Design of passive power filters for battery energy storage system in grid connected and islanded modes

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Abstract

This study presents an improved method to design passive power filters for a battery energy storage system operating in grid connected and islanded modes. The studied system includes appropriate controls according to the selected mode. The global system is composed of two power converters a DC–DC converter and a three phase four wires DC–AC converter. The passive power filters to be designed are the battery inductance, the neutral filter and the LCL filter. Conventionally filter design methods are performed considering only one operating mode parameters. This paper proposes an analysis of the design approaches reported in the literature for each mode separately and then provides a step by step design procedure taking into account constraints of each operation mode. The design is performed based on steady state equations for each mode. An overall system simulation with PSIM software has been developed. Simulation results illustrate the effectiveness of the investigated filter design.

Keywords Battery energy storage system · Filter sizing · Three-phase four-wire DC–AC converter · LCL filter · Resonant frequency

1 Introduction

Nowadays, existing power grid is facing power quality and system stability challenges due to high penetration of grid-connected photovoltaic systems. In this context, to cope with solar energy intermittent nature and time-varying load demand, energy storage systems are regarded as effective solutions for their space–time energy translation. Various energy storage systems are investigated, however, up to now; battery energy storage systems (BESS) are preferred for their price advantages, especially for residential applications.

Operation mode of BESS depends on application that can be in islanded mode for powering loads with electric energy and stable frequency and voltage control. [1], or in grid connected mode for battery charging and frequency

and voltage support [2], especially in low voltage networks, with high penetration of solar rooftops. The ability of BESS to ensure multiple applications as grid forming and grid supporting unit can be realized simultaneously with suitable control design as described in [3], with a smooth operation transition from one mode to the other [4].

In residential applications, BESS can be three-phase four-wire (3P4W) to feed single or three phase loads and solar inverter with symmetrical voltages. Among the different circuit topologies reported in the literature to generate a neutral point, the one with an additional neutral leg and actively balanced split DC link is preferred for its better DC link capacitor lifetime [5, 6]. It is commonly used in uninterruptible power supplies [7].

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This topology is adopted in this work, so BESS circuit will be composed of two power converters, a DC–DC and a three phase four wires DC–AC ones, and passive power filters (PPF): an input L type inductor, a DC Link Capacitor, a neutral inductor and an output LCL filter.

The purpose of LCL output filter is (1) to reduce harmonics generated by power device switching frequencies to avoid sensitive load disturbance and loss production, (2) to attenuate grid-side harmonics injection to meet harmonics requirements of IEEE 1547 [8] or VDE-AR-N 4105 [9] standards. But nowadays, these purposes are not yet sufficient and a reactive power support is also required [10]. In addition, as LCL filter presents an inherent resonance, proper design is of prime importance to avoid any system instability [11]. Grid impedance variation and its impact on stability system is another issue to be challenged for LCL design [12, 13].

LCL filter design had been widely reported in the literature, for rectifier applications [14–16] for solar rooftop [17], for high power voltage source converters [18], for DC traction station [19] and also for BESS [20–22]. Generally, filter design and sizing is conducted in parallel with control synthesis and new methods are proposed to improve damping [23, 24] and stability under different grid conditions [25–30].

Analytic approach based on transfer function is the most common LCL filter design approach, but other methods have been reported in the literature, such as tuned filter design for grid connected solar PV [31], or using recorded data [32]. Taking into account several addition constraints, like PPF lifetime, size and cost, design could become complex. So, authors in [33] propose an iterative approach, and those in [34] propose a step-by step procedure.

Although LCL filter design has received significant attention in the recent literature, the design of the other BESS PPFs, DC Link capacitor, neutral inductor and input L inductor, has also been reported in the literature.

The design of the DC link capacitor filter depends on DC–AC converter topology and application field. Generally, the control design leads to the bulk capacitor one, considering low-ripple DC link voltage and DC link capacitor lifetime. For example, authors in [35] investigate minimal required DC-link voltage level for DC–AC two levels three phase converter proper operation as reactive power ancillary service provider. Authors in [5, 36], consider four legs DC–AC converter with fourth wire formed by additional leg and split capacitors. The fourth leg control is decoupled from the three-phase converter, and ensures a neutral current flowing through the inductor instead of the capacitors, which leads to reduces capacitors size.

The battery bank is commonly connected to a DC–DC converter with an input L-type filter to limit DC current

ripples with minimum losses, [37]. However, some authors, [21, 38], propose to replace the L-type filter by an LCL one to reduce filter size, others in [39] by LC filter. In both cases, L and LCL filter types, batteries current ripple attenuation is the main design objective, since such current ripples generate heat which is a major factor for battery lifetime degradation. From another hand, when DC–DC converter design control is based on average model, it is necessary to ensure continuous mode operation and to avoid discontinuous one, [40–42]. This constraint is rarely reported in the literature for battery filter design but in DC–DC converter control.

In this paper, through the existing design of each of battery inductance, capacitor DC-Link, neutral inductance and LCL filters, a step by step design procedure is presented, taking into account constraints of each BESS operation mode. Hence, contributions of this paper over results reported in literature are as follows. First, the LCL filter design is performed with regard to large grid impedance variations on the connected mode as well as to load impedance variation in islanded mode. Second, the neutral inductor filter design ensures good performances whatever the operating mode. Third, the input L battery inductance helps ensure continuous conduction operation. Overall, this paper contributes to the field of power passive filter design, as well as to the emerging field of design and control of battery energy system for different applications, such as grid support, solar rooftop application.

The next section presents the description of the system under study. Section 3 explains the LCL filter design first at grid islanded mode, when BESS supplies power to the loads and second, at grid connected mode, in both cases: battery charging mode and grid support mode. Sections 4 and 5 details DC Link and battery inductance filter design. Simulation results and discussions are given in Sects. 6 and 7. Finally, Sect. 8 concludes this paper.

2 System description

The system under study is presented in Fig. 1. It is composed by a battery bank connected to the common point PCC through a DC–DC converter in series with a DC–AC converter and an LCL filter.

Three operation modes are considered according to the state of charge of the battery bank and the state of the grid. The first one, mode 1 is an islanded mode, with a BESS discharging mode. The other two operating modes are grid connected, mode 2 is a charging mode and mode 3 a grid support mode. Figure 2 depicts these three modes.

