SINGLE PHASE GRID CONNECTED CURENT SOURCE INVERTER: MITIGATION OF OSCILLATING POWER EFFECT ON THE GRID CURRENT

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Abstract

Although voltage source inverters (VSIs) are the most common DC-AC grid-tied converters, current source inverters (CSIs) are considered to be promising candidate, thanks to their low THD voltages/currents and inherent short-circuit proof. The natural oscillating power at the DC-link creates the main CSI's single phase application challenge. Hardware based solutions to this problem exhibits additional cost, components and size. Traditional software based solutions detect the oscillating power effect from a second harmonic component in the DC-link current; hence modify the carrier signal to mitigate the oscillation effect on the grid current. Those solutions are characterised mainly by excessive computational burden in addition to poor tracking. In this paper, a Proportional Resonant (PR) controller, tuned at the third harmonic, is utilized to minimize the oscillating power effect from the grid side, and hence acts as a harmonic cancellator (HC). The proposed technique features: (i) simple implementation, (ii) easy tuning, and (iii) superior steady-state elimination. In addition to simulation, experimental setup is implemented to validate the proposed technique effectiveness.

1 Introduction

Exponential growth of renewable energy based distributed power generation (DG) is remarked in the last decade. Hence, DGs are now considered as a potential player in the worldwide power generation market [1-2]. Microgrid concept has been proposed as a solution to the conundrum of integrating several power generation units without disturbing the utility [3-5].

Single phase grid connected inverters are the main DG power electronic based block as they represent the generation-grid link for the energy flow. Although voltage source inverters (VSIs) are common and widely utilized, current source inverters (CSIs) feature increasing attention because of their advantages, like inherent current short-circuit proof, simplified filtering requirement, boosting-up capability, and low THD for their output voltage [6-9].

Despite of these merits, single phase inverters suffer from natural oscillating power characteristic which appears as a second order harmonic in the inverter's DC side and consequently reflected, in the inverter's grid current, as a remarkable third order harmonic.

Several techniques have been proposed to mitigate the oscillating power effect. Classical addition of a third order harmonic signal of the reference was the first trial with a main disadvantage of being open-loop [10]. The technique was improved by feedback control to the added a third order harmonic signal [11]. Mitigation from the DC side by removing the second order harmonic from the controlled DC-link current was introduced with the disadvantage of poor-tracking and sluggish response [12]. A hardware based solution by the addition of parallel resonant circuit to the DC-link inductor was presented but with extra cost, size and complex tuning limitations [13]. Selective harmonic elimination (SHE) based techniques has been introduced as a solution either by calculating the required firing angles for variable modulation indexes [14-15] or injecting predetermined harmonics to vary the carrier signal [16-17]. However, SHE techniques are based on the assumption that the DC link current must be ripple-free and the elimination is effective at particular indexes. The modification of the carrier signal on a pulse amplitude modulation (PAM) base offered a significant improvement in the oscillating power effect mitigation with efficient and simple-implementation technique. The PAM varies the carrier signal with the second order harmonic oscillations in the DC-link current to indirectly mitigate its reflect on the grid current [18-19]. Further mitigation improvement was achieved by nonlinear pulse width modulation (NPWM) which is based on extracting the second order harmonic component from the DC-link current using high computational operations like band-pass filter, low-pass filter, phase-shifter block, and various division operations [20].

Proportional resonant (PR) controllers gained a large popularity in the last decade in current regulation of grid-tied systems [21] especially due to their capability of eliminating steady-state errors when regulating sinusoidal signals as they offer infinite gate at their tuned frequencies [22-24]. Superior performance of PR controllers opens the gate to their expansion in several applications ranging from accurate grid

frequency detectors [25], current sharing of parallel inverters [26], and harmonics extraction in active power filters [27].
PR controllers are considered as robust as H^{∞} controllers even in LCL filter based grid connected inverters [28-29].
In this paper, a technique for single phase CSI's oscillating power effect mitigation is proposed. The presented technique utilizes an additional PR controller as a harmonic compensator (HC) on the grid current to minimize its third order harmonic component. This PR controller is tuned at three times the grid frequency and works independent from the fundamental grid current PR controller, hence named 3HC-PR technique. The proposed technique offers excellent performance with simple implementation without aggressive computational burden.
The paper is organized in six sections. Following the introduction in Section I, system description is discussed briefly in Section II. Classical PAM based technique is investigated in Section III. In Section IV, the proposed technique is presented while the experimental setup is addressed in Section V, with practical results to validate the advantages of the proposed technique. Finally, a conclusion is given in Section VI.

