

Harmonic Mitigation in Three-Phase Power Networks with Photovoltaic Energy Sources

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Abstract: Energy systems based on photovoltaic (PV) cells have increased at a rapid pace. Therefore, power converters have been widely employed in power systems to enhance the quality and magnitude of the power drawn from renewable energy sources. An LCL filter for connection of an inverter to the grid is often used to reduce harmonics generated by the inverter. According to different design techniques, optimal parameters of LCL filter tend to vary in a wide range. This paper presents a new approach to an LCL filter. A phase shifting transformer placed in the structure of an LCL filter to minimize harmonic current. Methods and techniques described in this paper are particularly suitable for grid-connected PV power systems.

Keywords: Harmonic Mitigation, LCL Filters, PV Sources

1. Introduction

There is a widespread use of renewable energy in the distribution networks. The photovoltaic (PV) cells starts to have significant impacts to the power grid system. Therefore, more advanced filters, power electronic systems, and control solutions have to be introduced to improve the power quality, network reliability and stability [1-3].

Typically, photovoltaic (PV) cells are connected to the grid through multilevel voltage source inverters [4]. To mitigate the harmonic content of currents produced by power converters connected to the grid through multilevel voltage source inverters, a filter is needed between the inverter and the power grid. An inductor usually is used as the simplest solution. However, its large size and significant voltage drop are its disadvantageous. Therefore, an LCL passive filter is used to mitigate current harmonics caused by pulse width modulation. The LCL filters satisfy the standards for grid interconnection with smaller size and cost, comparing with a first-order L filter, particularly in high-power cases [5]. Moreover, due to the weight and size reduction, higher attenuation and cost savings are its additional advantages. Application of LCL filters in grid-connected inverters and PWM rectifiers is discussed in [6-7]. However, the LCL filter

may cause instability of a closed-loop control system, and trigger resonances between the inverter and the grid. To meet harmonic constraints, as defined by standards such as IEEE-519 [8], and IEEE-1547 [9], a lower switching frequency is achieved by harmonic attenuation. Moreover, mathematical models must be defined to design the filter effectively. Several suggested solutions have been proposed including active damping [10], passive damping [11], parameter choice to suppress possible resonances in the filter [12], and state feedback control with state observer [13]. Passive damping method is implemented by inserting a resistor in series with the capacitor in the filter. Although it is considered as a simple, effective, and reliable solution, it causes extra power loss and deteriorates the high-frequency harmonic attenuation ability of the filter.

To overcome these drawbacks, an RC circuit is inserted in parallel with the capacitor of the filter. However, to compare with an undamped filter, the high-frequency harmonic attenuation of the passively damped LCL filter deteriorates. Stability of the LCL filter and current control techniques in the LCL filter design are studied in [14]. In this paper, a phase shifting transformer (PST) is added into the LCL structure. PSTs allow an economical and reliable control of electricity transfer over parallel conduits of electricity. The power flow is controlled by changing the phase-shift angle

between the PST source- and load-side voltages [15]. However, in many cases the angles are controlled by humans. Reference [16] presents a method to control the phase angle by a voltage source converter. Phase shifting transformers are used into passive filter structures to mitigate the harmonic currents [17-18].

This paper shows that harmonic currents and the THD can be adjusted by changing the phase angle of the PST. The objective is to optimize its design for minimizing the total harmonic distortion (THD) of the filtered current. The PST is inserted in series with the capacitor, and changing the phase angle of the PST makes the filter controllable. Adjusting the phase angle of the PST allows significant reduction of the THD. The PST can also be used for harmonic mitigation, with no need for adjustment of the LCL parameters, when the switching frequency of the inverter or load changed.

The paper is organized as follows. The proposed filter is presented in Section II. Filter design procedure is discussed in Section III. Simulation of a case study is described in Section IV, and Section V concludes the considerations.