Fig. 1 Battery electrical energy storage system description

Fig. 2 BESS operation modes

3 Design of the LCL filter

The design is based on steady state relationships (1) to (7). Where $i = a, b$ or c and where (R_{Li}, L_{Li}) , (R_{f1}, L_{f1}) , (R_{f2}, L_{f2}) , (R_g, L_g) are resistance and inductance of the load, converter side filter, grid side filter, and grid impedance respectively.

$$I_i = \frac{V_i - V_{ci}}{sL_{f1} + R_{f1}} \quad (1)$$

$$I_{fi} = \frac{V_{ci} - V_{PCCI}}{sL_{f2} + R_{f2}} \quad (2)$$

$$I_i = I_{fi} + I_{ci} \quad (3)$$

$$V_{ci} = \frac{I_{ci}}{sC_f} \quad (4)$$

$$I_{Li} = \frac{V_{PCCI}}{R_{Li} + sL_{Li}} \quad (5)$$

$$I_{gi} = \frac{V_{PCCI} - V_{gi}}{sL_g + R_g} \quad (6)$$

$$I_{fi} = I_{Li} + I_{gi} \quad (7)$$

Filter resistances and resistive part of grid impedance are neglected ($R_{f1} = R_{f2} = R_g = 0$).

In the following, constraints due to each operating mode are analyzed, namely resonant frequency and DC Bus voltage level.

3.1 Analysis of operating mode constraints

3.1.1 Resonance frequency

Resonance frequency is derived from filter transfer function, which depends on the operating mode.

- Mode 1: BESS discharging mode

It is an islanded operation mode: CB circuit breaker is open and no current flows to PCC ($I_{gi} = 0$); Eqs. (3), (4), (5) and (8) to (10) are now to be considered. The derived transfer function $I_{fi}(s)/V_i(s)$ is given in (11) where “ s ” is Laplace operator. Figure 3 depicted the related block diagram.

$$I_i = \frac{V_i - V_{ci}}{sL_{f1}} \quad (8)$$

$$I_{fi} = \frac{V_{ci} - V_{PCCI}}{sL_{f2}} \quad (9)$$

$$I_{fi} = I_{Li} \quad (10)$$

$$I_{fi} = \frac{V_i}{s^3 C_f (L_{f2} + L_{Li}) L_{f1} + s^2 C_f L_{f1} R_{Li} + s(L_{Li} + L_{f2} + L_{f1}) + R_{Li}} \quad (11)$$

Bode diagram are plotted with load resistance, R_{Li} , varying from 0 to 100 Ω (Fig. 4) and load inductance, L_{Li} , from 0 to 40 mH (Fig. 5).

According to Bode plots shown in Fig. 4, load resistance has no impact on resonance frequency contrarily to load inductance L_{Li} , as illustrated in Fig. 5. Consequently, resonance frequency expression is established by neglecting load resistance, which leads to (12).

$$f_{res1} = \frac{1}{2\pi} \sqrt{\frac{L_{f2} + L_{Li} + L_{f1}}{C_f L_{f1} (L_{f2} + L_{Li})}} \quad (12)$$

Fig. 3 Block diagram of the LCL filter in islanded mode

Fig. 4 Bode diagram of the LCL filter in mode 1 when R_{Li} varies

Fig. 5 Bode diagram of the LCL filter in mode 1 when LL_i varies

Fig. 6 Poles locus transfer function when load inductance varies

Figure 6 shows the impact of L_{Li} variation on the transfer function poles and therefore on the resonance frequency.

The investigation of the input and output current transfer function of the LCL filter $h(s)$ especially for high frequencies (switching frequency) is recommended to complete the impedance sizing of this filter.

At high frequencies, Bode diagram of $h(s)$ shows no impact of the load resistance on the magnitude of the filter output current. So the transfer function between the LCL filter output and input current (I_{fi} and I_i respectively) especially at high frequencies can be approximate by (13).

Fig. 7 3-phase 4-wire DC-AC converter in grid support operation mode

$$h(s) = \frac{I_{fi}(s)}{I_i(s)} = \frac{I_{fi}(s)}{V_i(s)} \cdot \frac{V_i(s)}{I_i(s)} = \frac{L_{f1}}{C_f(L_{f2} + L_{Li})L_{f1}s^2 + (L_{f1} + L_{f2} + L_{Li})} \quad (13)$$

The expression of $h(s)$, derived from (12) and (13) is presented by (14)

$$h(s) = \frac{I_{fi}(j\omega)}{I_i(j\omega)} = \frac{1/C_f(L_{f2} + L_{Li})}{\omega_{res}^2 - \omega^2} \quad (14)$$

Relation (14) shows that the attenuation of the output filter current compared to the input filter current depends on grid side inductance L_{f2} and not on the converter side inductance. This relation expresses the main constraint for grid-side inductance design.

• Mode 2: BESS charging mode

As this charging mode is a grid connected one, transfer function and resonance frequency are the same as those for mode 3, discussed in the following section.

In this grid-connected mode, for design purpose, filter inductances are consider as a unique one $L = L_{f1} + L_{f2}$. So, by neglecting the voltage drop in the grid line, the PCC voltage will be equal to the grid voltage. Derived relationship (15) is a pure integrator.

$$I_i = I_{fi} = \frac{V_{gi} - V_i}{sL} \quad (15)$$

• Mode 3: grid supporting mode

In this operation mode, the DC-AC converter is connected to the grid (Fig. 7) and its control aims to support grid with frequency and grid voltage regulation [14].

Equations (3), (4), (6), (8) and (9) are used to establish filter output current expression given in (16).

$$I_{fi} = \frac{V_i + V_{gi}(1 + s^2 C_f L_{f1})}{s^3 C_f L_{f1} (L_{f2} + L_g) + s(L_{f1} + L_{f2} + L_g)} \quad (16)$$

Assuming that grid voltage total distortion harmonics is sufficiently low, high frequency grid voltage component $V_{gi_{HF}}(s)$ can be neglected. High frequency component of filter current is then deduced from (16) and expressed in (17). This current $I_{fi_{HF}}$ is resonant at the frequency is given by (18)

$$I_{fi_{HF}}(s) = \frac{V_{gi_{HF}}(s)}{s^3 C_f L_{f1} (L_{f2} + L_g) + s(L_{f1} + L_{f2} + L_g)} \quad (17)$$

$$f_{res_3} = \frac{1}{2\pi} \sqrt{\frac{L_{f2} + L_g + L_{f1}}{C_f L_{f1} (L_{f2} + L_g)}} \quad (18)$$

The resonance frequency depends on L_g grid inductance which is related to grid conditions: weak or strong grid. The effect of this inductance on filter design has been investigated and reported in several works, like [11–13, 28], where authors have also proposed a control that takes into account grid state variation.

