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Three-Level Converters based Generalized Unified Power Quality Conditioner

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Abstract**—**A generalized unified power quality conditioner (GUPQC) by using three single-phase three-level voltage source converters (VSCs) connected back-to-back through a common dc link is proposed in this paper as a new custom power device for a three-feeder distribution system. One of the converters is connected in shunt with one feeder for mitigation of current harmonics and reactive power compensation, while the other two VSCs are connected in series with the other two feeders to maintain the load voltage sinusoidal and at constant level. A new control scheme based on synchronous reference frame is proposed for series converters. The simulation analysis on compensation performance of GUPQC based on PSCAD/EMTDC is reported.

Keywords**—**Custom power device, generalized unified power quality conditioner, PSCAD/ETMDC, voltage source converter

I. Introduction

WITH the development in the process control and digital electronics communications, a number of sensitive critical loads which require sinusoidal supply voltage for their proper operation are extensively used. At the same time increased use of nonlinear loads by both electric utilities and end users has been affecting the quality of electric power, by causing major power quality disturbances in the distribution system such as voltage and current harmonics, imbalances, voltage flicker, voltage sag/swell and voltage interruptions etc. As such improvement of power quality in distribution systems is a major issue for utilities.It is well established by the application of custom power controllers in distribution sector that power quality can be significantly improved. A unified power quality conditioner (UPQC) [1] which integrates a series and a shunt active power filters is used to mitigate voltage and current imperfections in a distribution feeder. The shunt compensator of UPQC compensate for load current related problems such as current harmonic unbalance, power factor correction and reactive power required by the load while the series compensator can compensate for all voltage related problems such as voltage sag/swell, voltage harmonics etc. Many researchers have shown that UPQC as a versatile device to improve the power quality in distribution systems [2]-[4]. A flexible alternative current transmission system (FACTS) controller called as a generalized unified power controller (GUPFC) consisting of three or more VSCs, one connected in shunt and the other two or more VSCs connected in series with transmission lines capable of simultaneous control of the bus voltage of one line and independent active and reactive power flows of other transmission lines is employed as published in the last decade [5]-[6]. Based on the application in transmission system the concept of GUPFC can be extended to distribution systems. At recent times most of research work on distribution FACTS controllers has been centered on utilizing of two back-to-back VSCs. An interline unified power quality conditioner (IUPQC) consisting of two VSCs, one in shunt to regulate the bus voltage of one feeder and the other in series to regulate the voltage across a sensitive load of the other feeder is proposed in [7]. A multi-converter unified power quality conditioner (MC-UPQC) having three VSCs connected back-to-back by a dc link is reported in [8] to compensate both current and voltage imperfections in one feeder and voltage imperfections in another feeder.This paper proposes a novel power quality conditioner for three-feeder distribution systems, called as GUPQC which is realized by three single-phase three-level VSCs connected back-to-back by a common dc link capacitor. One VSC is connected in shunt to a feeder through a coupling transformer and the other two VSCs, each in series with a feeder, are connected to the other two feeders through injection transformers. As there is no published work on the GUPQC, it is essential to establish the validity of its compensation performance in distribution or industrial networks. A new controller strategy based on synchronous reference frame for series compensators is also proposed. Essentially the proposed GUPQC accomplishes the following:

a) The shunt VSC compensates current harmonics and reactive power required by one feeder. It also supports the real power required by the other two VSCs and regulates the voltage of dc link capacitor.
b) The two series VSCs mitigates voltage waveform distortion, voltage sag/swell and interruptions (protect the sensitive loads connected to the other two feeders against voltage imperfections).

The paper is organized as follows. The proposed model of GUPQC and its controller circuits are described in Section II and III, respectively. Simulation results based on case studies are presented in Section IV. Section V presents conclusions.

