

# Control Strategy to Maximize the Power Capability of PV Three-Phase Inverters During Voltage Sags

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**Abstract**—Under voltage sags, grid-tied photovoltaic inverters should remain connected to the grid according to low-voltage ride-through requirements. During such perturbations, it is interesting to exploit completely the distributed power provisions to contribute to the stability and reliability of the grid. In this sense, this paper proposes a low-voltage ride-through control strategy that maximizes the inverter power capability by injecting the maximum-rated current during the sag. To achieve this objective, two possible active power situations have been considered, i.e., high- and low-power production scenarios. In the first case, if the source is unable to deliver the whole generated power to the grid, the controller applies active power curtailment to guarantee that the maximum rated current is not surpassed. In the second case, the maximum allowed current is not reached, thus, the control strategy determined the amount of reactive power that can be injected up to reach it. The control objective can be fulfilled by means of a flexible current injection strategy that combines a proper balance between positive- and negative-current sequences, which limits the inverter output current to the maximum rated value and avoid active power oscillations. Selected experimental and simulation results are reported in order to validate the effectiveness of the proposed control strategy.

**Index Terms**—Distributed PV generation, low-voltage ride-through, maximum-rated current, reactive power injection, voltage sag.

## I. INTRODUCTION

IN recent years, environmental issues are increasing significantly the number of grid-connected distributed generation (DG) systems [1], [2]. However, the large-scale integration of DG systems can introduce a negative impact on the overall stability and reliability of the grid infrastructure, especially under grid fault conditions. In this sense, grid codes (GCs) of countries with high penetration level of DG have defined the profile of the faults that these systems should withstand, and the procedure that they should follow under such situations.

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In compliance with these requirements, DG sources must remain connected to the grid during voltage sags, following a predefined time/sag-depth profile before disconnection, which is known as low-voltage ride-through (LVRT). Additionally, wind GCs require the injection of the reactive power to support the grid voltage and to reduce the possibility of voltage collapse [3]–[5]. Consequently, it is expected that the continuously increasing number of grid-connected DG will promote new requirements on GCs. Upcoming GCs could demand also reactive power injection from distributed PV systems to fully exploit the reactive power provisions [4]–[6].

Under these requirements, different LVRT strategies have been proposed to enhance the performance of DG during voltage sags [3]–[6]. Most of reported works are based on symmetric sequences since this case increases the flexibility and leads to achieve particular control objectives such as the mitigation of active and reactive power oscillations, voltage support, and peak current limitation.

As presented in [7] and [8], by means of specific strategies it is possible to obtain different power quality levels at the point of common coupling (PCC) in terms of eliminating active and reactive power oscillations. However, avoiding active power oscillations results more favorable for the DG performance, since the active power oscillations are reflected as ripples in the dc-link voltage and could cause sudden disconnection of the voltage source inverter (VSI) if the maximum/minimum dc-link voltage is surpassed/under passed.

In voltage support strategies, the priority is to deliver only the reactive power during the sag. It can be attributed to the major impact that the reactive current can cause on the PCC voltages when a weak grid is considered. Depending on the type of sag, different reactive power strategies can be applied [9] and [10]. In [9], a reference-current generation algorithm that provides flexible voltage support was introduced. An improvement of [9] through limited to symmetric sags was presented in [10], where the PCC voltages can be restored if the DG system supplies enough reactive current. The authors in [9] present a voltage control scheme that can be used under any type of sag.

To avoid disconnection of the DG source due to overcurrent, the injected phase currents must be safely controlled at any time. In this regard, different strategies have been proposed. The control method presented in [11] ensures minimum peak values in the grid-injected currents when the whole generated power is delivered to the grid. However, current harmonic distortion was increased to meet the control objectives and the resulting minimum values always exceeded the VSI-rated current. In [12] and [13], the injection strategies avoid over current tripping, but the maximum output current was only related to the

87 maximum reactive power delivered by the VSI under  
 88 unbalanced grid conditions. As a drawback, the source is unable  
 89 to deliver the active power production. Moreover, the active and  
 90 reactive power present oscillations at twice the grid frequency.  
 91 The approach presented in [14] is based on the virtual flux  
 92 estimation method. In this paper, different active and reactive  
 93 power injection strategies have been proposed, however, not all  
 94 of them ensure maximum current limitation. In [15] and [16],  
 95 more flexible controllers have been proposed. These controllers  
 96 provide different LVRT services by injecting active and reactive  
 97 power by means of positive and negative sequences while main-  
 98 taining the injected current safely controlled to a predefined  
 99 maximum value. However, the control algorithms are complex  
 100 when comparing with previous schemes.

101 This paper proposes a compact LVRT control strategy that  
 102 guarantees the complete use of the power capabilities of the  
 103 distributed PV system under voltage sags. The proposal com-  
 104 prises a set of reference currents that provides flexible positive  
 105 and negative active and reactive power injection characteristics  
 106 that can be tuned to fulfill two objectives during voltage sags:  
 107 first, to inject maximum rated current independently of the sag  
 108 profile and, second, to avoid active power oscillations. Both  
 109 objectives will be always accomplished, although the achieve-  
 110 ment of first objective could be affected by the amount of the  
 111 generated power. In this concern, two main possible scenarios  
 112 may be considered, i.e., high- and low-power production sce-  
 113 narios. In the first case, the injection of the maximum current  
 114 can be achieved delivering only active power, which is in com-  
 115 pliance with present PV GCs. Moreover, if the source is unable  
 116 to deliver the whole generated power, the control strategy ap-  
 117 plies active power curtailment to avoid surpass the maximum  
 118 rated current and avoid disconnection due to overcurrent. In the  
 119 second case, a combination of active and reactive power will be  
 120 injected to reach the inverter maximum rated current. Therefore,  
 121 the PV system can provide support to the grid during the fault.  
 122 Although actual PV GCs do not require reactive power injection,  
 123 this functionality could contribute to better integration of  
 124 distributed resources in the near future.

125 Some of the reviewed control strategies provide peak-  
 126 current limitation and flexible operation under voltage sags.  
 127 However, none of the presented strategies so far is able  
 128 to determine the reference currents that optimize the VSI  
 129 power capabilities in an easy manner with simple and compact  
 130 reference expressions as presented here. Therefore, control  
 131 simplicity is one of the remarkable contributions of  
 132 this paper.

133 This paper is organized as follows. Section II describes the  
 134 grid-connected DG system, analyzes the PCC voltages and in-  
 135 verter currents under a voltage sag event, and describes the GC  
 136 requirements that must be applied under this situation. Section  
 137 III exposes the conditions that give rise to control objectives  
 138 and proposes a strategy to achieve it. Section IV develops the  
 139 theoretical basis of the control proposal. Section V corroborates  
 140 the expected features of the proposed controller by means of  
 141 selected simulation and experimental results. Also, a discussion  
 142 of the outstanding characteristics of the proposed strategy is  
 143 presented, including a comparison with reported peak current

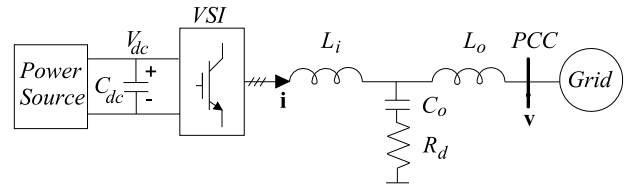


Fig. 1. Diagram of a grid-connected DG.