The approach applied for islanded mode is also adopted for grid connected mode, so using (17) and (18) the attenuation current function $h(s)$ for grid connected mode (mode 3) is given by (19)

$$h(s) = \frac{I_{fi}(j\omega)}{I_i(j\omega)} = \frac{1/C_f (L_{f2} + L_g)}{\omega_{res}^2 - \omega^2} \quad (19)$$

For a given grid impedance and filter capacitor the grid side inductance L_{f2} is designed to minimize this function $h(s)$.

3.1.2 Resonance frequency border conditions

The resonance frequency should meet border conditions expressed in (20) to avoid unexpected resonance problems [13].

$$10f_g \leq f_{res} \leq \frac{f_{sw}}{2} \quad (20)$$

where f_{sw} is a switching frequency.

Research results reported in [13, 24] shows that these limits depend on the control strategy. Indeed control methods can be mainly grouped in two major classes, namely control system with inverter-side current feedback (ICF) and with grid current feedback (GCF). For each class, resonance frequency border limits have been established, as expressed in (21) for the ICF control method, and in (22) for the GCF one [24].

$$\text{ICF control : } 10f_g \leq f_{res} \leq \frac{f_{sw}}{6} \quad (21)$$

$$\text{GCF control : } \frac{f_{sw}}{6} \leq f_{res} \leq \frac{f_{sw}}{2} \quad (22)$$

In this work, GCF control is adopted, since it does not require embedded current sensors in the converter, so limits given in (22) will be considered.

3.1.3 V_{dc} voltage constraints on 3-phase 4-wire system

Several studies have been reported for LCL filter and V_{dc} sizing in rectifier operating mode of the DC–AC converter [2, 35]. In this case, design is performed under the constraint of an unitary power factor. When space vector modulation is applied in DC–AC converter control, the lowest limit of the DC voltage V_{dc} is given by (23).

$$V_{dc\min} = \sqrt{3} V_{i1\max} \quad (23)$$

For an inverter use of the DC–AC converter the DC bus voltage is given by (24)

$$V_{dc1,3} = 2m_a V_{i1,\max} \quad (24)$$

where m_a is the modulation index that has a maximum value of 1 and $V_{i1\max}$ is the maximum fundamental AC voltage at the output of the converter.

The capacitor has great impedance for the fundamental signal, so the inverter output voltage V_i is derived from (25), where L is the total filter inductance, $L = L_{f1} + L_{f2}$

$$V_i = V_{PCCi} + jL\omega_g I_{fi} \quad (25)$$

The maximum value of V_i is calculated using (26)

$$V_{i\max} = \sqrt{V_{PCCi}^2 + (L\omega_g I_{fi\max})^2} \quad (26)$$

In mode 2 and 3, the PCC voltage and frequency are equal to grid ones. On the other hand, in mode 1 the PCC voltage and pulsation are controlled to be equal to the reference inputs.

Minimum DC bus Voltage depends on the inverter or rectifier operation of the DC–AC converter [35] and on the power flow on the system. For a 230 V PCC rms voltage, the minimum DC bus voltage is equal to 560 V in rectifier operation (mode 2) and to 653 V in inverter operation (mode 1 and 3). This value appears on the design of the converter-side inductance [13, 14]. Indeed the choice of this voltage is essential

- For the sizing of the converter-side inductance for the LCL filter, since this inductance, is physically linked

to the voltage of the DC bus through switches. This inductance has the role of attenuating ripple current at the output of the DC–AC converter.

- For sizing both capacitors of the DC bus to attenuate the fluctuations of the voltage V_{dc}

3.2 Design of the LCL filter

The design is performed using base values defined in (27) to (29), where P_{PCCN} , U_{PCCN} and $\omega_N = \omega_g$ are, nominal real power, nominal phase-to-phase voltage and nominal pulsation of the PCC bus respectively.

$$Z_B = \frac{U_{PCCN}^2}{P_{PCCN}} \quad (27)$$

$$L_B = \frac{Z_B}{\omega_N} \quad (28)$$

$$C_B = \frac{1}{\omega_N Z_B} \quad (29)$$

3.2.1 Maximum value of the total inductance

The total impedance must be lower than ten percent of L_B base inductance to reduce the drop voltage in the filter and to improve the system dynamic. In grid connected mode 3, this condition is expressed related to grid parameters (30)

$$L_{\max} = (L_{f1} + L_2)_{\max} = 0.1L_B = 0.1 \frac{U_g^2}{2\pi f_g P} \quad (30)$$

where U_g is phase-to-phase voltage rms value, f_g grid frequency, L_2 the equivalent inductance value of the grid side and P is the active power flowing on the system.

In mode 2, when the system operates in islanded mode, this condition is expressed in (31) where the PCC voltage bus is equal to the voltage references provided by the control.

$$L_{\max} = (L_{f1} + L_{f2})_{\max} = 0.1L_B = 0.1 \frac{U_{PCCref}^2}{2\pi f_{ref} P} \quad (31)$$

Usually PCC voltage and frequency references PCC are equal to those of the grid. In fact, if the condition (30) is verified, the equality (31) is necessarily checked.

3.2.2 Inductance L_{f1} tuning

The converter side inductor is crossed by the totality of the current (fundamental and harmonic), so it is designed to

reduce the DC–AC current ripple. The maximum ripple current can be selected into 10% and 25%.

For the three phase 4-wire DC–AC converter, the converter current is given by (32), [34]

$$L_{f1} \frac{di_i}{dt} = \begin{cases} V_i \approx L_{f1} \frac{\Delta i_{i1}}{T_{OFF}} (0 \leq t \leq T_{OFF}) \\ V_i - V_{dc} \approx L_{f1} \frac{\Delta i_{i2}}{T_{ON}} (T_{OFF} \leq t \leq T_{sw}) \end{cases} \quad (32)$$

Considering that $\Delta i_{i1} = -\Delta i_{i2}$ and according to (32) current ripple defined by $|\Delta i_i| = |\Delta i_{i1}| = |-\Delta i_{i2}|$ is expressed by (33)

$$|I_{ripple}| = |\Delta i_i| = \frac{V_i}{L_{f1}} \cdot \frac{V_{dc} - V_i}{V_{dc}} \cdot T_{sw} = \frac{m(1-m)V_{dc}}{L_{f1}f_{sw}} \quad (33)$$

where T_{sw} is the switching period and m is defined by the relationship $V_i = mV_{dc}$ which depends on the PWM method.

