supply voltage (injection of reactive power into the grid even though the active power throughput is the same). The benefits of the reduced input voltage whilst operating at high DC-link current are a clearly reduced DC-link current ripple and smaller switching losses.

3.3. Comparison of Semiconductor Power Losses

Table 1 presents a comparison of semiconductor losses for the standard vs the series caps CSI as included in [9]. The operating conditions (rated supply voltage, 40A DC-link current and a power throughput of 16.2kW) were chosen to match the capability of the reverse blocking IGBT [9].

Table 1. Comparison of Power Losses for a Standard vs. Series Caps CSI using RB-IGBTs

Losses	Standard CSI		CSI with series caps	
Conduction	227.3 W	1.40 %	225.9 W	2.41 %
Switching	247.9 W	1.53 %	210.1 W	1.10 %
Total	475.2 W	**2.94%**	436.0 W	**2.69%**

As expected, the conduction losses in both situations are almost the same mainly because the DC-link current which in average is the same for both converters, always flows through two devices independent on the modulation index and phase shift of the reference input current. A slightly smaller conduction loss for the series caps CSI results because of a smaller DC-link current ripple caused by a smaller DC-link voltage ripple (DC-link inductance is the same). Regarding the switching losses however, a significantly smaller switching loss is caused by the smaller voltage seen at the CSI input for the series caps CSI. In addition, it is expected that this smaller switching voltage ripple will also cause smaller core losses in the DC-link inductor which can be further reduced if a smaller value is chosen since it will be normally designed to impose a certain switching current ripple.

4. Conclusions

In this paper, the application of a Current Source Inverter (CSI) with series connected capacitors for converting the DC power produced by photovoltaic/fuel cells has been proposed. This is achieved by controlling the voltage drop across the series capacitors to match the external characteristic of the renewable DC sources such that the CSI will always operate with highest modulation index, whilst experiencing at the AC input minimum voltage stress. This will directly impact the switching losses which for a given DC link current is given by the AC voltage level, as well as the DC-link filter inductance, typically designed to limit the current ripple caused by DC-link voltage ripple (AC input voltage).

5. Appendix A

Parameters for simulations&experiments: $V_{in\text{-}line}$= 346V_{RMS}; f_{in}= 50Hz; L_{in}=1.4mH; C_{in}= 6.9µF/ph; L_{DC}= 13mH; R_L= 245/81Ω; C=33µF, f_{sw}=5kHz.

6. Literature

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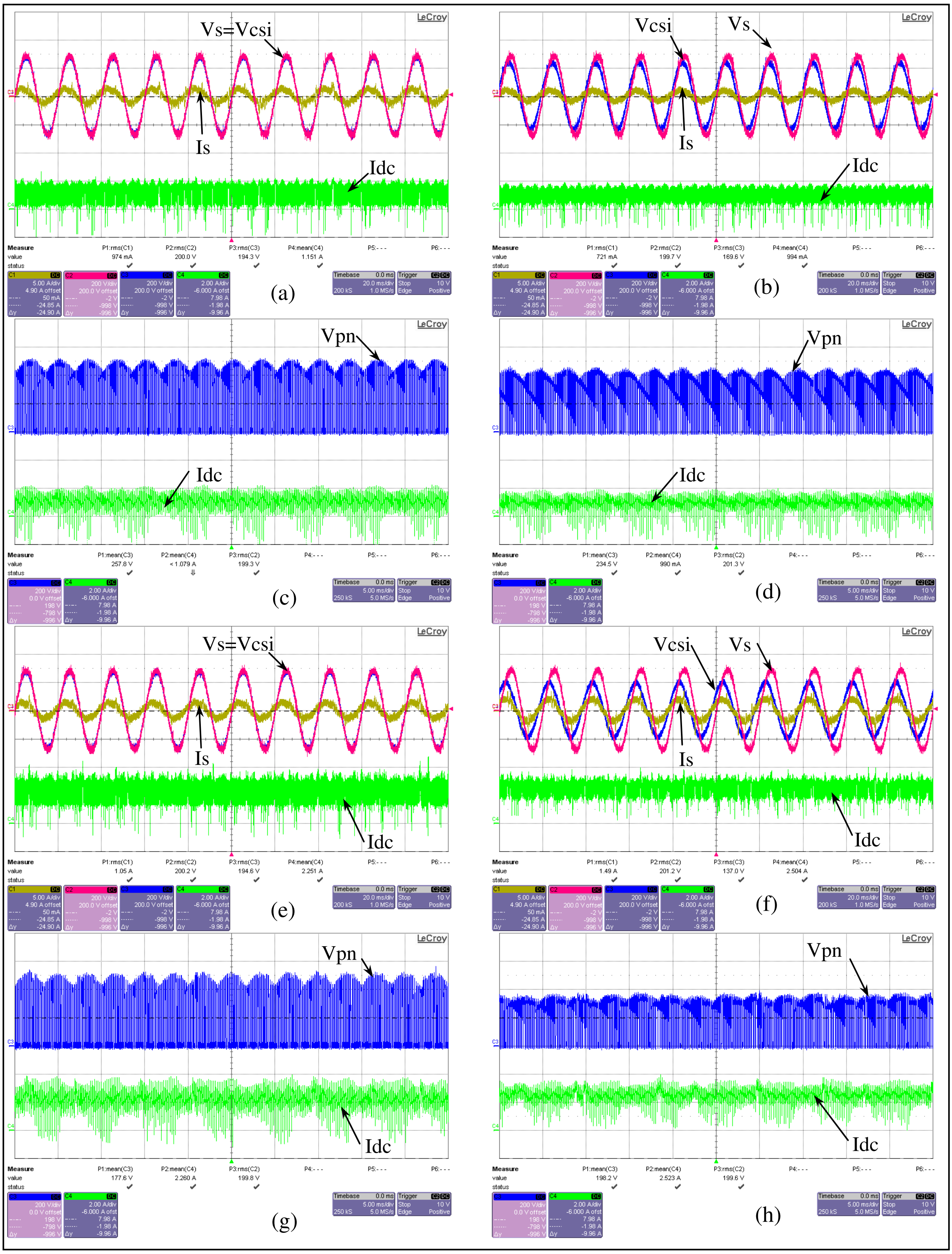

Fig. 4. Experimental evaluation of the standard (left side) vs. the series capacitor (right side) CSI at: a-d) light load (R_L=245Ω); and e)-h) high load (R_L=81Ω); Waveforms: Vs: supply phase-to-neutral voltage; Is: supply current; Vcsi: input phase voltage CSI side (for series connected capacitors); Vpn: DC-link voltage on the DC CSI terminals; Idc: dc-link current. Scales: Voltages: [100V/div]; Currents: [2A/div]; Time: a), b) e), f) [20ms/div]; c), d), g), h) [5ms/div].