144 limitation controllers. Section VI presents the conclusions of  
 145 this paper.

## 146 II. GRID-CONNECTED INVERTERS UNDER VOLTAGE SAGS

147 This section deals with the description and characterization  
 148 of the grid-connected VSI under voltage sags. Also, the basic  
 149 GC requirements during these disturbances are described.

### 150 A. Grid-Connected Three-Phase Inverter

151 A typical configuration of grid-connected DG based on  
 152 renewable resources is shown in Fig. 1 [2]. Basically, it is com-  
 153 posed by a source, a large dc-link capacitor employed for decou-  
 154 pling the source and the converter, and a three-phase three-wire  
 155 VSI connected to the PCC. The inverter uses an LCL filter to  
 156 reduce the high-frequency commutation harmonics [17], [18].  
 157 Commonly, the LCL filter includes a series damping resistors  
 158 in series with the capacitors in order to reduce the resonance ef-  
 159 fects [17]. The voltage in the dc link is regulated to extract the  
 160 maximum power from the source using a outer dc-link voltage  
 161 controller, which provides the generated active power reference  
 162 current should be injected into the grid. This controller has been  
 163 extensively studied in the literature, and thus, it is not described in  
 164 this paper [18], [19].

### 165 B. Voltage Sag Characterization

166 A voltage sag is a short-time reduction of the rms voltage  
 167 magnitudes in one or more grid phases which can be caused  
 168 by different types of line faults (phase to ground short-circuit,  
 169 phase to phase to ground short circuit), overload, or power-up  
 170 of large motors [20], [22]. During voltage sags, the VSI suffers  
 171 from a severe perturbation that can compromise its functionality  
 172 and reliability. For this reason, the voltage and current vectors  
 173 at the PCC must be properly characterized in order to deal with  
 174 such events.

175 The instantaneous PCC phase voltages during voltage sags  
 176 can be described as the addition of positive-, negative-, and  
 177 zero-sequence sequences. By means of Clarke transformation,  
 178 the instantaneous PCC phase voltages can be expressed in the  
 179 stationary reference frame (SRF) as

$$180 v_{\alpha} = v_{\alpha}^{+} + v_{\alpha}^{-} = V^{+} \cos(\omega t + \delta^{+}) + V^{-} \cos(\omega t + \delta^{-}) \quad (1)$$

$$181 v_{\beta} = v_{\beta}^{+} + v_{\beta}^{-} = V^{+} \sin(\omega t + \delta^{+}) - V^{-} \sin(\omega t + \delta^{-}) \quad (2)$$

182 where  $v_{\alpha}$  and  $v_{\beta}$  are the SRF components of the measured  
 183 voltage at PCC,  $v_{\alpha}^{+}$ ,  $v_{\beta}^{+}$ , and  $v_{\alpha}^{-}$ ,  $v_{\beta}^{-}$  are the SRF positive- and  
 184 negative-voltage sequences, respectively,  $V^{+}$  and  $V^{-}$  are the se-  
 185 quences amplitudes,  $\omega$  is the grid angular frequency, and  $\delta^{+}$

184 and  $\delta^-$  are the initial phase angles of positive- and negative-  
185 sequences, respectively. Note that the zero sequence is not con-  
186 sidered here, since it is not present in three-wire systems [8].

187 There are different types of voltage sags, which can be char-  
188 acterized by the sequences amplitudes,  $V^+$ ,  $V^-$ , and by the  
189 sequence phase angle  $\delta$ . The magnitudes of these parameters  
190 can be determined using the SRF theory [21], [22], as

$$V^+ = \sqrt{(v_\alpha^+)^2 + (v_\beta^+)^2} \quad (3)$$

$$V^- = \sqrt{(v_\alpha^-)^2 + (v_\beta^-)^2} \quad (4)$$

$$\delta = \delta^+ - \delta^- = \cos^{-1} \left( \frac{v_\alpha^+ v_\alpha^- - v_\beta^+ v_\beta^-}{V^+ V^-} \right). \quad (5)$$

### 191 C. Requirements for DG systems Under Voltage Sags

192 Under normal grid conditions, VSI delivers all the generated  
193 active power into the grid by controlling the amount of the  
194 injected current. During voltage sags, complementary services  
195 can be required by the GCs to increase the grid quality and  
196 reliability. Wind GCs require LVRT capabilities and support the  
197 grid with some amount of reactive current injection. This amount  
198 varies depending on the regulations of each country; in extreme  
199 cases, it can arrive to 100%. Furthermore, depending on the sag  
200 profile, GCs also require active and reactive power injection to  
201 simultaneously feed and support the grid [3]–[5]. Present GCs  
202 for PV systems only require the injection of the active power.  
203 However, reactive power injection could be demanded in the  
204 near future to fully exploit the reactive power provisions of  
205 distributed PV systems [4], [6].

## 206 III. PROBLEM FORMULATION

207 The purpose of this section is to explain the conditions that  
208 have set the foundation of the proposed current injection strategy  
209 and the objectives that can be reached. Furthermore, the control  
210 algorithm that leads to its practical implementation is presented.

### 211 A. Power Injection During Voltage Sags

212 According to the power theory [23], [24], the instantaneous  
213 active and reactive powers injected to the grid by a three-phase  
214 VSI depends on the injected currents and the voltage vectors ( $\mathbf{i}$ ,  
215  $\mathbf{v}$ ) at the PCC. Thus, the instantaneous power can be defined as

$$p = \frac{3}{2} (v_\alpha i_\alpha + v_\beta i_\beta) \quad (6)$$

$$q = \frac{3}{2} (v_\beta i_\alpha - v_\alpha i_\beta). \quad (7)$$

216 Additionally, the VSI current references can be decomposed  
217 in active and reactive components as

$$i_\alpha^* = i_\alpha^*(p) + i_\alpha^*(q) \quad (8)$$

$$i_\beta^* = i_\beta^*(p) + i_\beta^*(q). \quad (9)$$

218 In compliance with present GCs, the PV systems must only  
219 inject the active power into the grid. To achieve this requirement,  
220 the following set of reference currents in the SRF can be used

[25]

$$i_\alpha^*(p) = \frac{2}{3} \frac{v_\alpha^+}{(V^+)^2} P^* \quad (10)$$

$$i_\beta^*(p) = \frac{2}{3} \frac{v_\beta^+}{(V^+)^2} P^*. \quad (11)$$

222 In this scheme, the reference currents follow the positive-  
223 sequence voltage. Thus, the resulting currents are balanced and  
224 free of harmonics. However, during unbalanced voltage sags,  
225 this strategy introduces an oscillation in the injected active  
226 power at twice the grid frequency which affects negatively the  
227 dc-link voltage and may cause dc overvoltage problems [25].

