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Active Harmonic Compensation and Stability Improvement in High Power Grid-Connected Inverters Using Unified Power Quality Conditioner

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ABSTRACT

Objective: Multifunctional features of grid-connected inverters can be used for harmonic compensation of local load voltage and grid-injected current. But, in high-power grid-connected inverters, there is a challenge due to low switching frequency. On the other hand, simultaneous compensation of local load voltage and grid-injected current harmonics is an important issue in grid-connected inverters. Using a Unified Power Quality Conditioner (UPQC) at the Point of Common Coupling (PPC), an improved active harmonic compensation method is proposed which is appropriate for high-power low-frequency grid-connected inverters. The UPQC operates as a combination of a negative shunt virtual admittance and a negative series virtual impedance at the PCC. It suppresses the disturbances caused by local load variation and grid impedance change. Using a low-power, high-frequency UPQC, local load voltage and grid-injected current harmonics up to higher-order components are simultaneously compensated despite grid impedance changes and nonlinear local load variations. The control system is designed according to the impedance-based stability criterion to ensure the system's stability. The theoretical results are validated using different case study simulations in MATLAB/Simulink software.

Nomenclature

Y_T	Equivalent admittance at the PCC
Y_o	Output admittance of the grid-connected inverter
Y_l	Variable admittance of the local load
Z_g	The grid impedance
U_g	The grid voltage
U_{PCC}	PCC voltage
U_l	Nonlinear local load voltage
I_g	The grid-injected current
i_{o_h}	Harmonic components of the inverter output current
U_{PCC_h}	Harmonic components of the PCC voltage
i_I	The output current of the inverter
I_s	The current source in the grid-connected inverter model

I. Introduction

Along with the widespread utilization of renewable energy sources in power systems, large changes have occurred at transmission and distribution levels. Nowadays, the harmonic components generated by nonlinear loads and inverter-based distributed generation (DG) units, highly threaten the quality of grid-injected current.

A. Research Motivation

To alleviate problems caused by variations in nonlinear local load and grid impedance, appropriate power quality compensators should be designed [1]. The grid-connected inverter in inverter-based DG units should be designed and controlled in such a way that the grid-injected current harmonics are minimized. The IEEE 1547 standard determines the permissible limits for harmonic contents of the PCC voltage and grid-injected current [2]. If the THD of the PCC voltage increases over its permissible limit, then the THD of the grid-injected current increases, and consequently, the protective devices operate and the DG unit disconnects from the grid. The main challenge is related to the effect of changes in nonlinear local load and grid impedance on the increasing harmonic components and harmonic instability of the DG unit. On the other hand, the grid impedance variation causes resonant frequency variation. In this condition, the grid-connected inverter is stable if the ratio of the equivalent grid impedance to the inverter output impedance satisfies the Nyquist stability criterion [3].

B. Literature Review

Several control methods were recently proposed for suppressing harmonic disturbances at the PCC. Some of these methods are such as the grid voltage feedforward methods [4-5], H^{∞} repetitive controller [6-7], using auxiliary inverters [8-10], virtual impedance-based control techniques [11-21], and methods that shape the inverter output impedance [22-25]. Also, to solve the resonant problem, the capacitor current feedback was used in an active damping control loop to improve the system stability [26-27].

In [8], the authors used an auxiliary inverter containing a series LC filter. The parameter adjustment of the series LC filter increases the main inverter output impedance and consequently suppresses the harmonic components at the PCC. In [9] two shunt inverters were used to compensate for the grid-injected current and the PCC voltage harmonics, simultaneously. The local load voltage harmonics were reduced by the first inverter and the current harmonics caused by the nonlinear local load were reduced by the second one. Meanwhile, a parallel virtual admittance can be applied to the output of the inverter to compensate for the grid-injected current harmonics. Also, a virtual impedance can be applied in series to eliminate the voltage harmonics at the PCC [10-14]. Harmonic reference voltages were generated according to the harmonic virtual inductance and resistance in negative and positive sequences [15-17]. In reference [18], using an adaptive virtual impedance, the harmonic components of the load voltage were suppressed. The load voltage distortion was used to determine this virtual impedance. Another strategy for harmonic suppression is inverter output impedance shaping. If the equivalent output impedance of a current-controlled grid-connected inverter is set to infinite, the grid-injected current harmonics are eliminated. On the other hand, if the equivalent series impedance at the PCC is set to zero, the grid voltage harmonics do not affect the grid-injected current [19-23]. To reduce both the PCC voltage and grid-injected current harmonics, a hybrid virtual impedance method was proposed in [24]. In [25], the application of a series active power filter was introduced to compensate for the PCC voltage harmonics in case of grid impedance change. However, the nonlinear local load was not considered in this work. In previous works, the harmonic compensation method was usually designed based on the unchanged virtual admittance. However, the nonlinear local load and the grid impedance may be practically varied for several reasons. These variations cause variable current and voltage harmonics at the PCC. So, the value of applied virtual admittance should be adaptively changed.

This problem was investigated in our previous work where a single-phase low-power grid-connected inverter was considered [28]. In this reference, a variable virtual admittance was suggested, and it was implemented using the multifunctional capability of the grid-connected inverter. The switching frequency of the grid-connected inverter was high, and therefore the high-frequency components could be compensated. Also, in this reference, a series active power filter was used to compensate for the grid impedance effect. But, in high-power three-phase grid-connected inverters, the switching frequency is low, and therefore they cannot be used for harmonic compensation at high-frequencies.

In [31] a new adaptive harmonic voltage control method was developed for voltage-controlled DG inverters, which neither uses any PI regulators nor imposes stability issues associated with nonideal implementation of infinite gains of PR controllers. The developed control logic can be used for both grid-connected and islanding modes and is capable of accurate output voltage tracking by exploiting the property of an optimal switching vector controller.

In [32], a new strategy was designed based on multiple resonant current controllers and active damping feedback to improve the ability of the PV inverter to suppress harmonics under the grid background harmonic conditions. A passive impedance network was constructed using the impedance model of a PV inverter and then by analyzing the series resonance of the impedance network, the amplification coefficient of the harmonic voltage at the point of common coupling (PCC) was obtained. To solve the problem that the output harmonics exceed the standard limits under the background harmonic condition of the weak grid, a harmonic mitigation control strategy was implemented.