2. Proposed Filter

Figure 1 illustrates the proposed LCL filter, where L_G is the grid-side inductor, L_I is the inverter side inductor, C_f is a capacitor with a series R_f damping resistor, and V_I and V_G are the inverter and grid voltages. The inverter output current, the capacitor current, and the grid current are denoted by i_I , i_c

and i_G , respectively. The transfer function is $H_{LCL} = i_G / V_I$, where the grid voltage is assumed to be an ideal voltage source capable of damping all the harmonic frequencies. If one sets $V_G = 0$, which implies a current-controlled inverter, the transfer functions of the LCL filter with and without and the phase shifting transformer are defined as (1) and (2) respectively. Figure 2 shows the Bode plots of the PST-LCL filter for different phase angles. The insertion of a phase shifting transformer eliminates the gain spike, smoothing the overall response and rolling-off between -75° and -325° , instead of the -180° at high frequencies.

$$H_{PST-LCL}(s) = \frac{C_f R_f s + 1}{L_I C_f L_G s^3 \angle \Phi + C_f (L_1 + L_2) R_f s^2 + (L_I + L_G) s} \quad (1)$$

$$H_{LCL}(s) = \frac{C_f R_f s + 1}{L_I C_f L_G s^3 + C_f (L_1 + L_2) R_f s^2 + (L_I + L_G) s} \quad (2)$$

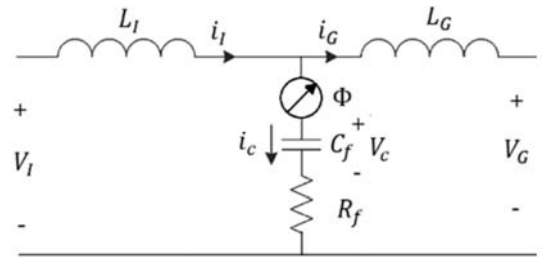


Figure 1. The proposed LCL filter (PST-LCL).

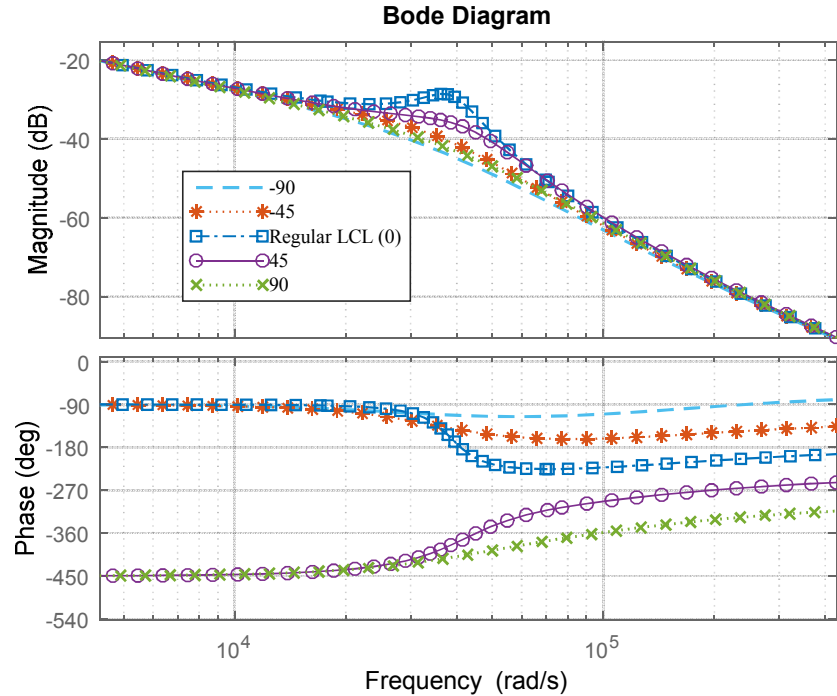


Figure 2. Bode plots of PST-LCL for different phase shifts.

3. Filter Design Procedure

Several specifications to design an LCL filter must be

considered, such as the filter size, switching ripple attenuation [19], maximum current ripple, or phase of the parallel capacitor branch on the filter. Passive or active damping, described in [20] and [21] respectively, are often