228 During the sag, the amplitude of the positive sequence  $V^+$   
229 will be reduced. Consequently, according to (10) and (11), the  
230 injected currents will increase to maintain the same amount of  
231 injected power previous to the sag. However, this conventional  
232 response may lead to tripping or damage of the converter be-  
233 cause the reference currents might surpass the inverter maximum  
234 rated current. In this situation, the source is unable to inject the  
235 whole generated power. Thus, safety mechanisms must be acti-  
236 vated to remove the excess of active power production that may  
237 produce dc-link overvoltage and overcurrent disconnection. A  
238 method to avoid these problems is the active power curtailment.  
239 It comprises the reduction of the active power according to specific  
240 requirements, by means of auxiliary systems such as dc-link  
241 voltage limiter units or by detuning the MPPT operation point  
242 [26], [27].

243 On the other hand, if the calculated reference currents do not  
244 exceed the maximum rated current during the sag, the inverter  
245 power capability is not completely exploited. In this situation,  
246 reactive power injection could be considered to reach the maxi-  
247 mum rated current and maximize the inverter power capability.

248 To solve the aforementioned issues during voltage sags (i.e.,  
249 to avoid active power oscillations, to avoid inverter tripping  
250 due to over current, and to inject the reactive power when is  
251 possible), a new current control strategy that maximizes the  
252 inverter power capability is proposed below.

### 253 B. Proposed Control Strategy

254 To achieve the previously mentioned control objectives, a set  
255 of flexible reference currents are needed. Thus, based on [9], a  
256 new set of reference currents is defined as

$$i_\alpha^*(p) = \frac{2}{3} \frac{k_p^+ v_\alpha^+ + k_p^- v_\alpha^-}{k_p^+ (V^+)^2 + k_p^- (V^-)^2} P^* \quad (12)$$

$$i_\beta^*(p) = \frac{2}{3} \frac{k_p^+ v_\beta^+ + k_p^- v_\beta^-}{k_p^+ (V^+)^2 + k_p^- (V^-)^2} P^* \quad (13)$$

$$i_\alpha^*(q) = \frac{2}{3} \frac{k_q^+ v_\beta^+ + k_q^- v_\beta^-}{k_q^+ (V^+)^2 + k_q^- (V^-)^2} Q^* \quad (14)$$

$$i_\beta^*(q) = -\frac{2}{3} \frac{k_q^+ v_\alpha^+ + k_q^- v_\alpha^-}{k_q^+ (V^+)^2 + k_q^- (V^-)^2} Q^* \quad (15)$$

257 where  $k_p^+$ ,  $k_p^-$ ,  $k_q^+$ , and  $k_q^-$  are the control parameters to bal-  
258 ance appropriately the positive and negative sequences. These

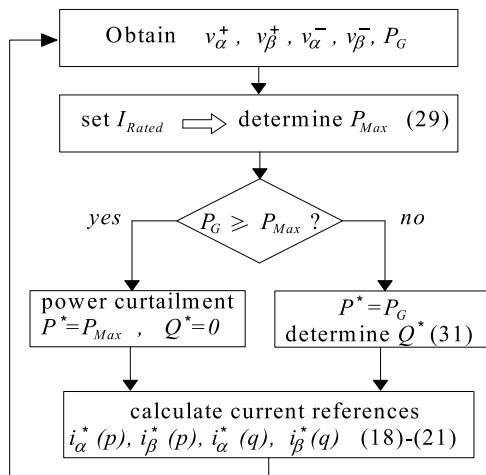


Fig. 2. Flux diagram of the proposed control strategy.

parameters can take any values in the range 0 to 1, which give rise to multiple injection strategies. For instance, the simple injection strategy represented by (10) and (11) can be implemented with the proposed reference currents by selecting the control parameter as  $k_p^+ = k_q^+ = 1$  and  $k_q^- = k_p^- = Q^* = 0$ . Thus, based on (12)–(15), a control strategy that determines adequately the power references ( $P^*$ ,  $Q^*$ ) to fulfill the proposed control objectives is presented. The operation of the proposed control strategy can be described by the algorithm shown in Fig. 2. In this figure, the generated active power reference  $P^*$  is obtained from the dc-link voltage regulator. The positive and negative-voltage sequences are obtained from the sequence extractor which let to determine the sag characteristics [28], [29]. Next, the maximum allowable active power  $P_{Max}$  is calculated considering the value of the maximum rated current that the VSI can provide ( $I_{Rated}$ ) and  $Q = 0$ . Afterward,  $P_{Max}$  is compared with  $P_G$  to determinate the suitable control action. If  $P_G$  is higher than  $P_{Max}$ , the strategy applies power curtailment to avoid exceeding  $I_{Rated}$ . Consequently, a new value to the active power reference has to be set as  $P^* = P_{Max}$  and the reactive power reference is maintained as  $Q^* = 0$ . On the other hand, if  $P_G$  is lower than  $P_{Max}$ , then, the inverter maximum rated current is not surpassed and, therefore, some amount of the reactive power can be injected up to reach  $I_{Rated}$ . In this case, the reactive power reference  $Q^*$  is calculated considering  $I_{Rated}$  and the generated power  $P_G$ . Finally, the reference currents are computed with the corresponding values of active and reactive power references. The selection of the control parameter and the development of the mathematical expressions that allows the online determination of  $P_{Max}$  and  $Q^*$  will be shown in Section IV.

#### IV. THEORETICAL APPROACH TO THE CONTROL STRATEGY

The purpose of this section is to develop the mathematical expressions that support the statements of the proposed control strategy. Furthermore, the effects that the proposed reference currents and control parameters cause in the instantaneous active and reactive power are presented.

##### A. Determining Maximum Injected Current

To fulfill the control objective of avoiding active power oscillations, the control parameters are selected as

$$k_p^- = -k_p^+ \quad (16)$$

$$k_q^+ = k_q^- \quad (17)$$

The achievement of this objective will be validated theoretically in Section IV-C and experimentally in Section V. Additionally, thanks to (16) and (17), the proposed reference currents (12)–(15) become simplified and normalized as follows:

$$i_\alpha^*(p) = \frac{2}{3} \frac{v_\alpha^+ - v_\alpha^-}{(V^+)^2 - (V^-)^2} P^* \quad (18)$$

$$i_\beta^*(p) = \frac{2}{3} \frac{v_\beta^+ - v_\beta^-}{(V^+)^2 - (V^-)^2} P^* \quad (19)$$

$$i_\alpha^*(q) = \frac{2}{3} \frac{v_\beta^+ + v_\beta^-}{(V^+)^2 + (V^-)^2} Q^* \quad (20)$$

$$i_\beta^*(q) = -\frac{2}{3} \frac{v_\alpha^+ + v_\alpha^-}{(V^+)^2 + (V^-)^2} Q^* \quad (21)$$