An improved fuzzy-controlled back-to-back electric spring was proposed in [33] that was used to improve power quality in microgrids. The proposed structure was controlled to operate simultaneously as an electric spring and shunt active power filter. That means, the series part of the back-to-back electric spring regulates the critical load voltage and applies the demand-side management and the parallel part operates as a shunt active power filter capable of power factor correction and current harmonic compensation.

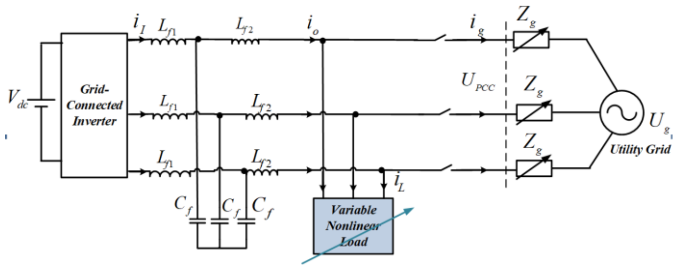


Fig. 1. Grid-connected inverter system with a variable nonlinear load that connected to a weak grid

C. The Necessity of the Research

In real conditions, the grid impedance and nonlinear local load may be changed. So, it is needed to propose a method that improves the power quality and stability in this condition. Also, in high-power grid-connected inverters, because of low switching frequency, the grid-connected inverter cannot be used for implementation of the virtual admittance concept to improve the power quality and stability. Therefore, this paper aims to propose a new UPQC-based structure for grid-connected inverters to compensate for the voltage and current harmonics and improve the system's stability in this condition.

D. Novelty and Main Contribution

In this paper, a low-frequency three-phase grid-connected inverter with an LCL filter has been considered under local load variation and weak grid conditions as shown in Fig. 1.

To implement a variable virtual admittance in parallel with the inverter and a variable virtual impedance in series with the grid, the application of a low-power high-frequency UPQC at the PCC is proposed. The proposed UPQC-based structure is capable of compensating the grid-injected current and PCC voltage harmonics in case of local load and grid impedance variations. The UPQC is the combination of a shunt and a series inverter which are connected in the DC-link. The shunt inverter is modeled as a harmonic current source and the series inverter is modeled as a harmonic voltage source. The series inverter injects a series voltage to compensate for the variable grid impedance effect and the shunt inverter injects a shunt current to compensate for the variable nonlinear local load effect. With the proposed UPQC-based structure, it is possible to suppress both the PCC voltage and grid-injected current harmonics and improve the system's stability.

Using the proposed structure in a low-frequency grid-connected inverter, the robustness of the system against the nonlinear local load and grid-impedance variations is maintained. The results of the proposed method were compared with the results without using the proposed structure.

E. Organization and Structure

The rest of the paper is organized as follows. The principle of the proposed harmonic cancellation method is described in section 2. In section 3, the control block diagram of the proposed system is introduced and then the simulation results are presented in section 4. Finally, concluding remarks are given in section 5.

II. Principle of the Proposed Harmonic Cancellation Method

The equivalent circuit of a grid-connected inverter is shown in Fig. 2. The grid-connected inverter is modeled as a current source (I_s) in parallel with the inverter output admittance (Y_o). In this model, I_g is the grid-injected current, U_l is the nonlinear local load voltage which is equal to the PCC voltage (U_{PCC}) and finally, U_g is the grid voltage. It is assumed that the nonlinear local load is variable. The grid impedance (Z_g) includes the transformer leakage impedance, the line impedance, and the output impedance of other inverters connected to the PCC. The grid impedance is variable because the grid structure is changed and the number of grid-connected inverters may be varied. If the local load is modeled as a variable admittance (Y_l), then equation (1) expresses the equivalent admittance at the PCC.

$$Y_T = Y_o + Y_l \tag{1}$$

According to Fig. 2, U_l and I_g can be written as (2) and (3), respectively. These equations show that the local load and grid impedance changes cause variable harmonics at the PCC. To solve this problem, the effects of the local load and grid impedance variations should be canceled.

$$U_l = I_s\left(\frac{Z_g * \frac{1}{Y_T}}{\frac{1}{Y_T} + Z_g}\right) + U_g\left(\frac{\frac{1}{Y_T}}{\frac{1}{Y_T} + Z_g}\right) \tag{2}$$

$$I_g = I_s\left(\frac{\frac{1}{Y_T}}{\frac{1}{Y_T} + Z_g}\right) - U_g\left(\frac{1}{\frac{1}{Y_T} + Z_g}\right) \tag{3}$$

A. Cancel Out the Grid Impedance Effect

An LCL filter has a resonant frequency that is varied due to the grid impedance variation. So, the harmonic stability analysis is important in weak grids. To overcome this challenge, an effective active damping method is necessary to guarantee the system's stability when connected to a weak grid. As shown in Fig. 3, the effect of grid impedance can be canceled out by applying $-Z_g$ as a series virtual impedance. This is done using a low-power series active power filter. According to (2) and (3), using the proposed cancellation method, U_l and I_g can be written as (4) and (5), respectively.

$$\lim_{Z_g \to 0} U_l = U_g \tag{4}$$

$$\lim_{Z_g \to 0} I_g = I_s - U_g Y_T \tag{5}$$

Equation (4) shows that the grid impedance effect on local load voltage harmonics is eliminated. Also, equation (5) shows that the grid impedance effect on grid-injected current harmonics is well eliminated. However, the local load variation effect on harmonic components of the grid-injected current is not canceled out due to Y_T presence.

B. Nonlinear Local Load Effect Cancellation

As shown in Fig. 2, the equivalent admittance at the PCC (Y_T) includes the parallel connection of inverter output admittance and variable local load admittance. To cancel out the effect of local load variation, an adaptive virtual admittance concept can be realized

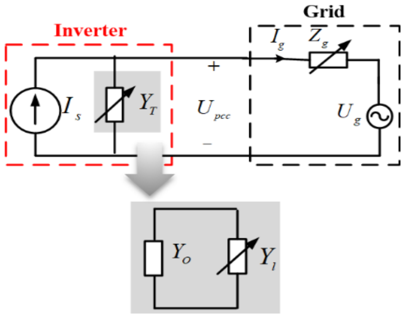


Fig. 2. Equivalent model of an inverter with a variable local load connected to a weak grid

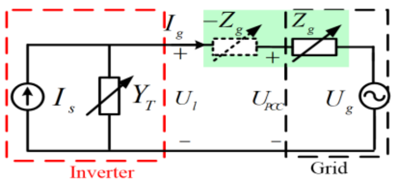


Fig. 3. Grid impedance cancellation method using series virtual impedance concept

