Harmonic Compensation in Integrated System Using Inductive UPQC

Ch. Rami Reddy, Ch. Narendra Kumar, N. Srinivas, M. Kondalu, A. V. Sudhakara Reddy, B. Srikanth Goud, and D. Raja Reddy

1 Introduction

The use of Nonlinear Load (NLL) and high penetration of Renewable Energy Sources (RES) with the grid produce the harmonics [1, 2]. The power electronic elements are the main sources of the harmonics which degrade the quality of power received by the end-users. The RES which is associated with the system at the distribution level is called Distributed Generation (DG) [3–5]. In the distribution networks, it is recommended to use the UPQC for harmonic compensation and reactive power compensation [6]. The UPQC can be installed on the grid side or NLL side or DG side. Various locations of UPQC on the integrated system are shown in Fig. 1. The UPQC is placed at the grid side and the NLL/RES is integrated with the grid through the special transformer. It can be observed from Fig. 1, the load current harmonics will flow through the special transformer which causes serious power quality problems such as extra core losses, copper losses, vibrations, and temperature rises [7–9]. For this position of UPQC, it is possible to bypass the harmonics from the grid, but the effect on the special transformer is unavoidable. In Fig. 2, the UPQC is placed on the DG side. In this configuration also, the special transformer is affected by the harmonics [10–12]. When the UPQC in this configuration, if operated in parallel with converter-based DG systems, it loses its stability [13–15]. The UPQC

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O. H. Gupta et al. (eds.), *Recent Advances in Power Systems*, Lecture Notes in Electrical
Engineering 812, https://doi.org/10.1007/978-981-16-6970-5_28

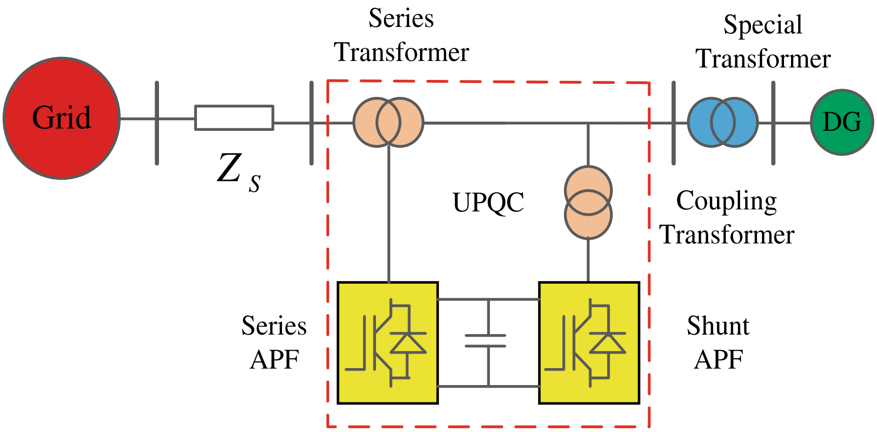

Fig. 1 Grid-side UPQC arrangement

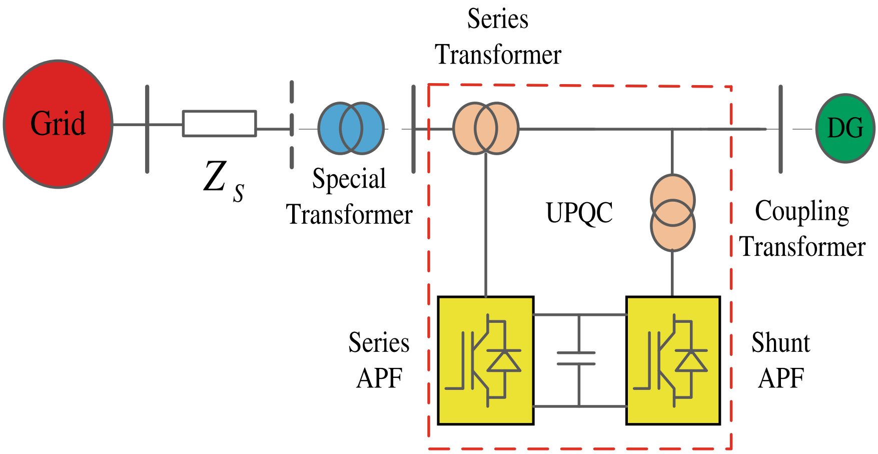

Fig. 2 Load-side UPQC arrangement

can perform simultaneous operations with series and Shunt Active Power Filter (SAPF). Various UPQC advancements are presented in the literature with the reduced number of switches, improved DC link voltage, and better power quality production. The inductive Power Filter (IPF) proposed in the literature mitigates the harmonic effect on the special transformer and also counters the source of harmonics in the system [16–20]. The IPF approach uses a set of single-tuned filters. The performance of these passive filters is limited. The strength of IPF in terms of voltage regulation and harmonic compensation is better.