placed in series with the capacitor to prevent potential resonances of the capacitor interacting with the grid, and caused by reactive power requirements. Data for the filter design are defined as P_n , rated active power, V_{LL} , line-to-line RMS voltage (inverter output), V_{ph} , phase voltage (inverter output), V_{dc} , DC-link voltage, f_{sw} , switching frequency, f_g , grid frequency, f_{res} , resonance frequency. The base impedance and capacitance are calculated as $Z_b = E_n^2/P_n$ and $C_b = 1/(\omega_g \cdot Z_b)$, where P_n is the rated active power absorbed by the converter, E_n is the line to line rms voltage, and ω_n is the grid frequency. Also, $\omega_{res} = k\omega_{sw}$, where ω_{res} and ω_{sw} are the resonance frequency and switching frequency respectively. Coefficient k represents the ratio of these two frequencies. The maximum power factor variations seen by the grid is assumed to be less than 5%. It means that the base impedance of the system is set to 5% of the base capacitor. A simplified circuit of the inverter shown in Figure 3 is employed for the design of the inverter-side inductor [22]. Equations (3)-(6) apply to three phase inverter [23]. The maximum peak-to-peak current ripple occurs at $m = 0.5$. The maximum per-unit ripple can be assumed between 5% and 25%. Let the ripple be 10% of the rated current, that is, $\Delta I_{L_{max}} = 0.1I_{L_{max}}$. The maximum peak-to-peak current ripple occurs at $m = 0.5$. Therefore, L_I can be derived from (6), where V_{dc} is the dc-link voltage, f_{sw} is the switching frequency, and V_{ph} is the phase voltage. The total inductance should be less than 0.1 p.u., because it may cause a drop of the ac voltage. Otherwise, a higher dc-link voltage would be required, which results in higher switching losses. The expected current ripple should be reduced to 20% by The LCL filter, which limits the ripple value to 2% of the output current [8]. In order to calculate the ripple reduction, the equivalent circuit of LCL filter is initially analyzed while the inverter is considered as a current source for each harmonic frequency. Equation (7) below gives the relation between the harmonic current generated by the inverter and the one injected in the grid (respectively $i_I(h)$ and $i_G(h)$). Simplifying this equation, results in (8) that represents the ripple attenuation factor. Equations (7) and (8) relate the harmonic current generated by the inverter with the one injected to the grid. Where x is the maximum power factor variation seen by the grid and the constant r is the ratio between the inductance at the inverter side and the one at the grid side. Then, L_G can be found from (9) where k_a is the desired attenuation. The transfer function of the filter at a particular resonant frequency can be evaluated by plotting the results for several values of r , depending on the nominal grid impedance [24].

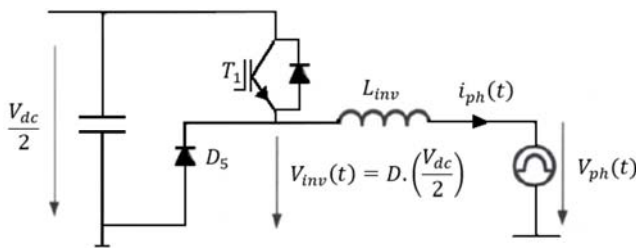


Figure 3. Simplified circuit of an inverter.

$$\Delta I_{L_{max}} = \frac{2V_{dc}}{3L_I} (1 - m) m T_{sw} \quad (3)$$

$$\Delta I_{L_{max}} = \frac{V_{dc}}{6 \cdot f_{sw} \cdot L_I} \quad (4)$$

$$I_{max} = \frac{P_n \sqrt{2}}{3V_{ph}} \quad (5)$$

$$L_I = \frac{V_{dc} \cdot V_{ph}}{2\sqrt{2} \cdot f_{sw} \cdot P_n} \quad (6)$$

$$\frac{i_G(h)}{i_I(h)} \approx \frac{Z_{LC}^2}{|\omega_{res}^2 - \omega_{sw}^2|} \quad (7)$$

$$\frac{i_G(h)}{i_I(h)} = \frac{1}{|1 + r[1 - L_I \cdot C_b \cdot \omega_{sw}^2 \cdot x]|} \quad (8)$$

$$L_G = \frac{\sqrt{\frac{1}{k_a^2} + 1}}{C_f \cdot \omega_{sw}^2} \quad (9)$$

$$f_{res} = \frac{1}{2\pi} \sqrt{\frac{L_I + L_G}{L_I \cdot L_G \cdot C_f}} \quad (10)$$

