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Sequence extraction-based low voltage ride-through control of grid-connected renewable energy systems

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Abstract

Various faults can cause voltage sag in the power grid at different voltage levels across the network. Balanced or unbalanced voltage sags lead to grid instability by tripping off a large number of wind or solar power plants from the electric power network. This is particularly problematic to maintain the stability of renewable ~~energy-rich~~energy-rich converter-dominated modern power systems. To mitigate the adverse effects of voltage sag, grid-connected converters (GCCs) need to be capable of operating in self-healing and fault-tolerant mode by embedding low voltage ride-through (LVRT) capability into the control system of GCCs. In order to facilitate the implementation of LVRT capabilities for unbalanced faults, fast and accurate frequency-adaptive sequence extraction of grid voltages and currents ~~are~~is essential. This motivated the present work of making a systematic comparison of adaptive observer-based sequence extraction techniques to provide LVRT capabilities into the control system of GCCs. In order to show the effectiveness of each observer, various comparative analyses were performed through Matlab-based numerical simulation. Different observers were benchmarked by the dynamic performance improvement during the low-voltage fault period. Experimental results using a laboratory-scale prototype GCC show that adaptive observers are a suitable choice of sequence extractors for LVRT operation of grid-connected converters in unbalanced and distorted grids. The results obtained in this work will contribute to enhancing the stability of modern power systems that are getting more and more converter-dominated. Word Count: ~~7695~~8244

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32 *Keywords:* **Grid-connected converters, low voltage ride-through,**
33 **grid codes, sequence extraction, grid-synchronization, adaptive**
34 **observers.**

35 **Nomenclature**

- 36 $\Delta\omega$ Deviation from the nominal frequency
- 37 ΔP Required power decrement
- 38 η Frequency adaptation tuning gain
- 39 \hat{x}, \hat{z} Estimated variables
- 40 $\mathcal{A}, \mathcal{A}_z$ State matrix
- 41 $\mathcal{C}, \mathcal{C}_z$ Output matrix
- 42 $\mathcal{L} = [\mathcal{L}_1 \ \mathcal{L}_2]$ Observer gain matrix
- 43 ω, θ Grid frequency and phase angle
- 44 ω_n Nominal frequency
- 45 $v_{a,b,c}$ Line voltages
- 46 $v_{a,b,c}^\perp$ Orthogonal line voltages
- 47 $v_{i_{a,b,c}}$ Inverter output voltages
- 48 ε_{max} Maximum line over-current
- 49 $i_{a,b,c}$ Line currents
- 50 i_{ref} Current references
- 51 i_{th} Threshold value of line currents
- 52 L Line filter inductance
- 53 O Observability matrix
- 54 p_0, p_{c2}, p_{s2} Instantaneous and oscillating terms of active power

55	P_{max}	Maximal generator power
56	P_{nom}	Nominal generator power
57	P_{ref}, Q_{ref}	Active and reactive power references
58	$qv_{a,b,c}$	Quadrature line voltages
59	q_0, q_{c2}, q_{s2}	Instantaneous and oscillating terms of reactive power
60	Q_p	Reactive current ratio
61	R	Line filter resistance
62	T	Transformation matrix
63	V_g	Grid voltage level
64	$x^{+,-,0}$	Positive, negative, and zero sequences
65	$x^{p,n}$	Positive and negative components terms
66	$x_{d,q}$	Direct and quadrature axes terms
67	ANF	Adaptive notch filter
68	DC	Direct current
69	DERs	Distributed energy resources
70	FRT	Fault ride-through
71	GAO	Global adaptive observer
72	GCCs	Grid-connected converters
73	GCs	Grid codes
74	GNAO	Gain normalized adaptive observer
75	IGBT	Insulated gate bipolar transistor
76	LVRT	Low voltage ride-through
77	PCC	Point of common coupling

- 78 PI Proportional integrator
- 79 PLL Phase-locked loop
- 80 PNS Positive and negative sequences
- 81 RES Renewable energy sources
- 82 SAO SOGI-type adaptive observer
- 83 SOGI Second-order generalized integrator
- 84 STF Self-tuning filter
- 85 SYRF Synchronous reference frame
- 86 THD Total Harmonic Distortion
- 87 VSI Voltage source inverter

88 **1. Introduction**

89 In light of the recent developments around the net-zero carbon emission
90 target by 2050, fossil fuels are slowly losing their position as the main source
91 of electric energy generation [1, 2]. The hazardous and harmful effects of fossil
92 fuel-based energy generation are well documented [3, 4]. Considering the role
93 of fossil fuels on harmful gas emissions, researchers around the world made
94 significant efforts to look for alternative sources of low-carbon electric power
95 generation [5, 6]. Out of various alternative solutions, renewable energy
96 sources (RES) became very popular in recent times as they are abundant,
97 clean, sustainable, and provide good economic value in the long-term. This
98 gives rise to the modern electric power systems where RES-based distributed
99 energy resources (DERs) are slowly starting to become a major supplier of
100 electric power to the utility grid, thereby significantly reducing overall carbon
101 emissions [7, 8].

102 As the penetration of DERs is slowly increasing, efficient integration of
103 these energy sources to the conventional power grid became a point of ma-
104 jor concern for electric utilities around the world [9]. DERs are typically
105 connected to the grid through grid-connected converters (GCCs), thereby
106 making the grid slowly converter-dominated [10, 11]. It is to be noted here

107 that high penetration of power converters will cause various adverse phe-
108 nomena on the utility grid, especially in terms of power quality, reliability,
109 voltage/frequency instability, etc. [12, 13]. This motivated researchers to
110 work on the control of GCCs to ensure efficient and grid-friendly integration
111 of GCCs into the utility grid [14].

112 Efficient integration of DERs in a converter-dominated power grid is a
113 very challenging task due to various power quality and voltage/frequency
114 stability issues [15]. To mitigate these issues, extensive rules and grid codes
115 (GCs) are developed by various regulating authorities around the world to
116 ensure stable, safe, and continuous electric power transfer from DERs into the
117 utility grid [16, 17]. Grid codes are typically very extensive and cover many
118 topics. Some of the popular requirements mentioned in the grid codes are
119 power quality standards at the point of common coupling (PCC) to the grid,
120 active and reactive power regulation, voltage and frequency control, accurate
121 grid-synchronization, fault ride-through (FRT) capability, etc. [18, 19].

122 Out of the various requirements mentioned in the GCs, the focus of this
123 work is particularly on the FRT capability. Momentary or short-term volt-
124 age fluctuations are very common in the utility grid. In practice, due to
125 various faults, grid voltage amplitude may drop well below (e.g. 50%) the
126 nominal value. Many GCs require that the DER be connected despite this
127 large voltage drop/sag. As such, FRT ability in the form of low voltage ride-
128 through (LVRT) capability should be embedded into the control system of
129 GCCs [20, 21]. This permits ~~to ensure~~ ensuring an uninterrupted grid in-
130 tegration even under large voltage sags and subsequently ~~enhance~~ enhances
131 the grid stability by voltage support strategy [22, 23]. Grid voltage sags are
132 categorized into two types, symmetrical when all phases have the same volt-
133 age level, and asymmetrical when the voltage levels of individual phases are
134 unequal. Problems that arise due to symmetrical and asymmetrical voltage
135 sags are summarized below [24, 25]:

- 136 • Fault-induced high-current injection by the GCC may damage the
137 IGBT switches due to over-current flow.
- 138 • Double fundamental frequency oscillation appears in the output power
139 and the DC-link voltage of the GCC.
- 140 • DC-link voltage oscillations reduce the capacitor lifetime.
- 141 • DC-link voltage oscillations make the reference current non-sinusoidal,
142 thereby deteriorating the power quality.

143 To mitigate the issues summarized above, symmetrical and asymmetrical
144 LVRT capable control scheme development is essential. The LVRT capa-
145 ble control system must ensure some objectives that are, 1) reactive power
146 injection to support the grid during voltage sags as per grid codes require-
147 ments [26], 2) active power curtailment depending on the fault depth [27],
148 3) real-time sequences extraction for negative sequence cancellation [28], 4)
149 new current references calculation in both positive and negative sequences
150 for double frequency active power oscillation mitigation under unbalanced
151 sag [29, 30], 5) limiting the injected currents to protect the inverter from
152 over-current tripping [31], and 6) dual current controller ensuring the safe
153 integration under a wide range of grid voltages [32]. Some recent results in
154 this topic that satisfy some of these objectives can be found in [33, 34].

155 It is to be noted here that in this work, our focus is on the LVRT
156 control of grid-connected RES, where a GCC acts as an interface between
157 the RES and the grid. In certain cases, e.g. doubly-fed induction generator
158 (DFIG)-based grid-connected RES, the stator of DFIG is directly connected
159 to the grid. This necessitates the development of DFIG-specific control
160 approaches such as demagnetization control [35, 36, 37] and feed-forward
161 control [38, 39, 40], which are typically not applicable to other types of
162 grid-connection topology. As such, a detailed review of LVRT control system
163 development for DFIG-based RES is avoided here and interested readers
164 may consult the review papers [41, 42, 43, 44], and the references therein for
165 a comprehensive overview of this topic.

166 As highlighted in the LVRT objectives, dual-loop, i.e., positive and nega-
167 tive sequence controllers are essential to mitigate the adverse effects of asym-
168 metrical voltage sags [45]. In order to facilitate the implementation of such
169 controllers, fast and accurate frequency-adaptive sequence extraction of grid
170 voltages and currents are essential. In this regard, several estimators are
171 available in the literature. Some popular estimators are Kalman filter [46],
172 demodulation [47, 48], second-order generalized integrator (SOGI) [49], adap-
173 tive notch filter (ANF) [50], open-loop techniques [51], self-tuning filter (STF) [52],
174 adaptive observers [53, 54], to name a few. These estimators have their own
175 merits and demerits.

176 These estimators operate by generating orthogonal signals from the mea-
177 sured three-phase voltages and currents. Then, by applying the symmetri-
178 cal components theory [55], positive and negative sequence components can
179 easily be separated. Separated components can be used inside a traditional
180 synchronous reference frame phase-locked loop (SYRF-PLL) [56] to make the

181 overall operation grid frequency-adaptive. In the relevant literature, SOGI
182 [49], ANF [50], and STF [52] are some of the most popular and widely used
183 orthogonal signal generators. These filters use a linear harmonic oscillator
184 model and based on this model the filtering task is performed. These
185 filters have ~~ban~~a band-pass property, which helps to reduce the effect of
186 harmonics. However, the dynamic tuning range of these filters is limited if
187 complex-conjugate poles are considered [57]. In the presence of noisy mea-
188 surements, the Kalman filter [46] can be considered as a suitable orthogonal
189 signal generator. However, it is difficult to tune, as it requires information
190 about the process and measurement noise characteristics. Moreover, it is also
191 computationally demanding for real-time applications [58]. In this context,
192 adaptive observer-based sequence extraction techniques can be considered
193 as a suitable choice since these observers have very fast convergence prop-
194 erties [53, 54] unlike second-order band-pass type filters. Moreover, they
195 are not computationally demanding like the Kalman filter and can be tuned
196 easily using ~~pole-placement~~pole placement. As such, in this work, adaptive
197 observers have been considered as the positive and negative sequence extrac-
198 tion techniques.

199 In a recent work [28, 59], a comparative analysis has been presented
200 to show the suitability of these adaptive observer-based sequence extrac-
201 tion techniques on synthetic grid voltages. This motivated the present work
202 of making a systematic comparison of these techniques to provide LVRT
203 capabilities into the control system of GCCs. For this purpose, sequence
204 extraction-based current controllers are adopted in this work, which is moti-
205 vated by [60]. The key features of this work are summarized as follows:

- 206 • A control solution is proposed for ensuring reactive power injection as
207 a priority to alleviate the negative effects of voltage sag. The reactive
208 power set-point is determined as per GCs requirements, ensuring stable
209 and reliable grid operation.
- 210 • The injected currents are limited within a threshold value under bal-
211 anced or unbalanced sags, which ~~help avoid converter over-current~~
212 ~~related tripping.~~ helps avoid converter over-current-related tripping.
213 Thus, the proposed solution ensures system stability and prevents unnecessary
214 interruptions in power delivery.
- 215 • The current limiting property is based on reducing the active power
216 reference while maintaining the reactive power reference within GCs

217 requirements. This proposed approach optimizes the power flow within
218 the maximum inverter capacity and ensures compliance with grid regulations.
219

- 220 • Grid voltage sequences and their angular frequency are synthesized us-
221 ing the studied adaptive observers. This proposed feature offers an
222 improved estimation and control framework compared to conventional
223 approaches, leading to enhanced performance and robustness in grid-connected
224 inverter systems.
- 225 • A detailed formulation is provided to calculate current references in
226 the synchronous reference frame (SYRF) in both positive and nega-
227 tive sequences (PNS)~~to suppress the~~. This formulation enables the
228 suppression of active output power oscillations, which is crucial for
229 maintaining grid stability and avoiding DC-link voltage fluctuations
230 leading to capacitors damage.
- 231 • Actual current sequences are obtained through the designed adap-
232 tive observers and then controlled separately using a dual-controller
233 approach to achieve all the LVRT common options. By employing these
234 adaptive observers, accurate estimation and flexible current control are
235 ensured, thereby enabling an effective LVRT implementation and grid
236 synchronization under various grid faulty conditions.

237 The rest of this paper is organized as follows: Section 2 introduces the
238 used system with its modeling in SYRF-coordinate. Moreover, all GCCs
239 control requirements are also detailed here. In section 3, details of the grid-
240 synchronizing PNS extraction techniques are given. Comprehensive numeri-
241 cal simulation results using various challenging LVRT scenarios are provided
242 in section 4. Details of the laboratory-scale hardware setup and extensive
243 experimental results are provided in section 5. Finally, section 7 concludes
244 the paper.