This paper presents a new inductive filter based hybrid UPQC for the elimination of voltage and current harmonics in the integrated system as presented in Fig. 3.

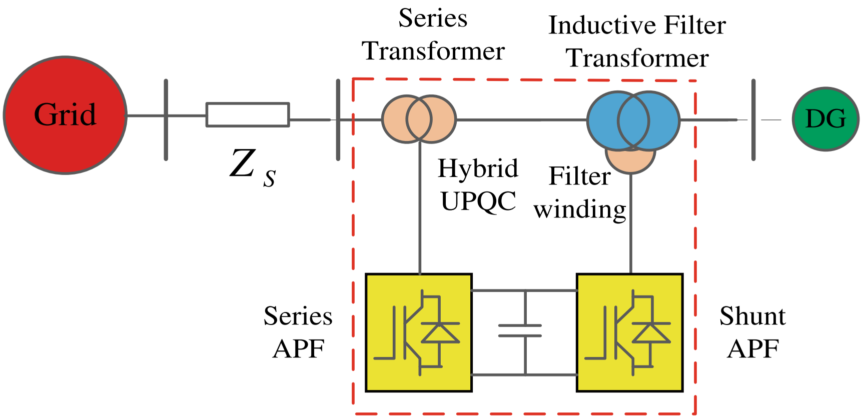

Fig. 3 Proposed UPQC arrangement

This hybrid UPQC integrates the benefits of IPF and hybrid SAPF (HSAPF). This integration will counter the effect on special transformers due to harmonics. The remaining paper is structured as follows. The remaining paper is structured as follows. Section II presents the test system proposed, Section III describes the proposed control mechanism, Section IV describes the proposed approach, Section V describes the results, and the conclusion is drawn in VI Section.

2 Inductive Hybrid UPQC Structure

The basic inductive hybrid UPQC is depicted in Fig. 4. It consists of a UPQC with HSAPF and series Active Power Filter (APF), Inductive Filtering Transformer (IFT), load with medium power ratings, and DG units. The HSAPF and series APF are connected back to back and designed based on the neutral point clamped converter principle [21]. The passive filer of HSAPF is a double resonant passive filter that has two resonant frequencies which can sustain more voltages. The passive filter of series APF is a low-pass LCR filter. The IFT is a three-winding transformer with YYD windings. The primary winding of IFT is connected to the utility grid through the series transformer. The secondary winding of IFT is connected to the DG units or medium power application loads [22]. The third filter winding of IFT is connected to the HSAPF. The inductive filtering is achieved with the IFT and HSAPF [23–25]. When the harmonic magnetic balance is achieved between the secondary winding and filtering winding, the harmonics in the secondary are compensated by the filtering winding which causes the reduction of harmonics in the primary of IFT. The benefit of this configuration is it compensates for the harmonics well on the transformer and supplies the load reactive power demand.

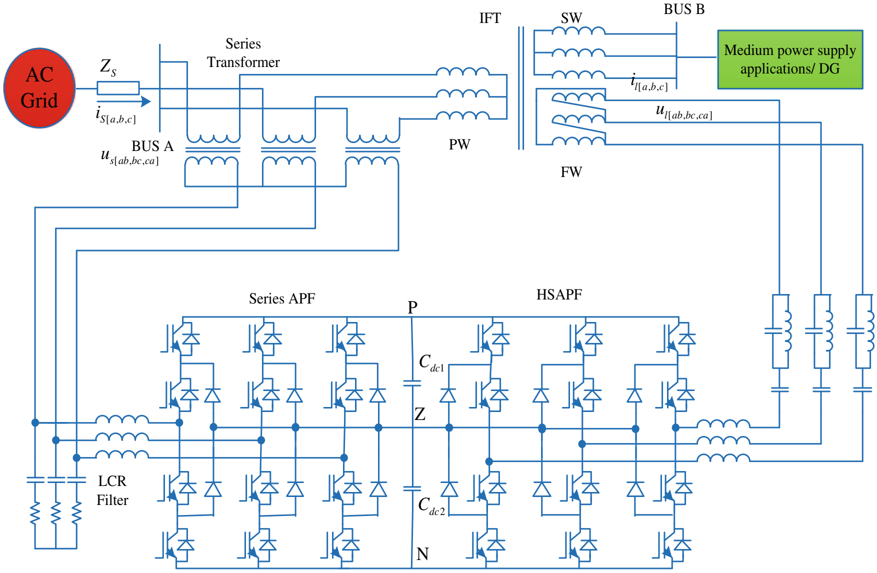

Fig. 4 Test system with proposed inductive hybrid UPQC

3 Proposed Control Mechanism

3.1 Equivalent Circuit Model

The circuit equivalent model of the proposed test approach is shown in Fig. 5. It is assumed that the DG is assumed as non-sinusoidal current source with impedance parallel. The HSAPF is treated as non-sinusoidal source current type in shunt with impedance. The series filter is treated as the controllable voltage source. The equivalent impedance of three windings PW, SW, and FW are Z_1, Z_2, and Z_3, respectively. The hybrid UPQC is installed between grid and DG with three windings, the proposed series transformer and IFT are step-down transformers.