Then, using (1), (18)–(21), the peak amplitude of the natural frame phase currents can be easily calculated by applying the inverse Park transformation to (8) and (9). The resulting amplitudes depend on the sag characteristics and the active and reactive power references as

$$I_a = \frac{2}{3} \sqrt{((V^+)^2 - 2V^+V^-\cos(\delta + \pi/3) + (V^-)^2) A} \quad (22)$$

$$I_b = \frac{2}{3} \sqrt{((V^+)^2 - 2V^+V^-\cos(\delta - 2/3\pi) + (V^-)^2) A} \quad (23)$$

$$I_c = \frac{2}{3} \sqrt{((V^+)^2 - 2V^+V^-\cos(\delta + \pi/3) + (V^-)^2) A} \quad (24)$$

where

$$A = \left( \frac{P^*}{(V^+)^2 - (V^-)^2} \right)^2 + \left( \frac{Q^*}{(V^+)^2 + (V^-)^2} \right)^2 \quad (25)$$

From (22)–(24) it can be clearly seen that the phase with the maximum current is related with the minimum value of the corresponding cosine function

$$\cos_{\min} = \min \{ \cos(\delta), \cos(\delta - 2/3\pi), \cos(\delta + 2/3\pi) \} \quad (26)$$

Then, measuring the sag characteristics ( $V^+$ ,  $V^-$ ,  $\delta$ ) and knowing the active and reactive power references, the maximum phase current amplitude can be easily determined as

$$I_{Max} = \frac{2}{3} \sqrt{((V^+)^2 - 2V^+V^-\cos_{\min} + (V^-)^2) A} \quad (27)$$

where  $I_{Max}$  is the maximum output current that the VSI will provide.

To avoid inverter damage or disconnection by the overcurrent,  $I_{Max}$  must be limited to the VSI-maximum-rated current by means of the following condition:

$$I_{Max} \leq I_{Rated} \quad (28)$$

### 320 B. Determining Maximum Active and Reactive Power

321 The maximum power that the VSI can deliver during the  
322 sag must be determined considering (28). Also, variations in  
323 the generated power due to different environmental conditions  
324 must be considered. Therefore, high- and low-power production  
325 scenarios can be studied during the occurrence of grid faults.

326 *Scenario 1(High power generation)*: In this case,  $I_{\text{Rated}}$  could  
327 be surpassed due to the generated power  $P_G$ . In this situation,  
328 the source is unable to inject the whole generated power, and active  
329 power curtailment is necessary. Then, the maximum active  
330 power that can be injected into the grid during the sag can be  
331 determined by using  $I_{\text{Max}} = I_{\text{Rated}}$ ,  $P^* = P_{\text{Max}}$ , and  $Q^* = 0$   
332 in (27), and solving the resulting expression for  $P_{\text{Max}}$

$$P_{\text{Max}} = \frac{3}{2} \frac{I_{\text{Rated}}}{\sqrt{B}} ((V^+)^2 - (V^-)^2) \quad (29)$$

333 where

$$B = (V^+)^2 - 2V^+V^- \cos_{\min} + (V^-)^2. \quad (30)$$

334 In this case, the active and reactive power references are  
335  $P^* = P_{\text{Max}}$  and  $Q^* = 0$ .

336 *Scenario 2(Low power generation)*: In this case, the generated  
337 power  $P_G$  is lower than  $P_{\text{Max}}$ , and the inverter maximum  
338 current cannot be reached, then, some amount of the generated  
339 power can be injected to increase the VSI output current to its  
340 maximum value in order to support the grid. Under this situation,  
341 the reactive power reference can be determined by using  $I_{\text{Max}}$ ,  
342  $I_{\text{Rated}}$  and  $P^* = P_G$  in (27) and solving the resulting expression  
343 for  $Q^*$

$$Q^* = \sqrt{\frac{2.25I_{\text{Rated}}^2}{B} - \left(\frac{P_G}{(V^+)^2 - (V^-)^2}\right)^2 ((V^+)^2 - (V^-)^2)}. \quad (31)$$

344 In this case, the active power reference is  $P^* = P_G$ .

345 It is worth mentioning that (29) and (31) are simple and compact  
346 expressions that facilitate the application of the proposed  
347 control strategy. As far as author's knowledge goes, these expressions  
348 have not been reported previously in the literature,  
349 thus, together with the flux diagram shown in the Fig. 2, these  
350 constitute the two main theoretical contributions of this paper.

### 351 C. Determining Power Oscillations Components

352 During voltage sag, the instantaneous active and reactive powers  
353 injected by the VSI can be decomposed in the following  
354 expressions:

$$p = P^+ + P^- + \tilde{P} \quad (32)$$

$$q = Q^+ + Q^- + \tilde{Q} \quad (33)$$

355 where  $P^+$ ,  $Q^+$ ,  $P^-$ ,  $Q^-$ ,  $\tilde{P}$ , and  $\tilde{Q}$  represents the positive and  
356 negative components and the oscillating terms of the active and  
357 reactive power, respectively.

358 By inserting (1)–(2) and (12)–(15) into (6) and (7), (32) and  
359 (33) can be developed as a function of  $V^+$ ,  $V^-$ ,  $\delta$ , and the

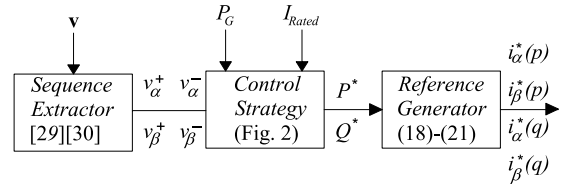


Fig. 3. Block diagram of the proposed control scheme.

control parameters as

$$P^+ = \frac{k_p^+ (V^+)^2}{k_p^+ (V^+)^2 + k_p^- (V^-)^2} P^* \quad (34)$$

$$P^- = \frac{k_p^- (V^-)^2}{k_p^+ (V^+)^2 + k_p^- (V^-)^2} P^* \quad (35)$$

$$\tilde{P} = \frac{(k_p^+ + k_p^-) V^+ V^- \cos(2\omega t - \delta)}{k_p^+ (V^+)^2 + k_p^- (V^-)^2} P^* \quad (36)$$

$$Q^+ = \frac{(k_q^+ - k_q^-) V^+ V^- \sin(2\omega t - \delta)}{k_q^+ (V^+)^2 + k_q^- (V^-)^2} Q^* \quad (37)$$

$$Q^- = \frac{(k_q^+ + k_q^-) V^+ V^- \sin(2\omega t - \delta)}{k_q^+ (V^+)^2 + k_q^- (V^-)^2} Q^* \quad (38)$$

$$\tilde{Q} = \frac{(k_q^+ + k_q^-) V^+ V^- \cos(2\omega t - \delta)}{k_q^+ (V^+)^2 + k_q^- (V^-)^2} Q^* - \frac{(k_p^+ - k_p^-) V^+ V^- \sin(2\omega t - \delta)}{k_p^+ (V^+)^2 + k_p^- (V^-)^2} P^*. \quad (39)$$

361 Then, by replacing the proposed control parameters ( $k_p^- =$   
362  $-k_p^+$  and  $k_q^+ = k_q^-$ ) in (34)–(39), the resulting instantaneous  
363 active and reactive power can be written as

$$p = P^+ + P^- + \tilde{P} \quad (40)$$

$$q = Q^+ + Q^- + \tilde{Q} \quad (41)$$

364 As can be seen from (40) and (41), the oscillation of the  
365 injected active power is removed completely, which brings benefits to  
366 the dc-link performance. On the other hand, the reactive  
367 power has oscillations at twice the line frequency, but ensuring  
368 a mean value  $Q^*$ .