According to (33) and considering a desired maximum ripple current defined as in percent of maximum current value by (ripple%) I_{max_Nom} , a minimum L_{f1} value is established as given in (34).

$$L_{f1} \geq \frac{m \max(1-m) V_{dc}}{f_{sw}(\text{ripple}\%) I_{\max Nom}} \quad (34)$$

3.2.3 Capacitance C_f calculation

The consumption of reactive power of the capacitor of the LCL filter must be less than 5% of the total reactive power of the system [14, 20, 24]. The filter capacitance should verify (35)

$$C_f \leq 0.05 \frac{P}{\omega_g U_g^2} \quad (35)$$

3.2.4 Inductance L_{f2} calculation

The grid side inductance, L_{f2} is proportional to the converter side inductance. Its value could be lower than L_{f1} one because it is crossed by an already filtered output current. A ratio a is defined between both inductances [14], as expressed in (36)

$$L_{f2} = aL_{f1} \quad (36)$$

A ratio h of the grid side current by the converter side current at the switching frequency is also defined in (37).

$$h = \left| \frac{I_{if}(sw)}{I_i(sw)} \right| \quad (37)$$

The transfer function $h(s)$ between the grid side current and the converter side current is discussed in Sect. 1 and given by (13) or (19) according to the operation mode.

By introducing (36) in (13) and by neglecting the grid inductance in the grid connected mode (mode 2 and mode 3), the expression (38) of h is derived, and then in (39), the ratio a between both filter inductances.

Otherwise for islanded mode or for important grid impedance, (13) and (19) are used for the grid side inductance tuning.

$$h = \left| \frac{1}{1 + a(1 - L_{f1} C_f \omega_{sw}^2)} \right| \quad (38)$$

$$a = \left| \frac{1 - h}{h(1 - L_{f1} C_f \omega_{sw}^2)} \right| \quad (39)$$

Several works, like those reported in [4] studied the control of transition from one mode to the other, but at our best knowledge, operation mode impact on power passive filter design of the system has not been considered.

Most studies investigate only the impact of the grid impedance on the LCL filter design especially on its resonance frequency in grid-connected mode, [11]. Nevertheless, LCL filter resonance frequency and parameters depend on what is connected to output filter. Indeed resonance frequency depends on the grid impedance in grid connected mode but on load impedance in islanded mode.

Here lies our added value, the impact analysis, on LCL filter parameters and resonance frequency choice, of load impedance, grid impedance and dc bus voltage, according to the different operation modes. Indeed, grid-side inductance ratio, which is reliant on converter output current attenuation function, is based on load impedance and on the grid impedance in islanded mode and in grid connected mode respectively.

The previous analysis leads to the proposed step by step procedure for optimized LCL filter design considering each operating mode. This procedure is summarized in the flowchart given in Fig. 8.

4 $L_N C_N$ filter design

The DC–AC converter under study is a three phase-four wires one, with four legs and a $L_N C_N$ filter as depicted in Fig. 9. The purpose of this filter is to balance the potential at the midpoint of the continuous bus

The control of the fourth arm has as a function therefore to pass the entire neutral current through the L_N filter and thus to keep a capacitor current I_C zero, [13, 15]. In this case

Fig. 8 Flowchart for LCL filter design

Fig. 9 Three-phase four legs DC–AC with $L_N C_N$ filter

the potential V_o will be null, where voltage V_o is defined as $V_o = V_{OL} + V_{OH}$.

The fourth leg control consists of two control loops, an inner loop of current and an outer loop of voltage.

4.1 Capacitor C_N Design

By noting ω_i and ω_v the cut-off frequency of the current and voltage regulation loops respectively, in the maximum value of its fundamental neutral sound, the offset can be expressed according to (40)

$$V_o \leq \frac{I_N}{\omega_i C_N} \quad (40)$$

where $C_N = C_{N1} = C_{N2}$.

Equation (40) shows that a large capacitance value C_N will more easily reduce the offset voltage V_o . By noting f the frequency of the fundamental of the neutral current, the value of the capacitance must satisfy the constraint indicated in (41), [5].

$$C_N \geq \frac{2 \cdot \pi \cdot f \cdot I_N}{\omega_i^2 \cdot V_o} \quad (41)$$

The pulsation ω_i is chosen by fixing the number of harmonics to be filtered (to pass through the L_N inductor and not by the midpoint). The example of filtering the 31st harmonic rank is given in [5], which leads to the ω_i pulse given in (42).

$$\omega_i = 31 \cdot f \cdot 2 \cdot \pi \quad (42)$$

4.2 Inductance L_N tuning

According to Fig. 9, assuming that V_o is set to 0 V. The purpose of the control is that the neutral current passes entirely through the inductor L_N ($I_{LN} = I_N$). Then the voltage V_{NO} is derived from (43)

$$V_{NO} = 2 \cdot \pi \cdot f \cdot L_N I_N \quad (43)$$

whereas $V_{NO} = m \frac{V_{dc}}{2}$, m depends on the PWM method ($m = 0.8$ to 1). Replacing this relation in (43) gives the condition (44) on the L_N inductance.

$$L_N \leq \frac{m V_{dc}}{4 \cdot \pi \cdot f \cdot I_N} \quad (44)$$

On the other hand, the design of L_N inductance must take into account the relation (45), according to [5]

$$L_N \geq \frac{\frac{1}{2} V_{dc}}{\delta_m} \quad (45)$$

where δ_m is possible maximum $\frac{di}{dt}$ for power switch.

It is to note that, in our case the neutral filter has not impact on the LCL filter parameters thanks to the control of the fourth DC-AC arm. Without fourth leg control, an LCL filter should be designed, and neutral filter L may affect the LCL filter characteristics, as reported in [34]. Fourth leg

control creates a neutral fictional ground and opposes the neutral current created by an unbalanced load.

5 DC-DC filter design

The peak to peak battery current ripple is determined by (46), which lead to the minimum battery side inductance value expressed in (47), where D is the duty cycle.

$$\Delta i_{Lbat} = \frac{1}{L_{bat}} \int_0^{DT_{sw}} V_{Lbat}(t) dt = \frac{V_{bat}}{L_{bat}} DT_{sw} \quad (46)$$

$$L_{batmin} = \frac{V_{bat}}{\Delta i_{Lmax} f_{sw}} D_{max} \quad (47)$$

In another hand the limit of a continuous operating of the boost converter is given by (48)

$$\langle I_{bat} \rangle_{min} = \frac{1}{2} \Delta I_{bat} \quad (48)$$

From (47) and (48) the minimum output current of the DC-DC converter is expressed by (49)

$$I_{dcmin} = \frac{V_{bat}}{2 L_{bat} f_{sw}} (1 - D) \quad (49)$$

DC bus total capacitor, $C = C_{N1} + C_{N2}$, is deduced from (48). Its minimum is given by (50)

$$C_{min} = \frac{I_{dc} D}{\Delta V_{dc} f_{sw}} \quad (50)$$

The design methodology has been applied for a 20 kVA system. Its parameters are detailed in Table 1.