3.2 Current Harmonic Control

This section describes the detailed analysis of the harmonic current compensation mechanism. The function of HSAPF is to compensate for the current harmonics and to make the load currents free from harmonics [26, 27]. From the magnetic balance principle of the transformer, the currents in three winding of transformer are (1)

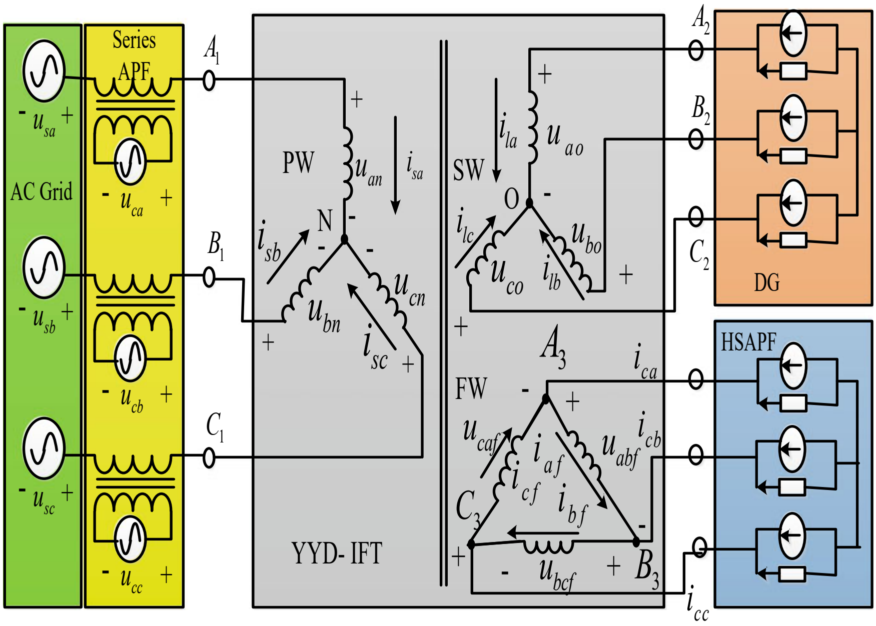

Fig. 5 Equivalent circuit of proposed UPQC arrangement

$$\begin{cases} N_{i1} i_{sa} + N_{i2} i_{1a} + N_{i3} i_{af} = 0 \\ N_{i1} i_{sb} + N_{i2} i_{1b} + N_{i3} i_{bf} = 0 \\ N_{i1} i_{sc} + N_{i2} i_{1c} + N_{i3} i_{cf} = 0 \end{cases} \tag{1}$$

Voltage signal equations of multiple winding based transformer are (2)

$$\begin{cases} V_{an1} - \frac{N_{i1}}{N_{i3}} V_{abf} = i_{sa} Z_1 - \frac{N_{i1}}{N_{i3}} i_{af} Z_3 \\ V_{bn1} - \frac{N_{i1}}{N_{i3}} V_{bcf} = i_{sb} Z_1 - \frac{N_{i1}}{N_{i3}} i_{bf} Z_3 \\ V_{cn1} - \frac{N_{i1}}{N_{i3}} V_{caf} = i_{sc} Z_1 - \frac{N_{i1}}{N_{i3}} i_{cf} Z_3 \end{cases} \tag{2}$$

As per the Kirchhoff current law, the current equations in filter winding are described as (3)

$$\begin{cases} V_{abf} = i_{zb} Z_{ob} - i_{za} Z_{oa} = (i_{zb} - i_{za}) Z_o \\ V_{bcf} = i_{zc} Z_{oc} - i_{zb} Z_{ob} = (i_{zc} - i_{zb}) Z_o \\ V_{caf} = i_{za} Z_{oa} - i_{zc} Z_{oc} = (i_{za} - i_{zc}) Z_o \end{cases} \tag{3}$$

The voltage equations of filter winding are described as (4)

$$\begin{cases} i_{sa}+i_{sb}+i_{sc}=0 \\ i_{1a}+i_{1b}+i_{1c}=0 \\ i_{af}+i_{bf}+i_{fc}=0 \\ \quad i_{af}=i_{cf}+i_{ca} \\ \quad i_{bf}=i_{af}+i_{cb} \\ \quad i_{cf}=i_{bf}+i_{cc} \end{cases} \tag{4}$$

