

Adequate Tuning of LCL Filter for Robust Performance of Converter Side Current Feedback Control of Grid Connected Modified-Y-Source Inverter

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In the grid-tied PV inverter systems, the design of a proper power conditioning system is an important issue to ensure high-quality power injection to the grid. Among various control methods for a grid-interfacing inverter with LCL filter, converter-side current feedback (CCF) method has been widely used due to its inherent resonance damping feature. Applying the CCF method requires extra attention to the delay effect of the control system. In such systems, the delay narrows stability region of the resonance frequency of the CCF control method, especially, in the presence of wide variations of the grid inductance. Adequate tuning of the LCL filter and consequently, the proper choice of the resonance frequency can remarkably affect the performance of the CCF control. In this paper, a tuning procedure for the LCL filter has been proposed. Mathematical tuning of the Proportional Resonant (PR) controller parameters has also been included to avoid typical trial and error procedures of tuning. Simulation of the overall system also includes solar panels, maximum power point tracking algorithm, Modified-Y-Source inverter, and LCL filter to model the grid-tied PV system with the most possible details. Simulations are carried out in MATLAB/Simulink, and it has been proved that the proposed control system maintains its stability against grid parameters variations.

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I. INTRODUCTION

Recently, PV systems have been used more in power generation due to more cost-effective prices of solar panels and of course environmental issues of the traditional energy resources. The combination of PV cells is intended to provide power to be injected into the grid or used by the consumer [1]. The output maximum power point (MPP) of the PV system might alter by variation of ambient temperature and solar irradiation. A lot of maximum power point tracking (MPPT) algorithms have been proposed in the literature to provide MPP

of the PV cells [2]. The commonly used methods are perturb and observation (P&O) [3] and incremental inductance (INC) [4]. As well as PV arrays, a typical grid-connected PV system consists of buck, boost or buck-boost DC-DC converter, an inverter, and an output filter. The DC-DC stage makes the output voltage level of the PV arrays suitable for inverter, and the filter is responsible for undesired harmonic mitigation [5].

The switching of the inverter bridge is an essential issue in the safety of PV systems. If a fault occurs in the switching process and both switches of one leg of the inverter turn on simultaneously, there might be a catastrophic fault in the system as the output of the typical converter is short circuit [6]. There have been revisions and structure modifications proposed in the literature to overcome the short circuit problem of the converters [7]. The Z-source inverter is capable of performing as a

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converter, and the voltage gain of the converter can be adjusted applying different modulation techniques to reach the desired result [8]. The interesting feature of Z-source inverters in tolerating short circuit has drawn a lot of attention. Numerous structures have been proposed based on Z-source inverters aiming to widen voltage gain range. Impedance source converters are interesting choice in grid-connected PV system applications [9], [10]. The Y-source converter is an impedance source converter with a high voltage gain. The voltage gain of this converter can flexibly alter by varying the shoot-through period [9]. The discontinuous input current of Y-Source converter is an obstacle in renewable power generation applications. To address this issue, the structure of the Y-Source converter has faced modifications, and several converters such as Modified-Y-Source converter [11] and Quasi-Y-Source converter [12] have been proposed. Choosing a suitable converter for the power conversion stage requires considering the voltage gain, continuous or discontinuous input current besides the number of converter elements. In terms of the number of elements, the converter proposed in [11], is better than the Quasi-Y-Source converter [12] utilizing one less element with the same performance [11].

As shown in Fig. 1, the output of the inverter, together with output filter, forms the injected power to the grid. In a grid-tied PV system, there are special standards which have been set to define the quality of the injected power to the grid. According to IEEE std. 1547, the total harmonic distortion of the injected current should be limited by 5% [13]. To fulfill the grid codes, the system must inject a sinusoidal current to the grid. This is realized by applying different output filter configurations. Among all filter types, LCL filters are the most suitable filter types due to their performance in mitigating current harmonics [5]. Designing the LCL filter is an issue that is depended on the power conditioning method. Different control schemes utilizing such filters have been proposed in the literature. Grid Current Feedback (GCF) and Converter Current Feedback (CCF) are the main methods that are adopted to ensure high-quality power [14]. In [15], an active damping approach has been proposed to suppress harmonics. The proposed method in [15] utilizes grid current and capacitor voltage feedback. Capacitor current feedback active damping along with grid current feedback have also been employed in [16]–[18]. In [19], resonance damping is realized by applying a CCF control scheme, which requires one less current sensor in comparison with GCF with capacitor current feedback control.

CCF method has an innate capability of suppressing LCL filter resonance frequency [20]. In this method, only one current sensor is required. The current sensor in the control scheme provides versatile goals, including injected current control and overcurrent protection. Therefore, the device will be protected against fault consequences. Reduced number of current sensors along with less complexity in control and, of course, its innate resonance damping are the factors that made the CCF method

more interesting [20], [21].

Sampling frequency (f_s) value should be considered in the design procedure of the LCL filters [22]. In the GCF method, the resonance frequency (f_{res}) should be in the range of $\frac{f_s}{6} < f_{res} < \frac{f_s}{2}$ to perform in the stable zone while the CCF method requires an LCL filter satisfying $f_{res} < \frac{f_s}{6}$ [22].

Different power conditioning systems for grid-tied inverters have been proposed, including the control scheme design, tuning of controller parameters, and active damping of resonance frequency [20], [23], [24]. As the LCL parameters play an important role in system stability, the first step should be the proper design of the LCL filter for any method. Parameter design of the LCL filter for the GCF method based on stable region and considering delay effect is scrutinized in [25]. In [26], a design procedure has been proposed for LCL with multi-tuned traps to deal with grid inductance variations.

Since distributed power generation is usually used in remote places where there is not a stiff grid, the grid oscillations should be taken into account. Grid inductance variation is a common issue in such grids. The control part of the grid-connected inverter system should be able to maintain system stability against variations in grid inductance. In [27], GCF control has been adopted in a multi-parallel grid-connected inverter system, and the LCL filter parameters are design based on resonance frequency limit defined by the Bode diagram to deal with uncertain grid inductance.

The main contributions of the current paper are as follows.

I. Adequate tuning of LCL filter for Converter Current Control of a grid-tied PV inverter system.

The tuning of the LCL filter parameters for the GCF control method has been investigated in [25]. CCF control method imposes a different stability region for resonance frequency. A tuning procedure is missing for LCL-type grid-connected inverter with the CCF control method. This study proposes a tuning method for the CCF control method considering limitations imposed by the delay effect.

II. Mathematical tuning of the Proportional Resonant (PR) controller parameters for CCF control based on the tuned values of LCL parameters.

PR controller performs well in tracking a sinusoidal reference. The proportional gain (K_p) and resonant gain (K_r) of the PR controller should be tuned according to the intended phase margin (PM) and gain margin (GM) of the system [28], [29]. A step-by-step tuning of the PR controller for GCF control with capacitor current active damping has been proposed in [17], [18]. In this paper, the tuning of the PR controller parameters has been exclusively provided for the CCF control method.

III. A power conditioning system considering for high-quality power injection of grid-connected Modified-Y-Source PV inverter system.

Different power conditioning systems have been proposed to provide high-quality power in the grid-connected PV systems.