245 **2. Overview of the Studied System**

246 *2.1. System description*

247 Figure 1 shows the overview of the considered system. It is composed
248 of a two-level voltage source inverter (VSI) which is typically powered by a
249 direct current (DC) source to emulate the RES. The VSI is then connected

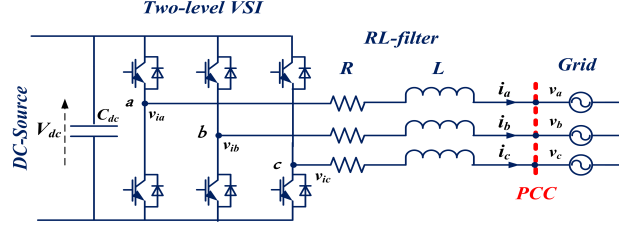


Figure 1: Three-phase distributed grid-connected renewable energy system.

250 to the main grid at the point of common coupling (PCC) through the output
 251 filter, which is inductive in our case. All the system parameters are listed in
 252 table 1.

Table 1: System Parameters.

Parameters	Symbol	Value
Nominal power	P_{nom}	500 W
DC link	V_{dc}	200 V
Grid voltage	$V_g^{rms}_{l-l}$	110 V
Grid frequency	f_g	50 Hz
Switching frequency	f_{sw}	10 kHz
Filter resistance	R	0.3 Ω
Filter inductance	L	11 mH
Sampling time	T_s	0.05 ms

253 By applying ~~the~~ Kirchoff's laws to the circuit in figure 1, the following
 254 relationships between the electrical parameters are obtained:

$$\begin{cases} L \frac{di_a}{dt} = v_{ia} - v_a - Ri_a \\ L \frac{di_b}{dt} = v_{ib} - v_b - Ri_b \\ L \frac{di_c}{dt} = v_{ic} - v_c - Ri_c \end{cases} \quad (1)$$

255 where v_a, v_b, v_c are the grid phase voltages, v_{ia}, v_{ib}, v_{ic} are the inverter output
 256 phase voltages. i_a, i_b, i_c are the grid line currents, L is the line filter inductor,
 257 and R is the parasitic resistance of the line inductor.

258 In order to study the system under generic grid voltages, i.e., balanced
 259 or unbalanced situations, both PNS should be considered. Considering the
 260 simplicity of the SYRF in grid-connected converters control [1], Eq. (1) is
 261 transformed in SYRF by taking into account both PNS:

$$\begin{cases} L \frac{di_d^p}{dt} = -Ri_d^p + L\omega i_q^p + v_{i_d}^p - v_d^p \\ L \frac{di_q^p}{dt} = -Ri_q^p - L\omega i_d^p + v_{i_q}^p - v_q^p \\ L \frac{di_d^n}{dt} = -Ri_d^n - L\omega i_q^n + v_{i_d}^n - v_d^n \\ L \frac{di_q^n}{dt} = -Ri_q^n + L\omega i_d^n + v_{i_q}^n - v_q^n \end{cases} \quad (2)$$

262 where subscripts d and q represent the direct and quadrature axes of SYRF,
 263 superscripts p and n represent the positive and negative sequence compo-
 264 nents of voltage and currents. The delivered powers can then be written
 265 as [61]:

$$\begin{cases} p(t) = p_0 + p_{c2} \cos(2\omega t) + p_{s2} \sin(2\omega t) \\ q(t) = q_0 + q_{c2} \cos(2\omega t) + q_{s2} \sin(2\omega t) \end{cases} \quad (3)$$

266 where p_0 and q_0 represent the instantaneous active and reactive powers. Un-
 267 der the fault-free state, p_0 and q_0 are constants and correspond to active and
 268 reactive power references without any oscillations. The oscillating terms p_{c2} ,
 269 p_{s2} , q_{c2} , and q_{s2} appear only under the unbalanced grid voltages. All the
 270 terms in Eq. (3) are expressed as:

$$\begin{bmatrix} p_0 \\ p_{c2} \\ p_{s2} \\ q_0 \\ q_{c2} \\ q_{s2} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} v_d^p & v_q^p & v_d^n & v_q^n \\ v_d^n & v_q^n & v_d^p & v_q^p \\ v_q^n & -v_d^n & -v_q^p & v_d^p \\ v_q^p & -v_d^p & v_q^n & -v_d^n \\ v_q^n & -v_d^n & v_q^p & -v_d^p \\ -v_d^n & -v_q^n & v_d^p & v_q^p \end{bmatrix} \begin{bmatrix} i_d^p \\ i_q^p \\ i_d^n \\ i_q^n \end{bmatrix} \quad (4)$$

271 2.2. Control requirements

272 In order to avoid the disconnection of GCCs from the utility grid un-
 273 der symmetrical or asymmetrical voltage sags, the control structure must
 274 meet some requirements to ride through this fault. These requirements are
 275 summarized below:

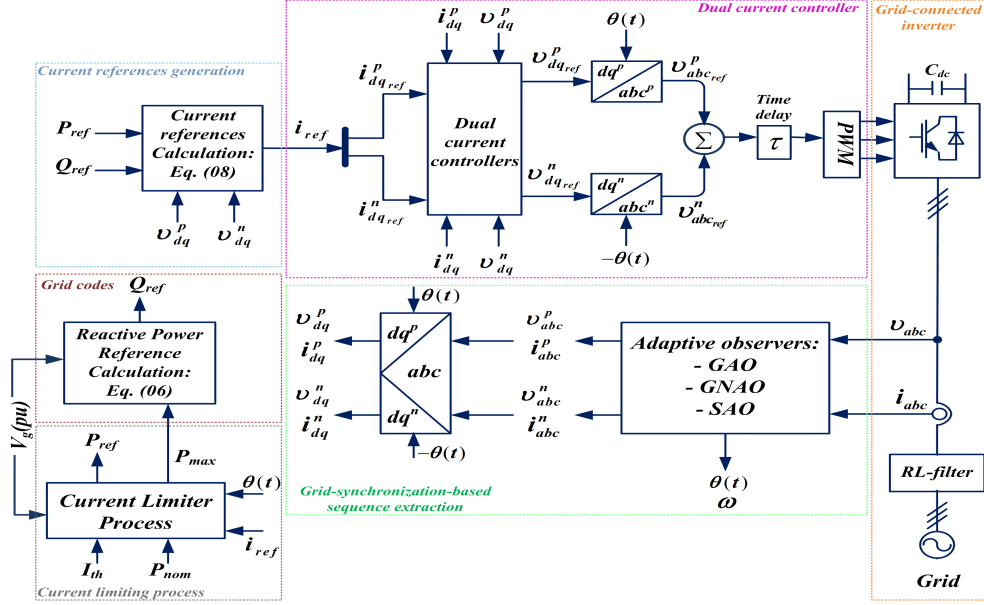


Figure 2: Block diagram of the proposed control strategy.

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- **Current-limiting control:** Peak current limiter-enabled LVRT control is necessary to improve the grid stability under voltage sags, protect the inverter and the ~~semi-conductor~~ semi conductor switches from over-current damages, ignore active power oscillations under unbalanced faults, and ensure a continuous grid connection even under faulty grid conditions.
 - **Reactive power injection:** The designed control architecture is focused mainly on reactive power injection as per GCs to support the grid during voltage sags, generate new current references on SYRF dealing with active power fluctuations, and maintain the injected currents below the threshold value even under balanced or unbalanced faults.

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These control requirements are achieved through the control structure shown in Figure 2. The remainder of this Section provides the details of individual blocks while the details of PNS extraction techniques are given in Sec. 3.

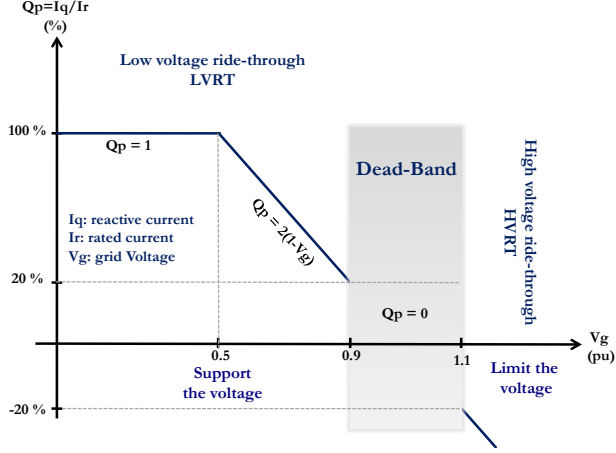


Figure 3: Reactive current injection to support/limit voltage during low voltage ride-through/high voltage ride-through.

291 *2.2.1. Grid code requirements*

292 Active and reactive power references are determined based on the grid
 293 voltage level. Under normal operation (i.e. $V_g(\text{p.u.})=1$), injected active
 294 power corresponds exactly to the nominal value of the GCCs with the reactive
 295 power being zero, i.e., $P_{ref} = P_{nom}$, $Q_{ref} = 0\text{VAr}$). However, under grid
 296 voltage sags ($V_g(\text{p.u.}) < 1$), recent GCs mandate reactive power injection to
 297 support the grid voltage and enhance its stability [26].

298 As shown in Fig. 3, the required reactive current is selected as a function
 299 of the rated converter current. This relationship is mainly based on the
 300 voltage level as expressed in the following equation:

$$Q_p = \begin{cases} 1, & 0 \leq V_g < 0.5 \\ 2(1 - V_g), & 0.5 \leq V_g < 0.9 \\ 0, & 0.9 \leq V_g < 1.1 \end{cases} \quad (5)$$

301 The new reactive power reference is therefore defined as:

$$Q_{ref} = Q_p \cdot P_{max} \quad (6)$$

302 where P_{max} is the full available power of the generator.

303 *2.2.2. Current reference generation*

304 As previously mentioned, unbalanced faults generate double the funda-
 305 mental grid-frequency active power oscillations. These oscillations should be

306 eliminated to facilitate smooth grid integration of the RES. ~~for~~ For this issue,
 307 SYRF reference currents are determined based on Eq. (4) by forcing both
 308 p_{c2} and p_{s2} to become zero:

$$\begin{bmatrix} i_{dref}^p \\ i_{qref}^p \\ i_{dref}^n \\ i_{qref}^n \end{bmatrix} = \frac{2}{3} \begin{bmatrix} v_d^p & v_q^p & v_d^n & v_q^n \\ v_d^n & v_q^n & v_d^p & v_q^p \\ v_q^n & -v_d^n & -v_q^p & v_d^p \\ v_q^p & -v_d^p & v_q^n & -v_d^n \end{bmatrix}^{-1} \begin{bmatrix} P_{ref} \\ 0 \\ 0 \\ Q_{ref} \end{bmatrix} \quad (7)$$

309 where, P_{ref} and Q_{ref} represent the active and reactive power references,
 310 respectively. Q_{ref} is selected using the grid code requirements, while P_{ref} is
 311 determined based on the active power curtailment process when the injected
 312 currents must be limited to the threshold value [62, 31]. Therefore, the
 313 current references represented in SYRF are expressed as [63, 60]:

$$\begin{bmatrix} i_{dref}^p \\ i_{qref}^p \\ i_{dref}^n \\ i_{qref}^n \end{bmatrix} = \frac{2P_{ref}}{3A} \begin{bmatrix} v_d^p \\ v_q^p \\ -v_d^n \\ -v_q^n \end{bmatrix} + \frac{2Q_{ref}}{3B} \begin{bmatrix} v_d^p \\ -v_q^p \\ v_d^n \\ -v_q^n \end{bmatrix} \quad (8)$$

314 where,

$$A = (v_d^p)^2 + (v_q^p)^2 - (v_d^n)^2 - (v_q^n)^2$$

315

$$B = (v_d^p)^2 + (v_q^p)^2 + (v_d^n)^2 + (v_q^n)^2$$

316 2.2.3. Current limiting process

317 The main purpose of the current limiter is to enhance the protective
 318 measures for the GCCs under faulty conditions. The current controller should
 319 prohibit the line currents to exceed their threshold value, which is defined as
 320 the maximum permissible peak line currents. The equation that describes
 321 this process in the natural reference frame is as follows [64]:

$$i_j^{ref} = \begin{cases} i_{th} & \left| i_j^{ref} \right| > i_{th} \\ -i_{th} & \left| i_j^{ref} \right| < -i_{th} \\ i_j^{ref} & \text{otherwise} \end{cases} \quad (9)$$

322 where, $j = a, b, c$ denote the individual phases and i_{th} is the threshold value
 323 of line-currents. i_{th} is considered as 1.5 p.u. in this paper.

324 Considering a sinusoidal signal $x(t)$ with an angular frequency ω , magni-
 325 tude A , and a phase shift ϕ , each line-currents can be expressed as follows:

$$x(t) = A \cos(\omega t + \phi) \quad (10)$$

326 Since the main issue in the current limiting implementation is the accurate
 327 magnitude calculation, the estimator considered in [62] is used here as it is
 328 fast and easy to implement:

$$A = \sqrt{(x(t))^2 + \frac{1}{\omega^2} \left(\frac{dx(t)}{dt} \right)^2} \quad (11)$$

329 As explained in [31], the used current limiter is based on current magni-
 330 tude regulation to the threshold value. This is achieved firstly by converting
 331 the obtained current references into the natural reference frame and comput-
 332 ing their magnitudes. Moreover, to consider both balanced and unbalanced
 333 situations, this limiter selects the maximum line currents and calculates its
 334 error regarding the threshold value. Thus, the following equation is obtained:

$$\varepsilon_{max} = \max(A_{i_a}, A_{i_b}, A_{i_c}) - i_{th} \quad (12)$$

335 Since the reactive power reference is selected by the grid codes, the only
 336 way to limit the line currents is to decrease the active power reference and
 337 observe its effect in the line-current magnitudes. The required power that
 338 should be reduced (ΔP) is determined via a simple integral controller with
 339 tuning gain k_i :

$$\Delta P = k_i \int \varepsilon_{max} \cdot dt \quad (13)$$

340 In this case, the new active power reference can be expressed mathemat-
 341 ically as:

$$P_{ref} = P_{nom} - \Delta P \quad (14)$$

342 It should be mentioned that under severe voltage sags, currents increase
 343 excessively, and ΔP will be higher than P_{nom} . In this case, the full available
 344 power of the generator P_{max} should be reduced and the power references can
 345 be calculated as follows:

$$\begin{cases} P_{ref} = 0 \\ P_{max} = 2 \cdot P_{nom} - \Delta P \\ Q_{ref} = Q_p \cdot P_{max} \end{cases} \quad (15)$$

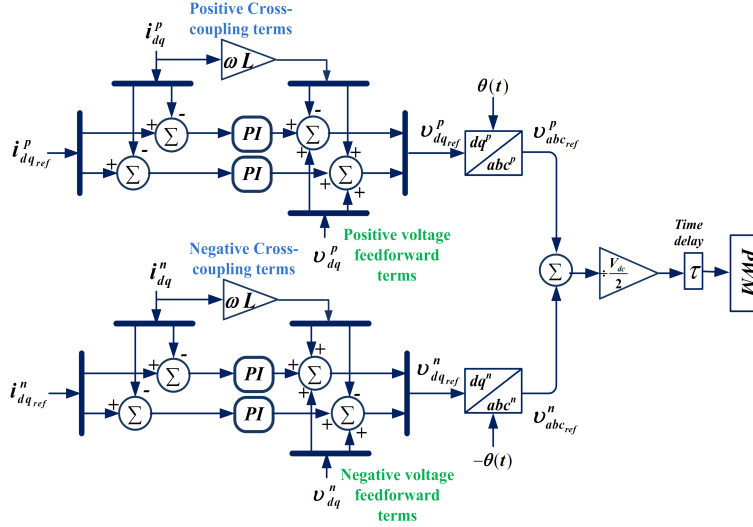


Figure 4: Overview of the used dual current controller.