From Eqs. (1)–(4), the grid currents can be obtained as (5)

$$\begin{cases} \dfrac{i_{sa}=V_{an1}-\frac{N_{i1}}{N_{i3}}(i_{ra}-i_{rb})Z_0-\frac{N_{i1}N_{i2}}{N_{i3}^2}(Z_3+3Z_0)i_{1a}}{Z_1+\frac{N_{i1}^2}{N_{i3}^2}(Z_3+3Z_0)} \\ \dfrac{i_{sb}=V_{bn1}-\frac{N_{i1}}{N_{i3}}(i_{rb}-i_{rc})Z_0-\frac{N_{i1}N_{i2}}{N_{i3}^2}(Z_3+3Z_0)i_{1b}}{Z_1+\frac{N_{i1}^2}{N_{i3}^2}(Z_3+3Z_0)} \\ \dfrac{i_{sc}=V_{cn1}-\frac{N_{i1}}{N_{i3}}(i_{rc}-i_{ra})Z_0-\frac{N_{i1}N_{i2}}{N_{i3}^2}(Z_3+3Z_0)i_{1c}}{Z_1+\frac{N_{i1}^2}{N_{i3}^2}(Z_3+3Z_0)} \end{cases} \tag{5}$$

From Eq. (5), the grid currents are majorly affected by currents of HSAPF, load currents, primary voltages, and grid currents. Assume the primary voltages are completely compensated and the current has no harmonics, then the HSAPF reference currents should meet Eq. (6)

$$\begin{cases} i_{ra}=\frac{N_{i2}}{N_{i3}}\frac{(Z_3+3Z_0)}{3Z_0}(i_{1c}-i_{1a}) \\ i_{rb}=\frac{N_{i2}}{N_{i3}}\frac{(Z_3+3Z_0)}{3Z_0}(i_{1a}-i_{1b}) \\ i_{rc}=\frac{N_{i2}}{N_{i3}}\frac{(Z_3+3Z_0)}{3Z_0}(i_{1c}-i_{1c}) \end{cases} \tag{6}$$

To remove the effect of Z_3 on filter performance, this impedance is diagnosed in such a way it is close to zero. Hence, the reference currents are simplified as (7)

$$\begin{cases} i_{ra}=\frac{N_{i2}}{N_{i3}}(i_{1c}-i_{1a}) \\ i_{rb}=\frac{N_{i2}}{N_{i3}}(i_{1a}-i_{1b}) \\ i_{rc}=\frac{N_{i2}}{N_{i3}}(i_{1c}-i_{1c}) \end{cases} \tag{7}$$

3.3 Voltage Harmonic Control

The series APF controls the voltages and is responsible for harmonic less sinusoidal voltages with suitable amplitudes. By controlling the secondary winding voltages of the IFT, the NLL voltages are controlled. Under no-load situations, the open circuit secondary voltages are presented as (8)

$$\begin{cases} V_{a0} = \frac{N_{i1}}{N_{i2}} V_{an1} \\ V_{b0} = \frac{N_{i1}}{N_{i2}} V_{bn1} \\ V_{c0} = \frac{N_{i1}}{N_{i2}} V_{cn1} \end{cases} \tag{8}$$

As per the Faraday law and Kirchhoff's voltage law, the primary voltages are written as (9)

$$\begin{cases} V_{an1} = V_{sa} + \frac{N_1}{N_2} V_{ca} \\ V_{bn1} = V_{sb} + \frac{N_1}{N_2} V_{cb} \\ V_{cn1} = V_{sc} + \frac{N_1}{N_2} V_{cc} \end{cases} \tag{9}$$

From (8) and (9), if the primary voltages deviate from the normal values, the reference voltages are written as (10)

$$\begin{cases} V_{cra} = \left(\frac{N_{i1}}{N_{i2}} V_{La}^{*} - V_{sa} \right) \frac{N_2}{N_1} \\ V_{crb} = \left(\frac{N_{i1}}{N_{i2}} VLb^{*} - V_{sb} \right) \frac{N_2}{N_1} \\ V_{crc} = \left(\frac{N_{i1}}{N_{i2}} V_{Lc}^{*} - V_{sc} \right) \frac{N_2}{N_1} \end{cases} \tag{10}$$

4 Proposed Controller

The suggested hybrid UPQC is controlled with a synchronous reference controller. Hear the HSAPF and series filter are independently controlled. The HSAPF compensates for the current harmonics and regulates the DC link voltage. The series regulator compensates for the load voltages.

4.1 Pre-filtering with SGDFT-Based PLL

Both series and shunt filters must be in association with utility. The conventional PLL provides weak achievement under nonideal voltage signals, hence in this paper, a new pre-filter approach is introduced which uses SGDFT. The basic controller structure of SGDFT filter based PLL is depicted in Fig. 6. It has three main parts they are positive sequence components separation, voltage normalization, and SRF PLL. The voltage normalization technique is provided to eliminate the achievement of changing input signals on synchronous reference PLL. The realization of SGDFT-based filter is shown in Fig. 7. This SGDFT based filter removes the serious deviations in voltages efficiently as the PI controller is tuned properly.