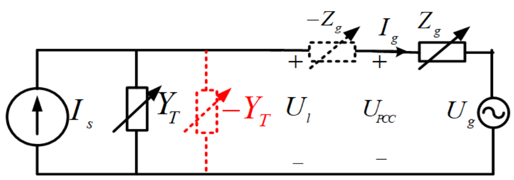


Fig. 4. Equivalent circuit model of a grid-connected inverter uses variable virtual admittance and variable virtual impedance concepts

using a shunt active power filter, as shown in Fig. 4. In this figure, the equivalent circuit model of a grid-connected inverter is shown which uses the proposed virtual admittance and virtual impedance concepts. Using the proposed active cancellation method, the undesired effects of nonlinear local load and grid impedance are removed. Therefore, the local load voltage (U_l) and grid-injected current (I_g) can be written as follows:

$$\lim_{\substack{Z_g \to 0 \\ Y_T \to 0}} U_l = U_g \tag{6}$$

$$\lim_{\substack{Z_g \to 0 \\ Y_T \to 0}} I_g = I_s \tag{7}$$

Regarding (6) and (7), by elimination of the nonlinear local load and grid impedance effects, the local load voltage (U_l) and grid-injected current (I_g) are exactly similar to the grid voltage and current reference of the DG unit, respectively. Following the grid-injected current harmonic compensation, the PCC voltage (U_{PCC}) harmonic components are reduced.

The harmonic stability of the proposed structure can be analyzed using the impedance-based stability criterion [29]. The bandwidth of the Phase Lock Loop (PLL) is usually less than 50 Hz, which is

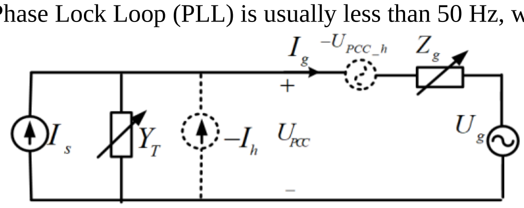


Fig. 5. Equivalent circuit model of a grid-connected inverter with the proposed UPQC-based structure

much less than the bandwidth of the internal current control loop (usually more than 1 kHz). So, the PLL effect is not considered in the output impedance of the grid-connected inverter. To check the impedance-based stability criterion, equation (3) is rewritten as follows:

$$I_g = (I_s - Y_T U_g) * \left(\frac{1}{1+\frac{Z_g}{\frac{1}{Y_T}}} \right) \tag{8}$$

According to equation (8), a grid-connected inverter will be stable if the ratio of the grid impedance to the inverter output impedance including nonlinear local load ($Z_g \;/(\frac{1}{Y_T})$ or $Z_g * Y_T$), satisfies the Nyquist criterion. Because of grid impedance cancellation using a series active power filter and nonlinear local load cancellation using a shunt active power filter, $Z_g * Y_T$ becomes zero and satisfies the Nyquist criterion. So, the grid-connected inverter will be stable in all conditions.

C. Principle Of UPQC

The active cancellation method which is proposed in previous sections is implemented using a low-power, high-frequency UPQC at the PCC. As shown in Fig. 5, the UPQC is operated as a shunt current source and a series voltage source, simultaneously.

The shunt current source injects the harmonic components of the inverter output current in the opposite sign. So, the harmonic components of the grid-injected current are canceled out at the PCC. Also, the series voltage source injects the PCC voltage harmonics in the opposite sign. So, the harmonic components of the local load voltage are canceled out at the PCC.

III. Control Block Diagram of the Proposed System

An LCL-filtered grid-connected inverter that uses the proposed UPQC-based structure is shown in Fig. 6. The grid impedance and the nonlinear local load are assumed to be variable. A PR controller is used to control the grid-connected inverter. The grid-injected current (i_g), the output current of the inverter (i_I) and the PCC voltage (U_{PCC}) are inputs of the controller. The control block diagram of the grid-connected inverter is shown in Fig. 7.

The *dq* reference currents are assumed to be i_d=100 and i_q=0. A PR controller with a transfer function of $G_{PR\_f}(s) = k_p + \sum_{i=1,5,7} \frac{2k_i\omega_c s}{s^2+2\omega_c s+\omega_0{}^2}$ is designed to minimize the steady-state error of the grid-injected current (i_g) in *αβ* reference frame. The pole-zero cancellation method is used to design the controller parameters. The shunt and series inverters in the UPQC structure are used to produce the harmonic components of the inverter output current (i_{o_h}) and PCC voltage (U_{PCC_h}), respectively. Low-power, high-frequency inverters in the UPQC structure are capable of harmonic compensation up to higher orders. The control block diagram of the series inverter is shown in Fig. 8. To eliminate the grid impedance variation effect, the harmonic content of the PCC voltage (U_{PCC}) is extracted using the *dq* reference frame and is inversely injected into the system using the series inverter. $G_{d2}(s)$ is the delay transfer function. Also, the control block diagram of the shunt inverter is

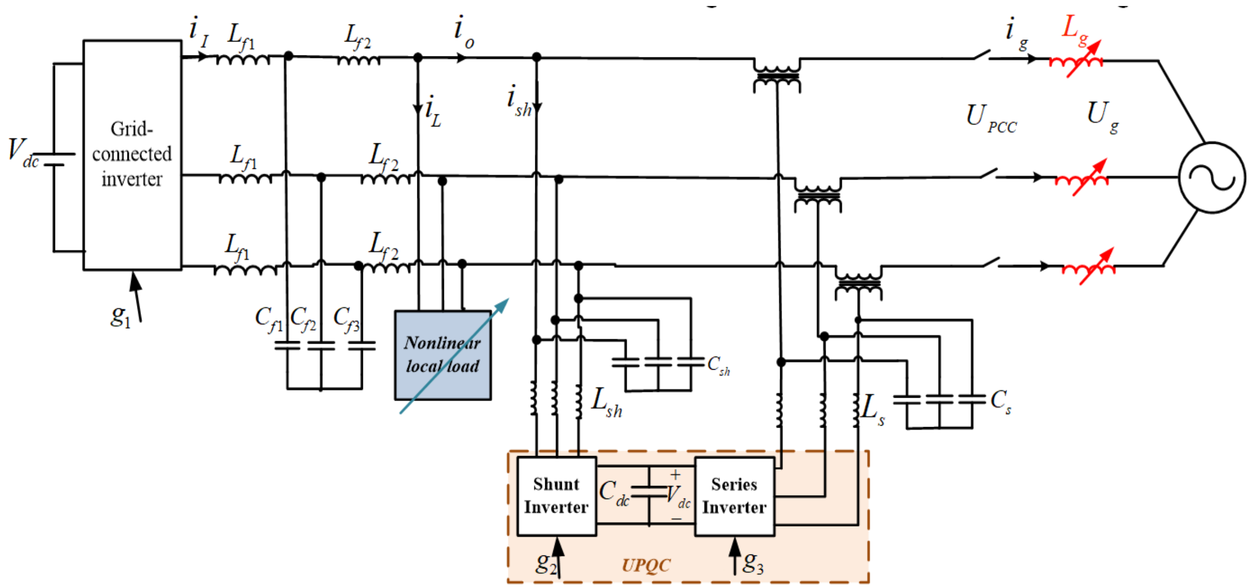


Fig. 6. An LCL-filtered grid-connected inverter that uses the proposed UPQC-based structure