346 2.2.4. Dual current controller

347 The adopted current controller shown in Fig. 4 is working at SYRF using
 348 proportional integrator (PI) regulators. The duality concept concerns the
 349 PNS control simultaneously, i.e., under normal grid voltages, injected power
 350 references are ensured only by regulating the positive currents. However,
 351 under faulty grid voltages, it is necessary to control the negative currents
 352 and eliminate the active power oscillations.

353 According to the power reference values, the current references are deter-
 354 mined based on Eq. (8). These currents are then regulated via PI controllers,
 355 added to the feedforward and cross-coupling terms, the obtained commands
 356 are sent to the inverter through a pulse width modulation block [31, 65]. For
 357 the controller, the objective is to achieve zero steady-state tracking error,
 358 i.e., $\lim_{t \rightarrow \infty} (i_{dq,ref}^m - i_{dq}^m) = 0, m \in \{p, n\}$, where *ref* indicates the reference
 359 value and the i_{dq}^m are obtained through the sequence estimators detailed in
 360 Sec. 3.

361 2.2.5. Grid-synchronization-based sequence extraction

362 In order to achieve better control of active and reactive powers under
 363 balanced or unbalanced grid voltages, accurate grid frequency estimation
 364 and voltages/currents sequences extraction are necessary. As discussed in
 365 the Introduction section, to address this issue, several estimators have been

366 proposed in the literature. The focus of the present paper is to make a
 367 systematic comparison of adaptive observer-based sequence extraction tech-
 368 niques in LVRT capabilities improvement. The following section discusses in
 369 detail these techniques.

370 ~~Sequences~~ Sequence separation is also important to quantify the voltage
 371 fault level and therefore apply the grid code requirements. The equation that
 372 describes this quantification is given as follows [66]:

$$V_g(pu) = \frac{v_d^p}{v_{nom}^{peak}} \quad (16)$$

373 where, $v_{nom}^{peak} = \sqrt{\frac{2}{3}} \cdot V_g^{rms}$, and v_d^p is obtained using voltage sequences
 374 estimator.

375 3. Adaptive Observer-based Grid-Synchronization

376 Grid voltages in a generic (symmetrical/asymmetrical) form are com-
 377 posed of positive (+), negative (-), and zero (0) sequence components. Since
 378 the studied system represents a three-leg three-wire inverter, the zero (0) se-
 379 quence component has no impact on the system control [67]. Therefore, the
 380 three-phase grid voltages in our case are expressed as:

$$\left\{ \begin{array}{l} v_a = \underbrace{A^+ \sin(\omega t + \phi^+)}_{v_a^+} + \underbrace{A^- \sin(\omega t + \phi^-)}_{v_a^-} \\ v_b = \underbrace{A^+ \sin\left(\omega t - \frac{2\pi}{3} + \phi^+\right)}_{v_b^+} + \underbrace{A^- \sin\left(\omega t + \frac{2\pi}{3} + \phi^-\right)}_{v_b^-} \\ v_c = \underbrace{A^+ \sin\left(\omega t + \frac{2\pi}{3} + \phi^+\right)}_{v_c^+} + \underbrace{A^- \sin\left(\omega t - \frac{2\pi}{3} + \phi^-\right)}_{v_c^-} \end{array} \right. \quad (17)$$

381 where $A \in \mathbb{R}_{\geq 0}$ represents the magnitude, $\phi \in \mathbb{R}$ is the initial phase shift,
 382 and $\omega \in \mathbb{R}_{> 0}$ is the angular frequency. It should be noted that according
 383 to the European standard EN 50160, the frequency can vary between 47
 384 and 52 Hz [68]. In the same way, the injected currents are expressed in
 385 their ~~steady-state~~ steady state. The following development concerns the grid
 386 voltages only and will be generalized also to the injected currents.

387 In order to extract both positive (+) and negative (-) sequences, and
 388 estimate the angular frequency ω from Eq. (17), it should be necessary to
 389 define the quadrature version of the grid voltages:

$$\left\{ \begin{array}{l} qv_a = \underbrace{A^+ \cos(\omega t + \phi^+)}_{qv_a^+} + \underbrace{A^- \cos(\omega t + \phi^-)}_{qv_a^-} \\ qv_b = \underbrace{A^+ \cos\left(\omega t - \frac{2\pi}{3} + \phi^+\right)}_{qv_b^+} + \underbrace{A^- \cos\left(\omega t + \frac{2\pi}{3} + \phi^-\right)}_{qv_b^-} \\ qv_c = \underbrace{A^+ \cos\left(\omega t + \frac{2\pi}{3} + \phi^+\right)}_{qv_c^+} + \underbrace{A^- \cos\left(\omega t - \frac{2\pi}{3} + \phi^-\right)}_{qv_c^-} \end{array} \right. \quad (18)$$

390 As it is clear from Eqs. (17) and (18), the PNS of the grid voltages can
 391 be determined using the following equations:

$$\begin{bmatrix} v_a^+ \\ v_b^+ \\ v_c^+ \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ -\frac{1}{2} & 1 & -\frac{1}{2} \\ -\frac{1}{2} & -\frac{1}{2} & 1 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} + \frac{1}{2\sqrt{3}} \begin{bmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} qv_a \\ qv_b \\ qv_c \end{bmatrix}, \quad (19)$$

$$\begin{bmatrix} v_a^- \\ v_b^- \\ v_c^- \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ -\frac{1}{2} & 1 & -\frac{1}{2} \\ -\frac{1}{2} & -\frac{1}{2} & 1 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \frac{1}{2\sqrt{3}} \begin{bmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} qv_a \\ qv_b \\ qv_c \end{bmatrix}. \quad (20)$$

393 As observed in Eqs. (19) and (20), the quadrature signals are necessary
 394 to determine the sequence components. In general, if the grid frequency is
 395 known, then, the quadrature signals can be obtained easily by applying a 90°
 396 phase shift on the original signals. This is equivalent to delaying the original
 397 signals by one quarter of the fundamental cycle. However, the grid frequency
 398 is unknown in practice. This motivated us to apply adaptive observer-based
 399 grid-synchronization techniques from the literature. These observers consider
 400 the grid voltages and the corresponding quadrature components as the state
 401 variables, while the grid frequency appears as an unknown parameter in the
 402 system dynamics. From the estimated parameter and state variables, the
 403 PNS components can be easily extracted in real-time by applying Eqs. (19)
 404 and (20). Details of the adopted frequency-adaptive observers are given in
 405 the following:

406 *3.1. Global adaptive observer*

407 The estimation principle based on the global adaptive observer (GAO)
 408 is detailed in [69]. In order to define the state-space model of the studied
 409 system, only phase "a" voltage is considered. Then, the developed model
 410 is generalized to the other phase voltages and also for the injected currents.
 411 The following state variables $x_1, x_2 \in \mathbb{R}$ are considered:

$$\begin{cases} x_1 = v_a = A^+ \sin(\omega t + \phi^+) + A^- \sin(\omega t + \phi^-) \\ x_2 = \dot{x}_1 = \dot{v}_a = \omega(A^+ \cos(\omega t + \phi^+) + A^- \cos(\omega t + \phi^-)) \end{cases} \quad (21)$$

412 According to Eq. (21), the continuous-time system model is expressed
 413 as:

$$\begin{cases} \dot{x}(t) = \mathcal{A}x(t) \\ y(t) = \mathcal{C}x(t) \end{cases} \quad (22)$$

414 where the state matrix $\mathcal{A} \in \mathbb{R}^{2 \times 2}$, output matrix $\mathcal{C} \in \mathbb{R}^{1 \times 2}$, and the state
 415 vector $x \in \mathbb{R}^{2 \times 1}$ are given by:

$$416 \quad \mathcal{A} = \begin{bmatrix} 0 & 1 \\ -\omega^2 & 0 \end{bmatrix}, \mathcal{C} = [1 \ 0], \text{ and } x = [x_1 \ x_2]^T.$$

417 Since the grid frequency ω is an unknown variable in the state matrix \mathcal{A} ,
 418 it is formulated in terms of the nominal grid frequency ($\omega_n = 100\pi$) as $\omega^2 =$
 419 $\eta\omega_n^2$, $\eta \in \mathbb{R}_{>0}$. This permits simplifying the adaptation law development of
 420 the grid frequency ω [53, 69]. The problem here is to estimate the state vector
 421 $x(t)$ from the measured output signal $y(t)$. Since the considered system is
 422 linear time-invariant in nature with an unknown parameter, this can be easily
 423 achieved by the conventional linear Luenberger observer together with an
 424 adaptation law for the unknown parameter. Before developing the observer,
 425 first, the observability of the system needs to be confirmed. In order to
 426 study the observability of the system presented by Eq. (22), the observability
 427 matrix O should be given:

$$O = \begin{bmatrix} \mathcal{C} \\ \mathcal{C}\mathcal{A} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (23)$$

428 As it is clear from Eq. (23), the rank of the matrix O is 2 which is the
 429 same as the state matrix \mathcal{A} . Thus, the system expressed by Eq. (22) is
 430 observable. The GAO design is provided in detail in [28, 69], which is based
 431 on the following coordinate transformation:

$$z = Tx \quad (24)$$

432 where $z = [z_1 \ z_2]^T \in \mathbb{R}^{2 \times 1}$ is the transformed state vector. The non-
 433 singular transformation matrix $T \in \mathbb{R}^{2 \times 2}$ is given below:

434

$$T = \frac{(1 + \eta)^{-1}}{\omega_n^2} \begin{bmatrix} 1 & -\frac{1}{\omega_n} \\ \eta\omega_n & 1 \end{bmatrix}.$$

435 The new system matrices $\mathcal{A}_z \in \mathbb{R}^{2 \times 2}$ and $\mathcal{C}_z \in \mathbb{R}^{1 \times 2}$ are obtained as $\mathcal{A}_z =$
 436 $T\mathcal{A}T^{-1} = \mathcal{A}$, $\mathcal{C}_z = \mathcal{C}T^{-1} = [\omega_n^2 \ \omega_n]$. Therefore, the transformed state-
 437 space model for the phase voltage v_a is formulated as:

$$\begin{cases} \dot{z}(t) = \mathcal{A}_z z(t) \\ v_a(t) = \mathcal{C}_z z(t) \end{cases} \quad (25)$$

438 The objective here is to estimate the states and the unknown grid fre-
 439 quency parameter with zero steady-state error from the measured grid volt-
 440 age, i.e., $\lim_{t \rightarrow \infty} (z - \hat{z}) = 0$ and $\lim_{t \rightarrow \infty} (\omega - \hat{\omega}) = 0$, where $\hat{\cdot}$ represents the
 441 estimated value. For this purpose, the Luenberger observer [70] is employed
 442 to estimate the phase voltage v_a of the system presented by Eq. (25) as
 443 follows:

$$\dot{\hat{z}} = \hat{\mathcal{A}}_z \hat{z} + \mathcal{L} (v_a - \hat{v}_a) \quad (26)$$

444 where \hat{z} and \hat{v}_a are the estimated state variables and the a phase voltage,
 445 respectively. The observer gain is given by the matrix $\mathcal{L} \in \mathbb{R}^{2 \times 1}$. Moreover,
 446 $\hat{\mathcal{A}}_z$ contains the estimated grid frequency term in the function of the nominal
 447 one as $\hat{\mathcal{A}}_z = \begin{bmatrix} 0 & 1 \\ -\hat{\eta}\omega_n^2 & 0 \end{bmatrix}$.

448 Using the Lyapunov approach, the stability and convergence analysis of
 449 this observer are studied in detail in [69]. Based on the Lyapunov function
 450 analysis in [69], the following frequency update law makes the overall system
 451 globally asymptotically stable:

$$\dot{\hat{\eta}} = -\gamma\omega_n^2 (v_a - \hat{v}_a) \hat{z}_1, \quad (27)$$

452 where the frequency update law tuning gain is given by the positive constant
 453 γ . Since the transformed state variables are available, the phase voltage v_a
 454 and its quadrature signal qv_a can be obtained through the following formula:

$$\hat{x} = \hat{T}^{-1} \hat{z} \quad (28)$$

455 where

$$\hat{T}^{-1} = \omega_n^2 \begin{bmatrix} 1 & \frac{1}{\omega_n} \\ -\hat{\eta}\omega_n & 1 \end{bmatrix}.$$

456 In the same manner, the other phase voltages v_b and v_c with their quadra-
 457 ture signals qv_b and qv_c are estimated. Through the Eqs. (19) and (20),
 458 positive and negative voltage sequences can be determined. The above de-
 459 velopment is generalized to the injected currents (i_a, i_b, i_c) to obtain the cur-
 460 rent sequence components and permit the dual current control process. Since
 461 the grid frequency is the same for voltage and currents, only one frequency
 462 update law is enough for voltage and currents.