2 System Description

The system under study is a single phase grid connected CSI as shown in Fig. 1where the CSI is connected to the grid via LC filter (L_s, C_s). Four IGBTs (S_1-S_4) and four series diodes (D_1-D_4) forms the CSI power components. A smoothing inductor (L_{dc}) is used in the DC-link side for minimizing the DC-link current ripples. The DC source (v_{dc}) represents any renewable energy source with its associate DC/DC converter as input to the CSI under study.
From control point of view, Fig. 2 shows the control technique adapted in the system under study. PR controller on the grid current acts as the main controller which drives a sinusoidal pulse width modulation (SPWM) block to generate the adequate CSI gating signals. The modulating signal (output from PR controller) is a normal sinusoidal signal while the carrier is a conventional saw-tooth, without modifications. The generated saw-tooth carrier signal is of constant amplitude while the amplitude of the modulating signal is varied by the PR controller.

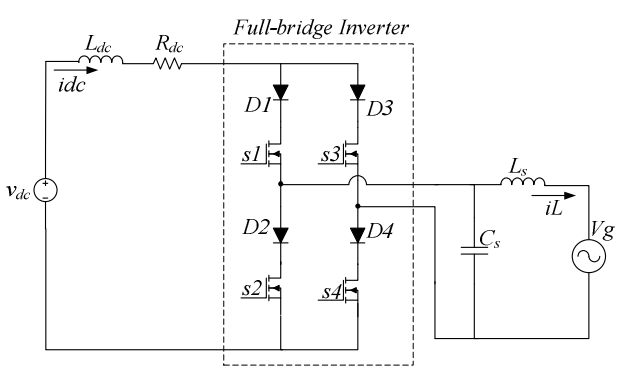


Fig. 1: System configuration

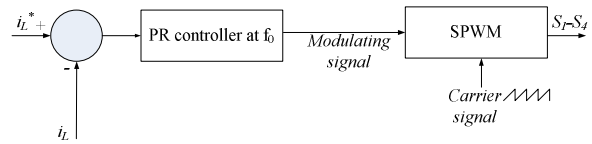


Fig. 2: Control system block diagram

In order to illustrate how the natural oscillating power feature of the single phase CSI affects the grid current harmonics, simulation for the system under study is shown in Fig. 3. The simulated system parameters are listed in Table. 1.

Parameter	*Value*
Grid voltage	220 V
Grid frequency	50 Hz
AC filter inductance	1 mH
AC filter capacitance	30 µF
Switching frequency	3 kHz
Reference grid current	1A

Table 1: Simulated system parameter

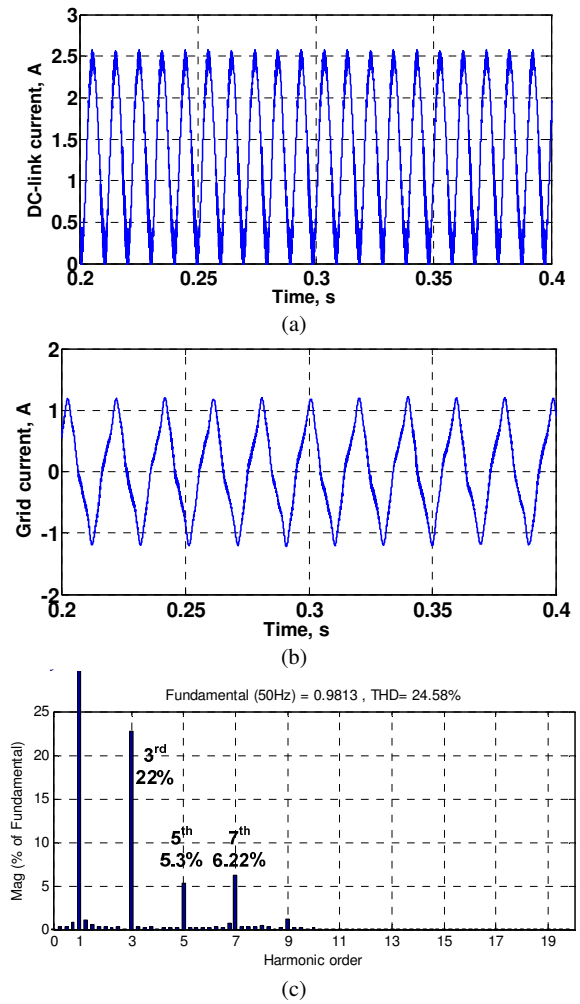


Fig. 3: Simulation results for single phase grid connected CSI without any oscillating power mitigation
(a) DC-link current, (b) grid current, and (c) grid current FFT