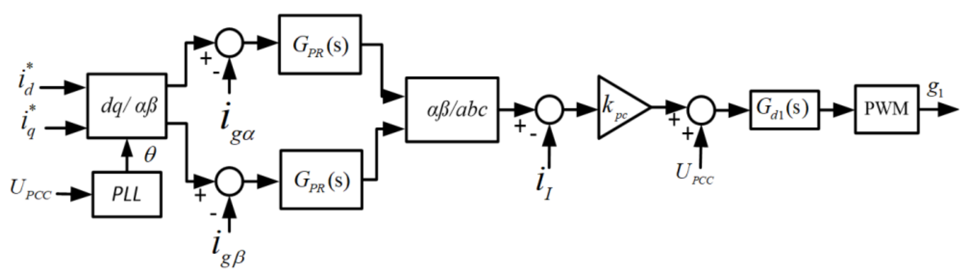


Fig. 7. Control block diagram of the grid-connected inverter

shown in Fig. 9. This control system is designed to eliminate the current harmonics and regulate the DC-link voltage. The grid-injected current harmonics are extracted using the *dq* reference frame and are used to generate the reference current. Therefore, the shunt inverter compensates for the harmonic components of the grid-injected current at the PCC. To regulate the DC-link voltage, a proportional-integral (PI) controller is used in a voltage feedback control loop. The output of the PI controller is added to the *d* component of the reference current. The shunt inverter is controlled using the hysteresis current control method. High-frequency switching harmonics in the outputs of the shunt and series inverters are damped using LC filters.

IV. Simulation Results

In this section, a 380V/50Hz three-phase grid-connected inverter that uses the proposed UPQC-based structure, as shown in Fig. 6, is simulated using MATLAB/Simulink software. Also, the control block diagram of the main grid-connected inverter is modeled based on Fig. 7, and the control block diagram of the series and shunt inverters in the UPQC structure are modeled based on Fig. 8 and Fig. 9. The simulation parameters are given in Table 1.

The grid inductance is changed between 0 and 7.2mH and a variable local load is connected to the inverter output. It is validated that the proposed structure has an excellent performance in case of local load and grid impedance changes.

The harmonic compensation capability of the proposed structure is evaluated in case the grid inductance is equal to 7.2mH and the nonlinear load2 (shown in Fig. 10(b)) is connected. Without using the UPQC-based structure, the PCC voltage and the grid-injected current waveforms and their THDs are shown in Fig. 11(a). As shown in this figure, the voltage and current THDs have exceeded the standard limits.

Also, the simulation results in the case of using the proposed UPQC-based structure are shown in Fig. 11(b). As shown in this figure, the voltage and current THDs are satisfied by the IEEE 1547 standard under the worst conditions.

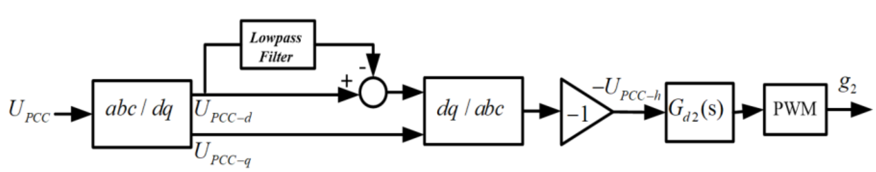


Fig. 8. Control block diagram of the series inverter

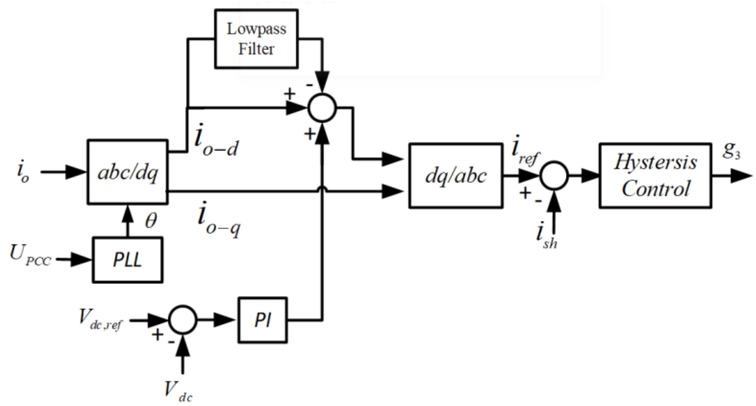


Fig. 9. Control block diagram of the shunt inverter

TABLE 1
SIMULATION PARAMETERS

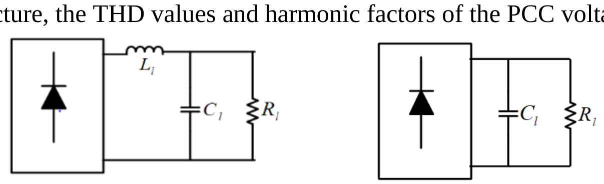
Symbol	Parameter	Value	Symbol	Parameter	Value
V_{dc1}	DC-link voltage of the grid-connected inverter	750V	L_g	Grid inductance	0~7.2mH
L_{f1}	Inverter side inductance	5.6mH	V_{dc2}	DC-link voltage of the UPQC	90V
L_{f2}	Grid side inductance	2μH	L_l	Nonlinear load inductance	300mH
C_f	Filter capacitance	45μF	R_l	Nonlinear load resistance	20Ω
L_{sh}	LC filter inductance of the shunt inverter	2mH	C_l	Nonlinear load capacitance	300μF
C_{sh}	LC filter capacitance of the shunt inverter	0.5μF	K_p	Proportional gain of the PR controller	0.2
L_s	LC filter inductance of the series inverter	3.5mH	K_i	Harmonic frequency resonant gains of the PR controller	9,5,4
C_s	LC filter capacitance of the series inverter	0.5μF	ω_c	The cut-off frequency of the PR controller	4Hz
C_{dc}	DC-link capacitance of the UPQC	4×2000μF	K_{pc}	Controller gain	2.5
U_{in}	The line-to-line voltage at PCC	380V	f_s	Switching frequency	2500Hz