463 3.2. Gain normalized adaptive observer

464 As highlighted in [53], the GAO has a longer convergence time in the
 465 presence of voltage sags due to the lack of gain normalization in the frequency
 466 update law. To overcome this issue, a gain normalized adaptive observer
 467 (GNAO) is proposed there, which is detailed in the following:

468 The same system model of Eq. (22) is employed for this observer. To
 469 consider the gain normalization in the frequency law estimation, the un-
 470 known frequency ω is formulated as: $\omega = \omega_n + \Delta\omega$, where $\Delta\omega \in \mathbb{R}$ is the
 471 frequency shift from its nominal value. Considering this new grid frequency
 472 formulation, the non-singular states transformation is given as:

$$z = Tx \quad (29)$$

473 where $T = \frac{1}{2\omega^3} \begin{bmatrix} \omega & -1 \\ \omega^2 & \omega \end{bmatrix}$. The system model is then expressed in the
 474 z-coordinate as:

$$\begin{cases} \dot{z}(t) = \mathcal{A}_z z(t) \\ v_a(t) = \mathcal{C}_z z(t) \end{cases} \quad (30)$$

475 where the new system matrices $\mathcal{A}_z \in \mathbb{R}^{2 \times 2}$ and $\mathcal{C}_z \in \mathbb{R}^{1 \times 2}$ are obtained
 476 as: $\mathcal{A}_z = TAT^{-1} = \mathcal{A}$, $\mathcal{C}_z = CT^{-1} = \begin{bmatrix} \omega^2 & \omega \end{bmatrix}$. Similar to the previous
 477 observer, the objective here is to estimate the states and the unknown grid
 478 frequency parameter with zero steady-state error from the measured grid
 479 voltage, i.e., $\lim_{t \rightarrow \infty} (z - \hat{z}) = 0$ and $\lim_{t \rightarrow \infty} (\omega - \hat{\omega}) = 0$. For this purpose,
 480 the Luenberger observer is applied to estimate the phase voltage v_a and its
 481 quadrature signal qv_a as follows:

$$\dot{\hat{z}} = \hat{\mathcal{A}}_z \hat{z} + \mathcal{L} (v_a - \hat{v}_a) \quad (31)$$

482 where $\mathcal{L} \in \mathbb{R}^{2 \times 1}$ with $\mathcal{L} = \begin{bmatrix} \mathcal{L}_1 & \mathcal{L}_2 \end{bmatrix}^T$ represents the observer gain matrix
 483 and

$$\hat{\mathcal{A}}_z = \begin{bmatrix} 0 & 1 \\ -(\omega_n + \Delta\hat{\omega})^2 & 0 \end{bmatrix}.$$

484 Utilizing the concept of [the](#) frequency-locked loop, the following dynamic
 485 frequency estimation law is obtained in [53]:

$$\Delta\dot{\omega} = -\frac{\gamma(\mathcal{L}_1 + \mathcal{L}_2)\hat{\omega}^3\hat{z}_1(v_a - \hat{v}_a)}{\sqrt{\frac{(\hat{z}_1 2\hat{\omega}^3)^2 + (\hat{z}_2 2\hat{\omega}^2)^2}{2\hat{\omega}^2}}} \quad (32)$$

486 where the constant $\gamma \in \mathbb{R}_{>0}$ is the tunable frequency identification gain. The
 487 gain introduced in the denominator of Eq. (32) normalizes the frequency
 488 estimation law by the estimated grid voltage magnitude. This gain permits
 489 achieving a good frequency estimation even in the presence of deep voltage
 490 sags [53, 28]. The stability analysis of this observer and the parameters
 491 tuning are studied in detail in [53] by adopting the Routh-Hurwitz criterion.
 492 Similarly to GAO, the phase voltage v_a and its quadrature signal qv_a can be
 493 obtained through the following transformation:

$$\hat{x} = \hat{T}^{-1}\hat{z} \quad (33)$$

494 where, $\hat{T}^{-1} = \begin{bmatrix} \hat{\omega}^2 & \hat{\omega} \\ -\hat{\omega}^3 & \hat{\omega}^2 \end{bmatrix}$.

495 All grid voltages and currents will be determined in the same way using
 496 the observer of Eq. (31). Positive and negative sequences are then obtained
 497 through Eqs. (19) and (20).

498 3.3. SOGI-type adaptive observer

Contrary to the previous observers, SOGI-type adaptive observer (SAO)
 employs another system model with new state variables $x_1, x_2 \in \mathbb{R}$ and state
 vector $x \in \mathbb{R}^{2 \times 1}$ with $x = [x_1 \ x_2]$ that are expressed as [54]:

$$\begin{cases} x_1 = v_a^\perp = -A^+ \cos(\omega t + \phi^+) - A^- \cos(\omega t + \phi^-) \\ x_2 = v_a = A^+ \sin(\omega t + \phi^+) + A^- \sin(\omega t + \phi^-) \end{cases} \quad (34)$$

The grid phase voltage v_a is formulated by the following dynamic system
 model:

$$\begin{cases} \dot{x}(t) = \mathcal{A}x(t) \\ v_a(t) = \mathcal{C}x(t) \end{cases} \quad (35)$$

499 where $\mathcal{A} = \begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix}$, $\mathcal{C} = [0 \ 1]$.

500 In order to confirm the observability of the system given by Eq. (35),
 501 the rank of observability matrix O should be the same as the state matrix
 502 \mathcal{A} rank. As observed in the following expression, the matrix O is of rank 2,
 503 therefore the system is observable:

$$O = \begin{bmatrix} \mathcal{C} \\ \mathcal{C}\mathcal{A} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\omega & 0 \end{bmatrix} \quad (36)$$

504 Similar to the design method used in the previous observers, the non-
 505 singular transformation is represented as:

$$z = Tx \quad (37)$$

506 where $T = \frac{1}{2\omega} \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}$. The obtained system is expressed in z-coordinate
 507 as:

$$\begin{cases} \dot{z}(t) = \mathcal{A}_z z(t) \\ v_a(t) = \mathcal{C}_z z(t) \end{cases} \quad (38)$$

508 where the new system matrices $\mathcal{A}_z \in \mathbb{R}^{2 \times 2}$ and $\mathcal{C}_z \in \mathbb{R}^{1 \times 2}$ are obtained as:
 509 $\mathcal{A}_z = T\mathcal{A}T^{-1} = A$, $\mathcal{C}_z = \mathcal{C}T^{-1} = \begin{bmatrix} \omega & \omega \end{bmatrix}$. Similar to the previous observers,
 510 the objective here is to estimate the states and the unknown grid frequency
 511 parameter with zero steady-state error from the measured grid voltage, i.e.,
 512 $\lim_{t \rightarrow \infty} (z - \hat{z}) = 0$ and $\lim_{t \rightarrow \infty} (\omega - \hat{\omega}) = 0$. For this purpose, the following
 513 Luenberger observer is applied to the system states given by Eq. (38):

$$\dot{\hat{z}} = \hat{\mathcal{A}}_z \hat{z} + \mathcal{L} (v_a - \hat{v}_a) \quad (39)$$

514 where $\mathcal{L} \in \mathbb{R}^{2 \times 1}$ with $\mathcal{L} = \begin{bmatrix} \mathcal{L}_1 & \mathcal{L}_2 \end{bmatrix}^T$ is the observer gain matrix. In
 515 addition, the observer states matrix is given by the following equation:

$$\hat{\mathcal{A}}_z = \begin{bmatrix} 0 & \omega_n + \Delta\omega \\ -(\omega_n + \Delta\omega) & 0 \end{bmatrix}.$$

516 The gain normalized frequency update law in this case is given by:

$$\dot{\Delta\omega} = -\frac{\gamma (\mathcal{L}_1 + \mathcal{L}_2) \hat{\omega} \hat{z}_1 (v_a - \hat{v}_a)}{\hat{z}^T \hat{z}} \quad (40)$$

517 where the constant $\gamma \in \mathbb{R}_{>0}$ is a tuning parameter. Details of the observer
 518 design and local stability analysis can be found in [54]. Given the estimated

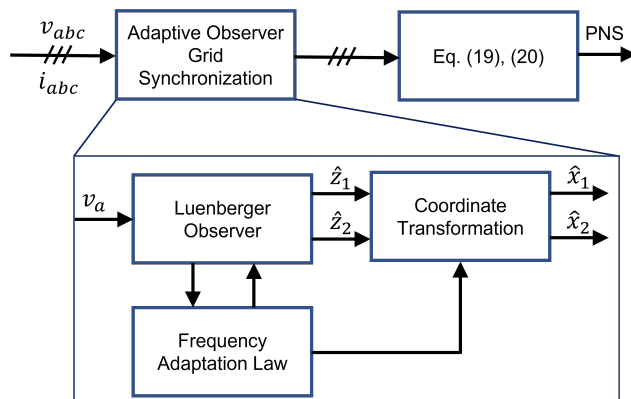


Figure 5: A general overview of the adaptive observer-based sequence extraction strategy.

519 state variables z , the individual phase voltage v_a and its orthogonal signal
 520 v_a^\perp can be evaluated using the following transformation:

$$\hat{x} = \hat{T}^{-1} \hat{z} \quad (41)$$

521 where, $T^{-1} = \hat{\omega} \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}$.

522 The same development is applied to other phase voltages and currents.
 523 Through the Eqs. (19) and (20), positive and negative sequences of the
 524 voltages and currents are calculated for further use. An overview of the
 525 adaptive observer-based sequence extraction strategies adopted in this work
 526 is given in Fig. 5.

527 3.4. Frequency Domain Analysis of the Sequence Extraction Techniques

528 The estimators presented in this Section assume that the grid has only \underline{a}
 529 fundamental frequency component. However, in practice, harmonic signals
 530 are often unavoidable. European standard EN 50160 [68] specifies the ac-
 531 ceptable harmonics limit in the grid voltage. According to this and various
 532 other international standards, a total harmonic distortion (THD) of 5% is
 533 often allowed. As such, sequence extraction techniques should also be able
 534 to work properly in a distorted grid. In the grid-synchronization literature,
 535 frequency domain analysis is the de facto standard for harmonic robustness
 536 analysis. The estimators presented in this Section are nonlinear in nature.
 537 As such, two approaches can be considered for the linear analysis of the es-
 538 timators. In the first case, the analytical approach is used by developing

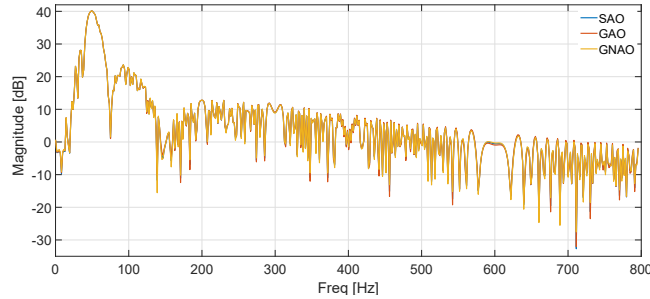


Figure 6: Frequency response of the selected sequence extraction techniques.

539 a small-signal model of the estimators. However, it often requires several
 540 assumptions. In the second method, a numerical approach is used through
 541 frequency response estimation. The second approach is widely popular due
 542 to ease of obtaining the frequency response using numerical simulation only.
 543 As such, this approach is considered here.

544 To obtain the frequency response, first the estimator gains need to be
 545 tuned. To ensure fair tuning, all the observers are tuned to have a similar dy-
 546 namic response when subject to step-change in the grid frequency. Through
 547 numerical simulation, it has been found that $\mathcal{L} = [0.0012 \ 2.6250]$ for both
 548 GAO and GNAO, and $\mathcal{L} = [0.3750 \ 2.6250]$ for SAO can provide similar
 549 dynamic response. Moreover, the value of γ is considered as 1000, 150, and
 550 0.2 for GAO, GNAO, and SAO, respectively to have roughly two-cycle con-
 551 vergence time. These values are also used in the subsequent Sections.

552 To obtain the frequency response, a sine stream signal with frequency
 553 range 1 – 5000 [rad/sec.] and amplitude of 0.01 is added as a perturbation
 554 to the base input signal of amplitude 1 and frequency 50Hz. The Bode
 555 magnitude plot of the three estimators for the transfer function $\hat{y}(s)/y(s)$
 556 can be found in Fig. 6. ~~Frequency~~ The frequency response plot shows that
 557 the three estimators have similar frequency ~~response~~ responses, and they
 558 show band-pass filtering ~~property~~ properties around the fundamental grid
 559 frequency. This is particularly important as the sequence estimators need to
 560 extract the fundamental component of the voltage/current from the measured
 561 harmonically distorted signals. The accuracy of sequence extraction plays an
 562 important role in ultimately achieving a lower THD, thereby improving the
 563 efficiency of the system.

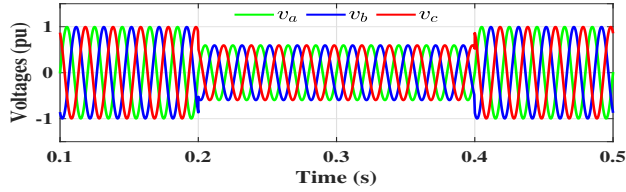


Figure 7: Grid voltages during the balanced voltage sag test.

564 4. Simulation Results

565 In order to achieve a comparative analysis of the observers detailed above
 566 in the closed-loop LVRT application, extensive simulation studies are con-
 567 sidered. The system parameters are listed in Table 1, which are employed in
 568 both simulation and experimental tests. To verify each observer and show its
 569 dynamic response in the presence of voltage sags, two test cases are consid-
 570 ered: (A) balanced grid voltage sags, and (B) unbalanced grid voltage sags.
 571

572 4.1. Balanced grid voltage sags

573 In this test a balanced voltage sag occurs from $t = 0.2\text{s}$ to $t = 0.4\text{s}$, the
 574 grid voltages are set to $V_g = 0.6\text{pu}$ during the faulty period, as shown in Fig.
 575 7. The same test is performed for evaluating the selected adaptive observers
 576 in the LVRT application.