II. System Configuration

The GUPQC connected to a multi-bus/three-feeder distribution system which supply a nonlinear load (load1) by feeder1 and two sensitive critical loads (load2 and load3) by feeder2 and feeder3, is as shown in Fig. 1. The shunt compensator, VSC1 which operates as a controlled current

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source is used to compensate feeder1 current harmonics, to provide the reactive power required by the load1 and to support the real power required by the two series compensators, VSC2 and VSC3. The two series compensators are used as controlled voltage sources to protect the sensitive loads (load2 and load3) of feeder2 and feeder3 against voltage imperfections.

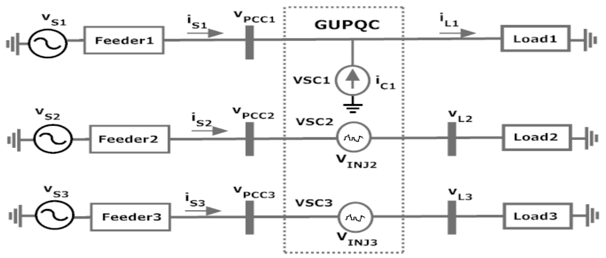


Fig. 1 Distribution system with the proposed GUPQC

In Fig. 1, v_S, v_{PPC}, v_L, v_{INJ} are supply, point of common coupling, load, and compensation voltages, respectively, and i_S, i_L, i_C are supply, load and compensation currents, respectively. The three VSCs of GUPQC are connected back-to-back on the dc side through a common dc link capacitor (C_{dc}) as shown in Fig. 2 and the impedances of feeders are denoted by R_S and L_S.

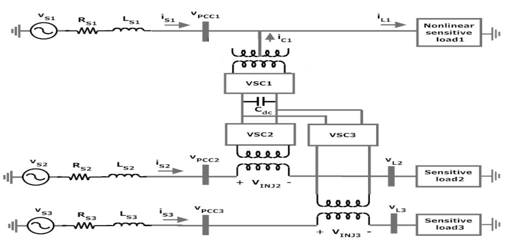
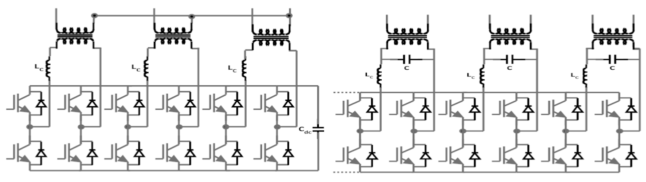


Fig. 2 Shunt and series compensators of GUPQC

Each three-level VSC in Fig. 2 consists of three single-phase H-bridge converters supported by a common DC link bus voltage as in Figs. 3 (a) and 3 (b), respectively. The AC side of each VSC is connected to the distribution system through a commutation reactor, L_C and by a single phase transformer.



(a) (b)

Fig. 3 Structure of a VSC: (a) shunt (b) series

III. CONTROL CIRCUITS OF PROPOSED GUPQC

As the controllers of GUPQC detect voltage and current imperfections and then generate corresponding gating signals to IGBTs, the control strategies of shunt and series compensators are important. In the published research as in [9]-[12] different control strategies are proposed for UPQC and shunt active power filter. In this paper, two different control strategies are used for shunt and series compensators. The sensed three-phase shunt compensator output currents of feeder1 are compared with the reference currents to generate the gating signals for IGBTs of VSC1. The estimation of reference signals is based on instantaneous reactive power theory or *p-q* theory introduced by Akagi, Kanazawa and Nabae in 2007 [12]. In the case of series compensator a new control method is proposed based on synchronous reference frame voltage transformation to estimate the reference voltages.

Fig. 4 shows the reference current signal generation by using *p-q* theory for shunt compensator. The feeder1 instantaneous three-phase load currents i_{L1} and the common coupling voltages v_{PCC1} are transformed from *a*, *b*, *c* coordinates to *α*, *β*, *0* coordinates by using Clark transformation as in (1) and (2), respectively, by using the transformation matrix (3).