In [10], the power conditioning system is designed for grid-connected trans-Z-source PV inverter. In [17], the power conditioning system has been improved by utilizing the LCL filter with GCF control. In this paper, the power conditioning system is designed based on incremental conductance maximum power point tracking (MPPT) algorithm and CCF control method.

In the rest of the paper section 2 is devoted to the tuning of the LCL filter. Principles of Modified-Y-Source converter is investigated in section 3. The tuning of the PR controller parameters is discussed in section 4. The other remaining parts include design examples and simulation results. And the last section concludes the paper.

II. LCL FILTER IN CONVERTER CURRENT CONTROL METHOD

A. LCL Filter in the Grid Tied Inverter Systems

A grid-connected PV inverter system is shown in Fig. 1, which includes PV arrays, an inverter, LCL filter, and the grid. The solar energy is absorbed by PV arrays, and the power is converted to AC form by the inverter. The LCL output filter conditions u_{inv} to be qualified enough to be injected into the grid.

The resonance frequency in the LCL filter is calculated by the following equation:

$$f_{res} = \frac{1}{2\pi} \sqrt{\frac{(L_1 + L_2)}{L_1 L_2 C}} \quad (1)$$

The grid is modeled by an AC voltage source and a series inductance (L_g) in Fig.1. In a stiff grid, L_g has a meager value while a weak grid possesses larger values of L_g , which influences the LCL filter performance by changing the resonance frequency. Thus, the resonance frequency can be calculated using the following equation:

$$f_{res} = \frac{1}{2\pi} \sqrt{\frac{(L_1 + L_2 + L_g)}{L_1 (L_2 + L_g) C}} \quad (2)$$

A grid-connected PV system with a LCL filter is shown in

Fig. 1. Writing Kirchhoff's laws for the LCL filter results in (3):

$$\begin{cases} L_1 \frac{di_{conv}}{dt} + R_1 i_{conv} = u_{inv} - u_c - R_c i_c \\ L_2 \frac{di_g}{dt} + R_2 i_g = u_c - u_g - R_c i_c \\ C \frac{du_c}{dt} = i_c \\ i_{conv} = i_g + i_c \end{cases} \quad (3)$$

where R_1 , R_2 and R_c are equivalent series resistances of filter inductances and capacitor. However, they are assumed zero in the design procedure to model the worst-case, so they are not shown in Fig. 1.

B. CCF Control for Grid-Connected Inverters with LCL Filter

In this paper, the CCF method has been chosen to control the injected power into the grid. As shown in Fig. 2, this control scheme requires one current sensor to sample the converter side current of the LCL filter and one voltage sensor to sample the voltage at the Point of Common Coupling (PCC). The control loop in Fig. 2 includes $G_c(s)$, $G_{d.total}(s)$, K_{inv} , $G_1(s)$, and K_i , representing compensator, delay function, inverter voltage and converter current sensor coefficient, respectively. $G_1(s)$ is the transfer function of converter current (i_{conv}) to the inverter output voltage (u_{inv}). $G_2(s)$ represents the transfer function of the LCL filter capacitor current (i_c) to converter side current (i_{conv}). $G_3(s)$ is the transfer function of the grid current (i_g) to i_c . The abovementioned transfer functions are summarized as below:

$$G_1(s) = \frac{i_{conv}}{u_{inv}} = \frac{(L_2 + L_g)C s^2 + 1}{L_1(L_2 + L_g)C s^3 + (L_1 + L_2 + L_g)s} \quad (4)$$

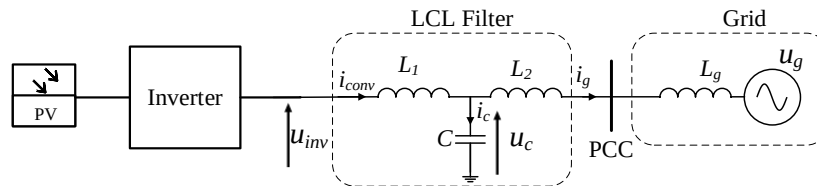


Fig. 1. Grid-tied PV inverter system with LCL filter

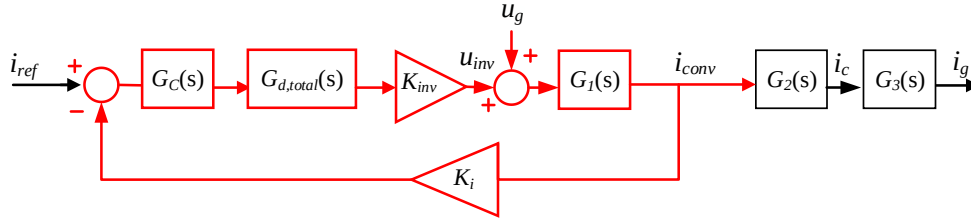


Fig. 2. Single-loop CCF control of the injected current

$$G_2(s) = \frac{i_c}{i_{conv}} = \frac{(L_2 + L_g)C s^2}{(L_2 + L_g)C s^2 + 1} \quad (5)$$

$$G_3(s) = \frac{i_g}{i_c} = \frac{1}{(L_2 + L_g)C s^2} \quad (6)$$

$$G_C(s) = K_p + \frac{2K_r \omega_{PRC} s}{s^2 + 2\omega_{PRC} s + \omega_1^2} \quad (7)$$

If the delay is not considered in the control loop, the CCF control is stable in all frequency ranges of the resonance frequency. Nevertheless, in practical circuits, the effect of delay is not negligible. The total delay is composed of Analog to Digital Conversion (ADC) delay, computational delay of the Digital Signal Processor (DSP), awaiting delay, and Zero-Order-Hold (ZOH) delay [30]. The sum of the first three delays is considered as λT_s . Where T_s is the sampling time and λ is chosen 0.5 or 1 in practical operations [31], [32].

$$G_d(s) = e^{-\lambda s T_s} \quad (8)$$

The ZOH delay is modeled as the following [30]:

$$G_{ZOH}(s) = \frac{1 - e^{-s T_s}}{s T_s} \approx e^{-0.5 s T_s} \quad (9)$$

Considering $\lambda = 0.5$, the total delay can be obtained by:

$$G_{d,total} = G_d(s) \cdot G_{ZOH} = e^{-(\lambda + 0.5)s T_s} = e^{-s T_s} \quad (10)$$

According to Fig. 2, the open-loop transfer function of the CCF control method is calculated as the following:

$$T_{ol}(s) = G_C(s) \cdot G_{d,total} \cdot K_{inv} \cdot G_1(s) \cdot K_i \quad (11)$$

Z transform of the open-loop transfer function is considered to investigate the stability of the system. The open-loop transfer function in Z-domain is obtained as below:

$$T_{ol}(z) = Z[G_C(z)] \cdot \frac{z-1}{z^\lambda} \left[\left(\frac{T_s}{L_1 + L_2} \right) \left(\frac{1}{(z-1)^2} \right) + \left(\frac{L_2}{L_1 \cdot (L_1 + L_2)} \right) \left(\frac{\sin(\omega_{res} T_s)}{z^2 - 2z \cos(\omega_{res} T_s) + 1} \right) \right] \quad (12)$$

Four sets of filter parameters have been considered in Table I to analyze the stable region of the control scheme. In [22], the stable region for LCL filter resonance frequency for $\lambda = 0.5$ is described as $f_{res} < \frac{f_s}{4}$. By applying $\lambda = 0.5$ and sampling frequency of $f_s = 1/T_s = 20$ kHz in the open loop

transfer function of (12) for different sets of filter parameters of Table I, the stability region in the bode diagrams of the open-loop transfer function in Fig. 3 confirm the results of [22]. The pole-zero map in Fig. 4 clarifies that closed-loop poles of the system with filter parameters of set 1 and 2 are within the unit circle. The other two sets possess two poles outside the unit circle, which confirms the instability of the system with resonance frequency higher than $\frac{f_s}{4}$.