577 4.1.1. Global adaptive observer

578 Starting with GAO, the obtained results are summarized in Fig. 8. SYRF
 579 grid voltages are calculated through the GAO, followed by sequence separa-
 580 tion through Eqs. (19) and (20). These voltages are plotted in Fig. 8a,
 581 which shows that SYRF voltages converge within one grid cycle, i.e., 20ms.
 582 The occurred fault requires a current exceeding the threshold value, which
 583 enables the current limiting process to ensure that the injected currents equal
 584 at most the threshold value, as depicted in Fig. 8b.

585 Since the dual current controller in SYRF is adopted in this work, positive
 586 and negative sequence components of the measured currents are needed to be
 587 available. For this purpose, the GAO is also used, and the results are shown
 588 in Fig. 8c. Within two cycles, steady-state values of direct and quadrature
 589 axis currents are obtained. Moreover, the injected currents are balanced
 590 without any negative sequence. In order to meet grid code requirements and

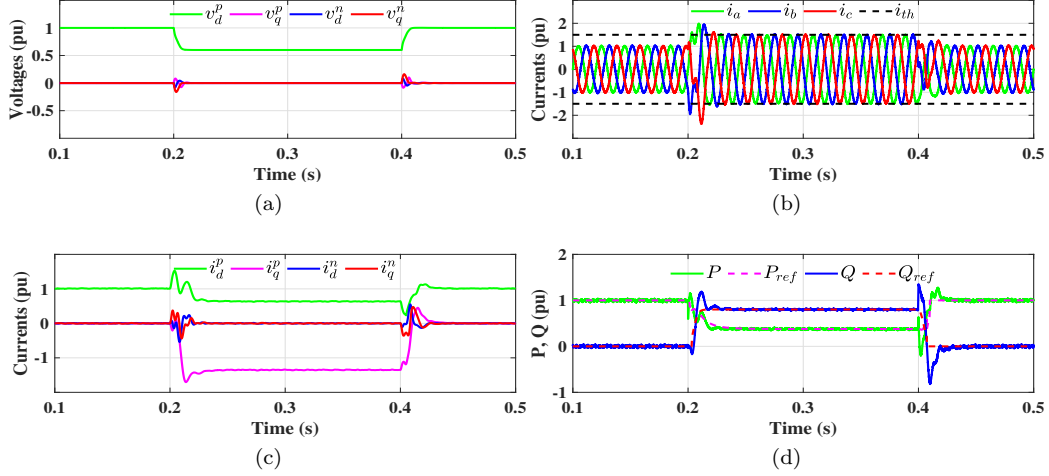


Figure 8: LVRT under the balanced voltage sag test using GAO: (a) SYRF grid voltages, (b) Injected currents, (c) SYRF injected currents, and (d) Injected active and reactive powers.

591 support the grid during voltage sags, reactive power is injected according
 592 to Eq. (5) which corresponds to 0.8pu Active power reference is reduced
 593 gradually due to the current limiting process as shown in Fig. 8d.

594 4.1.2. Gain normalized adaptive observer

595 The same balanced fault is applied to evaluate the performance of GNAO.
 596 The obtained results using GNAO as the sequence estimators are given in
 597 Fig. 9. These results confirm the suitability of gain normalized adaptive
 598 observers in LVRT capability improvements, which are ensured with a fast
 599 convergence around two grid cycles. As shown in Fig. 9a, the grid voltage
 600 sequences are obtained rapidly, with quick convergence to the steady-state
 601 values. The fast current limitation process during the grid fault period is
 602 clearly noticed in Fig. 9b. Current sequences overshoot is improved by using
 603 the GNAO as depicted in Fig. 9c. Grid code requirements are achieved by
 604 injecting the adequate powers as given in Fig. 9d according to the level of
 605 the balanced fault ($V_g = 0.6pu$).

606 4.1.3. SOGI-type adaptive observer

607 In this case, SAO is considered as the voltages and currents sequence
 608 components separation method for the LVRT control purpose. The obtained

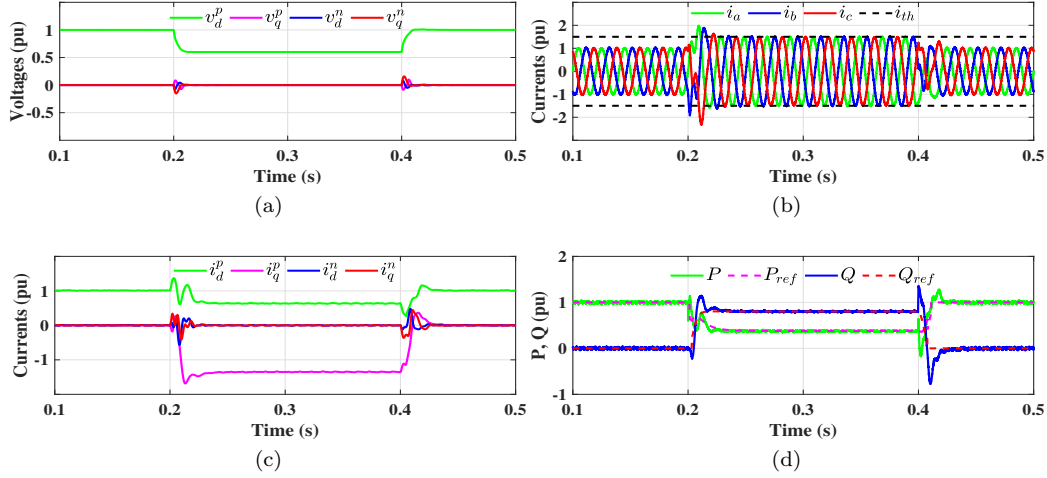


Figure 9: LVRT under the balanced voltage sag test using GNAO: (a) SYRF grid voltages, (b) Injected currents, (c) SYRF injected currents, and (d) Injected active and reactive powers.

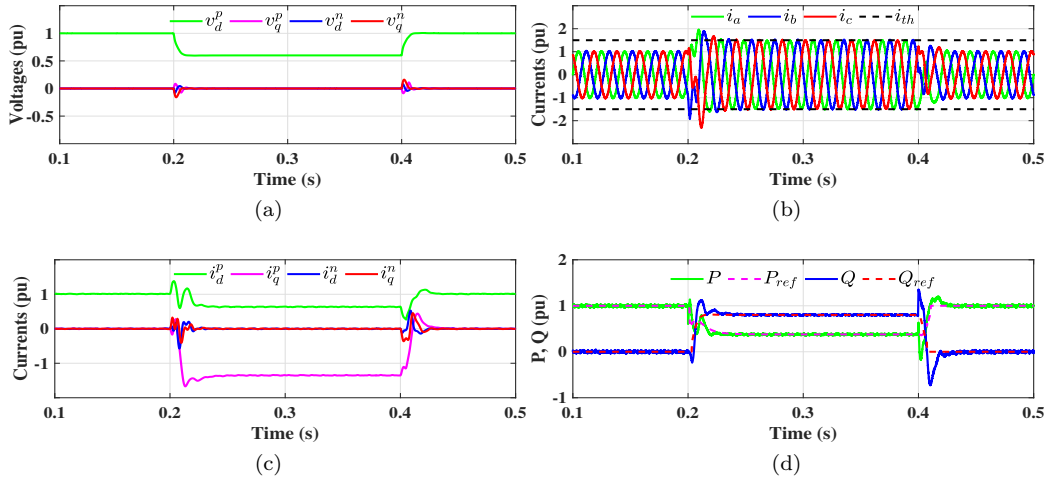


Figure 10: LVRT under the balanced voltage sag test using SAO: (a) SYRF grid voltages, (b) Injected currents, (c) SYRF injected currents, and (d) Injected active and reactive powers.

609 results given in Fig. 10 show that this adaptive observer can provide a fast
 610 and accurate response under large magnitude balanced voltage sag. Stability
 611 enhancement performance is achieved using this observer, as evidenced by

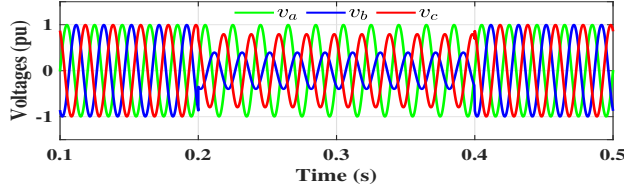


Figure 11: Grid voltages during the unbalanced voltage sag test.

612 the voltage and current sequences presented in Figs. 10a and 10c. All LVRT
 613 options are performed under this balanced fault, the injected currents are
 614 limited to avoid inverter damage, reactive power reference corresponds to
 615 the required value ($Q_{ref} = 0.8\text{pu}$), and a reduced active power reference
 616 generated by the current limiting algorithm. These points are presented in
 617 Figs. 10b and 10d.

618 4.2. Unbalanced grid voltage sags

619 In this case, an unbalanced voltage sag occurred from $t = 0.2\text{s}$ to $t = 0.4\text{s}$.
 620 The asymmetrical fault is created by putting $v_b = 0.4\text{pu}$ and $v_c = 0.8\text{pu}$ as
 621 illustrated in Fig. 11. Therefore, during the faulty period, the grid voltage
 622 will be equal to $V_g = 0.73\text{pu}$. The same simulation is carried out for evaluating
 623 the selected adaptive observers in the LVRT application.

624 4.2.1. Global adaptive observer

625 Simulation results under unbalanced voltage fault with GAO as the se-
 626 quence estimators are given in Fig. 12. From the SYRF voltages in Fig.
 627 12a, it can be seen that negative sequence voltages appear during the faulty
 628 period due to the asymmetrical fault. The current limiter process is en-
 629 abled under this fault to limit the injected currents at the threshold value
 630 as illustrated in Fig. 12b. Despite the difference between per-phase current
 631 amplitudes, this limiter provides fast and accurate protection of the inverter
 632 and its semiconductor components.

633 The GAO is also used to obtain the current sequences, which are subse-
 634 quently sent to the dual SYRF current controller. The current sequences are
 635 plotted in Fig. 12c which shows the negative sequence injection during the
 636 faulty period. The amount of this negative sequence is determined using Eq.
 637 10 to deliver the required power references without active power oscillations.
 638 As shown in Fig. 12d, the injected powers are in accordance with LVRT
 639 strategy requirements, i.e., reactive power of $Q_{ref} = 0.54\text{pu}$ is injected into

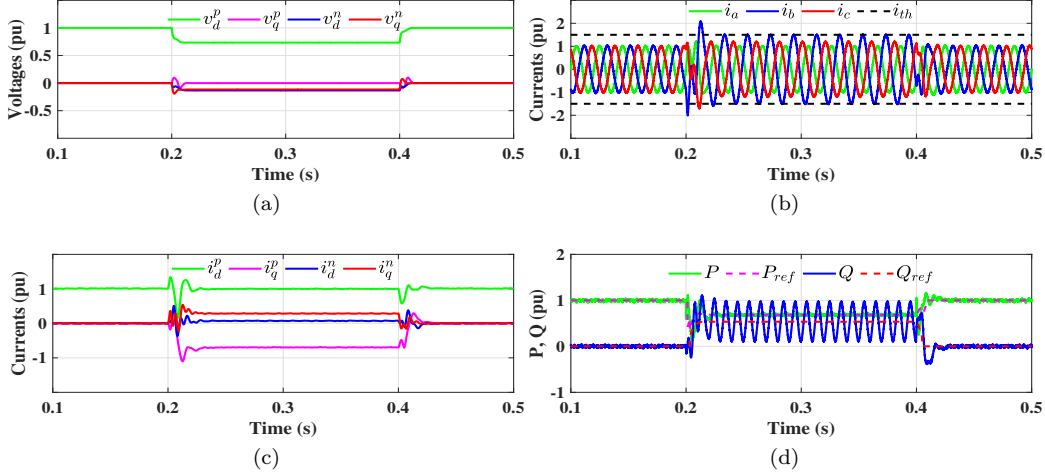


Figure 12: LVRT under the unbalanced voltage sag test using GAO: (a) SYRF grid voltages, (b) Injected currents, (c) SYRF injected currents, and (d) Injected active and reactive powers.

640 the grid to support this voltage sag, the active power reference is reduced
 641 due to the current limiting process, and double-frequency oscillations exist
 642 only on the reactive power.

643 4.2.2. Gain normalized adaptive observer

644 Figure 13 summarizes the obtained simulation results with GNAO as the
 645 estimator, which demonstrate the benefits of using this adaptive observer-
 646 based sequences extraction for LVRT capability application. The system
 647 steady-state is ensured after a delay of around two grid cycles. The grid
 648 voltage sequences including the negative ones are illustrated in Fig. 13a
 649 which are obtained during a very short duration under faulty conditions. The
 650 injected currents are sinusoidal, unbalanced, and limited to the threshold
 651 value, as shown in Fig. 13b. The unbalanced currents are caused by the
 652 necessary negative sequence amount that must be injected into the grid to
 653 deal with the active power oscillations. This is illustrated in Fig. 13c which
 654 shows a clear overshoot in current sequences transition as seen also in GAO
 655 results. As shown in Fig. 13d, injected powers correctly meet the grid code
 656 requirements mainly about the reactive power support ($Q_{ref} = 0.54$ pu) under
 657 voltage sags.

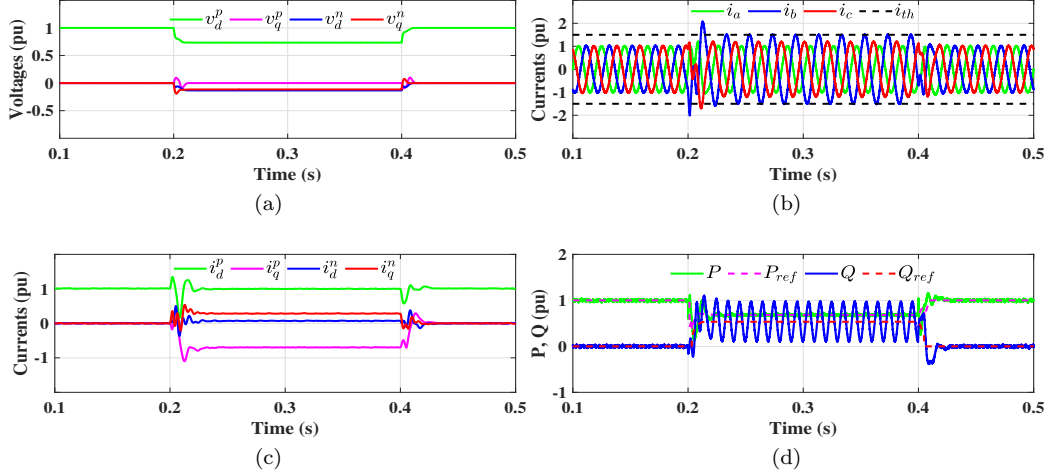


Figure 13: LVRT under the unbalanced voltage sag test using GNAO: (a) SYRF grid voltages, (b) Injected currents, (c) SYRF injected currents, and (d) Injected active and reactive powers.

