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Power Flow Control of a Multi-bus/Three-feeder Distribution System Using Generalized Unified Power Quality Conditioner

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Abstract – This paper analyses the power flow of a three-feeder/multi-bus distribution system by a custom Generalized Power Quality Conditioner (GUPQC). The GUPQC has been realized by three voltage source converters (VSCs) coupled back-to-back through a common DC-link capacitor on the DC-side. One feeder was controlled by the shunt compensator, whereas each of the other two feeders was controlled by the proposed novel series compensator. The GUPQC has the capability to simultaneously compensate voltage and current quality problems of a multi-bus/three-feeder distribution system. Besides that, the power can be transferred from one feeder to other feeders to compensate for poor power quality problems. Extensive simulation studies were carried out by using MATLAB/SIMULINK software to establish the ability of the GUPQC to improve power quality of the distribution systems under distorted supply voltage conditions.

Keywords: Voltage source converter, Shunt and series compensators, GUPQC, Power quality

1. Introduction

The Smart Grid concept and its implementation have a significant influence on the modern multi-feeder distribution system. Power quality (PQ) is the major concern of the distribution system users concerning the application of sensitive critical loads. At the same time, fully sinusoidal voltage and currents with a constant frequency are mandatory in same industrial sectors for the proper production process. The reliability of the operation of sensitive critical loads which does not tolerate disturbances in the supply system is essentially based on power supply quality. By integrating power electronic converters-based custom power devices in the existing distribution supply systems, it is possible to supply undistorted high quality power to sensitive loads in industrials or commercial centers. In order to overcome the PQ related problems, a unified power quality conditioner (UPQC) [1-3], by using series and shunt active power filters has been proposed to mitigate voltage and current imperfections in a single-feeder distribution system. Unfortunately, the UPQC cannot provide power quality solutions for multi-bus/multi-feeder distribution systems.

Based on the concept and applications of the flexible AC transmission systems (FACTS), devices in transmission lines the concept of the interline power flow controller (IPFC) and the generalized unified power flow controller (GUPFC) [4, 5] can be extended to the multi-bus/multi-feeder distribution systems. Along the same lines, extended version of the transmission line IPFC called as an interline unified power quality conditioner (IUPQC) consisting of two VSCs, one in the shunt to regulate the bus voltage of the one feeder in distribution system and the other in the series to regulate the voltage across a sensitive load of the other feeder, was proposed in [6]. A multi-converter unified power quality conditioner (MC-UPQC) having three VSCs connected back-to-back through a common DC-link capacitor was reported in [7] to compensate for both the current and voltage imperfections in one feeder and the voltage imperfections in the other feeder.

Extended version of transmission line GUPFC is proposed in [8] for PQ improvement of a multi-bus/three-feeder distribution system called, GUPQC which was realized by three VSCs connected back-to-back by a common DC-link capacitor on the DC side. By coupling three VSCs in back-to-back configurations the GUPQC can be operate with more flexibility and allow the active power to circulating from one VSC to the other to improve PQ of three-feeder/multi-bus distribution system. To benefit from the exchange of power between the feeders, one of the VSCs in the GUPQC system was 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 series injection transformers.

By this connection, the proposed GUPQC will simultaneously compensating voltage and current imperfections in multi-bus/three-feeder DS. Besides that, the power can be transferred from one feeder to other feeders to compensate for voltage and current quality problems of the system.

This present paper has addressed the power flow analysis and compensation performance of the GUPQC connected to a multi-bus/three-feeder distribution system based on

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the proposed new controller strategy for series compensators. The paper is organized as follows; the GUPQC model and the power flow analysis are described in section 2 and 3, respectively. The proposed controller strategy is illustrated in section 4. The simulation results are presented in section 5. Section 6 presents the conclusions.

2. GUPQC Topology

A multi-bus / three-feeder distribution system which supplies a sensitive nonlinear load (load1) by feeder1 and two other sensitive loads (load2 and load3) connected to the other two feeders is shown in Fig. 1(a). Each feeder is represented by the equivalent impedance which denoted by Z_S. The shunt compensator, VSC_1 is operates as a controlled current source which employed to compensate the harmonic currents of feeder1, the reactive power required by the load1 and to support the real power required by the two series compensators. At the same time, the DC-link capacitor voltage is to be maintained at a desired level.