The whole system shown in Fig. 1 is simulated in PSIM software with parameter values obtained by the proposed design. These parameters are given in Table 2

By applying design result defined in (21), the obtained minimum DC bus voltage is equal to 563 V. This value is a theoretical limit and depends on real and reactive power of the system [34]. So several simulations have

Table 1 System parameters

S	V_{PCCA}	f_g	V_{bat}	R_L	L_L	f_{sw}
20 kVA	200 V	50 Hz	400 V	13 Ω	4 mH	10 kHz

Table 2 Filter parameters given by the design

L_{f1}	L_{f2}	C_f	L_{bat}	L_N	C_N
2.2 mH	1 mH	15 μ F	10 mH	2.5 mH	400 μ F

Table 3 Case I Traditional design parameters

L_{f1}	L_{f2}	C_f	L_{bat}	L_N	C_N
2.2 mH	1.8 mH	19 μ F	4 mH	43 mH	400 μ F

Table 4 Case II Experimental parameters

L_{f1}	L_{f2}	C_f	L_{bat}	L_N	C_N
2.5 mH	2.5 mH	30 μ F	10 mH	2.5 mH	1100 μ F

Table 5 Load parameters

	Phase a	Phase b	Phase c
R_L	13 Ω	6.5 Ω	13 Ω
L_L	4 mH	4 mH	2 mH

been performed under several operating conditions, and, finally, the DC bus voltage V_{dc} is chosen equal to 800 V.

6 Simulation results

To validate the design of filters, two simulation cases are carried out. The first case, case I, is based on parameters given by traditional filter design where only grid connected mode is considered, without taking into account grid and load impedance variations and where passive filter parameter values are fixed to their limits. These parameters are shown in Table 3 and referred as traditional design parameters in following.

In case II, parameters are fixed as a compromise between those obtained by the proposed design and those available for experimental setup. They are given in Table 4 and referred as experimental parameters in following.

Analysis is based on simulation results carried out with PSIM software. It will be based on battery and grid current ripples, DC bus voltage ripples, grid voltage and the harmonic injection.

Result discussions will be conducted by comparing results obtained with the two sets of parameters and by verifying how they enable the system to meet standards and grid code requirements related to LV grid connection.

Only dynamic state performances are considered in this work, so simulation results are presented for steady state mode, in both cases, since $t = 0.4$ s.

The same load is used for all cases. It is an unbalanced load and its parameters are given in Table 5.

Fig. 10 PCC Voltage and currents obtained with traditional design parameters for grid-connected mode **Fig. 11** PCC voltage harmonic injection with traditional design parameters for grid-connected mode **Fig. 12** PCC currents harmonic injection with traditional design parameters for grid-connected mode

6.1 Harmonic injection

Simulations are first performed in grid-connected mode. Grid voltages and currents are shown in Fig. 10 and their harmonic injection in Figs. 11 and 12 respectively with traditional design parameters. Figure 10 shows the time

response of the voltage and the current of the three phases at the PCC point. It also shows that the 97% load unbalance leads to almost the same ratio current unbalance. The unbalance ratio is the division of the maximum deviation by the average voltage or current and multiplies by 100%

The corresponding harmonic injection shown in Figs. 11 and 12 presents the Fast Fourier Transform (FFT) for the grid voltages and currents respectively. Figure 11 shows a third harmonic of 2.5% at 150 Hz, an harmonic of 2.7% at 950 Hz and eight other harmonics with a maximum value of 0.4% for the voltage of phase a. These harmonics lead to a Total Harmonic Distortion (THD) of 4.29% that remains lower than the limits required by standards (5%).

Simulations results under the same conditions but with experimental parameters are shown in Fig. 13 and lead to lower THDv and THDi as illustrated in Figs. 14 and 15.

First the time response of the PCC voltages and currents of the three phases (phase a, phase b and phase c) are presented in Fig. 13. This Figure shows a direct balanced three-phase voltage system, in case of an unbalanced three sine waves of the current. The current unbalance is due to the load unbalance

In the traditional design of the LCL Filter method as developed in [11–17], the grid connected mode is usually adopted since the filters are sized to protect the grid against harmonics. For this reason the traditional design methods of the LCL filter present good performances and meet the grid code requirements in terms of harmonic injections and THDs.

Fig. 13 PCC voltages and currents obtained with experimental parameters for grid-connected mode

Fig. 14 PCC voltage harmonic injection with experimental parameters for grid-connected mode

The FFT presented in Fig. 14 shows the voltage harmonic injections in the PCC point, the mean value of the amplitude of the voltage harmonics between 0 Hz and 1 kHz for phase a is almost 0.2% and it reaches a 1.32% at 650 Hz and a 1.12% at 750 Hz. Consequently, the voltage THD is weak, it has a value of 2.9%.

The FFT of the PCC current for the phase a (Fig. 15), presents two maximum current harmonic at 650 Hz and 750 Hz with amplitude of 0.6% and 0.8% respectively. There are other harmonics with an average of amplitude of 0.15%. These values of voltage harmonics are small which leads to a lower THD of 1.8% for the phase a.

In islanded mode, PCC voltage and current waveforms are deteriorated with case I parameters (Fig. 16). Their THDv (Fig. 17) and THDi (Fig. 18) values become higher than standards limits ones.

The PCC voltages THDs are greater in this case (islanded mode). Figure 17 shows the amplitudes of voltage harmonics for the three phases. A zoom on the FFT of the phase a voltage shows a greater value of the third harmonic at 150 Hz with a value of 10.87%. It is due to a bad filtering of the LCL filter which was designed for a grid connected mode, without taking into account load impedance. This load impedance is part of the total impedance of the LCL filter as shown in Eq. (30) shows and in Eq. (12) related to the LCL Filter frequency resonance. So the load

Fig. 15 PCC current harmonic injection with experimental parameters for grid-connected mode

Fig. 16 PCC voltages and currents obtained with traditional design parameters for islanded-mode

Fig. 17 PCC voltage harmonic injection with traditional design parameters for islanded-mode

Fig. 18 PCC currents harmonic injection with traditional design parameters in islanded mode

impedance must be included in the flowchart of the design of the LCL filter.

A zoom on the FFT of the PCC current for this case is shown in Fig. 18; this figure shows a maximum value of the harmonic at 150 Hz with a 10.48%. For this reason a higher current THD value is reached. It is due to the same reasons explained for the voltage harmonics.