658 4.2.3. SOGI-type adaptive observer

659 To verify the effectiveness of the SAO under the same unbalanced fault, the voltage/current sequences are estimated by using the SAO. Figure 14 gives the obtained results, which confirm the benefits of using adaptive observers-based sequences extractor in GCCs control. Smooth transition and stable performance are demonstrated in SYRF voltages and currents, as represented in Figs. 14a and 14c, respectively. Unbalanced and limited currents are injected into the grid to deal with the active power oscillations, and also to meet the grid codes requirements by ensuring the suitable reactive power reference under this grid voltage fault, as shown in Figs. 14b and 14d, respectively.

669 In order to compare these adaptive observers in terms of grid frequency estimation, another simulation is carried out. Since the grid frequency update law is attached to the phase "a" voltage, a test of voltage sag of 0.6pu in this phase is performed. The obtained result is given in Fig. 15. It is interesting to notice the rapidity of all studied observers in frequency estimation. The delay to get the steady-state is approximated at around two grid cycles for the three observers, which confirms the tuning procedure for the observer gains. As discussed above, SAO and GNAO are less sensitive to the voltage sags compared to GAO, as shown at $t = 0.2s$ when the fault occurred. This is

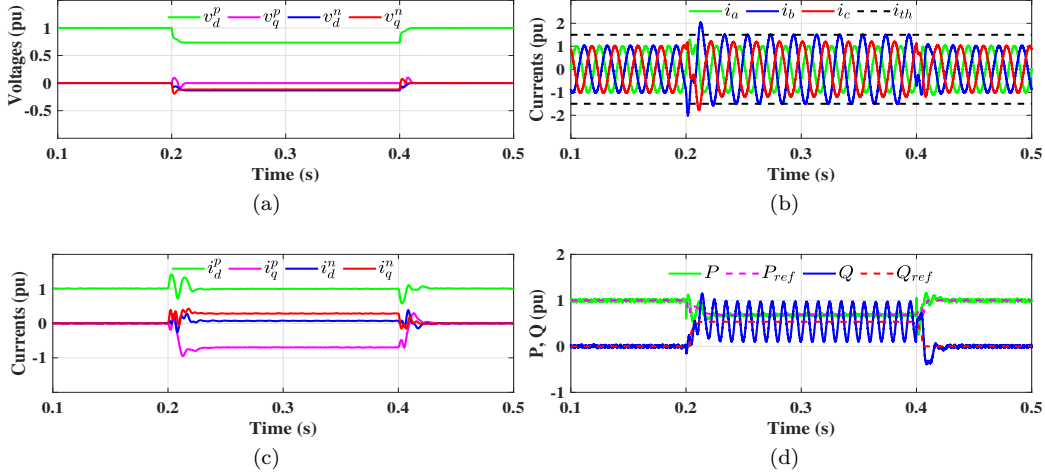


Figure 14: LVRT under the unbalanced voltage sag test using SAO: (a) SYRF grid voltages, (b) Injected currents, (c) SYRF injected currents, and (d) Injected active and reactive powers.

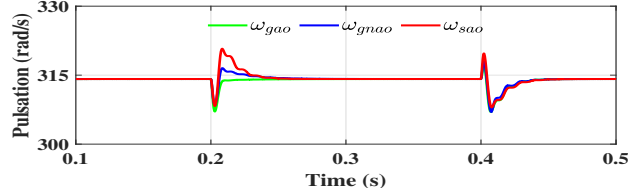


Figure 15: Estimated grid frequency under voltage sag of 0.6pu.

678 demonstrated by the small overshoot in SAO and GNAO compared to GAO.
 679

680 4.3. Control Performance in the Presence of Parameter Uncertainties

681 Due to aging and change in operational conditions, parameter uncertain-
 682 ties are often common in practice. In the case of VSI, the filter inductor
 683 value may change due to over-loading-related thermal stress, operating tem-
 684 perature, etc. Similarly, grid impedance may vary due to changes in the
 685 power generation/load pattern. These unforeseen events can manifest as an
 686 increase or decrease in the line inductor value, thereby directly influencing
 687 the performance of the current controller, potentially leading to instability if
 688 the controller's sensitivity has not been studied.

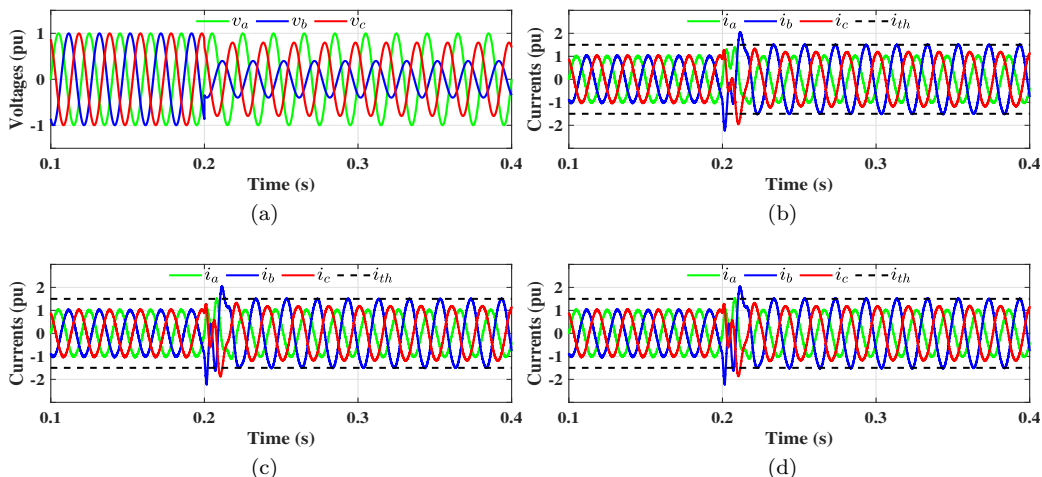


Figure 16: Grid voltages and currents during unbalanced situation and -25% of filter inductor: (a) Grid voltages, (b) Injected currents using SAO, (c) Injected currents using GAO, and (d) Injected currents using GNAO.

689 The effectiveness of the control structure shown in Fig. 4 is re-evaluated
 690 under an unbalanced situation, while also simulating a notable variation in
 691 the filter inductor. Two simulation studies have been considered with $\pm 25\%$
 692 variation from the nominal case while testing all adaptive observers.

693 As illustrated in Fig. 16, the designed control structure is able to operate
 694 even under decreased inductor filter. By using the three adaptive observers
 695 in the current control, no signs of instability are detected throughout the
 696 entire process, even when faced with an unbalanced fault, the system remains
 697 unfazed and continues to ensure LVRT capability seamlessly.

698 Similarly, Fig. 17 demonstrates the impact of increasing the filter inductor
 699 on the injected currents. An interesting observation is that the controller's
 700 sensitivity remains practically unaffected by the notable 25% increase. This
 701 remarkable finding underscores the robustness and reliability of the controller
 702 against parametric uncertainties.

703 Harmonic distortion level of the line currents is also computed to high-
 704 light the filter inductor variation effect on the THD of currents. As shown
 705 in table 2, the THD of currents is generally within acceptable limits for the
 706 different inductance values. Moreover, the three adaptive observers have
 707 demonstrated their suitability in facilitating grid-connecting inverters under
 708 asymmetric conditions. Additionally, it is noteworthy that higher induc-

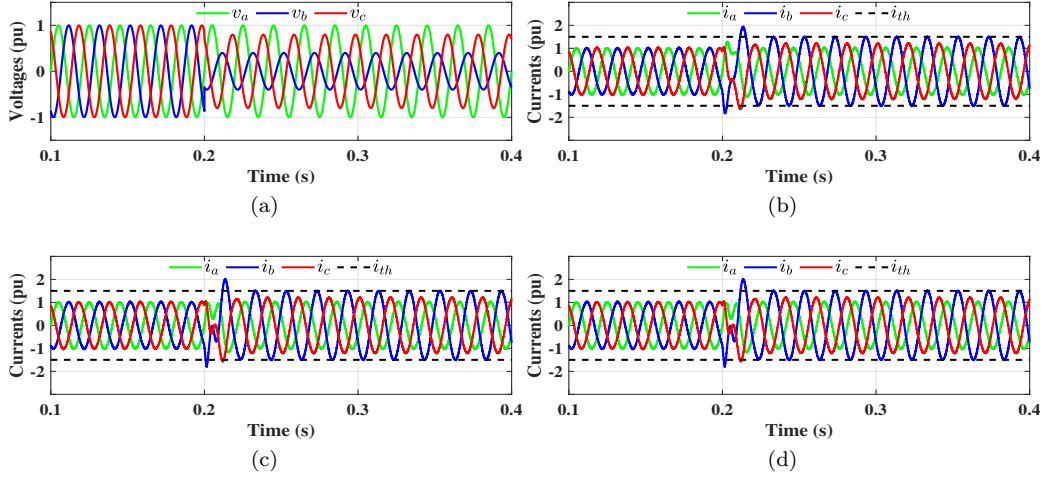


Figure 17: Grid voltages and currents during unbalanced situation and +25% of filter inductor: (a) Grid voltages, (b) Injected currents using SAO, (c) Injected currents using GAO, and (d) Injected currents using GNAO.

Table 2: Injected currents THD during line inductor variation.

Observer	Line inductor		
	$1.25L$	L	$0.75L$
SAO	1.61%	1.96%	2.51%
GAO	1.91%	2.05%	2.50%
GNAO	1.94%	2.00%	2.60%

709 tance results in better injected current quality, albeit at the cost of increased
710 response time due to the corresponding increase in the time constant.

711 In addition to the simulation studies presented here, interested readers
712 may consult [71] for an analytical sensitivity analysis of the control subject
713 to parametric uncertainties.

714 5. Experimental Results

715 For the experimental validation, a laboratory platform based on a two-
716 level voltage source inverter equipped with an RL filter is built. The same
717 system parameters are also used for the practical implementation, as listed in

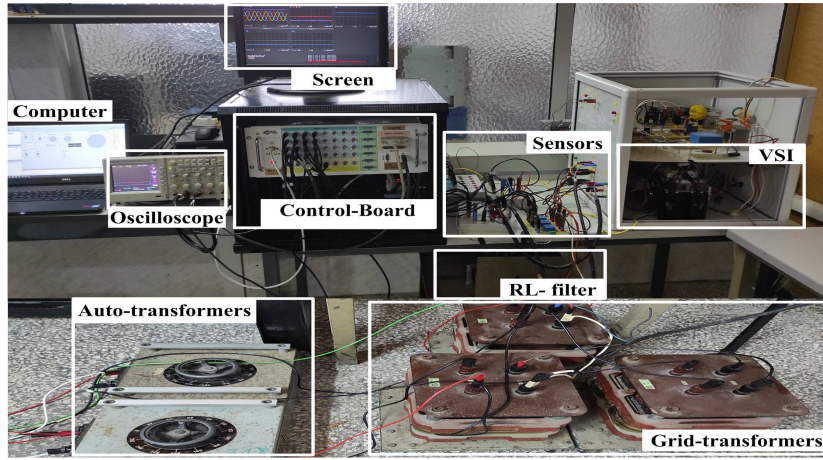


Figure 18: Experimental test setup.

718 Table 1. Figure 18 shows the considered laboratory test setup, which is com-
 719 posed of a step-down grid transformer ensuring a low grid voltage level, two
 720 single-phase autotransformers to create asymmetrical voltage faults, a real-
 721 time control board based on dSPACE associated with MATLAB/Simulink,
 722 and measurement equipment including grid voltage and injected current sen-
 723 sors with an oscilloscope and a real-time screen.

724 In order to be consistent with the simulation tests, both balanced and
 725 unbalanced voltage sags are studied in practice while using the adaptive
 726 observers as discussed above.

727 5.1. *Balanced grid voltage sags*

728 A symmetrical voltage sag occurs from $t = 40\text{s}$ to $t = 60\text{s}$. The grid
 729 voltages are equal to $V_g = 0.6\text{pu}$ during the faulty conditions, as depicted in
 730 Fig. 19. This fault is maintained in order to evaluate each adaptive observer
 731 and show its performance under an abrupt balanced voltage sag.

732 5.1.1. *Global adaptive observer*

733 As can be seen in Fig. 20, the obtained results confirm the suitability of
 734 GAO as sequence estimators for LVRT applications. Grid voltages in SYRF
 735 are estimated rapidly and accurately as shown in Fig. 20a. Since the voltage
 736 fault is balanced, the negative sequence is estimated as zero during the faulty
 737 interval. If any current limiter process is employed in this case, the injected
 738 currents exceed the threshold value and can damage the inverter. However,

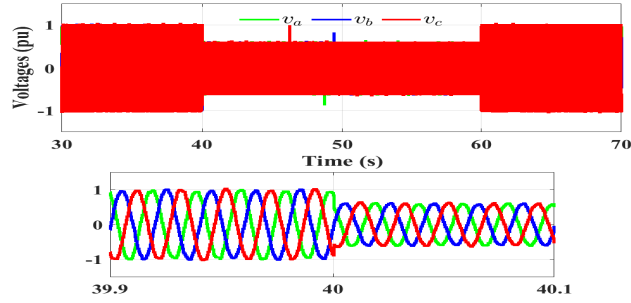


Figure 19: Grid voltages during the balanced voltage sag test.