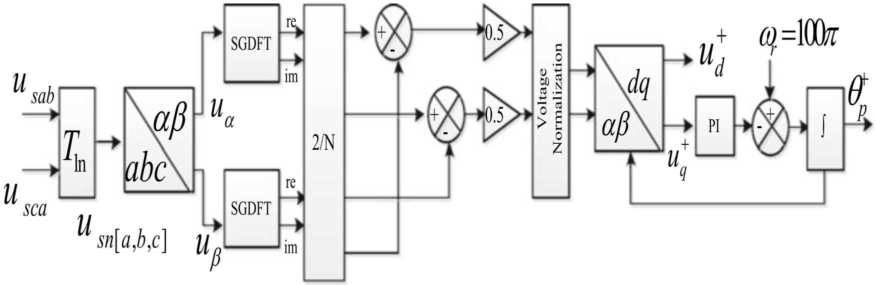

Fig. 6 SGDFT-based SRF controller

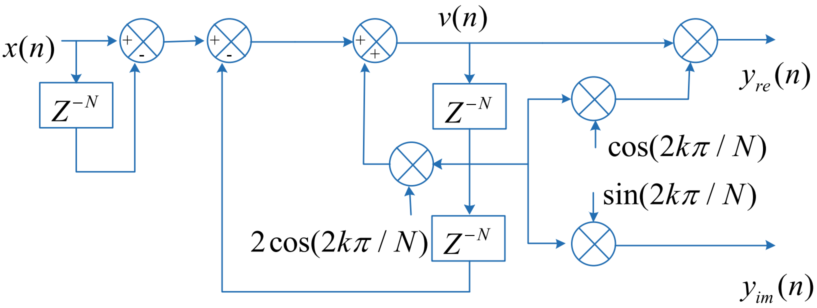

Fig. 7 Arrangement of SGDFT filter

4.2 Control Scheme for HSAPF

The proposed controller for HSAPF is shown in Fig. 8. It has six majorly parts. It has Carrier-Based PWM (CBPWM), reference voltage calculation, link DC voltage controller, current controller, voltage control, and voltage balancer. The base current is obtained with the load ampere signal by using SGDFT. The reference DC link

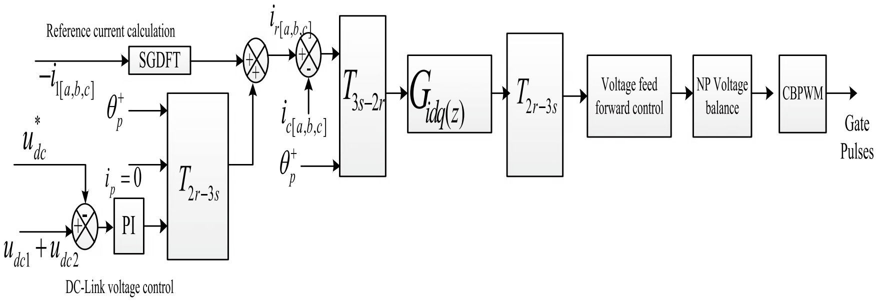

Fig. 8 HSAPF controller

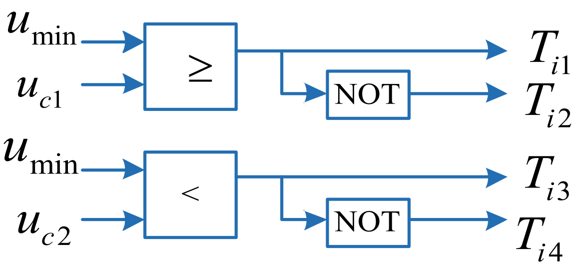

Fig. 9 Design of CBPWM

voltage is provided stationary using a PI controller. PR controller is used to extract the reference current. The voltage feed-forward controller eliminates the disturbances in the voltage. The design of detailed information of CBPWM is depicted in Fig. 9.

4.3 Series Active Power Filter Controller

The series active filter controller is shown in Fig. 10. It has a major reference voltage calculator, load voltage controller, current controller, and CBPWM. The reference voltages are obtained from the grid voltages and load voltages. The current feed-forward controller removes the current harmonics and this controller is not responsible for the control of DC-link voltage.

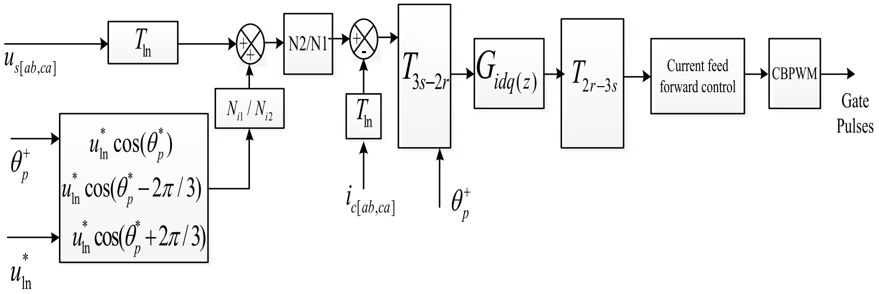

Fig. 10 Series active power filter controller

5 Simulation Results and Discussion

The performance of the proposed approach is achieved on MATLAB/Simulink platform. The hybrid UPQC is connected between grid and load. Power electronic controller is used as nonlinear load with twenty degrees triggering angle. The simulation results of grid and load voltages before and after compensation are depicted in Figs. 11 and 12. The compensation currents are depicted in Fig. 13. Because of the application of the proposed UPQC, the THD of the grid is reduced from 11.65% to 2.24% which is recorded in Figs. 18 and 20. The grid current, load current, and compensation currents with UPQC are depicted in Figs. 14, 15, and 16, respectively. The THD of grid current is decreased from 30.97% to 1.53%, respectively, because of the application of the proposed UPQC (Figs. 17, 19 and 21).