### 369 D. Proposed Control Scheme

370 A simplified diagram of the control proposal is shown in  
371 Fig. 3. The inputs of the controller are the measured phase  
372 voltages  $\mathbf{v}$  at the PCC, and the generated power  $P_G$  provided by  
373 the dc-link voltage controller. Voltage vector  $\mathbf{v}$  is converted into  
374 SRF values by means of Clarke transformation. Then, voltages  
375  $v_\alpha$  and  $v_\beta$  are decomposed into symmetric components using

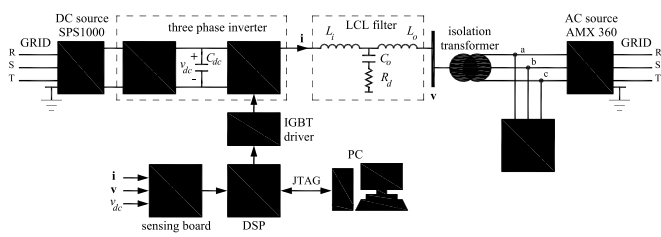


Fig. 4. Diagram of the experimental setup.

TABLE I  
SYSTEM PARAMETERS

Nominal rated power (base power)	$S_b$	2.3 kVA
Generated active power	$P_G$	300, 900, and 1300 W
Nominal grid voltage	$V_g$	110 Vrms
Rated current amplitude	$I_{Rated}$	10 A
Nominal grid frequency	$f_o$	60 Hz
DC-link voltage	$V_{dc}$	350 V
DC-link capacitor	$C_{dc}$	1.5 mF
LCL inverter-side inductances	$L_i$	5 mH
LCL filter capacitors	$C_o$	1.5 $\mu$ F
LCL damping resistors	$R_d$	68 $\Omega$
LCL output-side inductances	$L_o$	2 mH
Sampling/Switching frequency	$f_s$	10 kHz

376 a sequence extractor. The core of the controller is the control  
 377 strategy block, whose operation has been described by Fig. 2.  
 378 It uses the information provided by the sequence extractor  
 379 the inputs,  $P_G$  and  $I_{Rated}$ , to calculate the power reference  
 380 necessary to implement the proposed reference currents.

## V. EXPERIMENTAL RESULTS

382 Fig. 4 shows a diagram of the experimental setup. An experi-  
 383 mental prototype rated at 2.3 kVA was built using SEMIKRON  
 384 three-leg bridge, an LCL power filter, a three-phase power trans-  
 385 former, and a local load. A TMS320F28335 floating-point digital  
 386 signal processor is used as the control platform. The DC source  
 387 behavior is emulated using an AMREL-SPS1000 dc source.  
 388 The utility grid is emulated by means of a programmable three-  
 389 phase Pacific AMX-360 ac source connected to the PCC. The  
 390 sequence extractor is implemented with generalized integrat-  
 391 ors [28], [29]. The current controller consists of proportional-  
 392 resonant controllers [30]. Table I lists the parameter values for  
 393 both the inverter and the controller.

394 Throughout this paper, two power production scenarios have  
 395 been considered: high and low. However, an additional medium  
 396 production scenario has been also included in this section, in or-  
 397 der to highlight the flexible characteristic of the proposed con-  
 398 trol scheme. Then, three different power production tests have been  
 399 considered to obtain experimental results: low-, medium-, and  
 400 high-production scenarios.

401 A variable-profile voltage sag has been programmed in the ac  
 402 source to evaluate the behavior of the system. The programmed  
 403 sag in three different power production tests will follow the  
 404 same sequential behavior. First, during 0.1 s, the grid voltages  
 405 are roughly balanced with the following rms voltages: 1.018,

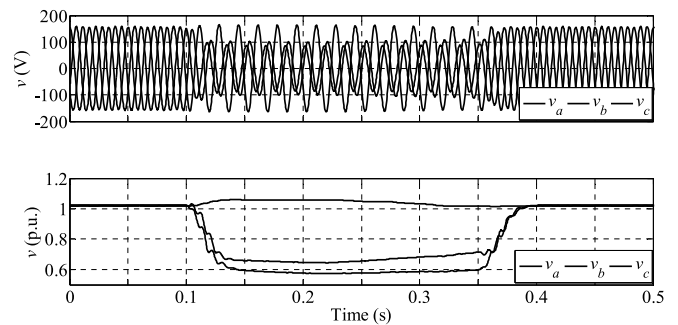
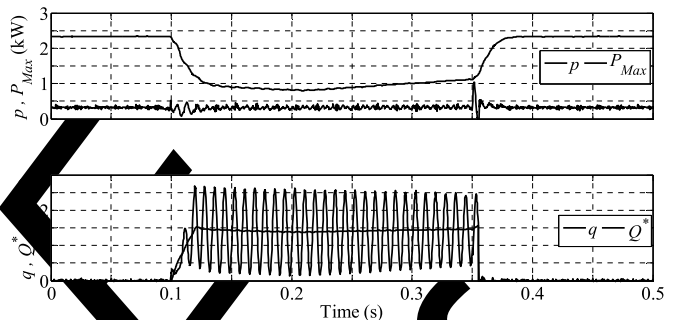


Fig. 5. Experimental PCC phase voltages during the sag (top), and its rms values (bottom).

Fig. 6. Experimental results for low injection scenario,  $P_G = 300$  W. Top: measured active power,  $p$ , and maximum power  $P_{Max}$ . Bottom: measured reactive power,  $q$ , and reference reactive power  $Q^*$ .

406 1.025 and 1.021 p.u. Then, at  $t = 0.1$  s, a voltage sag appears and  
 407 two phases voltages drop well below 0.7 p.u., with a minimum of  
 408 0.5 p.u. Afterward, during 0.25 s (from  $t = 0.1$  s to  $t = 0.35$  s)  
 409 the sag profile changes slightly, in order to show the behavior of  
 410 the control strategy. Finally, at time  $t = 0.35$  s, the sag is cleared  
 411 and the dropped voltages begin to return to its presag values.  
 412 Fig. 5 shows the PCC phase-to-neutral phase voltages during the  
 413 sag and its rms per unit values.