Fig. 3(a) show that the oscillating power in the DC side appears in the DC-link current as harmonic component at double the grid frequency. On the other side as shown in Fig. 3 parts (b) and (c), a significant 3rd harmonic component is remarked in the CSI's grid current as a reflection from the DC to the AC side. Form this point; the two philosophies of detecting the oscillating power effect evolve: either indirectly from the DC side by detecting the 2nd harmonic component in the DC-link current or directly from the AC side through the 3rd harmonic component in the grid current.

3 Grid Current 3rd Harmonic Component Mitigation using PAM Technique

In this section, theory and operation of the classical PAM technique is illustrated [18-20]. This technique relies on varying the amplitude of the saw-tooth carrier signal proportionally with the DC-link current. Hence, the mitigation of the oscillating power effect is performed by detecting its effect from the DC side of the CSI. The CSI control block diagram using the classical PAM is shown in Fig. 4 where the variable-amplitude saw-tooth carrier signal generator block is triggered at fixed intervals. The PAM concept varies the amplitude of the inverter current pulses proportionally with their duration in order to keep the pulse area constant.

In order to illustrate the PAM technique, Fig. 5 shows the system performance under PAM technique. As shown in Fig. 5(a), the oscillating nature of the DC-link current is compensated by the PAM technique using the variable amplitude saw-tooth carrier signal, illustrated in Fig. 5(b). Fig. 5 parts (c) and (d) show that the PAM technique manages to decrease the 3rd harmonic component in the grid current to be 2.9% of the fundamental. Moreover, the THD of the grid current is improved, 6.4%. Hence, PAM efficiency is proven.

4 Proposed Grid Current 3rd Harmonic Component Mitigation Technique

The proposed technique is based on cancellation of the 3rd harmonic component from the inverter's grid current using harmonic cancellator based proportional-resonant controller, hence named (3HC-PR). As shown in Fig. 6, an additional PR controller, tuned at three times the grid frequency, is introduced to the system's main PR controller which is tuned at the grid fundamental frequency. Also, the proposed system is simple in its implementation utilizing conventional SPWM with constant amplitude symmetrical saw-tooth carrier.

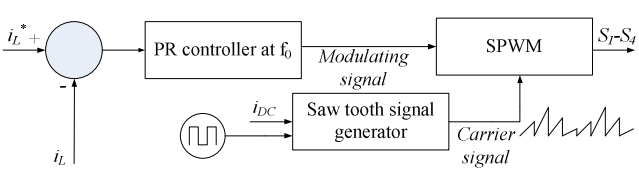
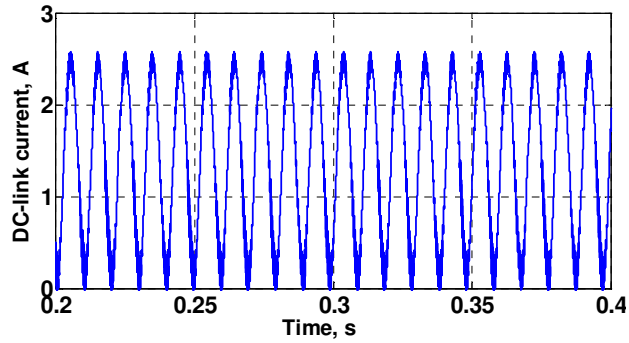
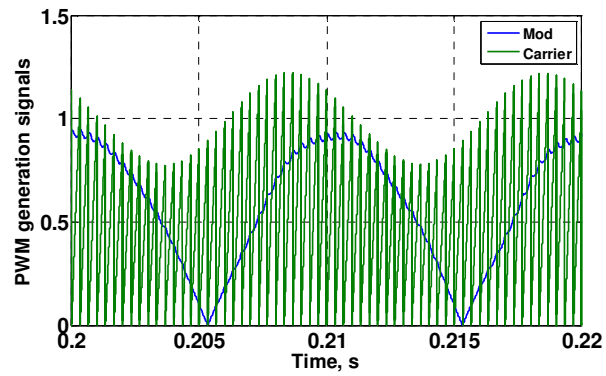


Fig. 4: System control block diagram with conventional PAM technique [18-20]



(a)