 TABLE I
FILTER PARAMETERS

Filter set	Filter parameters	Resonance frequency
Filter 1	$L_1 = 700 \mu\text{H}$, $L_2 = 250 \mu\text{H}$, $C = 15 \mu\text{F}$	$f_1 = 3027$ Hz
Filter 2	$L_1 = 700 \mu\text{H}$, $L_2 = 250 \mu\text{H}$, $C = 8 \mu\text{F}$	$f_2 = 4145$ Hz
Filter 3	$L_1 = 700 \mu\text{H}$, $L_2 = 250 \mu\text{H}$, $C = 3.6 \mu\text{F}$	$f_3 = 6180$ Hz
Filter 4	$L_1 = 700 \mu\text{H}$, $L_2 = 250 \mu\text{H}$, $C = 2.8 \mu\text{F}$	$f_4 = 7007$ Hz

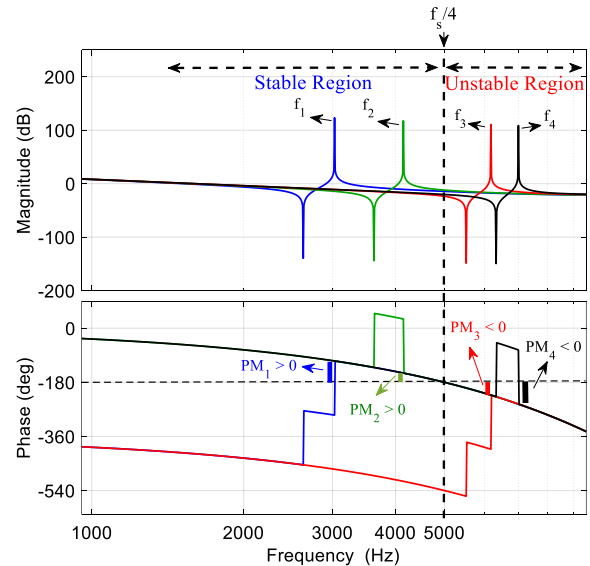


Fig. 3. Bode diagram of the open loop transfer function of the system in different resonance frequencies

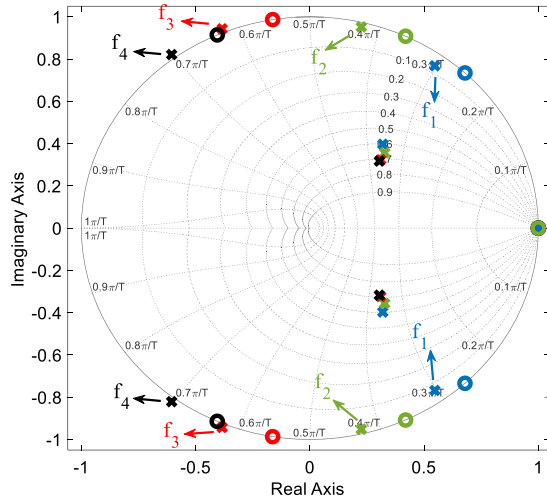


Fig. 4. Pole-Zero map of the closed-loop system in different resonance frequencies

C. Design of LCL Filter parameters for CCF Control

The design of LCL filter parameters depends on system power rating, inverter input voltage, switching frequency, modulation technique, grid voltage, grid frequency, and other application-dependent factors such as size, cost, etc. Different methods have been proposed to help researchers with designing the LCL filter parameter.

In the previous subsection, it has been proved that resonance frequency is a key factor in CCF control system stability. By applying $\lambda = 0.5$, the stable territory for LCL filter performance has been defined as $f_{res} < \frac{f_s}{4}$. As mentioned before, λ is chosen 0.5 or 1 in practical operations. $\lambda = 1$ imposes a stricter limitation on the resonance frequency, and the resonance frequency reduces to $f_{res} < \frac{f_s}{6}$. Therefore, the worst case is considered in the design of the LCL filter for the CCF control method, and λ is considered 1 in the design procedure.

1) Designing the Converter Side Inductance of LCL Filter:

The converter side inductance (L_1) in the LCL filter configuration is responsible for suppressing inverter output current ripple. In [5], the minimum value for L_1 is calculated by applying the following equation:

$$L_{1,\min} = \frac{V_{in}}{2 \cdot k_M \cdot k_r \cdot f_{sw} \cdot I_{conv,rms}} \quad (13)$$

where V_{in} is the input DC voltage of the inverter and $I_{conv,rms}$ is the RMS value of the converter current at the fundamental frequency. In the single-phase grid-connected inverter $I_{conv,rms} = P_n / v_g$, where P_n is the nominal power, v_g is the RMS value of grid voltage, and k_M is depended on the modulation technique. In bipolar SPWM, k_M is considered 1, and in the unipolar SPWM, k_M equals 4. k_r is the ripple coefficient which equals to $k_r = \Delta i_{conv} / I_{conv,rms}$.

The ripple coefficient is usually chosen as a value in the range of 0.2-0.3 [33].

The maximum value of L_1 is depended on the LCL filter capacitor voltage and grid fundamental frequency along with the ratio of the voltage across L_1 (v_{L1}) and capacitor voltage (v_C). This ratio is defined as $k_V = v_{L1} / v_C$. Therefore $L_{1,\max}$ is obtained as the following:

$$L_{1,\max} = \frac{k_V u_C}{2\pi f_g I_{conv,rms}} \quad (14)$$

where f_g represents the grid frequency. Since the grid side ohmic impedance is negligible, the voltage across the capacitor of the LCL filter can be approximated by the grid voltage ($u_C \approx u_g$).

As depicted in (15), the sum of the converter side inductance and the grid side inductance ($L_T = L_1 + L_2$) should be limited by 10% of the total impedance of the system to prevent ac voltage drop. If L_T exceeds 10% limit, then higher dc-link voltage is needed to ensure the stable performance of the control system [34, 35]. Therefore, the lower value of k_V results in the lower value of L_1 . k_V is typically chosen below 0.1.

$$L_{T,\max} = \frac{1}{10} \frac{u_g^2}{2\pi f_g P_n} \quad (15)$$

2) Designing the Capacitor of LCL Filter

The amount of consumed reactive power by the LCL filter capacitor should be limited in the design procedure. Thus, the reactive power coefficient (k_{re}) defines limitation in the capacitor formula as following [5]:

$$C = \frac{k_{re} P_n}{2\pi f_g u_g^2} \quad (16)$$

k_{re} is chosen in the range of 0.03 – 0.05 for proper design [5].