Fig. 19 PCC voltages and currents obtained with experimental parameters in islanded-mode

Fig. 20 PCC voltage harmonic injection with experimental parameters in islanded-mode

For case I filter parameters, Fig. 16 shows deteriorated PCC voltages and currents. This poor quality of energy is explained by voltage and current harmonics high values shown in Figs. 17 and 18. Indeed, as the LCL filter was designed for grid-connected mode, it provides poor performances in filtering harmonic when the operating mode switches to islanded mode.

Whereas, with case II parameters, waveforms are not deteriorated. Currents have the same ratio of unbalance (Fig. 19) and harmonics injections remain lower than 5% and 3% for PCC voltage (Fig. 20) and current (Fig. 21), respectively. These values are higher than those obtained in grid-connected mode but still lower than standards limits.

Fig. 21 PCC currents harmonic injection with experimental parameters in islanded mode

Fig. 24 Battery ripple current with experimental parameters for islanded-mode

Fig. 22 Battery ripple current with experimental parameters in grid-connected mode

Fig. 23 Battery ripple current with traditional design parameters in grid-connected mode

Fig. 25 Battery current ripple with traditional design parameters in islanded-mode

Fig. 26 DC bus voltage ripple with traditional design parameters in grid-connected mode

6.2 Battery current ripples

Simulation results in grid-connected mode with experimental parameters are shown in Fig. 22. Battery current is in continuous conduction mode and its ripple is almost 17% which remains lower than the limit range of 20% fixed by the design.

The same simulations are carried out with traditional design parameters. In this case, Fig. 23 shows large battery current ripples that reach 150%. This is due to small value of the battery inductance L_{bat} .

In islanded mode, battery current ripples increase by 6% with case II experimental parameters (Fig. 24) but

they are still under the design limit. This increase is by 33% when Case I parameters are used (Fig. 25) and non-continuous operation mode for the DC–DC converter is reached in this case.

6.3 DC bus voltage ripple

The DC bus voltage ripples for a grid-connected mode are shown in Fig. 26 with traditional design parameters. It shows a 25% voltage ripple which is a little higher than design limit.

Better performances are obtained with experimental parameters as shown in Fig. 27. In this case, voltage ripples drop to 7% which is lower than the limit of 20% fixed by the design.

Fig. 27 DC bus ripple voltage with experimental parameters in grid-connected mode

Fig. 30 Voltage V_o (V), Neutral current I_N (A) and inductor L_N current I_{LN} (A) obtained with traditional design parameters

Fig. 28 DC bus ripple voltage with traditional design parameters in islanded-mode

Fig. 31 Voltage V_o (V), Neutral current I_N (A) and inductor L_N current I_{LN} (A) obtained with experimental parameters

Fig. 29 DC bus ripple voltage with experimental parameters in islanded-mode

In islanded mode the DC bus voltage ripples value become twice more important with Case I filters parameters (Fig. 28) whereas but they remain unchanged with Case II experimental parameters (Figs. 28, 29).

6.3.1 Neutral filter currents

Figures 30 and 31 show the middle point of the DC bus voltage V_o , the neutral current and the neutral filter current for both case I and case II respectively. Simulation starts at 0.4 s in a islanded-mode and at 0.6 s, the system switches to a grid-connected mode.

The voltage V_o (Fig. 30) reaches a maximum deviation of 10 V in grid-connected mode with case I parameters. This value is higher than the required value fixed at 1 V.

Figure 31 shows that with case II parameters, voltage V_o is maintained equal to 0 V to keep DC bus voltage balanced and the current in the inductor L_N is controlled to compensate the neutral current. So, the L_N current is equal to the neutral current and in opposition of phase, which proves the effectiveness of L_N and C_N parameters design.

6.4 Resonance frequency

According to (12) and (18), the resonance frequency of the LCL filter with experimental parameters is 684 Hz and it is equal to 1497 Hz for a traditional design where the grid and the load impedances are neglected. According to (20) the high limit of resonance frequency is the half of the switching frequency, $f_{sw}/2$. Simulations start with a 10 kHz switching frequency and at 0.6 s, a frequency change is applied, to 2 kHz in a first step and to 1 kHz in a second step. The two cases are simulated for grid-connected mode.

Figures 31 and 32 show the simulation results: in Fig. 32 a resonance is detected when the switching frequency switches to 2 kHz, in return there is no resonance for the LCL filter with experimental parameters (Fig. 33).

Fig. 32 PCC voltage for traditional design parameters when frequency switches to 2 kHz

Fig. 35 PCC voltage for experimental parameters when frequency switches to 1 kHz

Fig. 33 PCC voltage for experimental parameters when frequency switches to 2 kHz

Fig. 36 Phase a PCC current for different loads in islanded mode obtained with experimental parameters

Fig. 34 PCC voltage for traditional design parameters when frequency switches to 1 kHz

Now for the both cases case I and case II, simulation start with a 10 kHz switching frequency and at 0.6 s the switching frequency is changed to 1 kHz for grid-connected mode. Figures 34 and 35 show the resonance of the LCL filter for the two cases. The occurrence of this resonance can be explained by the fact that in both cases the resonance frequency is lower than a half switching frequency.

6.5 Grid and load impedances variations

In this section system with experimental parameters (case II) is studied. To check system response under large load and grid impedance variation, simulations are firstly performed in islanded mode by applying different loads (load resistance change from 10 to 100 Ω). Figure 36 shows that there is no resonance of the LCL filter and that the voltage and current THD complies with standards.

By varying the grid impedance L_g from 4 to 16 mH in grid-connected mode, Fig. 37 shows V_{PCC} voltage THD values obtained for each L_g value.

7 Discussions

The simulation results for the two filter cases, case I filter and case II filter, are summarized in Table 6. The voltage and current THD are presented to evaluate the performance of the LCL filters. The DC voltage ripple, the DC current ripple and the deviation of the midpoint of the DC bus voltage are given to demonstrate the effectiveness of the DC and Neutral filters.

In grid connected mode and in islanded mode, the voltage and current at case II LCL filter output show

Fig. 37 Phase a PCC voltage for different grid impedances in connected mode obtained with experimental parameters

Table 6 Comparative results

	Case I	Case II	Requirements
THDi a	2.8% GCM* 10.68% IM**	1.8% GCM 2.5% IM	< 5%
THDv a	4.2% GCM 11.4% IM	2.9% GCM 3.8% IM	< 5%
DC ripple voltage	25% GCM 50% IM	7.25% GCM 8% IM	< 20%
Battery ripple current	150% GCM 200% IM	17% GCM 18.4% IM	< 20%
Vo deviation	10 V GCM 5 V IM	0.1 V GCM 0.1 V IM	< 1 V

*GCM: Grid-Connected Mode **IM: Islanded Mode

three-phase systems of voltage and current with low THD and then an almost sinusoidal wave (Figs. 13, 19).