$$10 \cdot f_g < f_{res} < 0.5 f_{sw} \quad (11)$$

$$R_f = \frac{1}{3\omega_{res} \cdot C_f} \quad (12)$$

For effective attenuation, damping is needed as the transfer function of the filter peaks at certain frequencies, which may increase the ripple [23]. The resonant frequency can be calculated from formula (10) below, and it should be between ten times the grid frequency and a half of the switching frequency as stated in (11) to avoid resonance problems where f_g is the grid frequency, f_{res} is the resonant frequency, and f_{sw} is the switching frequency. To avoid the resonance, a damping resistance is added in series with the capacitor attenuates part of the ripple at the switching frequency. As shown in (12), One third of the impedance of the filter capacitor at the resonant frequency can be taken as the damping resistance R_f [25]. In this section, a PST is inserted in series into the $R_f - C_f$ branch. PSTs have been used to decrease the THD. Low-order harmonics of the input current, the fifth harmonic in particular, are minimized by PSTs in [26]. The input power factor is improved and the THD of the input current is reduced by a PST in [27]. However the large size and weight are considered as its disadvantages. In this paper, the PST is employed to minimize the filter impedance at the switching frequency. Figure 4 shows the simplified circuit of the proposed LCL filter, where I_h is the harmonic current (assumed to be less than 5% of the main current), Φ is the phase-angle difference between I_h and the grid voltage, and θ is the phase angle of the PST. Figure 5 shows phase diagrams for different phase angles at the switching frequency. The goal is to minimize harmonic currents at the switching frequency. Equations (13) and (14) define the phase angle, δ , between V and V_{Grid} caused by the harmonic currents at the switching frequency.

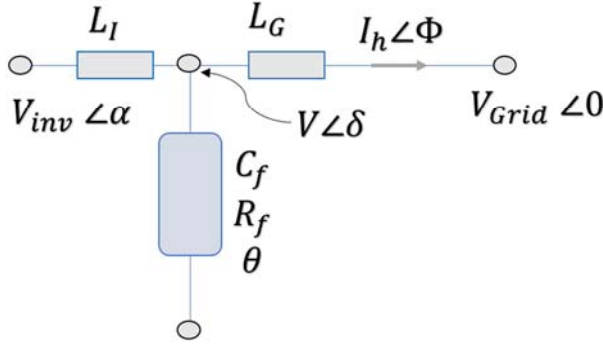


Figure 4. Simplified circuit of the proposed LCL filter.

$$\delta_a = \cot^{-1} \left(\frac{|V_{Grid}|}{\omega_{sw} \cdot L_G \cdot |I_h|} \cdot \sec(\Phi) + \tan(\Phi) \right) \quad (13)$$

$$\delta_b = \cot^{-1} \left(\frac{|V_{Grid}|}{\omega_{sw} \cdot L_G \cdot |I_h|} \cdot \sec(\Phi) - \tan(\Phi) \right) \quad (14)$$

Therefore, the phase angle of the phase shifter transformer, θ , should be optimized. The phase angle of the voltage across the $R_f - C_f$ branch should be the same as the phase angle of the impedance of that branch. Thus, the phase shift θ of the PST should equal the difference of the phase angle of the $C_f - R_f$ branch and the phase angle of V . Consequently, the optimum value of θ is given by

$$\theta = -\tan^{-1} \frac{1}{R_f \cdot C_f \cdot \omega_{sw}} - \cot^{-1} \left(\frac{|V_{Grid}|}{\omega_{sw} \cdot L_G \cdot I_h} \sec(\Phi) \pm \tan(\Phi) \right) \quad (15)$$

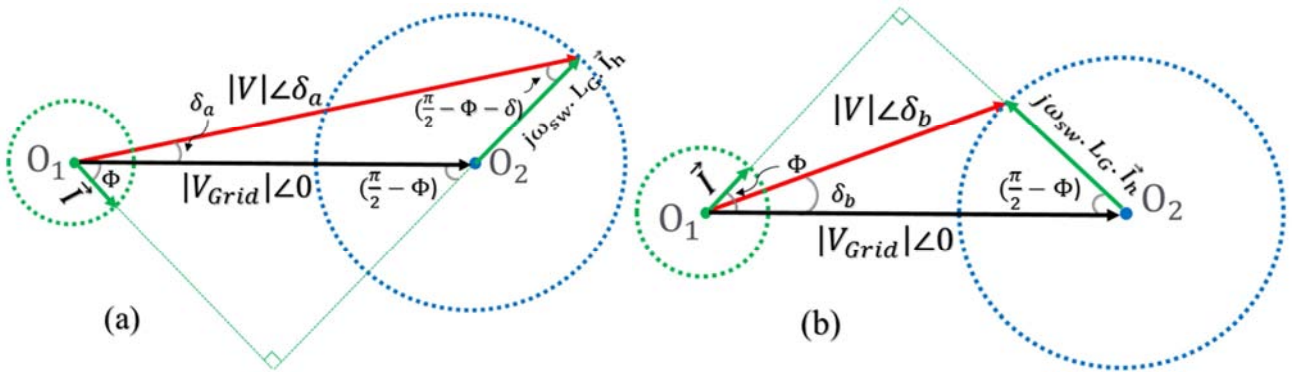


Figure 5. Phasor diagrams of the LCL filter at the switching frequency: (a) lagging current, (b) leading current.