A. *Local Load Variation*

At First, a three-phase linear resistive load (R=55Ω) is connected to the output of the inverter. At t=0.1s, the resistive load is replaced with a nonlinear load (load1 as shown in Fig. 10(a)). Also, at t=0.2s, load1 is replaced with another nonlinear load (load2 as shown in Fig. 10(b)). The load current is shown in Fig. 12. The PCC voltage (U_{PCC}) and the grid-injected current (i_g) without and with using the proposed UPQC structure are shown in Figs. 13 and 14, respectively.

Without using the proposed UPQC structure, the THD of the PCC voltage and THD of the grid-injected current have exceeded the permissible limits.

However, as shown in Fig.14, when using the proposed UPQC structure, the THD values and harmonic factors of the PCC voltage and grid-injected current are acceptable according to the limits determined by the IEEE 1547 standard.



(a) (b)

Fig. 10. Nonlinear loads (a) load1 (b) load2

B. *Grid Impedance Variation*

In this subsection, the grid impedance variation effect on the performance of a grid-connected inverter with a nonlinear local load (load2) is investigated. Firstly, the grid impedance is equal to 4mH. At t=0.1s, it is increased to 7.2mH, and at t=0.2s it is decreased to 5mH. Waveforms and frequency spectrums of U_{PCC} and i_g, without and with using the proposed UPQC structure are shown in Figs. 15 and 16, respectively. As shown in Fig. 15 the THD of the grid-injected current is decreased when the grid inductance is increased. This is because the grid inductance acts as a first-order lowpass filter. As the grid inductance increases, the crossover frequency of this filter decreases, and consequently, the THD of the grid-injected current decreases. It is observed that without using the proposed UPQC structure, THDs of U_{PCC} and i_g and the harmonic factors of the individual voltage and current components are beyond the permissible limits. But, when the proposed UPQC structure is used, the THD values and the harmonic factors of the individual voltage and current components are satisfied by the IEEE 1547 standard.

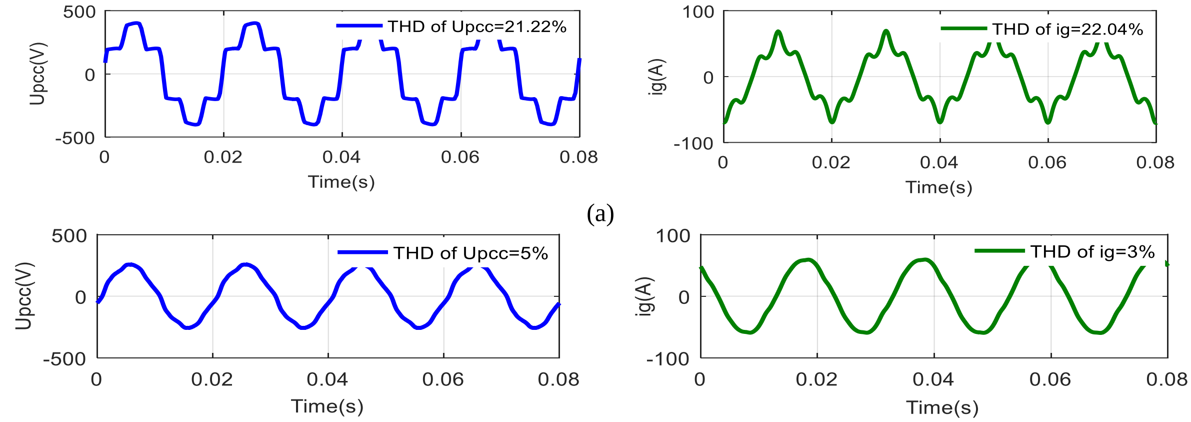


Fig. 11. PCC voltage (U_{PCC}) and grid-injected current (i_g) (a) without UPQC-based structure (b) with UPQC-based structure