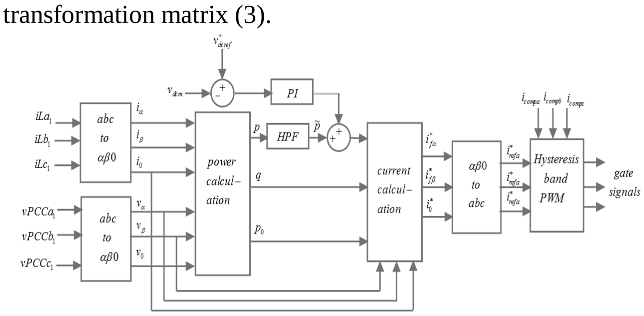


Fig. 4 Shunt compensator control

$$i_{\alpha\beta0} = C_{abc}^{\alpha\beta0}\, i_{L1\_abc} \tag{1}$$

$$v_{\alpha\beta0} = C_{abc}^{\alpha\beta0}\, v_{PCC1\_abc} \tag{2}$$

$$C_{abc}^{\alpha\beta0} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix},\quad C_{\alpha\beta0}^{abc} = {C_{abc}^{\alpha\beta0}}^{-1} \tag{3}$$

The three instantaneous powers, real power, *p*, imaginary power, *q* and zero sequence power, p_0 are defined from the instantaneous three-phase load currents and common coupling voltages based on *α*, *β*, *0* coordinates as in (4).

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \tag{4}$$

The instantaneous powers include both average or dc component and oscillating component which are expressed as in (5).

$$P = \bar{P} + \tilde{P},\quad q = \bar{q} + \tilde{q}\,,\quad p_0 = \bar{p}_0 + \tilde{p}_0 \tag{5}$$

The shunt compensator is to supply instantaneous powers, $\tilde{p}$, q and p_0 to the load while the load receives only $\bar{p}$. A high pass filter (HPF) is used to extract $\tilde{p}$ from the total instantaneous power, p. In addition it also compensates the switching power losses, p_{loss} of compensators and provides active power required to maintain the dc link capacitor voltage at consistent level as in (6).

$$\begin{bmatrix} i^*_{f\alpha} \\ i^*_{f\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} + p_0 + p_{loss} \\ q \end{bmatrix} \tag{6}$$

The three-phase reference currents are obtained by using α, *β*, *0* to *a*, *b*, *c* transformation as in (7).

$$i^{refc}_{abc} = C^{abc}_{\alpha\beta 0}\, i^*_{f\alpha\beta 0} \tag{7}$$

To generate gating signals for IGBTs of shunt compensator the reference currents as in (7) are compared with sensed three-phase shunt compensator output currents. The error signals are then processed by the hysteresis band PWM controller before sending the signals to the gates of shunt compensator switches.

The series compensators reference voltage signals are evaluated by using the proposed method based on synchronous reference frame as shown in Fig. 5.

To ensure that the load2 or load3 receive pure sinusoidal voltage with constant amplitude even if the source voltage of feeder2 and feeder3 are distorted, the maximum load voltage of feeder2 and feeder3 are transformed from *d*, *q*, *0* to *a*, *b*, *c* by using inverse Park transformation as in (8) which generates three-phase balanced sinusoidal voltages.

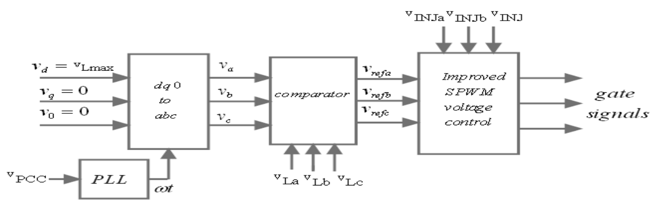


Fig. 5 Series compensator control

$$\begin{bmatrix} v_{refa} \\ v_{refb} \\ v_{refc} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(\omega t) & \cos(\omega t) & 1 \\ \sin(\omega t - 120^\circ) & \cos(\omega t - 120^\circ) & 1 \\ \sin(\omega t + 120^\circ) & \cos(\omega t + 120^\circ) & 1 \end{bmatrix} \begin{bmatrix} v_{L\max} \\ 0 \\ 0 \end{bmatrix} \tag{8}$$

The reference voltages are generated by comparing the sinusoidal three-phase voltages which are calculated by using (8) and the sensed load voltages v_{L2}, v_{L3}. Then the reference voltages are processed by using improved sinusoidal pulse width modulation (SPWM) technique in order to generate gating signals to the IGBTs of series compensators.