4. Simulation Results

Figure 6 illustrates the case study. The 250-kW SunPower SPR-415E-WHT-D source consists of 88 seven-module strings. Specifications of this PV array are listed in Table 1.

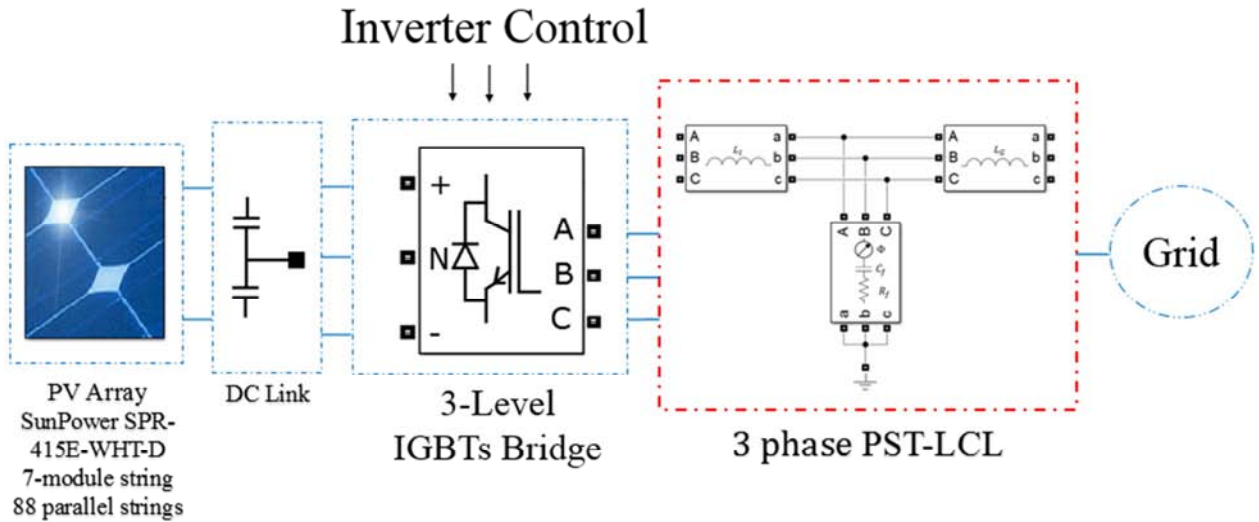


Figure 6. System in the Case Study.

Grid structure in the case study is shown in Figure 7. Table 2 lists specifications of the grid. Two 4-nF stray capacitances are located directly after the PV cells. A DC link stabilizes the DC voltage supplying three VSIs. The bipolar PWM

method is employed. The grid voltage is 249 V. The step-by-step design of the PST-LCL is outlined subsequently. System specifications are: $P_s = P_n = 250$ kW, $E_n = 249$ V, $V_{DC} =$

482 V, $f_{sw} = 1980$ Hz, $\omega_g = 2\pi \cdot 60$ rad/s, $x = 0.05$, and $k_a = 20\%$. Consequently, the base impedance and capacitance are $Z_s = 0.25 \Omega$, and $C_B = 10.6$ mF. Assuming the 10% allowed ripple, Eq. (6) yields $L_I = 1.36$ mH. In order to be within the limit of 5% of the base value of C_B , the maximum capacitor value, C_f , is set to 0.53 mF. For the desired attenuation factor, L_G is found from Eq. (9) to be

0.073 mH. Substituting the calculated parameters of L_I , C_f , and L_G into Eq. (10) gives $f_{res} = 830.49$ Hz, which meets condition (11). Eq. (14) determines the damping resistance $R_f = 0.12 \Omega$. Angle Φ equals 40° , making $\delta_b = 3.47^\circ$. The phase angle of the $C_f - R_f$ branch is -51.64° and, from Eq. (15), the phase angle of the PST is -55.11° .