3) Designing the Grid Side Inductance of LCL Filter

In the grid-connected inverter systems with the LCL filter, one of the main aims of the overall control system is to ensure stability during the grid inductance variation. Due to the importance of resonance frequency and grid inductance variation in the CCF control stability, this subsection is dedicated to designing of the grid side inductance for CCF control of a grid-connected inverter system. The upper limitation for resonance frequency in CCF control method has been limited as $f_{res} < \frac{f_s}{6}$, considering $\lambda = 1$ in the delay function. After designing L_1 and C, the minimum value of the L_2 can be obtained as follows:

$$f_{res} = \frac{1}{2\pi} \sqrt{\frac{L_1 + L_2}{L_1 L_2 C}} < \frac{f_s}{6} \quad (17)$$

$$L_2 > \frac{L_1}{\frac{\pi^2 f_s^2 L_1 C}{9} - 1} \quad (18)$$

The lower limit for resonance frequency is set by a critical frequency (f_{cx}). According to the following equation, this lower boundary for resonance frequency can be calculated:

$$f_{res} > f_{cx} \Rightarrow \frac{1}{2\pi} \sqrt{\frac{L_1 + L_2}{L_1 L_2 C}} > f_{cx} \quad (19)$$

Therefore, L_2 in (19) equals to:

$$L_2 < \frac{L_1}{4\pi^2 f_{cx}^2 L_1 C - 1} \quad (20)$$

The denominator of the right side of (20) should be positive to make sense:

$$4\pi^2 f_{cx}^2 L_1 C - 1 > 0 \Rightarrow f_{cx} > \frac{1}{2\pi \sqrt{L_1 C}} \quad (21)$$

After defining L_1 and C , the minimum value for f_{cx} can be calculated using (21). Afterward, the minimum value of f_{res} for stable operation of the control system will be defined applying (19). By replacing f_{cx} with a minimum value of f_{res} , which is resulted from (21) to (20), the maximum value for L_2 will be calculated.

Considering grid inductance variation (L_g), the resonance frequency of the LCL filter is varied according to (2). The sum of L_2 and L_g should be in the range of (18) and (20) to guarantee the stable operation of the CCF control.

4) The Design Sequence:

- ✓ The design procedure is proposed considering $\lambda = 1$. In the beginning, the minimum and maximum values of the converter-side inductance ($L_{1,min}$ & $L_{1,max}$) in the LCL filter are calculated by applying (13) and (14). The LCL filter capacitor value is calculated using (16).
- ✓ Considering $L_1 = L_{1,max}$, and C in (14) and (16), respectively, the minimum and maximum values of the grid-side inductance ($L_{2,min}$ & $L_{2,max}$) is obtained as expressed in (18) and (20).
- ✓ In the next step, the designer can select the value of L_2 in the range of $L_{2,min} < L_2 < L_{2,max}$. The sum of the converter side inductance and the grid side inductance ($L_T = L_1 + L_2$) should be limited by 10% of the total impedance of the system to prevent AC voltage drop [34, 35]. $L_{T,max}$ can be obtained by (15). The sum of $L_{1,max}$ and the selected L_2 value is compared with $L_{T,max}$. If L_T exceeds $L_{T,max}$, the value of the selected L_2 should be decreased. Otherwise, L_T is in the allowed range.

III. PRINCIPLES OF MODIFIED-Y-SOURCE CONVERTER

The emergence of Z-Source converters has yielded different structures to ease power conversion. Modified-Y-Source converter is based on Y-Source converter configuration which uses a three winding coupled inductor with turn ratios of N_1 , N_2 & N_3 . Fig. 5 shows a grid-tied Modified-Y-Source converter. As demonstrated in this figure, there is an additional capacitor (C_1) in comparison with the typical Y-Source converter.

Modified-Y-Source converter, like other Z-Source based converters operates in both shoot-through and non-shoot-through states. Shoot-through states are the intervals that the upper and lower switches of at least one leg of H-bridge module are simultaneously in ON mode to charge the inductances of impedance source converter. At the impedance source inverters, due to the presence of inductances between the input DC source and the H-bridge module, simultaneous conduction of the switches in a certain leg of H-bridge module will not result in the occurrence of a short circuit in the mentioned leg. One of the most important benefits of the impedance source inverters is their capability of eliminating the dead-time, which results in reducing the waveform distortion of the inverter output current. Clearly, non-shoot-through states are the conditions that the impedance source inverter operates in conventional switching states containing active or zero states.

Modified-Y-Source converters are capable of providing a voltage boost in their shoot-through mode. If T , t_{nsh} and t_{sh} represent switching period, none-shoot-through duration, and shoot-through duration ($D_{sh} = t_{sh}/T$), respectively, voltage boost will happen in t_{sh} with a B factor ($V_o = BV_{dc}$). B is a function of the duty cycle of the shoot-through state and the winding factor (K_w), which can be derived from Modified-Y-Source equations. Voltages of capacitors C_1 and C_2 and the boost factor can be expressed as following [11]:

$$\begin{cases} V_{C1} = \frac{(\frac{N_1+N_3}{N_3-N_2}-1)D_{sh}V_{in}}{1-\frac{N_1+N_3}{N_3-N_2}D_{sh}} = \frac{(K_w-1)D_{sh}V_{in}}{1-K_wD_{sh}} \\ V_{C2} = \frac{(1-D_{sh})}{1-K_wD_{sh}}V_{in} \\ B = \frac{1}{1-\frac{N_1+N_3}{N_3-N_2}D_{sh}} = \frac{1}{1-K_wD_{sh}} \end{cases} \quad (22)$$

where D_{sh} is a value between 0 and a maximum value which is equal to $1/K_w$ as the following:

$$0 \leq D_{sh} < D_{sh,max} = 1/K_w \quad (23)$$

There are five shoot-through states along with two active and two zero states in the possible performance modes in

Modified-Y-Source inverter. Therefore, according to Fig. 5 and Table II different control signals can lead to different switching modes.

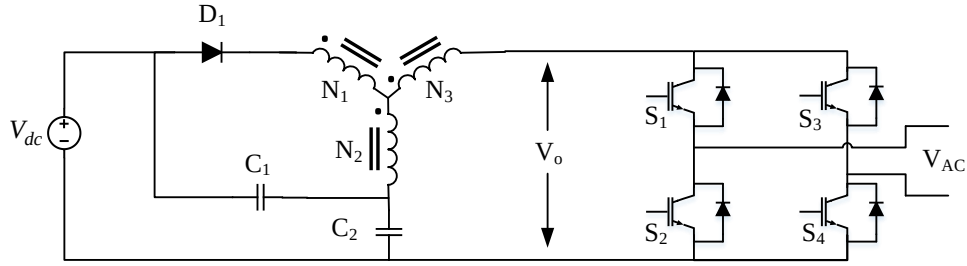


Fig. 5. Grid-connected DC-DC Modified-Y-Source Converter

TABLE II

FILTER PARAMETERS SWITCHING MODES IN A SINGLE-PHASE MODIFIED-Y-SOURCE INVERTER

Switching modes	S ₁	S ₂	S ₃	S ₄
Shoot-through	1	1	0	0
Shoot-through	1	1	1	0
Shoot-through	0	1	1	1
Shoot-through	1	0	1	1
Shoot-through	1	1	1	1
Active	1	0	0	1
Active	0	1	1	0
Zero	0	1	0	1
Zero	1	0	1	0

Winding factor, K_W , is a function of winding turn ratios and defines the maximum shoot-through time, can possess different values according to Table III.