IV. Rating of Proposed GUPQC

The VSCs of GUPQC are to be designed to provide power required by the loads during voltage and current disturbances, inject current to suppress load current harmonics and inject voltage to compensate voltage deficiency of source. A novel method is proposed in this paper to estimate the volt-ampere rating of GUPQC based on the power rating of UPQC developed in [13], [14]. Three schemes are proposed in [13] for developing the volt-ampere rating of UPQC based on the angle of the injected voltage by series VSC. In the first scheme, the injected voltage by VSC is in quadrature with the source current (UPQC-Q). In the second scheme, the injected voltage is in phase with source current and voltage (UPQC-P). However in the third scheme, the injected voltage is at a certain angle with respect to the source current (UPQC-minimum). The loading of series and shunt compensators of the proposed GUPQC are based on the analysis of UPQC-Q and UPQC-P, respectively, and the corresponding phasor diagrams are as in Figs. 6 and 7.

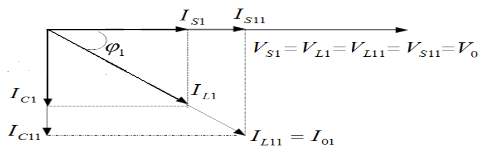


Fig. 6 Phasor representation of shunt compensator loading

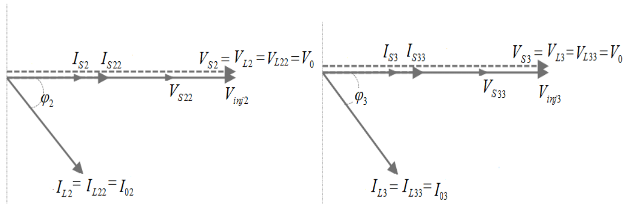


Fig. 7 Phasor representation of series compensators loading

The currents, voltages, voltage drops and power factors of feeders 1, 2, 3 as illustrated in Figs. 6 and 7 are as follows:

I_{S1}, I_{S2}, I_{S3}	normal source currents
I_{S11}, I_{S22}, I_{S3}	source currents in case of voltage sag
I_{L1}, I_{L2}, I_{L3}	normal load currants
$I_{L11}, I_{L22}, I_{L33}$	load currants in case of voltage sag
I_{C1}	normal compensation current
I_{C11}	compensation current in case of voltage sag
I_{01}, I_{02}, I_{03}	nominal load currents
V_{S1}, V_{S2}, V_{S3}	normal source voltages
V_{L1}, V_{L2}, V_{L3}	normal load voltages
$V_{S11}, V_{S22}, V_{S33}$	source voltages in case of voltage sag
$V_{L11}, V_{L22}, V_{L23}$	load voltages in case of voltage sag
V_{INJ2}, V_{INJ3}	injected voltages in feedeer2 and feeder3, respectively
Z_{SHU}	shunt inductance impedance

x_1, x_2	voltage drops in pu
$\varphi_1, \varphi_2, \varphi_3$	load power factor angle
V_0	load voltage nominal value

Assuming that the GUPQC has no losses, the active power demand of the three feeders is same and from Figs. 6 and 7,

$$V_{S1}I_{S1} = V_{L1}I_{L1}\cos\varphi_1 \tag{9}$$
$$V_{S2}I_{S2} = V_{L2}I_{L2}\cos\varphi_2 \tag{10}$$
$$V_{S3}I_{S3} = V_{L3}I_{L3}\cos\varphi_3 \tag{11}$$