Table 1. The case study parameters.

PV Array			
Trina Solar TSM-250PA05.08			
Irradiance (W/m^2)	950	Max Power (W)	414.801
Temperature (Deg. C)	43	Cells per module (Ncell)	128
Open Circuit Voltage (V)	85.3	Short-Circuit Current (A)	6.09
Voltage at maximum power point Vmp (V)	72.9	Current at maximum power point Imp (A)	5.69
Light-generated current IL(A)	6.09	Shunt Resistance Rsh (Ohms)	419.8
Diode Ideality Factor	0.9977	Parallel	88
Series Resistance Rs(Ohms)	0.25	Series	7
Dc Link & Stray Capacitance			
Stray Capacitance		DC Link	
Capacitance (F)	4e-9	Capacitance (F)	2.87e-3
		Capacitor initial voltage (V)	425
Inverter Control			
Power (KVA)	250	Frequency (Hz)	60
Primary voltage (Vrms LL)	25 K	DC voltage (V)	480
Secondary voltage (Vrms LL)	249.8	Output limits (V)	[357, 583]
Output increment (V)	0.01	Carrier frequency (Hz)	1980
DC Voltage Controller		Current Regulator	
Proportional gain	1.5	Proportional gain	0.25
Integral gain	387	Integral gain	18

Table 2. The specification of the grid in the case study.

Three Phase Source			
Phase-to-phase rms voltage (KV)	122.4	3-phase short-circuit level at base voltage(MVA)	2500
Base voltage rms (KV)	120	X/R ratio	7
Three Phase Transformer A (Y/ Δ)		Frequency (Hz)	60
Nominal power (MVA)	47		
Winding 1 (V1 rms [120 KV], R1(pu) [0.0003], L1(pu) [0.08])			
Winding 2 (V2 rms [25 KV], R2(pu) [0.0003], L2(pu) [0.08])			
Load A: 250 KW	Load B: 2 MW	Load C: 30 MW and 2 Mvar	
Three Phase Transformer B (Y/ Δ)			
Nominal power (KVA)	250	Frequency (Hz)	60
Winding 1: (V1 rms [25 KV], R1(pu) [0.0012], L1(pu) [0.03])			
Winding 2: (V2 rms [249.8 V], R2(pu) [0.0012], L2(pu) [0.08])			
Feeder A: 14 Km R:0.115(Ohms/km), L: 1.05(mH/km), C: 11.33(nF/km)			
Feeder B: 8 Km R:0.115(Ohms/km), L: 1.05(mH/km), C: 11.33(nF/km)			

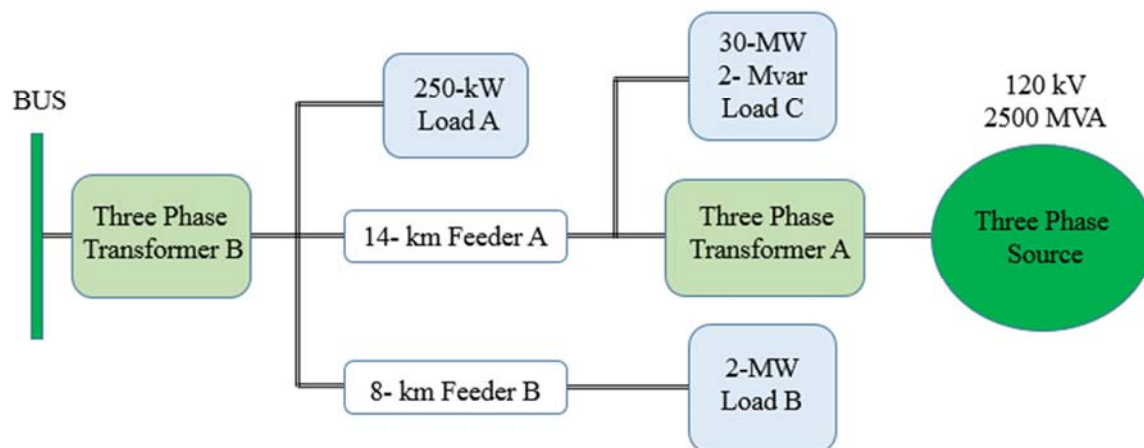


Figure 7. Grid structure in the case study.