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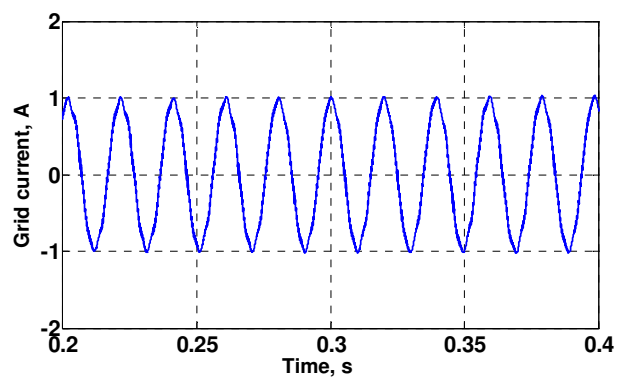
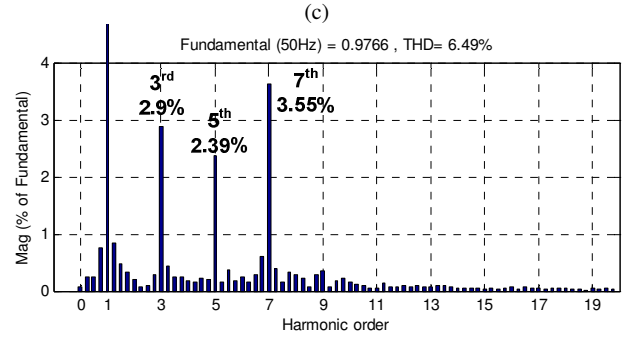


(c)



(d)

Fig. 5: Simulation results for single phase grid connected CSI using PAM technique
(a) DC-link current, (b) modulating and carrier signals, (c) grid current, and (d) grid current FFT

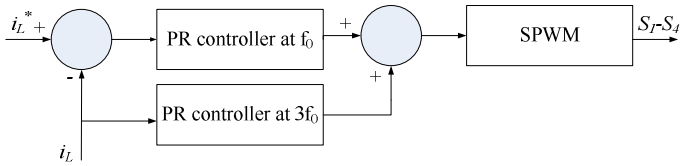


Fig. 6: System control block diagram with proposed 3HC-PR technique

Fig. 7 illustrates the system performance under the proposed technique. The introduction of the additional PR controller modifies the modulating signal by adding adequate 3rd harmonic component as shown in Fig. 7(b).
Hence, it counterparts the 3rd harmonic component in the grid current as illustrated in Fig. 7 parts (c) and (d). The ability of the proposed technique to decrease the 3rd harmonic component to be only 0.3% reflects its superior mitigation capabilities. Also, the grid current THD is remarkably improved as it reaches 3.4%.

5 Experimental Setup

For more illustration of the proposed technique and emphasis on its validity, an experimental rig is prepared. The prepared experimental setup is a single phase grid connected system with grid current control using PR controllers and 3 kHz switching frequency.
Table. 2 lists the experimental setup elements while Fig. 8 shows the experimental setup photography.

Element	*Value/Manufacturer*
Target board DSP	TI TMS320F28335
Inverter IGBT (4)	Fairchild FGL60N100BNTD
Inverter series fast diode (4)	IXYS DSEI60-10A
Voltage transducer	LEM LV20-P
Current transducer	LEM HAS50-S
Gate drivers	Semikron SKHI22AH4R
DC link inductor	10 mH
AC Filtering capacitor	28 µF
AC Filtering inductor	1 mH

Table 2: Experimental setup elements' list

Fig. 9 parts (a-d) show the experimental results of the single phase grid connected CSI without any oscillating power effect mitigation technique applied while parts (e-h) shows those of the proposed 3HC-PR mitigation technique.
The DC-link current and the grid voltage are not affected by the proposed technique as shown in Fig. 9 parts (a, b, e, and f). The AC capacitor voltage quality is significantly improved when the proposed 3HC-PR technique is applied as shown in Fig. 9 parts (c, and g).