TABLE II

SWITCHING MODES IN A SINGLE-PHASE MODIFIED-Y-SOURCE INVERTER [11]

$K_W = \frac{N_1 + N_3}{N_3 - N_2}$	$D_{sh, max}$	Boost Factor	$N_1 : N_2 : N_3$
3	1/3	$(1 - 3D_{sh})^{-1}$	(1:1:2), (4:2:5), (3:1:3)
4	1/4	$(1 - 4D_{sh})^{-1}$	(2:1:2), (5:1:3), (8:1:4)
5	1/5	$(1 - 5D_{sh})^{-1}$	(2:2:3), (3:1:2), (7:1:3)

IV. POWER INJECTION CONTROL IN THE GRID-CONNECTED SYSTEM

Different aspects should be considered to ensure high-quality power injection to the system. As shown in Fig. 6, the power conditioning system consists of MPPT, PLL, PR

compensator, and PWM. These different components should work together both in the converter level and the control system stage to meet IEEE1547 std. in power delivery.

A. MPPT Technique

PV arrays behave in a non-linear manner due to their Voltage-Current curve. This behavior is an issue in tracking their maximum power point so that researchers have proposed different algorithms to make MPPT possible in different weather conditions (illumination and temperature change). In this paper INC method [4] has been chosen to be used to track the maximum power point. The control scheme is responsible for MPPT and injecting high-quality power into the grid. These challenging tasks are realized by controlling the shoot-through mode, as depicted in Fig. 6. The output of the applied MPPT is $U_{sc} = 1 - D_{sh}$ that controls the shoot-through mode of the switching modulation, and then considering V_{ref} as the other input, the PWM sends appropriate signals to the switches.

B. Control of Injected current to the grid

As depicted in Fig. 6 the applied control scheme is converter-side current feedback. LCL filter, along with the control scheme, are responsible for controlling total harmonic distortion of the injected current up to IEEE1547 standard limits. The current sensor, which is placed on the converter side, samples converter current. This sampled current value is subtracted from the reference current. The phase of i_{ref} is defined by the phase locked loop (PLL) block to ensure unity power factor.

A Proportional Resonance (PR) compensator is applied for controlling the error signal of the reference current and the converter side current.

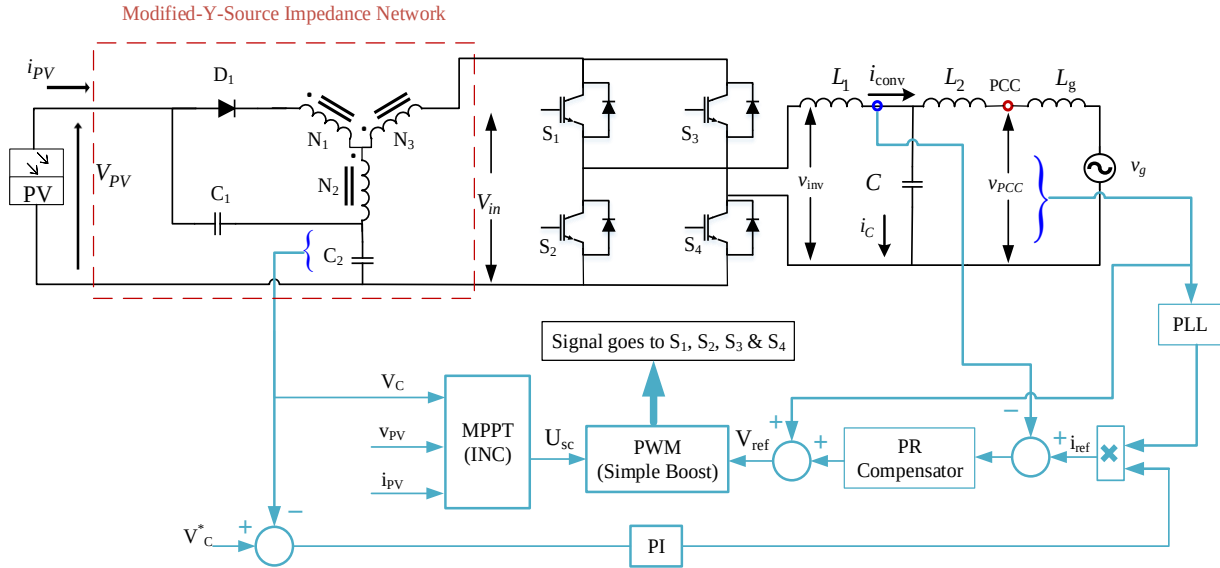


Fig. 6. Overall power and control scheme of PV based Modified-Y-Source grid-tied inverter with LCL filter

The harmonic contents of the grid voltage may also lead to distortions in the grid current. The feedforward of the grid voltage can be helpful in mitigating the harmonic distortions of grid current. Therefore, the feedforward of PCC voltage is also considered for better performance of the control system.

Since the output filter is of a high order, accurate tuning of the PR controller parameters might be challenging due to the complexity of high order systems. A mathematic straightforward method is proposed for tuning the PR controller in the next section.

C. Tuning the PR controller Parameters

After the proper design of LCL filter parameters in section 2-3, accurate tuning of the PR controller will lead to the best possible control performance of CCF control. The PR controller parameters can be tuned considering the open-loop transfer function of the CCF control system of Fig. 2 as the following:

$$T_{ol}(s) = G_C(s) \cdot K_{inv} \cdot G_1(s) \cdot K_i \quad (24)$$

In the following subsections, a step-by-step procedure of tuning the PR controller parameters is elaborated.

1) Proportional Gain (K_p) of the PR Controller

Selecting the crossover frequency (f_c) is the starting point for the design procedure. In [14], it has been suggested that $f_c = 0.3 f_{res}$. Equation (24) can be rewritten as following [25]:

$$T_{ol} = K_{inv} \cdot K_i \cdot \left(K_p + \frac{2K_r \omega_{PRC} s}{s^2 + 2\omega_{PRC} s + \omega_1^2} \right) \times \left(\frac{(L_2 + L_g) C s^2 + 1}{L_1(L_2 + L_g) C s^3 + (L_1 + L_2 + L_g) s} \right) \quad (25)$$

In an ideal grid, the grid side inductance (L_g) is neglected. In the following equations, the grid is assumed ideal. Since $f_c \gg f_1$, (7) can be simplified as follows:

$$G_C(j\omega_c) \approx K_p \quad (26)$$

In the next step, considering $f_c < 0.1 f_{sw}$, the open-loop transfer function at $f = f_c$ is simplified by assuming $C = 0$ (the capacitor effect can be overlooked in low frequencies). The open-loop Transfer function can be rewritten as following [23]:

$$|T(j2\pi f_c)| \approx \left| \frac{K_i K_{inv} K_p}{(L_1 + L_2) j2\pi f_c} \right| \quad (27)$$