In normal operation and in case feeder2 and feeder3 are subjected to voltage sag, the shunt compensator, VSC1 is to support the real power needed by the VSC2 and VSC3 for compensation of the voltage imperfections. Then feeder1 active power demand becomes as in (12) and (13), respectively.

$$V_{S1}I_{S11} = V_{L11}I_{L11}\cos\varphi_1 + V_{L22}I_{L22}\cos\varphi_2 + V_{L33}I_{L33}\cos\varphi_3 \tag{12}$$
$$V_0 I_{S11} = V_0 I_{01}\cos\varphi_1 + x_2 V_0 I_{02}\cos\varphi_2 + x_3 V_0 I_{03}\cos\varphi_3 \tag{13}$$

From (12) the source current of feeder1 due to the voltage sag in feeder2 and feeder3 can be calculated as in (14).

$$I_{S11} = I_{01}\cos\varphi_1 + x_2 I_{02}\cos\varphi_2 + x_3 I_{03}\cos\varphi_3 \tag{14}$$

From Fig. 6 the injected current by shunt compensator VSC1 can be calculated as in (15).

$$I_{C11} = \sqrt{I_{01}^2 + I_{S11}^2 - 2I_{01}I_{S11}\cos\varphi_1} \tag{15}$$

Thus the rating of shunt VSC1 of feeder1 is as in (16).

$$S_{VSC1} = 3V_0\left(\sqrt{I_{C11}^2 + (I_{02}x_2\cos\varphi_2)^2 + (I_{03}x_3\cos\varphi_3)^2}\right) + I_{C11}^2 Z_{SHU} \tag{16}$$

The rating of the two series VSCs of feeder2 and feeder3 can be expressed as in (17) and (18), respectively.

$$S_{VSC2} = 3x_2 I_{02} V_0 \tag{17}$$

$$S_{VSC3} = 3x_3 I_{03} V_0 \tag{18}$$

Thus the total power rating of GUPQC is derived as,

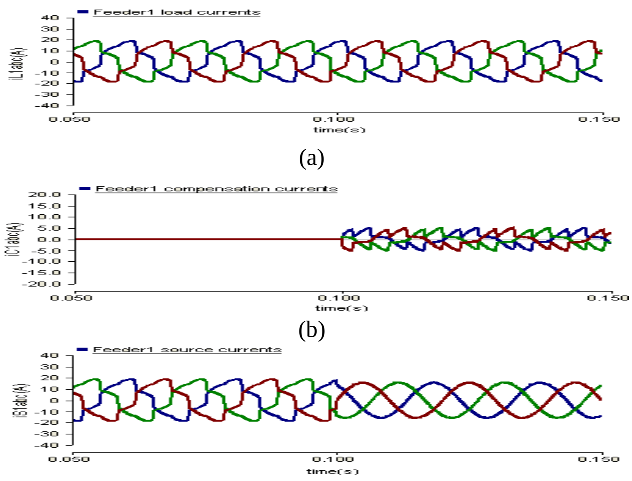
$$\begin{aligned} S_{GUPQC} &= S_{VSC1} + S_{VSC2} + S_{VSC3} \\ &= 3V_0\Big(\sqrt{I_{C11}^2 + (x_2 I_{02}\cos\varphi_2)^2 + (x_3 I_{03}\cos\varphi_3)^2} \\ &\quad + x_2 I_{02} + x_3 I_{03}\Big) + I_{C11}^2 Z_{SHU} \end{aligned} \tag{19}$$

V. Simulation Studies

The performance of the simulation model of GUPQC in a three-feeder distribution system as in Fig. 2 is analyzed by using PSCAD/EMTDC. The supply voltages of the three feeders are set to 380 V, 50 Hz. The feeder1 load is a combination of a three-phase R-L load (R = 27 Ohms, L = 116 mH) and a three-phase diode bridge rectifier followed by R-L load on dc side (R = 52 Ohms, L = 21 mH) which draws harmonic current. Similarly to introduce distortion in supply voltages of feeder2 and feeder3, 5th and 7th harmonic voltage sources, which are 11.5 % of fundamental input supply voltages are connected in series with the supply voltages v_{S2} and v_{S3}, respectively. The sensitive loads (load2 and load3) on feeder2 and feeder3 are 3-phase R-L loads (R = 25 ohms, L = 100 mH). In order to demonstrate the performance of the proposed model of GUPQC three simulation case studies are carried out.