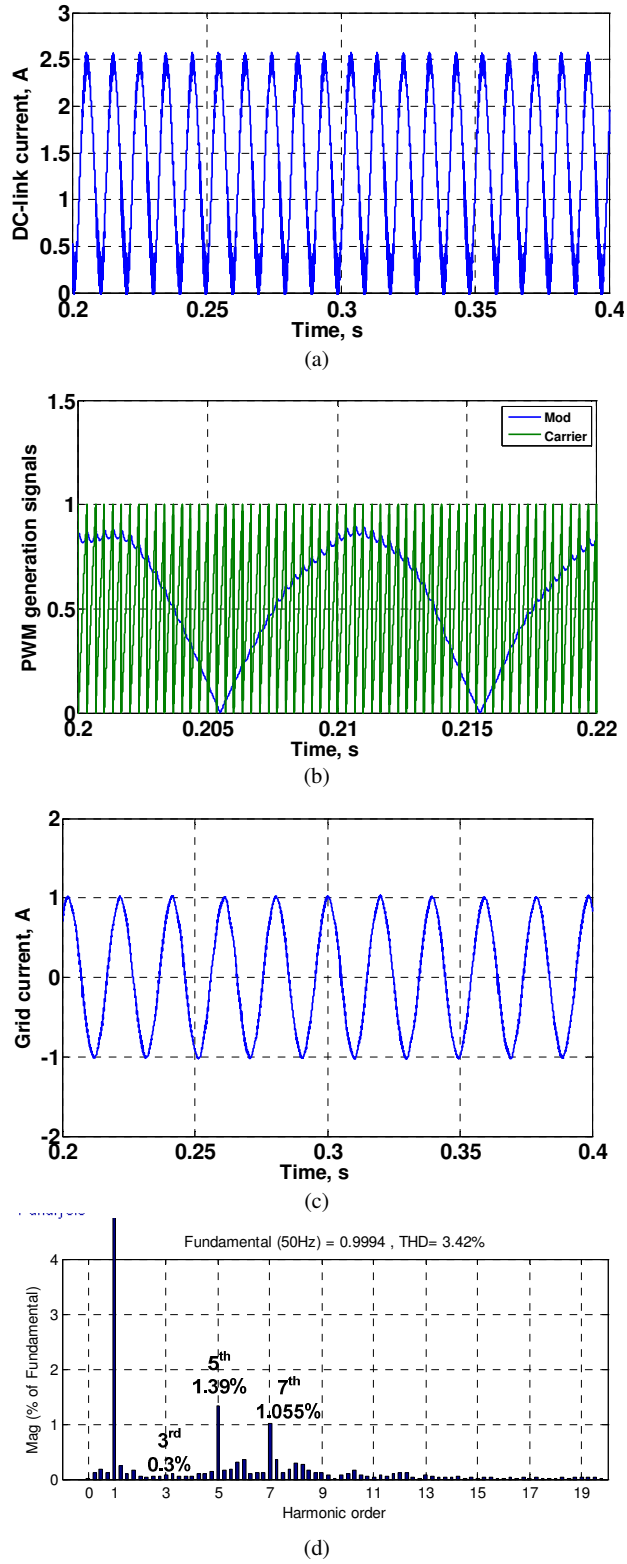


Fig. 7: Simulation results for single phase grid connected CSI using the proposed 3HC-PR technique
(a) DC-link current, (b) modulating and carrier signals, (c) grid current, and (d) grid current FFT