The Fast Fourier Transformer FFT is used to analyze the voltage and current harmonics. Figures 14 and 15 show an average value of 0.15% and 0.2% for the amplitudes of the currents harmonics and voltage harmonics respectively at the output of the LCL filter in grid connected mode. So the current and voltage THDs are respectively 1.8% and 2.9%. These THDs increase a little to reach 2.5% for currents and 3.8% for voltages in islanded mode.

In both modes, grid connected mode and islanded mode, the current and voltage THD are lower than the THD recommended by the grid code requirements (5%).

To highlight the effect of the grid impedance variations, simulation results presented in Fig. 37 show that there is no resonance but it has to be remarked that the PCC voltage THD increases with grid impedance.

So for weak grid, THD increases and may no longer complies with the standards. Solutions are then proposed in literature, like the use of active damping methods for the LCL filter in case of weak grid.

Filter with case II parameters is designed with the proposed design procedure, as detailed in the design

algorithm flowchart presented in Fig. 8. It takes into account the islanded mode and the variation of the load and the grid impedances which constitutes the main contribution of this paper.

Usually the design of the LCL filter is made in grid connected mode to block the circulation of harmonics in the grid. So a traditional filter design was presented in the bibliography [10–17], Zhiding presents an optimal filter parameters which leads to a 0.15% current THD. In [10] and in [14] Liserre developed an LCL filter design for a three-phase active rectifier uses, At the output of the LCL filter, the current THD is equal to 3% but the voltage THD had 1% in grid connected mode.

By applying the traditional filter design method to our system, the parameters of the LCL filter are the case I parameters. The voltage and current THD have 4.2% and 2.8% respectively; these values reach the grid requirement code. But in islanded mode Figs. 17 and 18 show a high current and voltage third order harmonic of a 10.48% and 10.87% respectively. The current THD is equal to 10.68% and the voltage THD is 11.4%. These values are greater than the requirements and lead to a poor harmonics filtration which can be seen in the current and voltage deteriorated waveforms of the current and the voltage, shown in Fig. 16. In fact, the traditional filter design algorithm was developed only for grid connected mode. So it does not take into account the load impedance in total inductance filter computing or for the resonance frequency calculation, like in [11–17].

Another mismatch between the grid connected mode and islanded mode is that:

- The model system in grid connected mode has as input the grid voltage modeled as a three phase ideal voltage source. In this way the battery energy storage system have a role of grid feeding, the voltage waveform is fixed mostly by the grid
- In islanded mode the DC–AC converter of the battery energy storage system is a grid forming converter since the voltage waveform is forming only by this converter.

To deal with this limit of the traditional design, when developing the proposed LCL filter design flowchart, all the operating mode are considered. So the total filter impedance is constituted by the inductors of the LCL filter in series with the grid impedance and the load impedance as shown in Eq. (30).

The resonance frequency also depends on the variation of the load and grid impedances as shown in Eq. (13) and proved by the simulation results of the Figs. 32, 33, 34 and 35.

8 Conclusion

This paper deals with the design of the LCL filter and the passive elements of a battery energy storage system. These power passive filters are used to reduce the switching frequency current harmonic produced by the power converters in order to respect the grid code requirements. Compared to other related design methodologies discussed in the literature, the developed one provides a systematic design of a BESS filters with regards to system operation mode and control. Indeed an analysis of the impact of the loads and the grid state has been conducted taking into account the chosen converter topology. The design procedure is based on a detailed mathematical representation. Throughout the mathematical model, it has been proven that the load impedance in islanded mode and the grid impedance in connected mode have a great impact on the resonance frequency of the LCL filter. On the other hand, the proposed study shows that there is no impact of the neutral filter on the LCL filter characteristics. This design also allows a continuous conduction of the DC–DC converter for each mode.

A flowchart has been proposed to describe the step-by-step proposed algorithm for optimal LCL filter parameters design. Tuned filter parameters were tested with PSIM Software. Simulation results have been given to illustrate the behavior of the global system. These simulation results have proven the effectiveness of the proposed procedure for each operation mode.

In addition the performances of the filters were tested under several conditions like a large variation of the load impedance in islanded mode and fluctuation of the grid impedance in grid-connected mode.

For further work, in case of high power systems, interlaced filter structure of the DC–DC converter can be studied and active damping method could be added to improve the stability of the system.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest

References

- Kim YS, Kim ES, Moon S (2015) Frequency and voltage control strategy of standalone microgrids with high penetration of intermittent renewable generation systems. *IEEE Trans* 31:718–728
- Xu Y, Li Z, Zhao J, Zhang J (2018) Distributed robust control strategy of grid-connected inverters for energy storage systems' state-of-charge balancing. *IEEE Trans* 9:5907–5917
- Ovaskainen M, Oorni J, Leinonen A (2019) Superposed control strategies of a BESS for power exchange and microgrid power quality improvement. In: IEEE international conference on environment and electrical engineering and IEEE industrial and commercial power system Europe IEEEIC and I&CPS Europe
- Kim HJ, Shin ES, Lee YS, Kim JH (2017) Smooth operation transition scheme for stand-alone power system with EG and BESS-PV panels. *IEEE Trans* 8:2042–2044
- Zhong QC, Hobson L, Jayne MG (2005) Classical control of the Neutral point in 4-wire 3-phase DC–AC converters. *Electr Power Qual Util J* 11(2):111–119
- Bozalakov D, Meersman B, Bottenberg A, Rens J, Desmet J, Vandeveld L (2017) DC-bus voltage balancing controllers for split dc-link four-wire inverters and their impact on the quality of the injected currents. In: International conference and exhibition on electricity distribution CIREC
- Koska K, Ruzsarczyk A, Wawro M (2015) Control of 3-leg 4-wire inverter with passive LC output filter operating with nonlinear unbalanced load. In: Scientific conference control in power electronics and electric drive Poland
- IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems, IEEE Std. 1547–2003, Jul. 28, 2003
- VDE-AR-N 4105 Anwendungsregel:2018-11, Power Generating systems connected to the Low-voltage distribution network
- Wu Z (2018) A novel design method of LCL filters for optimal reactive power compensation in microgrids. In: IEEE international power electronics and applications conference and exposition PEAC
- Han Y, Yang M, Li H, Yang P, Xu L, Coelho EAA Guerrero J (2019) Modeling and stability analysis of LCL—type grid-connected inverters: a comprehensive overview. *IEEE Access*, 30 August 2019, Digital Object Identifier. <https://doi.org/10.1109/access.2019.2935806>
- Lu M, Al-Durra A, Mueen SM, Leng S, Loh PC, Blaabjerg F (2018) Benchmarking of stability and robustness against grid impedance variation for LCL-filtered grid-interfacing inverters. *IEEE Trans Power Electron* 33(10):9033–9046
- Rosso R, Cassoli J, Buticchi G, Engelken S, Liserre M (2019) Robust stability analysis of LCL filter based synchronverter under different grid conditions. *IEEE Trans Power Electron* 34:5842–5853
- Liserre M, Blaabjerg F, Hansen S (2005) Design and control of an LCL-filter based three-phase active rectifier. *IEEE Trans* 41:1281–1291
- Kouchaki A, Nyman M (2017) Analytical design of passive LCL filter for three-phase two-level power factor correction rectifiers. *IEEE Trans* 33:3012–3022
- Rizk G, Salameh S, Kannan HY, Rachid EA (2014) Design of passive power filters for a three-phase semi-controlled rectifier with typical loads. In: IEEE conference on industrial electronics and applications
- Boonseng C, Rapeepornpat B, Suksawat D, Nilnimit N, Inwanna W, Manee A, Juntason T, Ki V (2019) Design and installation of passive power filter for grid-connected solar rooftop applications at industrial plants. In: IEEE PES GTD grand international conference and exposition Asia GTD Asia
- Sanatkar-Chayjani M, Monfared M (2017) High-order filter design for high-power voltage-source converters. *IEEE Trans* 65:49–58
- Popescu M, Bitoleanu A, Preda A (2018) A new design method of an LCL filter applied in active DC-traction substation. *IEEE Trans* 54:3012–3022