### A. Low Active Power Injection Scenario

414 Fig. 6 shows the instantaneous active and reactive power  
 415 during the first case, using  $P_G = 300$  W, i.e., a low-production  
 416 scenario. The mean value of the active power is 300 W for the  
 417 duration of the test (see the line depicted in blue). In red line,  
 418 the maximum active power  $P_{Max}$  that could be injected without  
 419 surpassing  $I_{Rated}$  is depicted in the figure. Then, when the sag  
 420 begins, the proposed current controller calculates on-line  $P_{Max}$   
 421 for this specific fault. Observe that  $P_{Max}$  is reduced from 2.3  
 422 kW to a minimum value of 800 W during the sag. As it can be  
 423 seen, the power produced by the system never reaches  $P_{Max}$ ,  
 424 thus  $P^* = P_G$  during the entire test. Under this condition, the  
 425 inverter is able to provide some reactive power till the maximum-  
 426 rated current  $I_{Rated}$  of the inverter is reached. The measured  
 427 mean value of the injected reactive power is almost 1.4 kVar  
 428 during the sag, clearly following its reference value  $Q^*$ . When  
 429 the sag takes place, the system becomes unbalanced and an  
 430 oscillation at twice the line frequency appears in the reactive  
 431 power. In the case of the active power, observe that thanks to  
 432

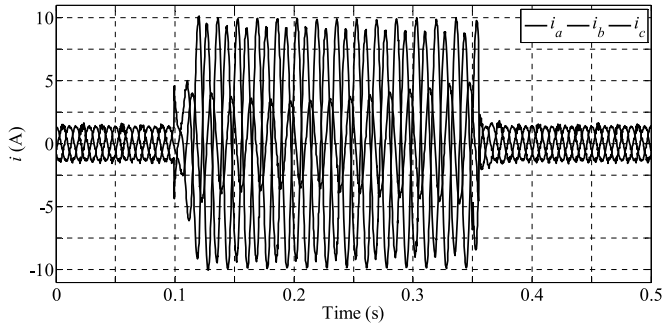


Fig. 7. Experimentally measured line currents for low injection scenario,  $P_G = 300$  W.

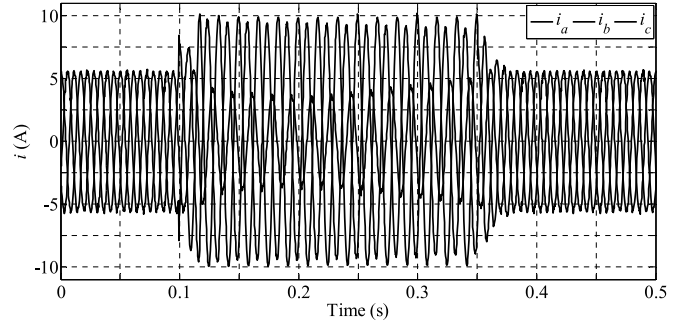


Fig. 9. Experimentally measured line currents for high injection scenario,  $P_G = 1300$  W.

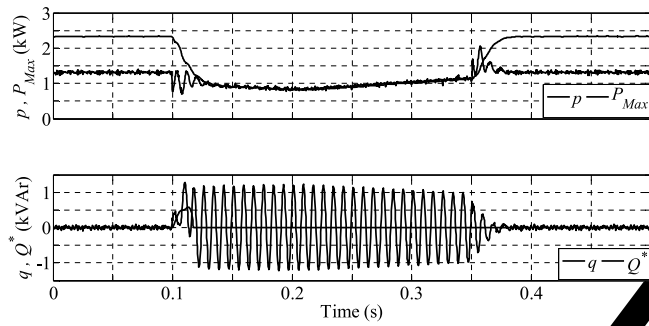


Fig. 8. Experimental results for high injection scenario,  $P_G = 1300$  W. Top: measured active power  $p$ , and maximum power  $P_{Max}$ . Bottom: measured reactive power  $q$ , and reference reactive power  $Q^*$ .

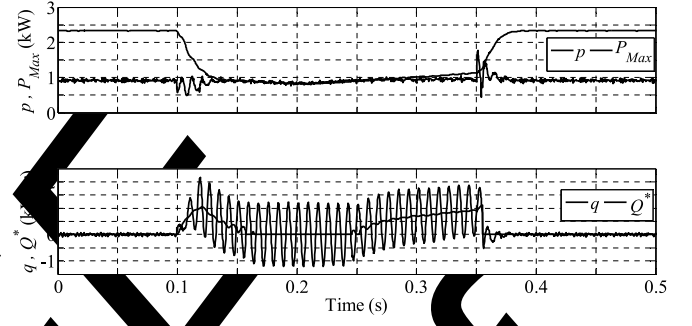


Fig. 10. Experimental results for medium injection scenario,  $P_G = 900$  W. Top: measured active power  $p$ , and maximum power  $P_{Max}$ . Bottom: measured reactive power  $q$ , and reference reactive power  $Q^*$ .

433 the selection of the control parameters (16), (17) and oscillations  
434 have been avoided as desired.

435 Fig. 7 shows the injected currents during the test. After 0.02 s  
436 of the sag appearance, the objective of injecting the maximum  
437 allowed current is fulfilled in one phase. Note that the amplitudes  
438 of the other phase currents are changing continuously due to  
439 the variable profile of the voltage sag and never reach the  
440 maximum-rated current.

#### 441 B. High Active Power Injection Scenario

442 Fig. 8 shows the instantaneous active and reactive powers  
443 during the fault considering  $P_G = 1300$  W, i.e., a high-  
444 production scenario. The mean value of the injected active  
445 power is 1300 W before and after of the sag,  $P^* = P_G$ . On the  
446 other hand, as it can be observed, the maximum active power  
447  $P_{Max}$  is surpassed by the produced power during the sag. Under  
448 this condition, the power production must be curtailed to  
449 avoid overcurrent and disconnection. During the sag, the active  
450 power reference is limited to  $P_{Max}$ , i.e.,  $P^* = P_{Max}$ . Thus, in  
451 this test, no reactive power can be provided since the maximum  
452 output current of the inverter  $I_{Rated}$  has been reached. It is im-  
453 portant to note that the voltage sequences detector has a one  
454 grid-cycle settling-time response, which introduces a delay in  
455 the reactive power reference  $Q^*$  calculation. This effect can be  
456 observed at the beginning of the sag, when the reactive power  
457 injection is not zero and reaches 500 VAR during one grid cycle.  
458 However, after this small time interval, the reactive power

reference reaches its expected value  $Q^{**} = 500$  VAR (also mean  
459 value). Also, an oscillation in the reactive power at twice the  
460 line frequency is observed, which corroborates the prediction of  
461 the previous analysis. Fig. 9 shows the injected currents during  
462 the test. After 0.015 s of the sag appearance, the objective of  
463 injecting the maximum allowed current is fulfilled.  
464

#### 465 C. Medium Active Power Injection Scenario

466 Fig. 10 shows the instantaneous active and reactive power  
467 during the fault considering  $P_G = 900$  W, i.e., a medium-  
468 production scenario. The mean value of the injected active power  
469 is 900 W before and after the sag,  $P^* = P_G$ . A combination of  
470 the previous scenarios can be observed in Fig. 10, from the be-  
471 ginning of the sag until 0.15 s and from 0.25 s to the end of  
472 the sag, in which the active power generated by the system is  
473 below  $P_{Max}$  and some reactive power can be injected. Among  
474 these two intervals,  $P_{Max}$  is surpassed and the power production  
475 must be curtailed ( $P^* = P_{Max}$ ) to avoid overcurrents. Fig. 11  
476 shows the injected currents during this test. This test reveals the  
477 excellent dynamic properties of the proposed control strategy  
478 which provide smooth transitions between the operation modes  
479 (i.e., active power curtailment and reactive power injection).