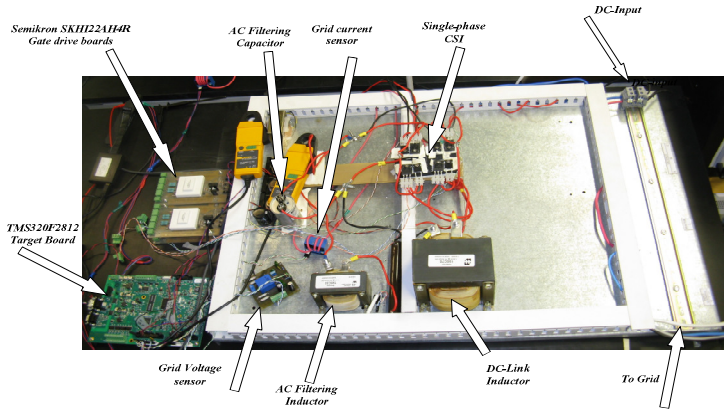


Fig. 8: Experimental setup

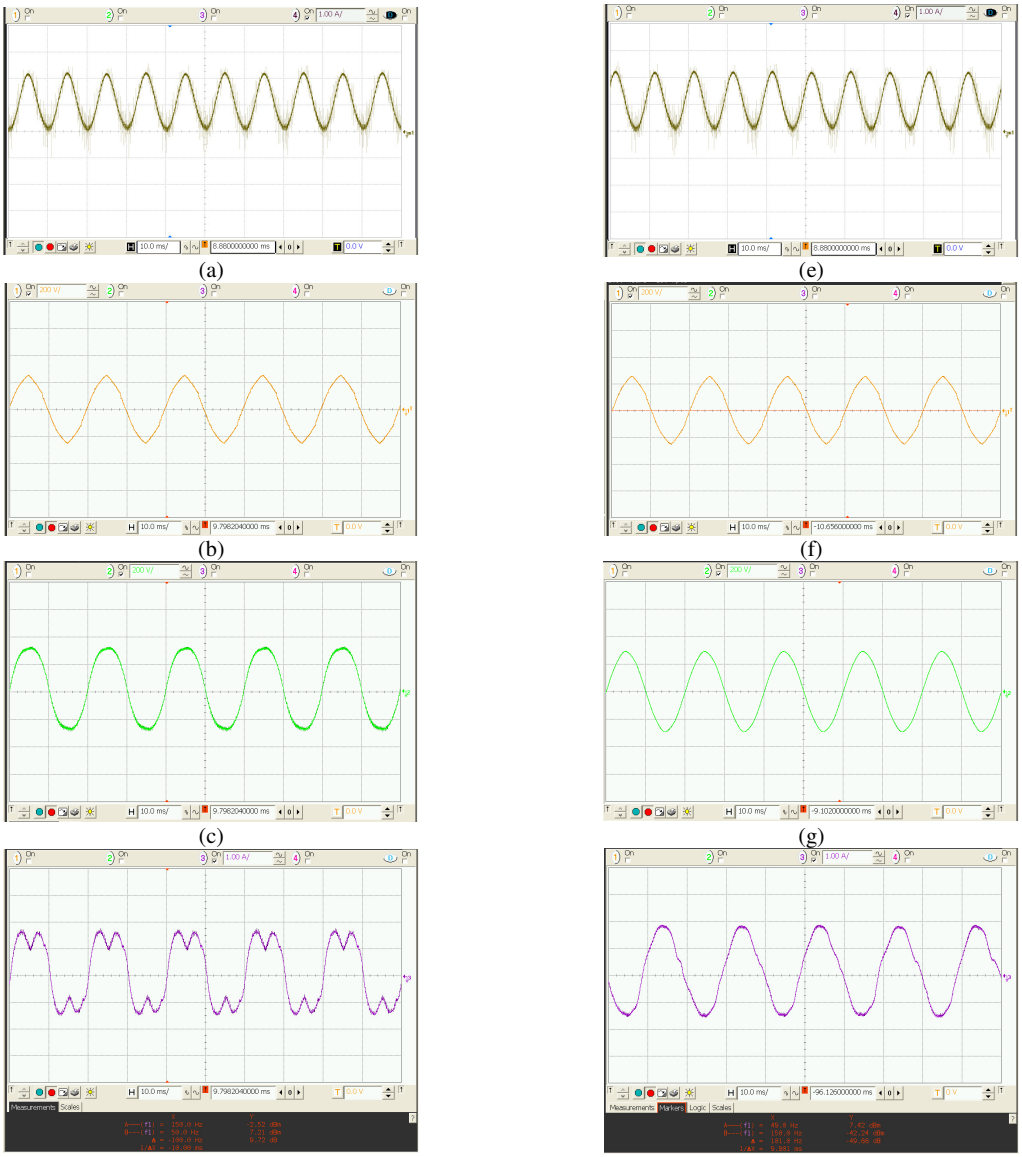


Fig. 9: Experimental results: (a-d) no oscillating power mitigation, (e-h) proposed 3HC-PR technique
(a-e) DC-link current, (b-f) grid voltage, (c-g) AC capacitor voltage, and (d-h) grid current

The grid current exhibits 3rd harmonic of nearly 29% (-2.52 dB) as shown in Fig. 9 (d). When the proposed oscillating power mitigation technique is applied, the grid current 3rd harmonic component significantly reduced to be 0.43% (-42.24 dB) as shown in Fig. 9 (h), hence the proposed technique superior mitigation capability is verified and illustrated.

6 Conclusion

In this paper, the naturally oscillating power of grid connected single phase CSIs has been illustrated. It has been shown that the classical PAM based mitigation technique reduces the oscillating power effect on the grid current indirectly from the DC-link side. An oscillating power mitigation technique, based on PR controller tuned at three times the grid current frequency, has been proposed. The presented technique, named 3HC-PR, is simple, robust and directly targets the 3rd harmonics in the grid current. A comparison between the classical PAM based technique and the proposed one has been held and has proven the proposed technique superiority. Finally, an experimental setup has been carried out to validate the proposed technique effectiveness.

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