The amplitude of system frequency response is zero at crossover frequency, which implies $G(j2\pi f_c) = 1$ in (28). Therefore K_p is calculated using (29):

$$20 \log |G(j2\pi f_c)| \approx 20 \log \left| \frac{K_i K_{inv} K_p}{(L_1 + L_2) j2\pi f_c} \right| = 0 \quad (28)$$

$$K_p = \frac{2\pi f_c (L_1 + L_2)}{K_i K_{inv}} \quad (29)$$

2) Resonant Gain (K_r) of the PR Controller

The PR compensator transfer function at fundamental frequency can be rewritten as:

$$G_{PR}(j\omega_1) = K_p + \frac{2K_r \omega_{PRC}(j\omega_1)}{(j\omega_1)^2 + 2\omega_{PRC}(j\omega_1) + \omega_1^2} = K_p + K_r \quad (30)$$

According to (25) and (30), it can be concluded that:

$$|T(s)|_{s=j\omega_1} \approx \left| \frac{K_{gi}K_{inv}(K_p + K_r)}{(L_1 + L_2)(j\omega_1)} \right| \quad (31)$$

(31) yields to (32) and (33).

$$\begin{cases} T_{f1} = 20 \log |T(j\omega_1)| \\ T_{f1} = 20 \log \left| \frac{K_i K_{inv}(K_p + K_r)}{(L_1 + L_2)(j\omega_1)} \right| \end{cases} \quad (32)$$

Therefore, the lower limit for K_r is:

$$K_r = \frac{2\pi(L_1 + L_2)}{K_i K_{inv}} (10^{\frac{T_{f1}}{20}} f_1 - f_c) \quad (33)$$

The upper limit for K_r is obtained by setting (29) and $f = f_c$ in (25) and assuming the intended phase margin of the system be PM (usually $40^\circ \sim 65^\circ$):

$$\angle T(j\omega_c) = PM - \pi \quad (34)$$

V. DESIGN EXAMPLE

A. LCL Filter Parameters Design Example

The system specifications of the single-phase full-bridge grid-connected inverter are summarized in Table IV. Using (13) and considering $k_M = 4$, $k_r = 0.2$, and $I_{conv,rms} = 21.81$ A, the minimum value for converter side inductance of the LCL filter is calculated as $L_{1,min} = 243 \mu H$. $L_{1,max} = 668 \mu H$ is obtained by applying $k_v = 0.05$ in (14). By defining the lower and upper boundaries of converter side inductance, L_1 is chosen to be $700 \mu H$. $k_{re} = 0.03$ in (16) yields to $C = 15.7 \mu F$.

TABLE IV
SYSTEM PARAMETERS

Parameter	Value
Rated Power (P_n)	2400 W
Grid Voltage (RMS)	110 V
Grid frequency	60 Hz
Switching frequency	10 kHz
Sampling Time (T_s)	1/20000 s

For stable operation of the CCF control, $L_{2,min}$ is obtained using (18), which leads to $L_{2,min} = 80 \mu H$ and $f_{cx,min}$ is defined as 1607 Hz in (21). Applying $f_{cx} = 1650$ Hz in (20) will result in $L_{2,max} = 13.13$ mH. Considering $L_2 = 250 \mu H$ with the values of $L_1 = 700 \mu H$ and $C = 14 \mu F$ will lead to the resonance frequency of 3134 Hz, which is less than $f_s/6 = 3333$ Hz.

B. PR Controller Parameters Design Example

The control parameters of the PR controller can be designed with the help of the abovementioned systematic procedure. According to system parameters' values in Table IV and assuming $f_c = 940$ in (29), K_p is calculated as 0.82. The

amplitude of system frequency response in the fundamental frequency, T_{f1} , is a parameter that is considered a value above 40 dB [17]. Therefore, by applying (9) and $T_{f1} = 45$ dB in (16), the minimum value for the resonance gain will be 8.5. The maximum value for tuning K_r is 635. As K_r increases toward the maximum value, Phase Margin of the system decreases. By decreasing the value of K_r to the minimum designed value ($K_{r,min}$), the crossover frequency is decreased. The delay block is also applied in the control loop to simulate a practical system in which delay might affect the stability of the system.

VI. SIMULATION RESULTS

Simulations are conducted based on parameters of Tables IV and V. As depicted in Fig. 7, by setting the PR controller parameters ($K_p = 0.82$ and $K_r = 70$), infinite gain margin, and PM = 73.8° are obtained.

To analyze the credibility of the proposed design procedure of parameters, the control system is supposed to be in a weak grid, where the grid impedance is considerably inductive. So (L_g) is increased from $L_g = 100 \mu H$, with steps of $200 \mu H$, to $L_g = 1100 \mu H$ to model a very weak grid. The more the value of L_g increases, the less resonance frequency decreases. As demonstrated in Fig. 8, the system maintains its stability in a highly inductive grid.

TABLE V
CONVERTER AND FILTER PARAMETERS

Transformer turn ratio $N_1:N_2:N_3$	30:30:60
Winding factor K	3
DC blocking capacitors	$C_1 = 900 \mu F$, $C_2 = 1800 \mu F$
Filter inverter side inductance (L_1)	700 μH
Filter capacitance	14 μF
Filter grid side inductance (L_2)	250 μH
K_i	0.04

The main goal of a power conditioning system is to inject high-quality power to the grid. Fig. 9 depicts that the grid voltage and grid current are at the same phase yielding to the unity power factor of the injected power. Fig. 10 shows the THD of the grid current. Considering a single current sensor control for the power conditioning system, THD = 1.61% is a satisfactory value for suppressing undesired harmonic contents of the grid current.