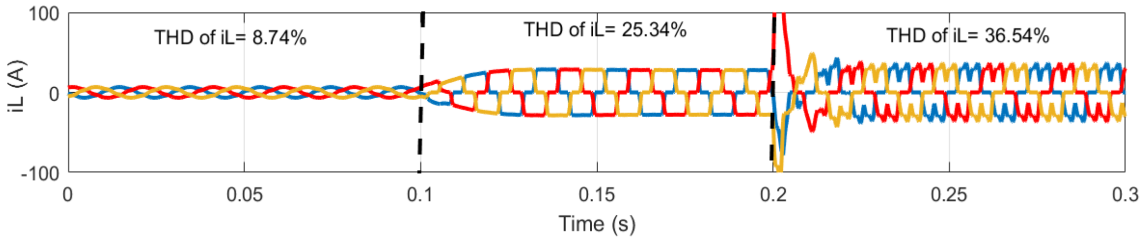


Fig. 12. Local load current in case of load variation

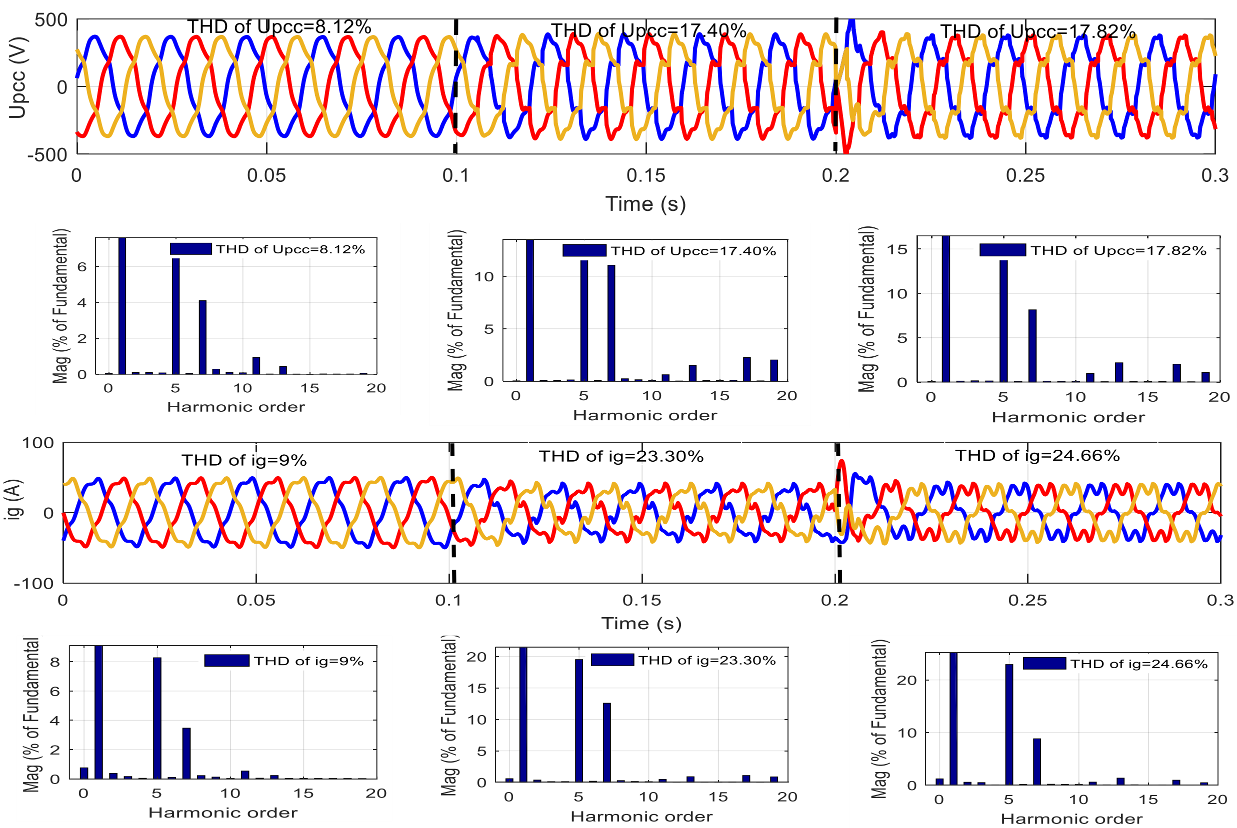


Fig. 13 PCC voltage ($\mathbf{U_{pcc}}$) and grid-injected current ($\mathbf{i_g}$) in case of variable local load without UPQC-based structure

C. Performance analysis considering the grid voltage distortion

The grid voltage distortion deteriorates the performance of grid-connected inverters. According to the IEEE 519 standard [30], the maximum permissible limit of the grid voltage THD is 8%. In this study, the THD of the distorted grid voltage is considered 7%. According to previous works, the grid voltage harmonic rejection can be done using the grid voltage or the capacitor voltage of the

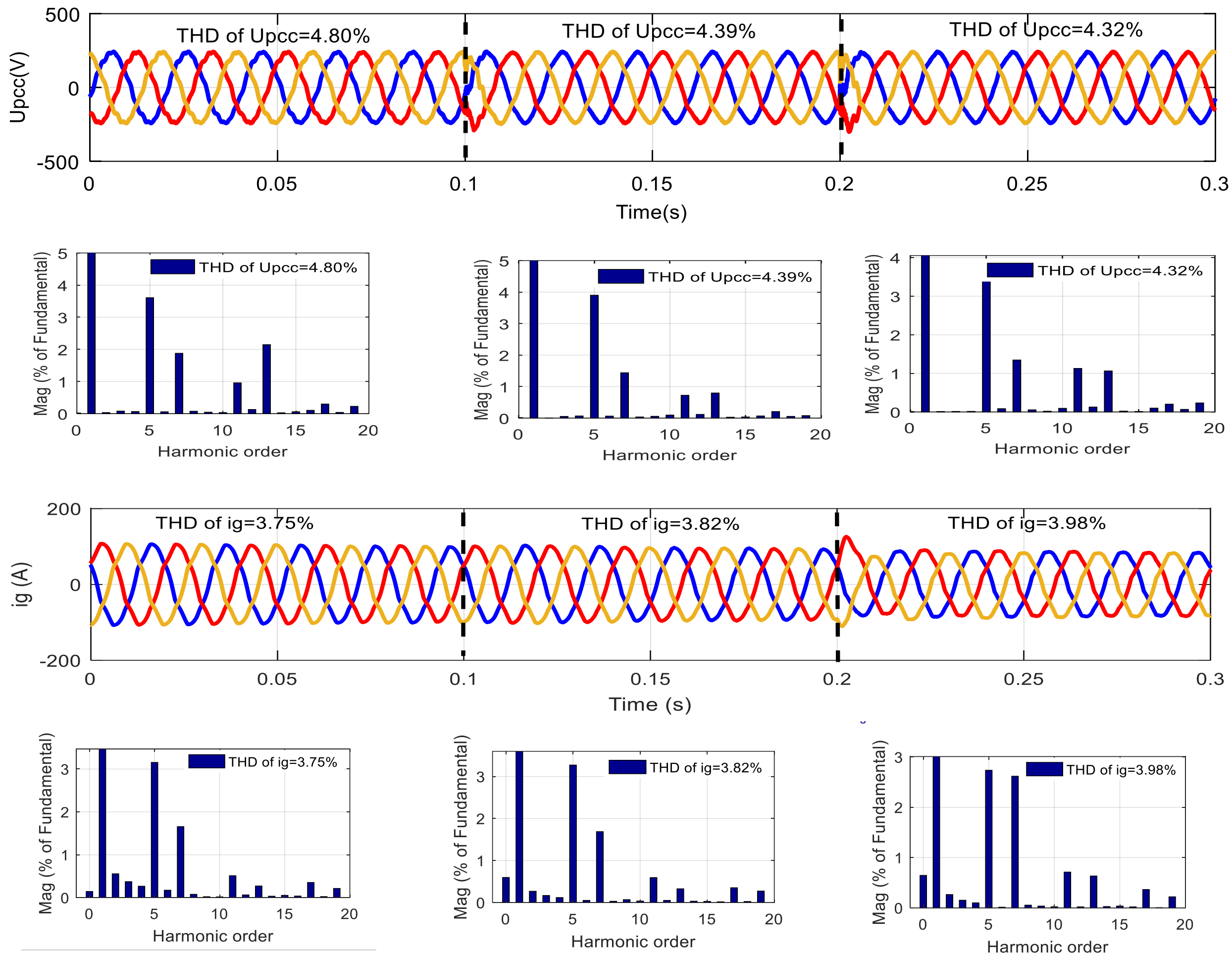


Fig. 14 PCC voltage (U_{pcc}) and grid-injected current (i_g) in case of variable local load with UPQC-based structure

LCL filter as a feedforward signal. As shown in Fig. 7, in the proposed strategy, the grid voltage is proportionally injected as a feedforward signal to the output of the control loop. In this case, the grid impedance is equal to 7.2mH and the nonlinear load (load2) is connected. Waveforms and frequency spectrums of the grid-injected current and the PCC voltage are shown in Fig. 17.