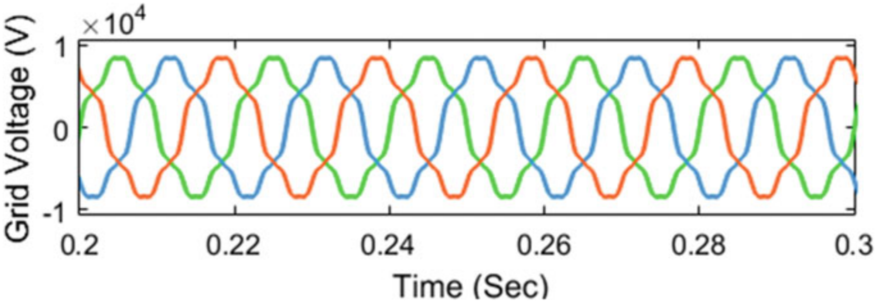

Fig. 11 Grid voltage before compensation

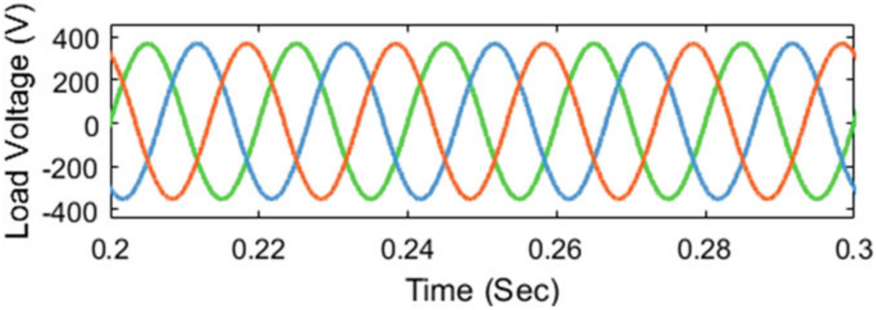

Fig. 12 Load voltage after compensation

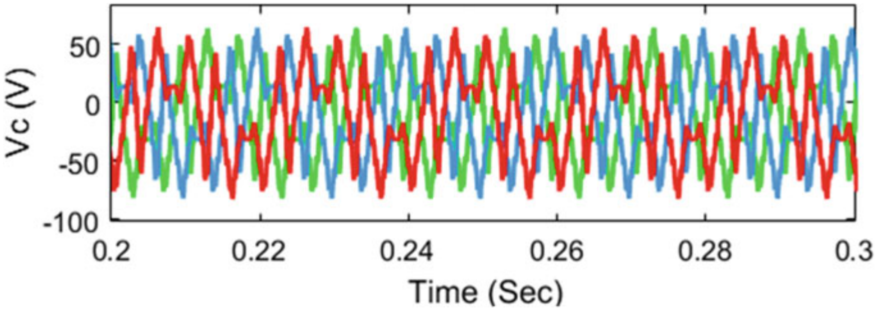

Fig. 13 Compensating voltage

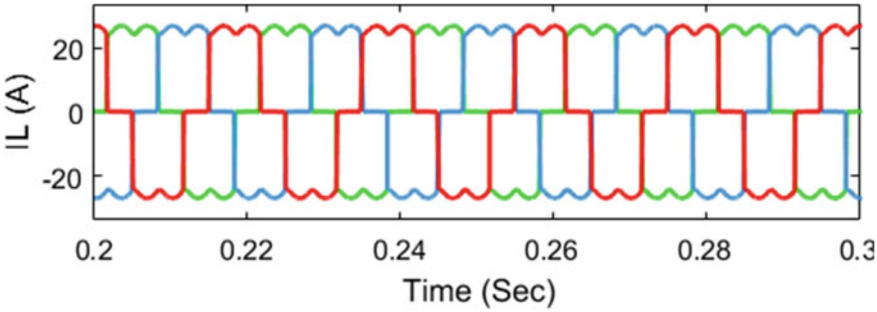

Fig. 14 Load current before compensation with UPQC

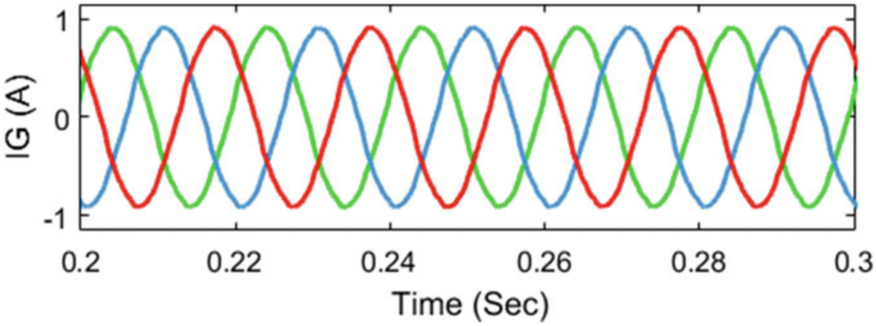

Fig. 15 Load current after compensation with UPQC

6 Conclusion

This article proposes a new advanced hybrid UPQC for harmonic compensation of renewable energy