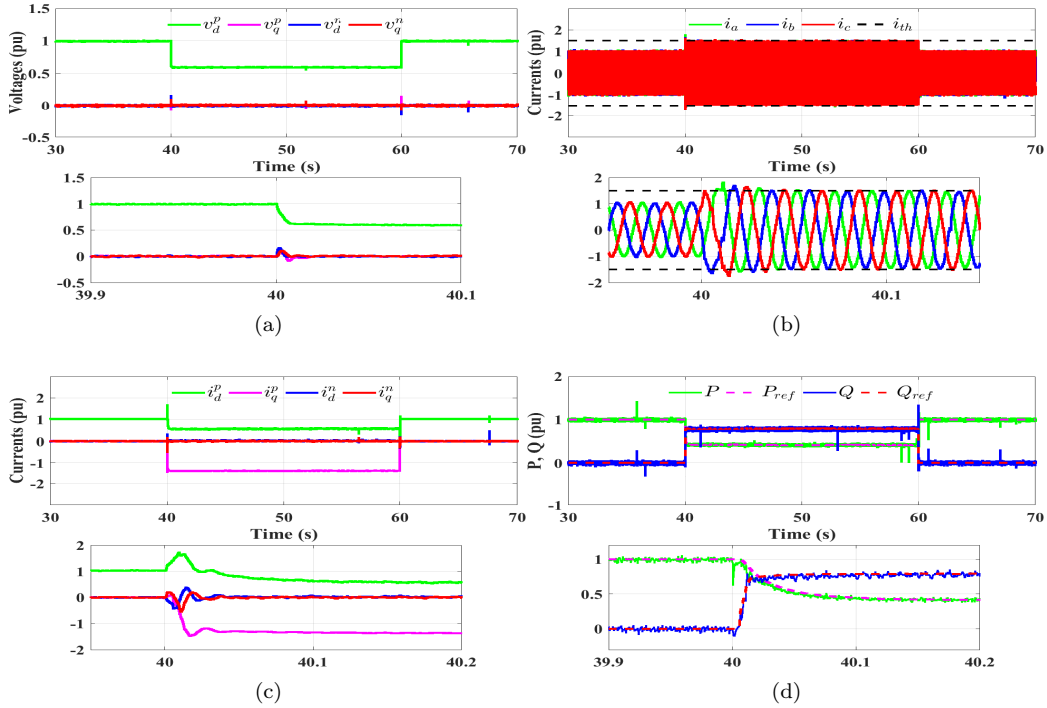


Figure 20: Experimental LVRT under the balanced voltage sag test using GAO: (a) SYRF grid voltages, (b) Injected currents, (c) SYRF injected currents, and (d) Injected active and reactive powers.

739 the effectiveness of the used current limiter is clearly proven in Fig. 20b,
 740 which ensures a safe operation of the inverter with a very small transient
 741 period.

742 Injected currents in SYRF are represented in Fig. 20c. In order to meet

743 grid code requirements, the exact reactive power amount must be injected
744 according to the voltage fault level. As depicted in Fig. 20d, the reactive
745 power reference is modified from zero to $Q_{ref} = 0.8\text{pu}$ which corresponds
746 exactly to 0.4pu of grid voltage sag. Due to the current limiting process,
747 active power reference is reduced gradually to maintain the injected currents
748 at most equal to the threshold value.

749 *5.1.2. Gain normalized adaptive observer*

750 The obtained results with GNAO-based sequence components estimators
751 are represented in Fig. 21. Due to the fault appearance at $t = 40\text{s}$, LVRT
752 options are ensured after a short transient period for the system recovery.
753 Grid voltages in SYRF converged rapidly to steady-state values, as seen in
754 Fig. 21a. Injected currents are well limited to avoid any over-current inverter
755 damage as shown in Fig. 21b. Current sequences as plotted in 21c are also
756 estimated using GNAO which allows a better estimation under the presence
757 of balanced voltage sags. Figure 21d shows the injected powers during the
758 experiment. Some reactive power is injected into the grid as per grid codes to
759 support the grid voltage sags. In addition, active power reference is reduced
760 due to the current limiting process. As can be seen in Fig. 21d that the
761 injected powers have a little more high-frequency fluctuations compared with
762 those using GAO.

763 *5.1.3. SOGI-type adaptive observer*

764 The obtained experimental results using SAO are summarized in Fig. 22.
765 The suitability of this estimator to improve LVRT capability is clearly re-
766 flected in the obtained results. Enhanced stability and short settling time are
767 achieved in voltage and current sequences separation by using this adaptive
768 observer, as can be seen in Figs. 22a and 22c, respectively. Injected currents
769 are sinusoidal and limited during the faulty conditions to protect the inverter
770 from over-current damage, as shown in Fig. 22b. Grid code requirements
771 are ensured by injecting the exact value of reactive power according to the
772 voltage fault level. This observer is much better in terms of high-frequency
773 power fluctuations compared with those using GAO or GNAO. Moreover,
774 the settling time in power convergence is improved using SAO. These points
775 are clearly noticed in Fig. 22d.

776 *5.2. Unbalanced grid voltage sags*

777 In order to experimentally validate the selected observer under unbal-
778 anced voltage sag, extensive experiments are carried out. An unbalanced

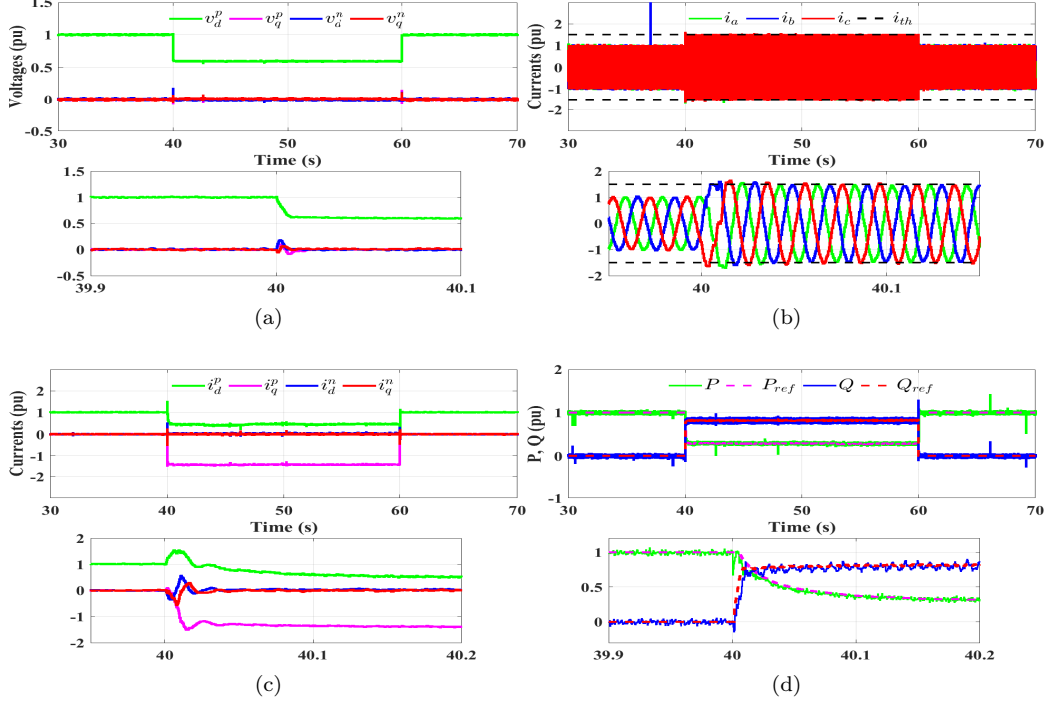


Figure 21: Experimental LVRT under the balanced voltage sag test using GNAO: (a) SYRF grid voltages, (b) Injected currents, (c) SYRF injected currents, and (d) Injected active and reactive powers.

779 voltage sag occurs from $t = 40$ s to $t = 60$ s by putting $v_b = 0.4$ pu and
 780 $v_c = 0.8$ pu as illustrated in Fig. 23. Therefore, the grid voltage will be equal
 781 to $V_g = 0.73$ pu during the faulty period. This fault is maintained to evaluate
 782 the selected adaptive observers at the same conditions while ensuring LVRT
 783 objectives.

784 5.2.1. Global adaptive observer

785 The obtained results are provided in Fig. 24. The SYRF grid voltages
 786 are estimated firstly by GAO in natural reference frame via Eqs. 19 and
 787 20. These voltages are then transformed into SYRF with the help of the
 788 abc - dq transform. As shown in Fig. 24a, the voltage sequences are available
 789 during the entire experiment duration even under the unbalanced fault. The
 790 negative sequence also exists in the direct and quadrature axis due to the
 791 type of fault. The chosen current limiter shows its performance in terms of

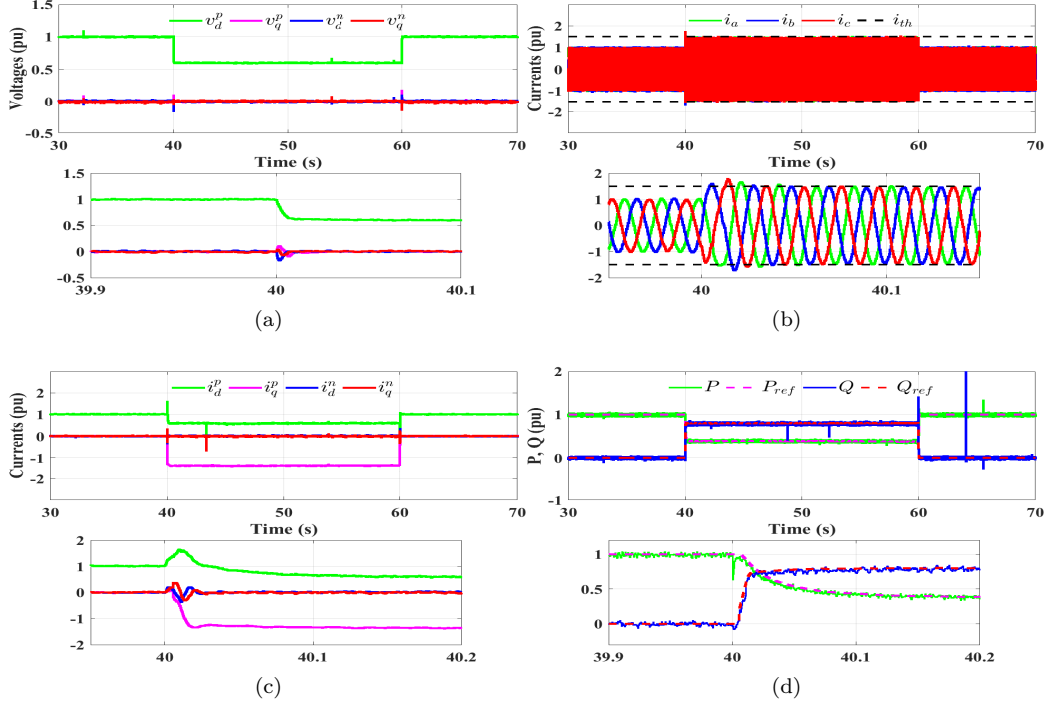


Figure 22: Experimental LVRT under the balanced voltage sag test using SAO: (a) SYRF grid voltages, (b) Injected currents, (c) SYRF injected currents, and (d) Injected active and reactive powers.

792 rapidity and stability, as can be noticed in Fig. 24b. The injected currents
 793 are unbalanced, sinusoidal, and well-limited at the threshold value during
 794 the fault period. This is achieved with sub-two-cycle convergence time.

795 The current sequences are obtained in the same way as the voltage ones.
 796 These current sequences are required for controlling the GCCs under faulty
 797 conditions, i.e., in presence of both positive and negative sequence currents.
 798 As illustrated in Fig. 24c, negative sequence currents are injected into the
 799 grid for active power oscillations elimination under asymmetrical fault. The
 800 injected powers are plotted in Fig. 24d which shows very good compliance
 801 to grid codes requirements under this voltage fault level, i.e., $Q_{ref} = 0.54$ pu
 802 is injected to support a voltage sag of 0.27pu. Moreover, no active power
 803 oscillations confirm the exact values of the injected negative currents into
 804 the grid.

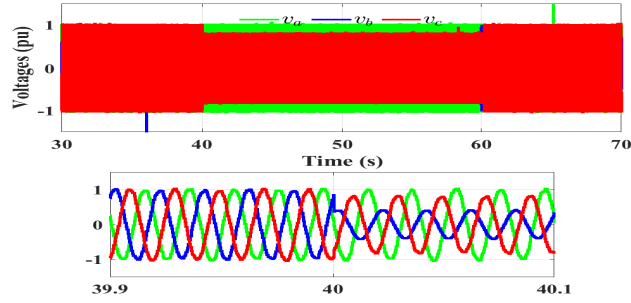


Figure 23: Grid voltages during the unbalanced voltage sag test.