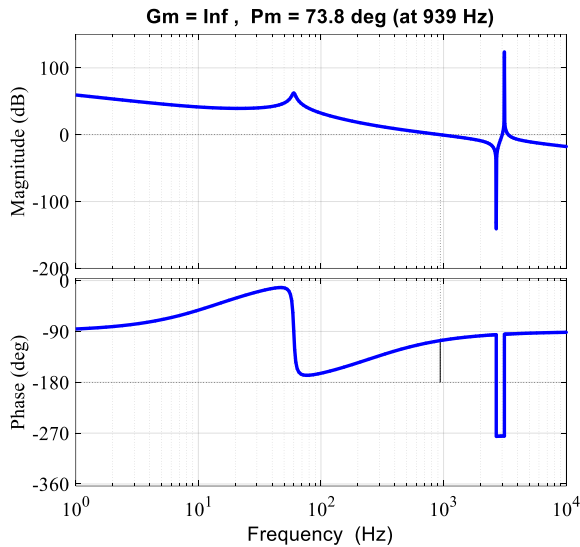


Fig. 7. Bode diagram of open-loop transfer function of the system

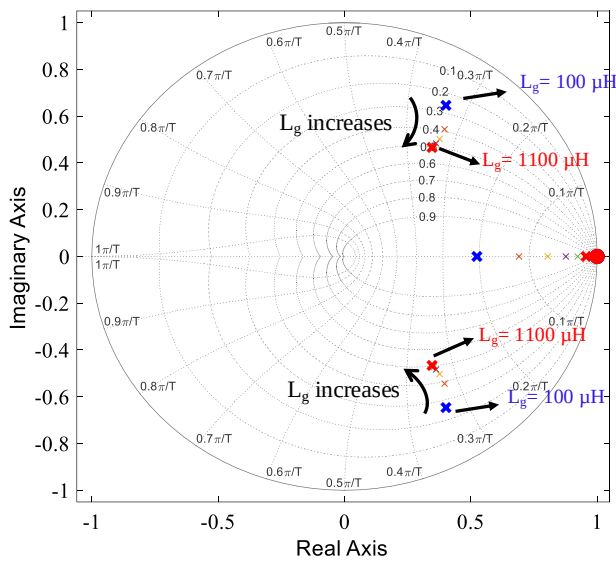


Fig. 8. Pole-Zero map of the system by varying L_g

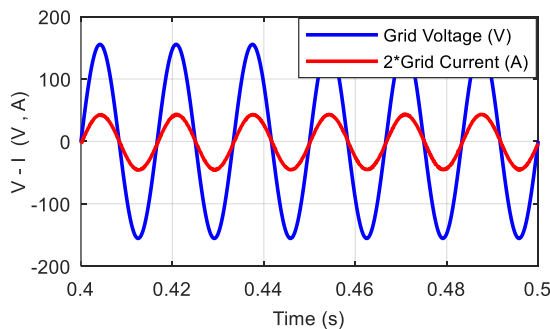


Fig. 9. Grid voltage and injected current to the grid

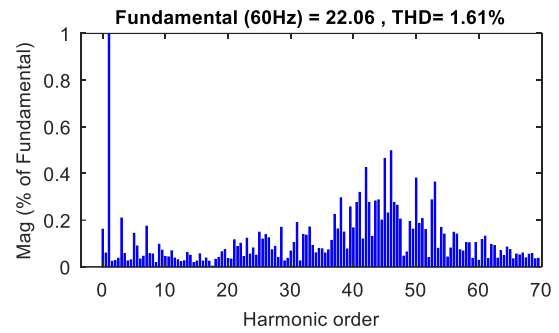


Fig. 10. Total Harmonic Distortion of the injected current to the grid

PV based power generations are more common in places with a weak electric grid. In such areas, the grid is exposed to oscillations. Other elements like irradiance variations, are effective are also effective in PV power generations. Therefore, these circumstances should be considered in the design stage. To model these issues in a weak grid, L_g is increased by 100% of L_2 (Fig. 11), and in the other scenario, the grid side inductance (L_g) is assumed to be 1.1mH (Fig. 12). In both cases, the control system has a satisfactory performance.

Table VI summarizes the specifications of the solar panel. In weak grids, the grid voltage is exposed to oscillation. In Figs. 13 and 14, the voltage is decreased by 0.2 p.u. and increased by 0.1 p.u., respectively. In both cases, the grid current and the grid voltage have the same phase, and the grid current waveform remains sinusoidal.

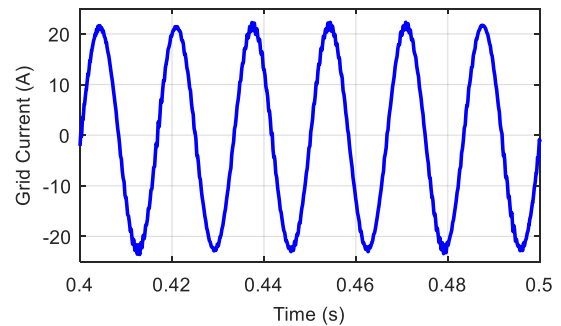


Fig. 11. L_g is increased by 100% between $t = 0.41s$ to $t = 0.49s$

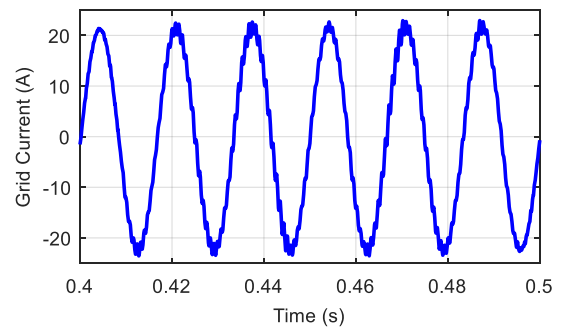
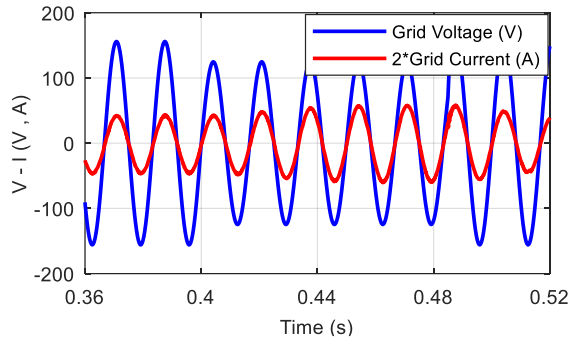
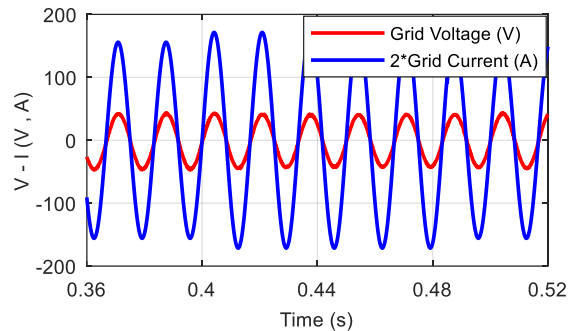


Fig. 12. L_g assumed to be 1.1 mH between $t = 0.41s$ to $t = 0.49s$

TABLE VIPARAMETERS OF THE SOLAR PANEL AT 25° C AND SOLAR IRRADIANCE OF 1000 W/m²

Parameter	Value
I_{mp}	30.44 A
V_{mp}	78.9 V
P_{max}	2400 W
I_{sc}	32.84 A
V_{oc}	98.7 V
N_s	3
N_p	4