A. Compensation of current and voltage harmonics

Simulation is carried out in this case study under distorted conditions of current in feeder1 and supply voltages in feeder2 and feeder3. Figs. 8(a) to (c) represents three-phase load, compensation and source currents of feeder1 before and after compensation. It is to be noted that the shunt compensator injects compensation current at 0.1 s as in Fig. 8(b). The effectiveness of GUPQC is evident from Fig. 8(c) as the source current becomes sinusoidal and balanced from 0.1 s. The Total Harmonic Distortion (THD) of load and source currents is identical before compensation and is observed to be 17.27 %. After compensation at 0.1 s the source current THD is observed to be 0.51 %.

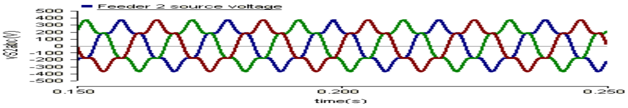


(a) (b) (c)

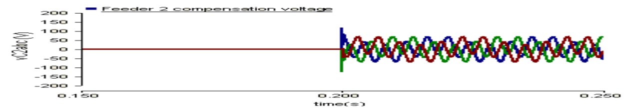
Fig. 8 Feeder1 currents: (a) load (b) compensation (c) source

The compensation performance on voltage harmonics in feeder2 and feeder3 by GUPQC is illustrated as in Figs. 9(a) to 9(c) and Figs. 10(a) to 10(c), respectively. The series compensator, VSC2 injects compensation voltage at 0.2 s as in Fig. 9(b) and subsequently the load voltage is observed to be sinusoidal as in Fig. 9(c). Similarly the series compensator, VSC3 in feeder3 injects compensation voltage at 0.3 s as in

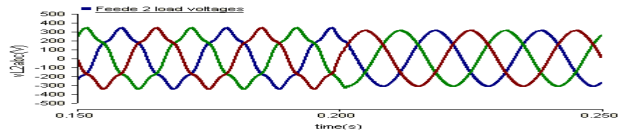
Fig. 10 (b) minimizing the voltage distortion and improves the load voltage to nearly sinusoidal as in Fig. 10(c).



(a)

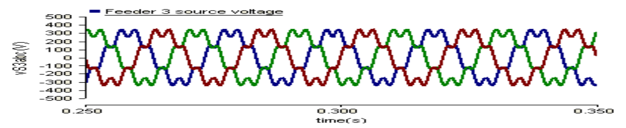


(b)

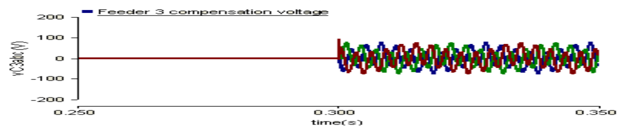


(c)

Fig. 9 Feeder2 voltages: (a) supply (b) compensation (c) load



(a)



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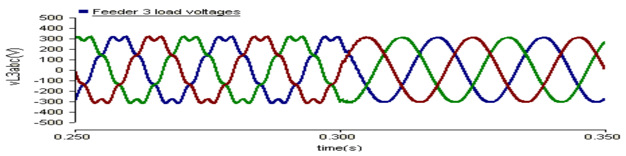