applications. The proposed UPQC integrates IFT with HSAPF, which eliminates the harmonics in the system compared to the conventional UPQC.

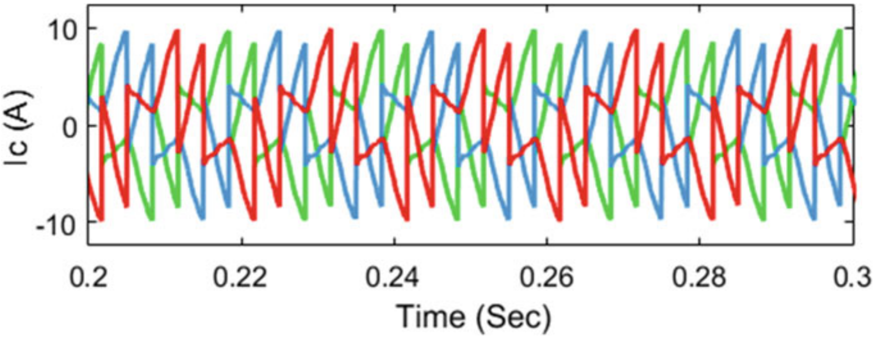

Fig. 16 Compensation current

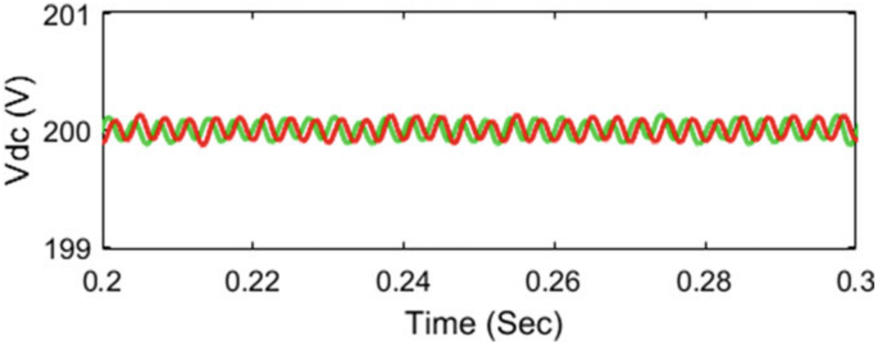

Fig. 17 DC split link voltages

The simulation results indicate that the proposed UPQC reduces the voltage THD from 11.65% to 2.24% and current THD from 30.97% to 1.53%, respectively. It makes the proposed control system is very efficient in the control of load current harmonics.