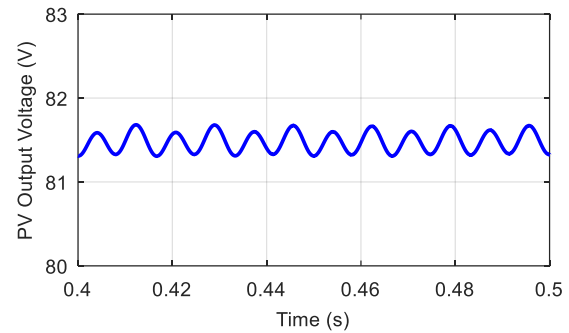
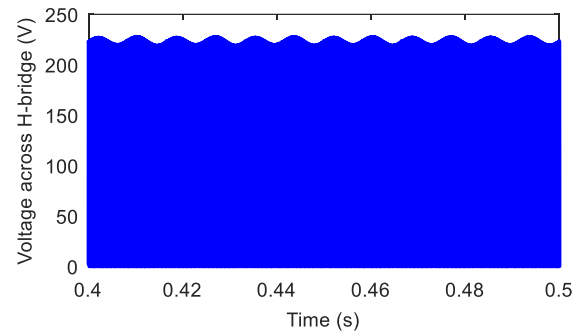
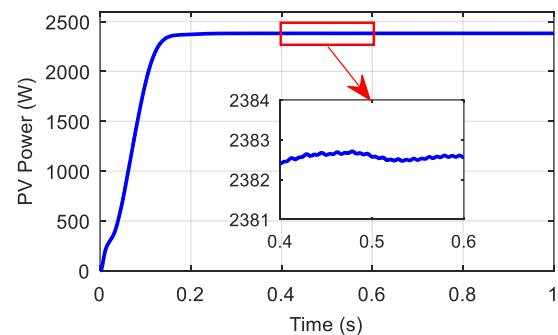
**Fig. 13.** Grid voltage is decreased by 0.2 p.u. between $t = 0.4$ s to $t = 0.48$ s**Fig. 14.** Grid voltage is increased by 0.1 p.u. between $t = 0.4$ s to $t = 0.48$ s

As demonstrated in Fig. 15, the output voltage of the PV array has a considerably low ripple. The voltage across the DC side of the H-bridge module is also depicted in Fig. 16. According to this figure, the Modified-Y-Source converter, boosts the PV output voltage by about 2.6 times using the parameters of Table V.

In conventional grid-connected systems, a two-stage power electronic interface which consists of a DC-DC converter and a DC-AC inverter has been used as the interface power conversion unit. In two-stage power conversion, a DC-link composed of a capacitor splits the two sides, and the voltage across the DC-link capacitor is a constant DC voltage. However, in single-stage interface units, the power is directly converted using a DC-AC inverter. In this paper, the single-stage power conversion unit has been applied. Fig. 16 depicts

the output voltage of the Modified-Y-Source converter (the input of the H-Bridge inverter) to verify the voltage boost capability of Modified-Y-Source converter. The voltage in Fig. 16 is not a DC-link voltage, and it contains severe ripple due to shoot-through states of Modified-Y-Source converter. At the impedance source inverters, the severe voltage variations across the H-bridge module will not affect to AC output voltage because the shoot-through states occur at the intervals that the instantaneous output voltage of the inverter is equal to zero.

The power curve depicted in Fig. 17 proves constant power generation by the control system with the least possible ripple. A passing cloud or other shading elements might influence the power obtained from the solar panels.

**Fig. 15.** PV output voltage between $t = 0.4$ s to $t = 0.5$ s**Fig. 16.** Voltage across the DC side of H-bridge module between $t = 0.4$ s to $t = 0.5$ s**Fig. 17.** Generated power by PV system

Figures 18 and 19 depict a situation where the irradiance is decreased from 1000 W/m² to 800 W/m² between $t =$

0.4 s to $t = 0.48$ s. It can be deduced that, the MPPT unit successfully tracks the maximum power point during the irradiation change, and grid current remains sinusoidal. Moreover, the P-V characteristic of the photovoltaic array for different irradiation (1000 W/m^2 and 800 W/m^2) according to the datasheet of PV array is depicted in Fig. 20.

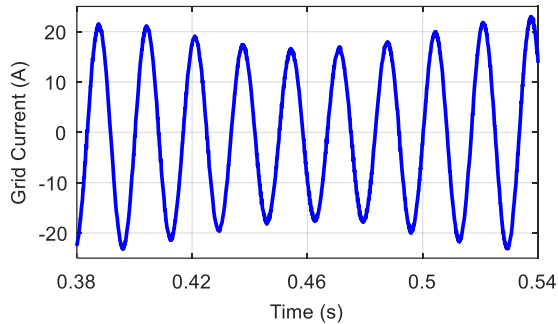


Fig. 18. Grid current when irradiance decreases from 1000 W/m^2 to 800 W/m^2 between $t = 0.4$ s to $t = 0.48$ s

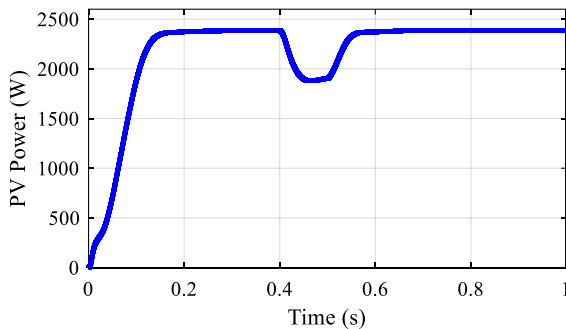


Fig. 19. PV output power when the irradiance is decreased from

1000 W/m^2 to 800 W/m^2 between $t = 0.4$ s to $t = 0.48$ s

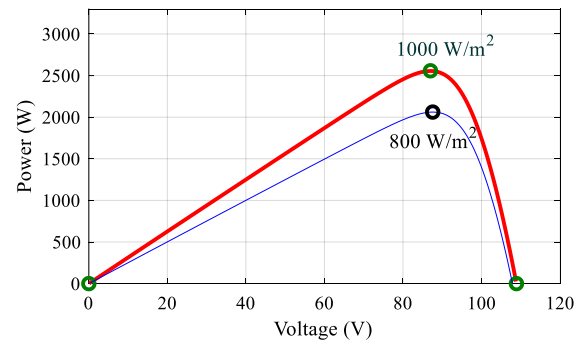


Fig. 20. P-V curve of the photovoltaic array

At the end of simulation results, a comparison between presented research with similar ones is considered. The quality of the proposed design procedure of LCL filter parameters and the power conditioning system in LCL-type grid-connected inverters can be evaluated in terms of the THD of the injected current into the grid as well as current sensor count. Similar works in the design of LCL filter parameters or power conditioning system are compared in Table VII.

TABLE VII
COMPARISON BETWEEN SIMILAR WORK AND THE CURRENT WORK

Compared parameters	Grid-connected voltage source converter (VSC) [26]	Grid-connected PV system in [10]	Grid-connected boost inverter [36]	Grid-connected PV inverter [17]	Proposed system
Converter type	VSC	Trans-Z-Source	Boost inverter	Trans-Z-Source	Modified-Y-Source
Output filter	LCL with multi-tuned traps filter	L	L	LCL	LCL
Controller	PR	PR	State feedback control	PR	PR
Number of current sensors	2	1	1	2	1
THD	2.5%	2.9%	4.52%	1.24%	1.61%

VII. CONCLUSION

In this paper, the LCL filter parameters are designed properly to have improved performance in the Converter Current Control of the grid-tied PV inverter. Applying a power conditioning system to the overall system, which links the

shoot-through period of the Modified-Y-Source inverter to the injected current control part, has made it possible to inject power with high quality. The PR controller in the single-loop control scheme is applied to track sinusoidal reference in the best possible way. Tuning of the PR controller parameters along with the proper design of the LCL filter parameters

successfully suppressed undesired current harmonics even in weak grids, where grid side inductance is exposed to variation all the time. Simulation results of the pole-zero map as well as the Simulink environment in different conditions verify the credibility of the proposed control procedure in maintaining system stability against extreme variations of grid inductance.

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