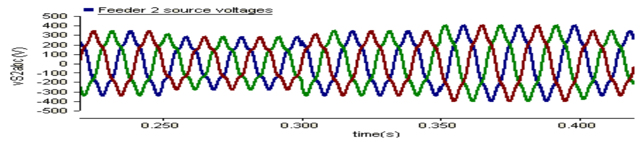
(c)

Fig. 10 Feeder3 voltages: (a) supply (b) compensation (c) load

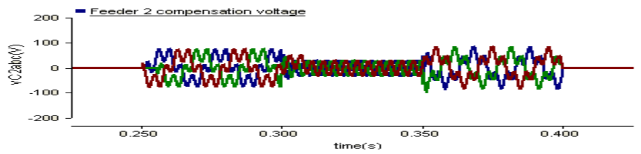
The THD of load voltages of feeder2 and feeder3 are reduced from 10.28 % to 0.86 % and 0.24 %, respectively, by the series compensators. Thus a significant improvement in the frequency spectrum and THD after compensation is clearly demonstrated by GUPQC.

B. Compensation of voltage harmonics, voltage sag/swell

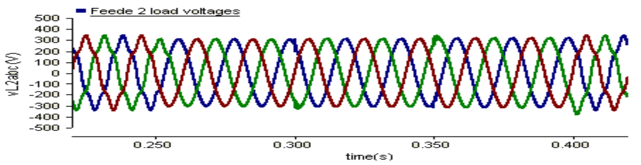
In this case study, the supply voltage of feeder2 is distorted by introducing a 5th harmonic voltage, a 20 % voltage sag from 0.25 s to 0.3 s and a 20 % voltage swell from 0.35 s to 0.4 s as in Fig. 11(a). In order to compensate source voltage harmonics, voltage sag/swell of feeder2, the series compensator injects corresponding voltages in feeder2 as in Fig. 11(b). It is to be noted that by these injected voltages, the voltage imperfections are minimized and the load voltage of feeder2 is maintained free from harmonics and at the desired level as in Fig. 11(c). Similarly the supply voltage of feeder3 is also subjected to voltage distortions as in Fig. 12(a) by introducing a 7th harmonic voltage, a 20 % voltage swell from 0.3 s to 0.35 s and a 20 % voltage sag from 0.40 s to 0.45 s. Fig. 12(b) shows the simulation results of corresponding compensation injected voltages by VSC2 and the resultant sinusoidal load voltage in feeder3 as in Fig. 12(c).



(a)

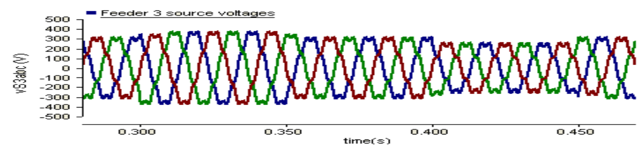


(b)

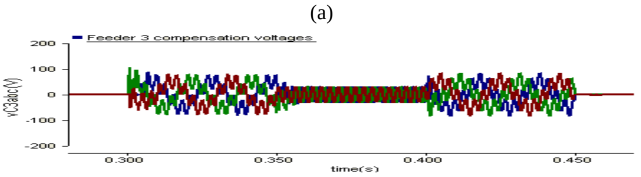


(c)

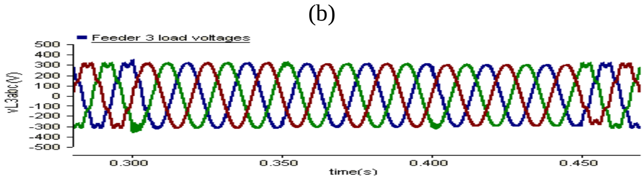
Fig. 11 Feeder2 voltages: (a) supply (b) compensation (c) load



(a)



(b)