Regarding frequency spectrums in Fig. 17, the harmonic factors of the individual harmonic components are within permissible limits determined by the IEEE 1547 standard. The grid-injected current THD is less than 5%. Also, the proposed structure is capable of reducing the THD of the PCC voltage significantly. For better comparison, Table 2 gives the local load voltage and grid-injected current THDs for all case studies.

V. Conclusion

In this work, the variable virtual admittance and variable virtual impedance concepts were applied using a UPQC-based structure for low-frequency grid-connected inverters. The proposed structure has the capability of harmonic compensation and stability improvement in case of local load changes and variable grid impedance. The principle of this method is based on the impedance-based stability criterion for grid-connected inverters. The nonlinear local load changes and the grid impedance variations lead to the variable harmonic content of the local load voltage, PCC voltage, and grid-injected current. In high-power grid-connected inverters, the variable virtual admittance concept cannot be applied by the inverter because of the low switching frequency. Therefore, the harmonic distortion at the PCC does not satisfy the requirements of the IEEE 1547 standard.

In this paper, the topic of cancellation of the negative effects caused by local load changes and grid impedance variations in a high-power three-phase grid-connected inverter was presented. It was verified that by using a low-power high-frequency UPQC, the output admittance of the inverter and the grid impedance became zero at the point of load connection. Therefore, the harmonic components were removed even under the change in local load and grid impedance variation. Also, in the proposed method, the system stability was ensured based on the impedance-based stability criterion. The effectiveness of the proposed method was verified using different simulation results in MATLAB/Simulink software. In this work, the system under study was a balanced 3-phase 3-wire system. The unbalanced 3-phase 4-wire systems can be considered in future works.

TABLE 2
THDs OF THE LOCAL LOAD VOLTAGE AND GRID-INJECTED CURRENT (%)

		Without the proposed UPQC-based structure		With the proposed UPQC-based structure	
		local load voltage	grid-injected current	local load voltage	grid-injected current
Variable local load	Resistive load	8.12	9	4.80	3.75
	Nonlinear load	17.4	23.3	4.39	3.82
	Highly Nonlinear load	17.82	24.66	4.32	3.98
Variable grid impedance	Z_g=4mH	18.61	29.63	4.37	3.81
	Z_g=7.2mH	19.05	20.87	2.64	3.86
	Z_g=5mH	18.99	25.22	2.85	4.14
Considering grid voltage distortion		-	-	6.44	4.31

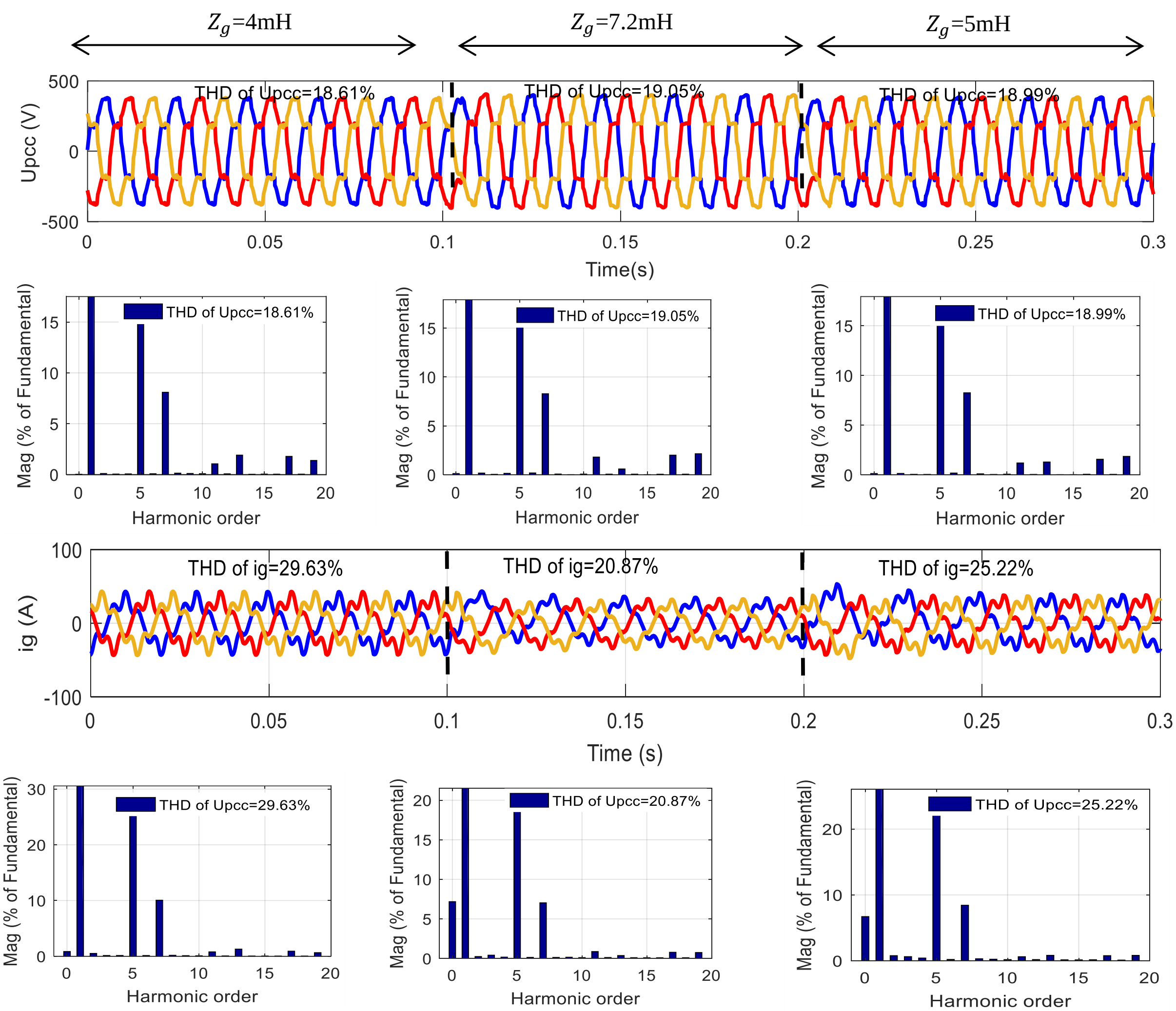


Fig. 15 PCC voltage ($\mathbf{U_{pcc}}$) and grid-injected current ($\mathbf{i_g}$) in case of variable grid impedance without UPQC-based structure