#### 480 D. Supporting Different Types of Voltages Sags

481 A complete set of simulations has been carried out to further  
482 demonstrate the effectiveness of the control proposal under any  
483 type of voltage sag. The system with parameters described in

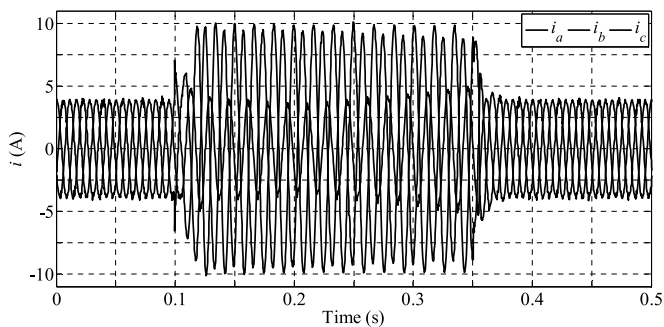


Fig. 11. Experimentally measured line currents for medium injection scenario,  $P_G = 900$  W.

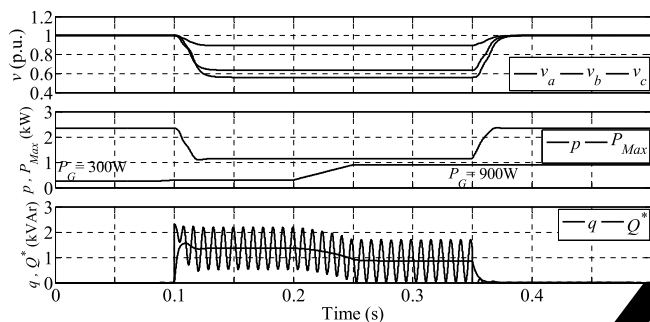


Fig. 12. Simulation waveforms for type-II sag ( $V^+ = 0.68$ ,  $V^- = 0.22$ ,  $\delta = 10^\circ$ ). Top: PCC rms phase voltages. Middle: generated active power,  $p$ , and maximum power  $P_{Max}$ . Bottom: measured reactive power,  $q$ , and reference reactive power  $Q^*$ .

484 Table I has been simulated under three types of sags character-  
 485 ized by its positive- and negative-sequence voltages,  $V^+$  and  
 486  $V^-$ , and the sequence phase angle  $\delta$  [9], [32]. In this test, a positive  
 487 gradient change in the active power has been programmed  
 488 during the sag, beginning at  $t = 0.2$  s, to demonstrate the capa-  
 489 bility of the proposed strategy to react against transient operation  
 490 conditions.

491 Fig. 12 shows the simulation results when the system is per-  
 492 turbed by a type-II sag ( $\delta = 10^\circ$ ). The mean value of the injected  
 493 active power is 300 W before the sag and 900 W after the sag  
 494 due to the programmed active power change. As it can be seen,  
 495 the generated power never reaches  $P_{Max}$ , thus,  $P^* = P_G$  during  
 496 the entire simulation. Under this condition, the inverter is able  
 497 to provide some reactive power till the inverter maximum-rated  
 498 current  $I_{Rated}$  is reached. Note that the reactive power adapts its  
 499 profile online to the changes produced in the generated power  
 500 in order to safely maintain the inverter-rated current controlled  
 501 at its maximum value.

502 Fig. 13 depicts the line-to-neutral voltage at phase b and the  
 503 corresponding current during the type-II sag. Observe that the  $i_b$   
 504 peak current change according to the delivered power. Before the  
 505 sag, the peak current is low (approximately 1 A). During the sag,  
 506 it reaches  $I_{Rated}$  because  $v_b$  is the most dropped phase voltage.  
 507 After the sag, the peak current decrease up to approximately 4 A  
 508 due to the increment in the active power. Note that the maximum  
 509 rated current is not surpassed at any time.

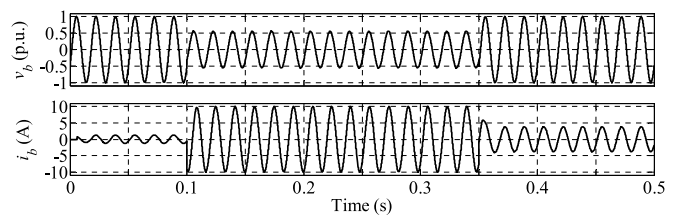


Fig. 13. Phase b voltage and current during the type II sag. Top: PCC line-to-neutral voltage. Bottom: phase current.

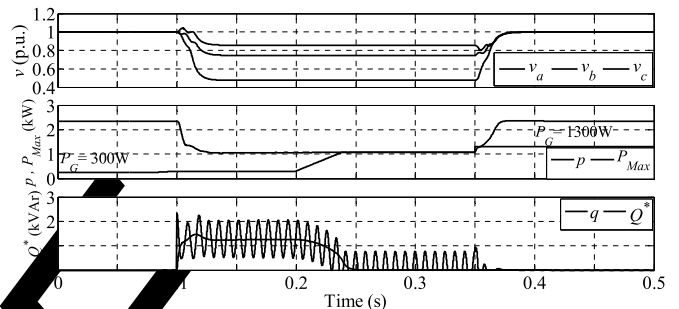


Fig. 14. Simulation waveforms for type-I sag ( $V^+ = 0.68$ ,  $V^- = 0.22$ ,  $\delta = 280^\circ$ ). Top: PCC rms phase voltages. Middle: generated active power,  $p$ , and maximum power  $P_{Max}$ . Bottom: measured reactive power,  $q$ , and reference reactive power  $Q^*$ .