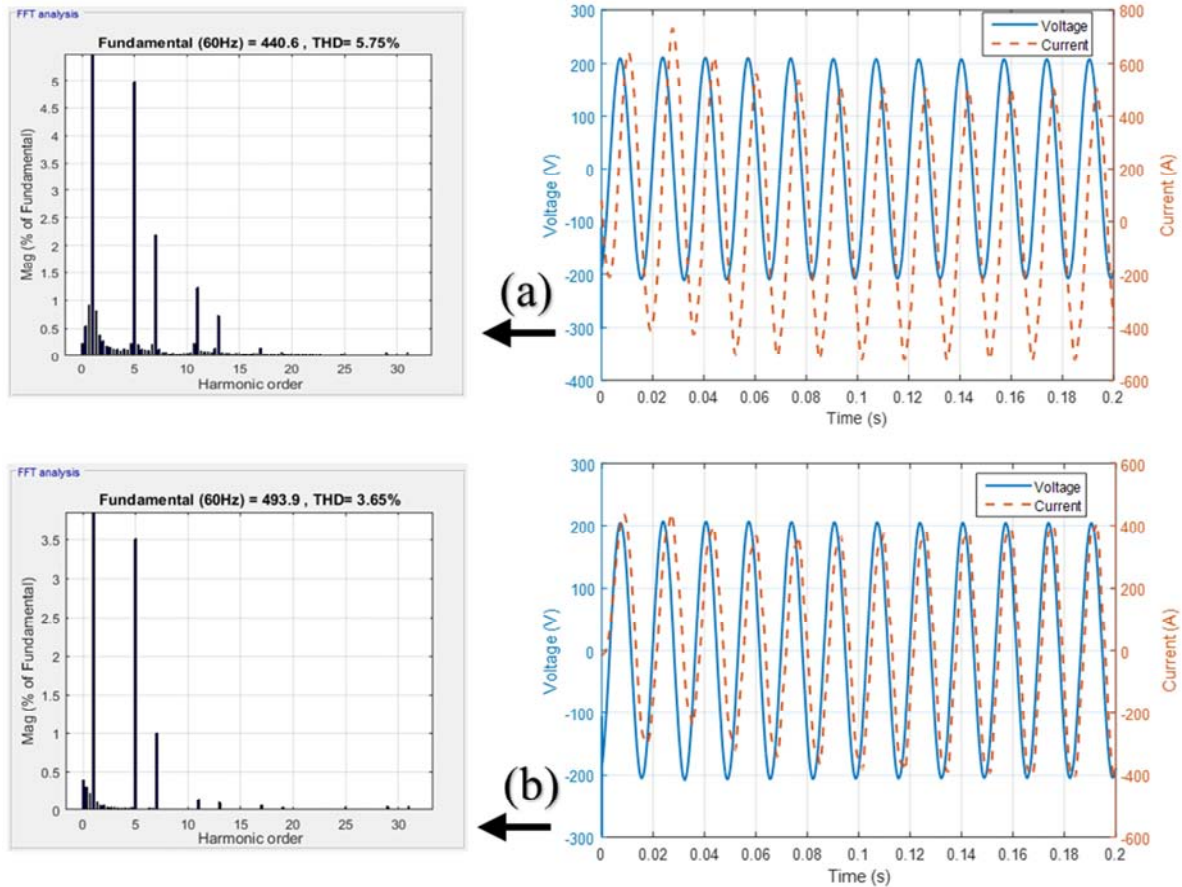


Figure 8. Currents injected into grid – FFTs and waveforms: (a) LCL filter; (b) PST-LCL filter.

Comparative FFT analysis for the LCL and PST-LCL filters is illustrated in Figure 8. The THD in presence of the LCL filter is 5.75%, and it decreases to 3.6% for the PST-LCL one. Figure 8 also shows waveforms of voltage and current in the inverter. It can be observed that, compared to the regular LCL filter, the harmonic currents in presence of the proposed filter has been considerable reduced.

5. Conclusion

A new approach to mitigate harmonic currents in three-phase grid-connected PV sources has been proposed. A phase shifting transformer is added into the regular LCL filter structure which enhances the filter performance. Harmonic currents are greatly reduced improving operation of the involved utility grid. The proposed is fully controllable which allows reducing the current THD to a desired range. The comprehensive design procedure of the PST-LCL filter has been described in detail.

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