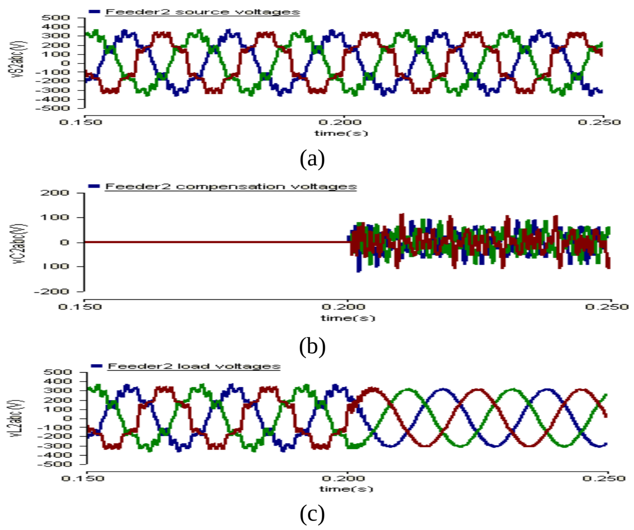


(c)

Fig. 12 Feeder3 voltages: (a) supply (b) compensation (c) load

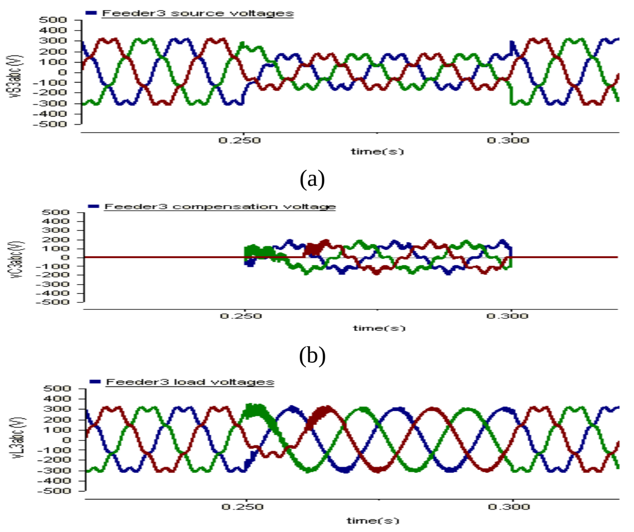
C. Compensation of high voltage harmonics and voltage sag

In this case study highly distorted harmonic voltage sources (5th - 9.5 %, 7th - 11%, 11th - 9.2%, 13th - 7.1%, 19th - 8.4%) are connected in series with the supply voltages v_{S2} of feeder2. The simulation results for three-phase supply, compensation and load voltages of feeder2 are shown in Figs. 13(a) to (c), respectively. It is to be noted that by injecting compensation voltage by VSC2, the load voltage is effectively established as sinusoidal after 0.2 s. Similarly the supply voltage of feeder3 is also distorted by introducing a 7th harmonic voltage and 50 % voltage sag from 0.25 s to 0.3 s. Figs. 14(a) to (c) illustrate simulation results of the supply voltage, injected voltage by VSC3 and resultant load voltage of feeder3 during the interval 0.25 s to 0.35 s.



(a) (b) (c)

Fig. 13 Feeder2 voltages: (a) supply (b) compensation (c) load



(a) (b) (c)

Fig. 14 Feeder3 voltages: (a) supply (b) compensation (c) load

It is evident from the simulation case study results that the proposed GUPQC successfully compensated current/voltage harmonics in three-feeder distribution system by injecting corresponding current/voltage signals. Also voltage sag/swell mitigation in feeder2 and feeder3 is effectively managed by the series compensators of GUPQC by injecting corresponding voltage and achieving nearly sinusoidal load voltage.

VI. Conclusions

A new custom power device named as GUPQC based on three single-phase three-level VSCs is designed to mitigate current and voltage harmonics, to compensate reactive power and to improve voltage regulation. The compensation performance of shunt and a novel series compensator are established by the simulation results on a three-feeder, multi-bus distribution system. The proposed GUPQC can accomplish various compensation functions by increasing the number of VSCs. The GUPQC is expected to be an attractive custom power device for power quality improvement of multi-bus/multi-feeder distribution systems in near future.

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