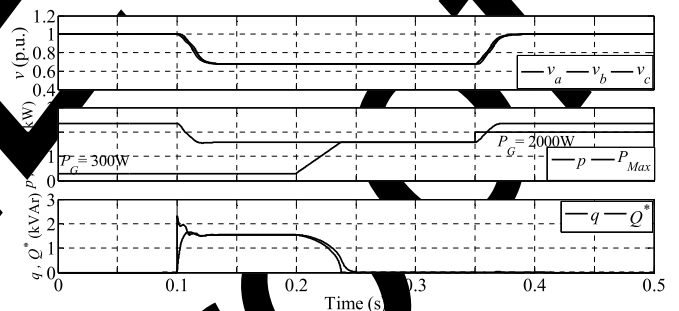


Fig. 15. Simulation waveforms for type-II sag ( $V^+ = 0.68$ ,  $V^- = 0.22$ ,  $\delta = 0^\circ$ ). Top: PCC rms phase voltages. Middle: generated active power,  $p$ , and maximum power  $P_{Max}$ . Bottom: measured reactive power,  $q$ , and reference reactive power  $Q^*$ .

510 Fig. 14 shows the simulations for the type I sag ( $\delta = 280^\circ$ ).  
 511 The active power change has been programmed from 300 W  
 512 up to 1300 W. In this test, the injection of the active power is  
 513 curtailed by the controller approximately at  $t = 0.23$  s, once the  
 514 generated power reaches  $P_{Max}$ . Thus, from this point till the  
 515 sag is cleared,  $P^* = P_{Max}$ . After the sag, the delivered active  
 516 power increases up to 1300 W. During this test, it is verified that  
 517 the inverter provides reactive power meanwhile the generated  
 518 power is below the limit  $P_{Max}$ .

519 The well performance of the system during type-III sag is  
 520 similar to that obtained in previous tests, as shown in Fig. 15.  
 521 In this case, the change in the generated power has been pro-  
 522 grammed from 300 W up to 2000 W. Thus, the system is able to  
 523 deliver this maximum value of the active power once the sag is  
 524 cleared. Since the voltage droop is balanced in the three phases,



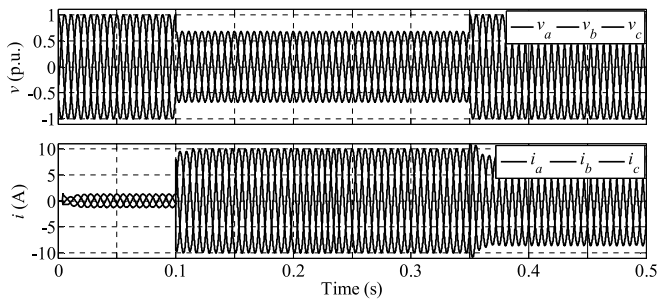


Fig. 16. Voltage and phase currents waveforms during the type-III sag. Top: PCC phase voltages. Bottom: phase currents.

TABLE II  
PEAK CURRENT VALUES DURING DIFFERENT SAGS

Sag type	I	II	III
Sag	$V^+ = 0.68$	$V^+ = 0.68$	$V^+ = 0.68$
Characteristics	$V^- = 0.22$	$V^- = 0.22$	$V^- = 0$
	$\delta = 280$	$\delta = 10$	$\delta = 0$
$i_a$ (A)	7.69	5.51	10.00
$i_b$ (A)	6.01	10.00	10.00
$i_c$ (A)	10.00	9.32	10.00

525 the output currents are also balanced with maximum amplitudes  
526 of 10 A as shown in Fig. 16.

527 The simulations results obtained during the tests verify the  
528 outstanding dynamics properties of the proposed strategy. The  
529 is able to handle both different types of sags, and the change  
530 in the generated power. Table II summarizes the results for the  
531 three simulation tests. Note that the maximum current is 10 A in  
532 only one phase for type-I and type-II sags, while in the type-III  
533 sag, the current amplitudes are 10 A in all the phases.

#### 534 E. Discussion on the Benefits of the Proposed Strategy

535 The performance of VSI under voltage sag has been widely  
536 investigated. However, the best strategy is still an open research  
537 topic and depends on many aspects such as grid stiffness, DG-  
538 rated power, type of prime mover, type of sag, external require-  
539 ments, etc. The control strategy presented in this paper is based  
540 on a flexible reference current generator that can be adjusted  
541 by means of two control parameters to obtain different results  
542 in terms of power quality, balance among positive and negative  
543 sequences, active and reactive power injection characteristics,  
544 among others. In fact, it can reproduce previous injection strate-  
545 gies by proper selection of the control parameters.

546 One of the contributions of this paper is a particular selection  
547 of the control parameter which permits to preserve one  
548 remarkable feature of previous strategies such as the mitigation  
549 of active power oscillation. Furthermore, thanks to the proposed  
550 parameter selection, the referent current generator (see (12)–  
551 (15)) turns into a simple and normalized structure that permits  
552 to develop two simple and compact expressions (see (29) and  
553 (31)). It is worth mentioning that these expressions incorporate  
554 the peak current limitation function and facilitate the devise  
555 of the proposed control strategy as shown in Fig. 2. The pro-

TABLE III  
COMPARISON WITH PREVIOUS STRATEGIES

Strategy	Deliver to the grid	Peak current limitation	Injected current THD	Reduce $p$ oscillation	Control Complexity
[11]	only P	No	High	No	Low
[12]	only Q	Yes	Low	No	Low
[13]					
[15]	P and Q	Yes	Low	No	High
[16]	P and Q	Yes	Low	Yes	High
	P and Q	Yes	Low	Yes	Low
Proposal					

500 posed strategy gives priority to the injection of active power  
501 which matches correctly with the actual PV GCs requirements.  
502 Furthermore, under sag situation, a reactive power reference is  
503 online computed based on the remaining VSI current capacity.  
504 This property permits to support the grid during contingencies  
505 and, at the same time, it protects the inverter against overcurrent.  
506 The proposed strategy shares important features with some previous  
507 strategies such as peak current limitation and mitigation of active  
508 power oscillation. Furthermore, it reduces the implementation  
509 complexity by integrating these functionalities in two compact ex-  
510 pressions. In addition, the proposed strategy provides outstand-  
511 ing dynamic behavior that permits to obtain smooth transitions  
512 under active power variations and also during changes in the op-  
513 eration mode (i.e., active power curtailment and active power  
514 injection). To summarize the discussion, Table III compares the  
515 main features of the proposal and previous strategies.

## 516 VI. CONCLUSION

517 This paper has presented a VSI control strategy that max-  
518 imizes the power capabilities of distributed PV inverters under  
519 voltage sag. By means of the proposed flexible current injection  
520 strategy, two main objectives have been achieved. First, to safely  
521 maintain the injected currents controlled by the maximum rated  
522 value independent of the sag depth and generated power and,  
523 second, to avoid oscillations in the injected active power. Both  
524 objectives contribute to improve the grid stability and ensure an  
525 optimized use of the whole VSI power capability, improving the  
526 quality of the injected power. The effectiveness of the proposed  
527 control strategy has been validated by a comprehensive set of  
528 simulation and experimental results.

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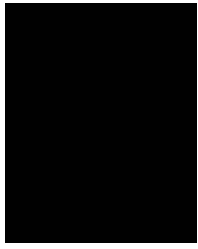
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