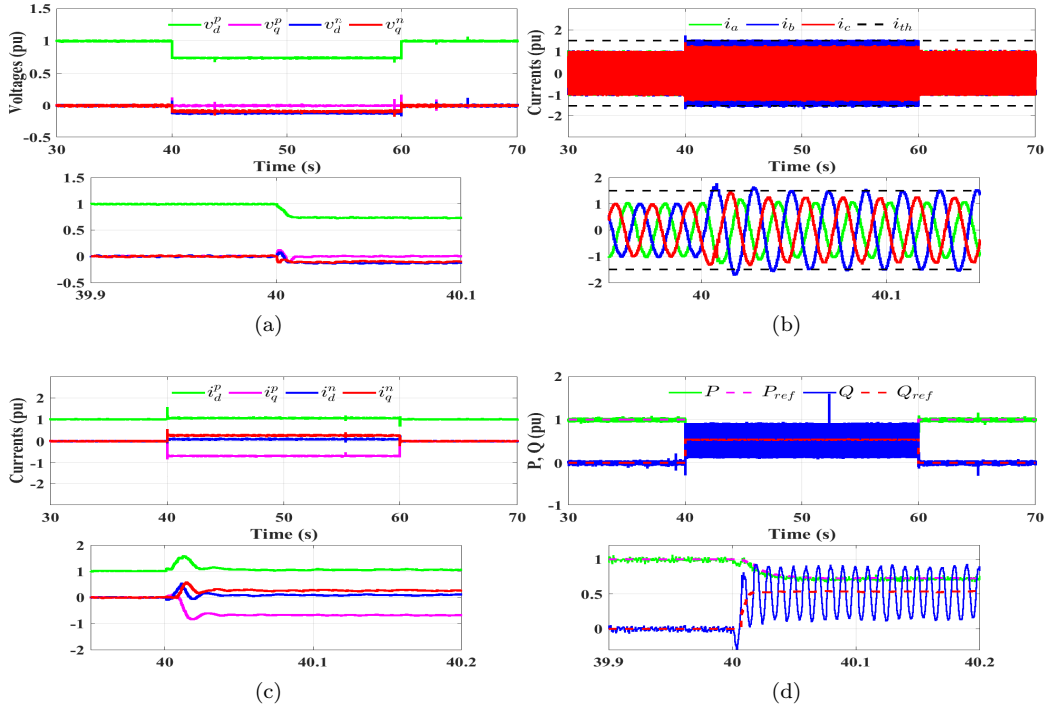


Figure 24: Experimental LVRT under the unbalanced voltage sag test using GAO: (a) SYRF grid voltages, (b) Injected currents, (c) SYRF injected currents, and (d) Injected active and reactive powers.

805 *5.2.2. Gain normalized adaptive observer*

806 Figure 25 details the obtained experimental results under asymmetrical
 807 voltage sags using GNAO. The grid voltage sequences are represented in Fig.
 808 25a which show a good performance in terms of rapidity and robustness even

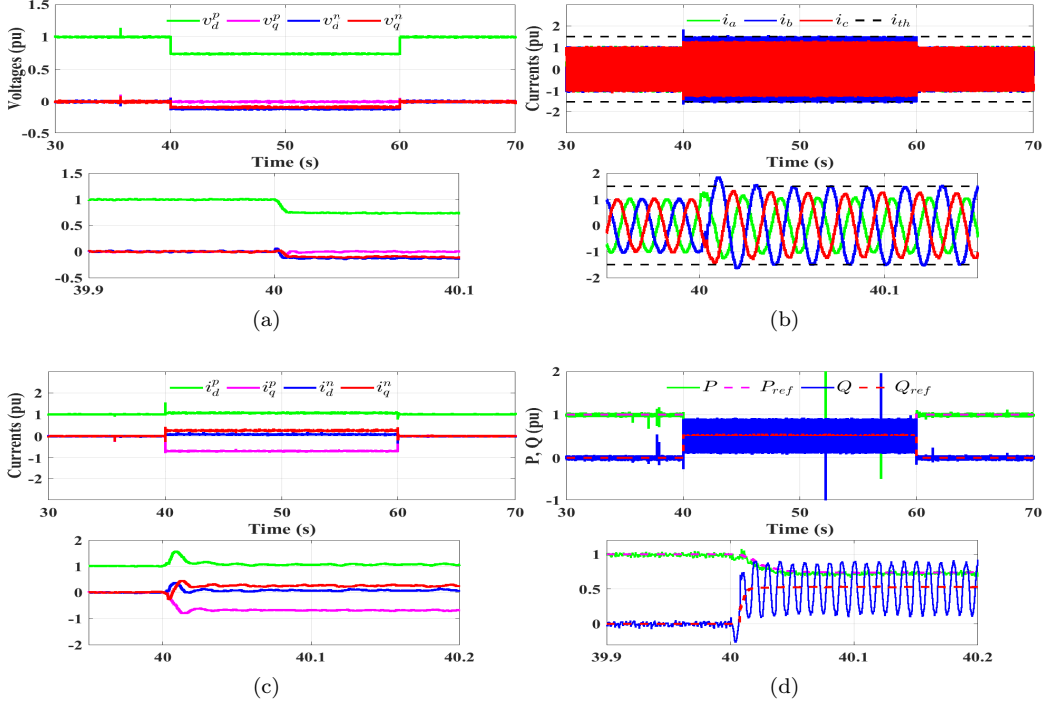


Figure 25: Experimental LVRT under the unbalanced voltage sag test using GNAO: (a) SYRF grid voltages, (b) Injected currents, (c) SYRF injected currents, and (d) Injected active and reactive powers.

809 under unbalanced faults. The negative-sequence voltages are estimated per-
810 fectly to give an accurate fault quantification. The current limiter is enabled
811 to avoid inverter damage by ensuring the injected currents equal at most
812 the threshold value even with the difference in per-phase amplitudes, as il-
813 lustrated in Fig. 25b. The settling time for current sequences estimation
814 is improved by using GNAO with a little overshoot compared to the previ-
815 ous observer, i.e., GAO. This result is represented in Fig. 25c. All LVRT
816 ancillary services are achieved in this experiment as shown in Fig. 25d by
817 injecting the suitable reactive power to support the grid during voltage sag,
818 suppressing active power oscillations during the fault, and decreasing active
819 power reference due to the current limiting process.

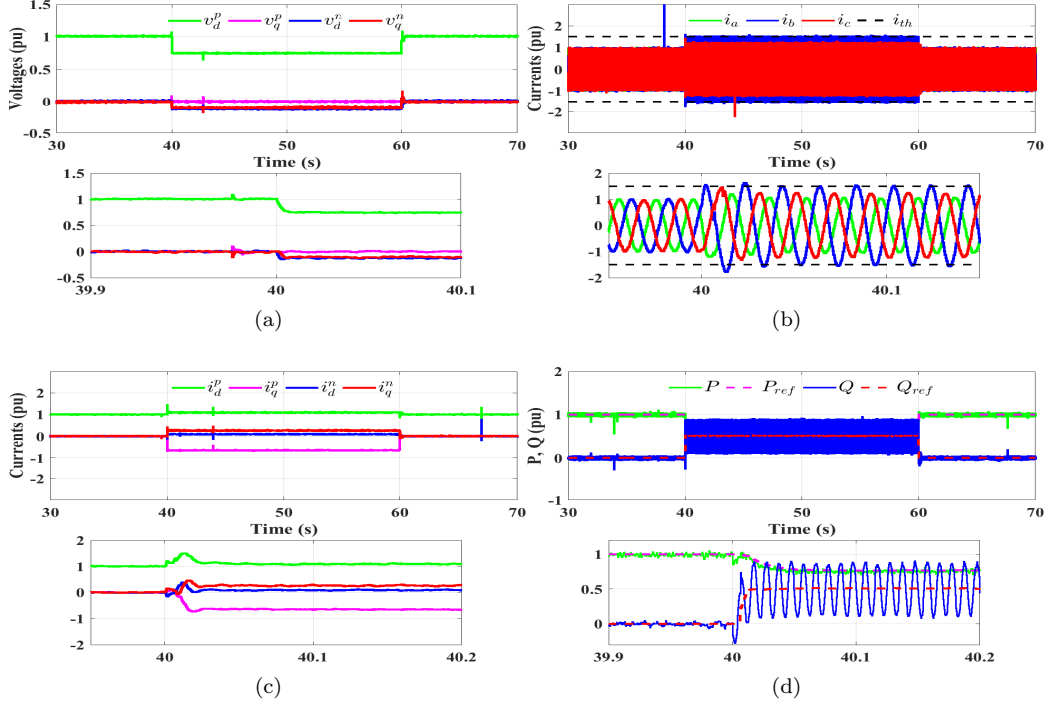


Figure 26: Experimental LVRT under the unbalanced voltage sag test using SAO: (a) SYRF grid voltages, (b) Injected currents, (c) SYRF injected currents, and (d) Injected active and reactive powers.

820 5.2.3. SOGI-type adaptive observer

821 The obtained experimental results using SAO-based sequence components
 822 estimators are given in Fig. 26. The benefits of using an adaptive observer
 823 in GCCs control scheme are clearly visible. Improved performance is of-
 824 fered by using SAO compared to the other estimators such as short settling
 825 time, smooth transition at fault appearance, and more stability in the esti-
 826 mated sequences. These points are demonstrated in Figs. 26a and 26c, which
 827 give grid voltage and injected current sequences, respectively. The achieved
 828 advantages using SAO allow the fast response of the current limiting algo-
 829 rithm and improved injected powers according to the grid code exigences with
 830 negligible high-frequency fluctuations. The injected currents in the natural
 831 reference frame and powers are plotted in Figs. 26b and 26d, respectively.

832 In order to verify each adaptive observer and show its performance in
 833 terms of grid frequency estimation, an experimental test is carried out. Same

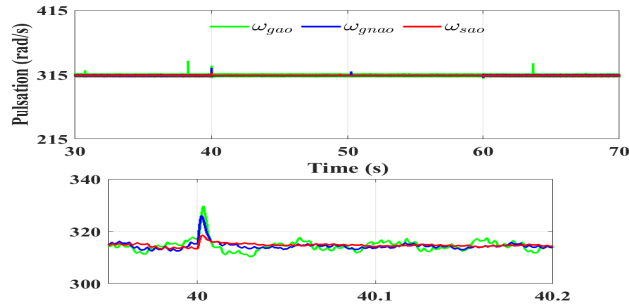


Figure 27: Experimental test to estimate grid frequency under voltage sag of 0.6pu.

834 to the simulation scenario explained in Fig. 15, the fault is created in phase
 835 "a" voltage, which is responsible for the frequency update law. As can be seen
 836 in Fig. 27, the grid frequency is estimated even in presence of grid voltage
 837 sags. This result confirms also the less sensitivity of SAO and GNAO to
 838 the voltage sags, which have a small overshoot at $t = 40$ s. Since SAO has
 839 negligible high-frequency ripples, it is judged as the best observer in frequency
 840 estimation for grid-synchronization purposes.

841 By carefully observing all the simulation and experimental results, it can
 842 be seen that the experimental results demonstrate a high degree of congru-
 843 ence with the simulated results. This validates the results developed in this
 844 work. ~~Moreover, based on the results,~~

845 6. Discussions

846 The achieved results highlight the remarkable suitability of adaptive observers
 847 in enhancing the control of GCCs, particularly when confronted with grid
 848 voltage disturbances. By accurately estimating voltage and current sequences,
 849 the adaptive observers contribute significantly to the improved performance
 850 of GCCs, enabling them to maintain stable and accurate operation in adverse
 851 grid conditions.

852 The efficiency of the employed techniques becomes readily apparent through
 853 various experimental results, showcasing a superior real-time response in
 854 comparison to relatively medium computational complexity. Moreover, the
 855 desired objectives of LVRT applications are achieved in all simulations or
 856 experiments demonstrating how the observers effectively estimate voltage/current
 857 sequences, react to grid disturbances, calculate the desired active and reactive
 858 powers, and provide accurate control signals.

859 The accuracy of the implemented observers is thoroughly assessed through
 860 experimental evaluation, with a focus on tracking the desired reactive power.
 861 The results demonstrate a notable distinction in accuracy performance among
 862 the different observer types. Specifically, when using the SAO, an impressive
 863 accuracy level of approximately 95% is achieved under balanced voltage sags.
 864 On the other hand, when employing the GAO or GNAO, the reactive power
 865 tracking accuracy is observed to be around 87%. These findings highlight the
 866 superior accuracy attained by SAO in comparison to the alternative observer
 867 methods, underscoring its efficacy in accurately tracking the desired reactive
 868 power in the presence of balanced voltage sags. All discussed results are
 summarized in Table 3.

Table 3: Comparative analysis of the adaptive observers-based LVRT control.

Features	SAO	GAO	GNAO
Dynamic response	Very fast	Very fast	Very fast
Voltage sag sensitivity	Low	High	Low
Computational complexity	Medium	Medium	High
Harmonics sensitivity	Low	Medium	Medium
Accuracy	High	Medium	Medium

869 Based on the results illustrated in Table 3, one can find that SAO-based
 870 controllers achieved better results in terms of convergence time, sensitivity
 871 to harmonics, accuracy, etc. compared to GAO and GNAO. This finding
 872 can be useful to readers and industrial practitioners in selecting the right
 873 sequence estimation methods for LVRT control of grid-connected converter-
 874 based renewable energy sources.
 875

876 7. Conclusion

877 A comparative study of three adaptive observers-based ~~sequences~~ sequence
 878 separation methods is performed in this paper. ~~These~~ To ensure a fair
 879 comparison between the observers, a systematic gain-tuning procedure has
 880 been followed using the settling-time criterion. Despite being fairly tuned,
 881 these observers have their own merits and demerits in terms of dynamic
 882 response, voltage sag and harmonics sensitivity, computational complexity,

883 and accuracy. The selected observers prove their suitability for LVRT ca-
884 pability enhancement under balanced and unbalanced grid faults. The pro-
885 posed control strategy ensures all LVRT ancillary services while embedding
886 the adaptive observers for grid-synchronization issues. Required reactive
887 power is injected into the grid according to GCs requirements to improve
888 grid stability under voltage sags, avoid converter over-current related trip-
889 ping by limiting the injected currents using an online active power reducing
890 approach, estimate the positive and negative sequences of the grid voltage
891 and currents and obtain their angular frequency through the studied adap-
892 tive observers, suppress active power oscillation under asymmetrical faults by
893 calculating new current references in SYRF, and via the adaptive observers,
894 the actual currents sequences are regulated separately to follow these new
895 references.

896 Simulation results of all observers clearly highlight the effectiveness and
897 suitability of the studied adaptive observers within LVRT control under sym-
898 metrical/asymmetrical faults. A laboratory-scale setup is considered, which
899 is composed of an inductive filtered grid-connected inverter and dSPACE
900 real-time control board to benchmark the proposed control strategy includ-
901 ing the adaptive observers comparative study. Obtained results are in ac-
902 cordance with simulation ones and confirm also the flexibility and rapidity
903 obtained by using adaptive observers-based grid-synchronizing sequence ex-
904 traction strategies in LVRT control architecture. In addition, qualitative
905 performance comparisons between the observers are presented, which will
906 guide practitioners to select the right observer for their LVRT controller
907 development for GCC application.

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