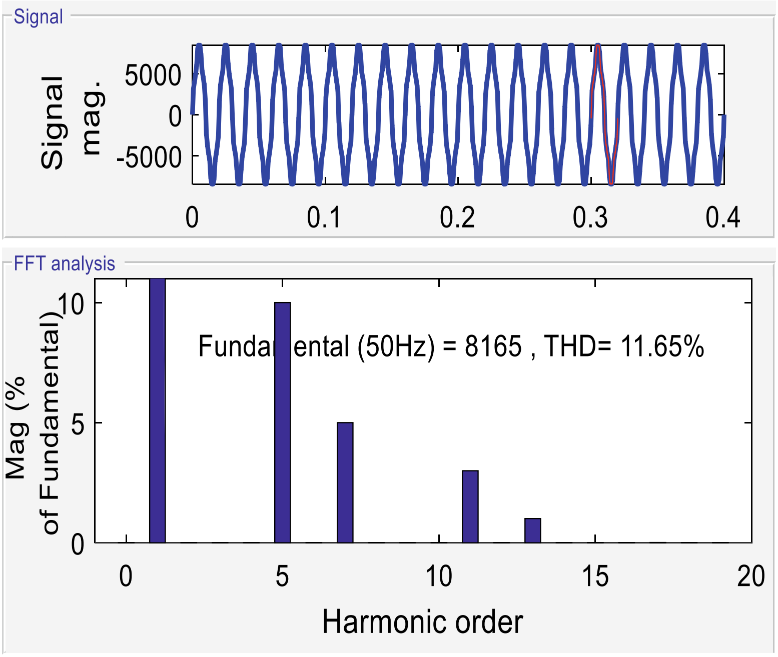

Fig. 18 Grid voltage THD before compensation

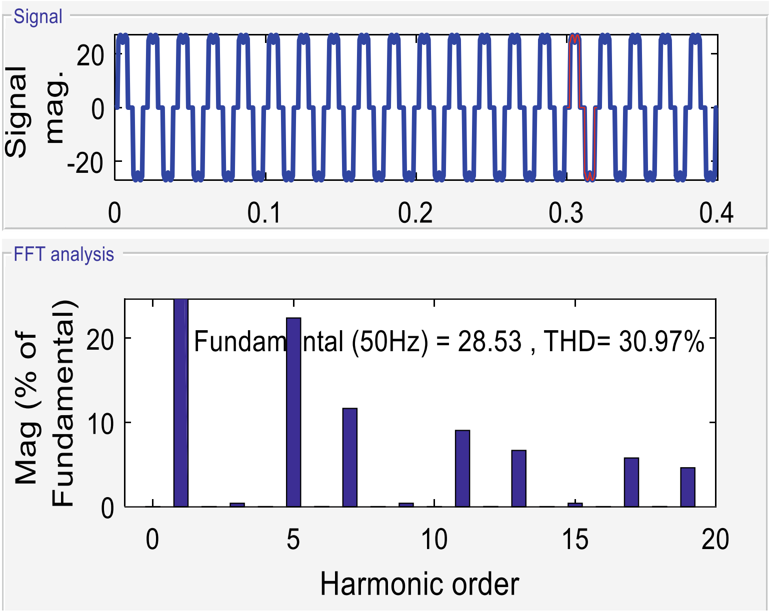

Fig. 19 Grid current THD before compensation

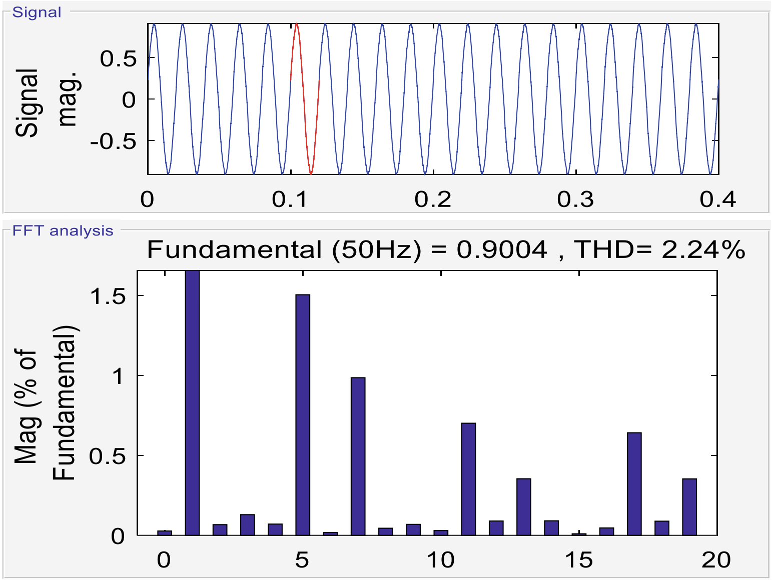

Fig. 20 Load voltage THD after compensation with proposed UPQC

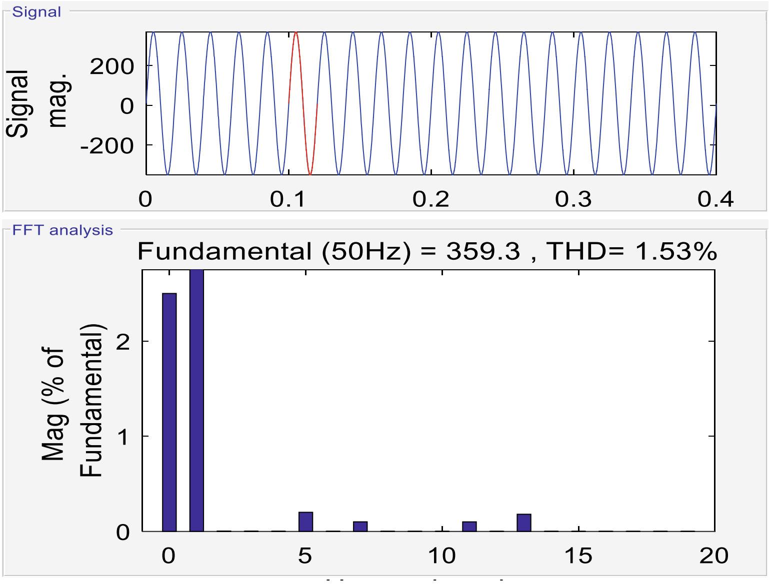

Fig. 21 Load current THD after compensation with proposed UPQC

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