20. Li J, Zhang T, Duan S, Li H (2019) Design and implementation of lead-carbon battery storage system. *IEEE Access* 7:32989–33000
21. Atmaka O, Erol E, Kamal T, Karabacak M (2019) Design of an H-bridge bidirectional DC–DC converter with LCL filter for high power battery applications. In: Global power, energy and communication conference GPECOM
22. Kim TH, Kim SH, Kwon BK, Kim BS (2011) A procedure to design LCL filter for energy storage system. In: International conference on power electronics ACCE Asia
23. Jiang S, Liu Y, Liang W, Peng J, Jiang H (2019) Active EMI filter design with a modified LCL-LC filter for single-phase grid-connected inverter in vehicle-to-grid application. *IEEE Trans* 68:10650–10693
24. Xin Z, Mattavelli P, Yao W, Yang Y, Blaabjerg F, Loh PC (2018) Mitigation of grid current distortion for LCL-filtered voltage source inverter with inverter current feedback control. *IEEE Trans Power Electron* 33(7):6248–6261
25. Wang X, Beres R, Blaabjerg F, Loh PC (2015) Passivity-based design of passive damping for LCL filtered voltage source converter. In: IEEE energy conversion congress and exposition (ECCE)
26. Yao W, Yang Y, Zhang X, Blaabjerg F, Loh PC (2016) Design and analysis of robust active damping for LCL filters using digital notch filters. *IEEE Trans* 32:2360–2375
27. Pan D, Ruan X, Bao C, Li W, Wang X (2014) Capacitor-current-feedback active damping with reduced computation delay for improving robustness of LCL-type grid-connected inverter. *IEEE Trans* 29:3414–3427
28. Ben Said-Romdhane M, Naouar MW, Slama Belkhdja I, Monmasson E (2017) An improved LCL filter design in order to ensure stability without damping and despite large grid impedance variations. *Energies* 10(3):336
29. Jia L, Ruan X, Zhao W, Lin Z, Wang X (2018) An adaptive active damper for improving the stability of grid-connected inverters under weak grid. *IEEE Trans* 33:9561–9574
30. Buduma P, Panda G (2018) Robust nested loop control scheme for LCL-filtered inverter-based DG unit in grid-connected and islanded modes. *IET Renew Power Gener* 12:1269–1285
31. Yong BH, Ramachandaramurthy VK (2015) Double tuned filter design for harmonic mitigation in grid connected solar PV. In: IEEE international conference on power and energy PECon
32. Boonseng C, Boonseng R, Kularbphettong K (2019) Harmonic filter design using actual recorded data to prevent resonance in the synchronous generator for biomass power plants. In: International conference on electrical machines and systems ICEMS
33. Tong L, Chen C, Zhang J (2019) Iterative design method of LCL filter for grid-connected converter to achieve optimal filter parameter combination. *IET J Eng* 2019:1532–1538
34. Bao C, Ruan X, Wang X, Li W, Pan D, Wang K (2014) Step-by-step controller design LCL-type grid-connected inverter with capacitor-current-feedback active damping. *IEEE Trans* 29:1239–1253
35. Merai M, Naouar MW, Slama-Belkhdja I, Monmasson E (2019) Grid connected converters as reactive power ancillary service providers: technical analysis for minimum required DC link voltage. *Math Comput Simul* 158:344–354
36. Liu Y, See KY, Simanjorang R, Lai JS (2017) LCL + L filter for three-phase four-wire high power density converter. In: Conference: 2017 Asian conference on energy, power and transportation electrification (ACEPT)
37. Fares A, Ajram S, Cathébras G (2014) Simplified review of DC-DC switching noise and spectrum contents. In: Conference on Ph.d research in microelectronics and electronics PRIME
38. Zhou X, Yu X, Lukic S, Huang A (2012) LCL filter utilized in battery charging applications to achieve compact size and low ripple charging. In: IEEE energy conversion congress and exposition ECCE
39. Jung M (2016) Optimized design of DC-DC converter LC output filter for EV battery charging applications in terms of defined battery current and voltage ripple as well as overall system efficiency. In: European conference on power electronics and applications EPE'16 ECCE Europe
40. Kanchera S, Tripathi RK (2009) Nonlinear average current mode control for a DC-DC buck converter in continuous and discontinuous conduction modes. In: TENCON
41. Jothy R, Prasana K, Ramprasath S, Vijayasarithi N (2016) Design and analysis of hybrid DC-DC boost converter in continuous conduction mode. In: International conference on circuit, power and computing technologies ICCPCT
42. Chub A, Vinnikov D, Kosenko R, Liivik E, Galvin I (2019) Bidirectional DC-DC converters for modular residential battery energy storage systems. *IEEE Trans* 67:1944–1955

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