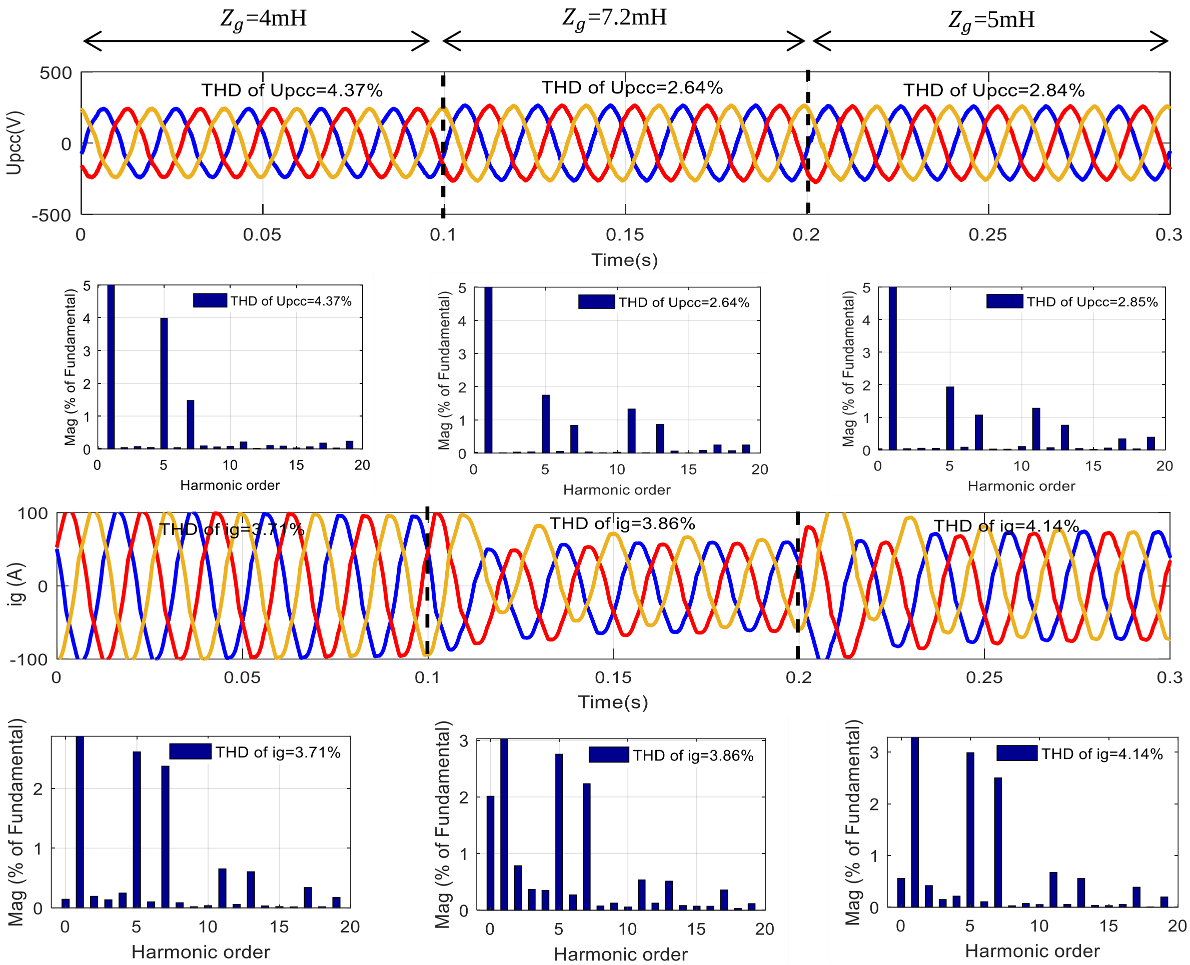


Fig. 16 PCC voltage (U_{PCC}) and grid-injected current (i_g) in case of variable grid impedance with UPQC-based structure

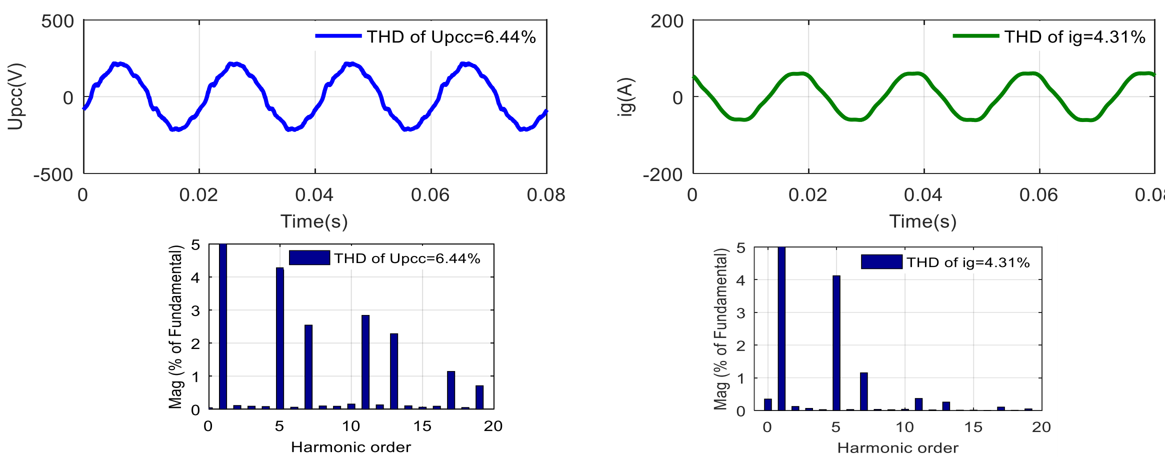


Fig. 17 PCC voltage ($\mathbf{U_{pcc}}$) and grid-injected current ($\mathbf{i_g}$) considering the grid voltage distortion

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