The two series compensators, VSC_2 and VSC_3, are used as controlled voltage sources to protect the two sensitive loads (load2 and load3) against voltage imperfections. Each of the series compensators is designed to provide the missing voltage between the supply side and the ideal load side voltages such that the load bus voltage of the respective feeder is always sinusoidal and at desired level. In Fig. 1, v_{Sn}, v_{Tn}, v_{Ln}, v_{Cn} are the supply, terminal, load, and compensation voltages respectively, and i_{Sn}, i_{Ln}, i_{Cn} are the supply, load and compensation currents respectively, while the subscript n is for the feeder index. Each VSC in Fig. 1 consists of three single-phase H-bridge converters supported by a common DC-link bus voltage as illustrate in section 4. The AC side of the shunt compensator, VSC_1 is connected to the distribution system through a commutation reactor and a single-phase transformer, while the AC side of each of the series compensators, VSC_2 or VSC_3, is connected to the distribution system through a series injection transformer and L-C filter which is used to prevent the flow of switching harmonics into the distribution system. The selection of L and C was based on the technique presented in [9].

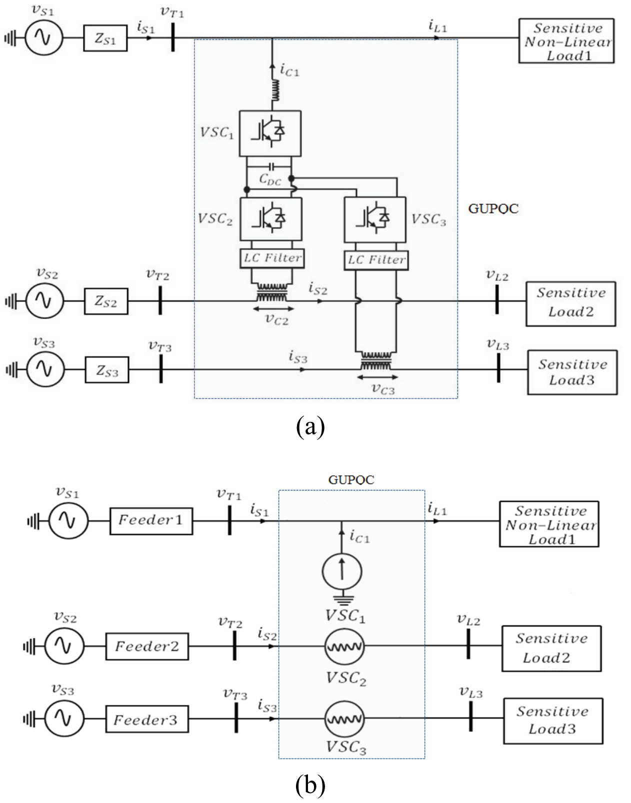


Fig. 1. GUPQC connected to multi-bus/three-feeder distribution system (a) Typical model (b) Equivalent circuit

3. Power Flow Analysis

The power flow analysis was carried out under normal and disturbed conditions of the feeders based on the fundamental components of voltage and current. Based on Fig. 1(b) by considering the lagging power factor loads on the feeders, the load voltages and currents can be written as shown in (1) and (2) respectively:

$$\overline{v}_{Ln} = V_{Ln}\angle 0^{\circ} \tag{1}$$

$$\overline{i}_{Ln} = I_{Ln}\angle -\varphi_{Ln} \tag{2}$$

where, the feeder index n =1, 2, or 3. In case of system voltage sag/swell etc., the source voltage fluctuation factor, x_n can be defined by (3).

$$x_n = \frac{V_{Sn} - V_{Ln}}{V_{Ln}} \tag{3}$$

Then, the injected voltage by the series compensators can be calculated by (4).

$$\overline{v}_{Cn} = \overline{v}_{Ln} - \overline{v}_{Sn} = -x_n V_{Ln}\angle 0^{\circ} \tag{4}$$

Under consideration of the lossless power of GUPQC system, the active power demanded by the loads should be equal to the active power supplied by the sources. Then, the system active power is expressed by using equation (6):

$$V_{Sn} I_{Sn} = V_{Ln}\left(1 + x_n\right) I_{Sn} = V_{Ln} I_{Ln} \cos\varphi_{Ln} \tag{6}$$

Thus, the source current becomes:

$$I_{Sn} = \frac{I_{Ln}}{\left(1 + x_n\right)} \cos\varphi_{Ln} \tag{7}$$

From (7) both I_{Ln} and φ_{Ln} are constant for a particular type of load. Thus, the source current depends on the source voltage fluctuation factor, x_n. If the supply side voltage of feeder2 or feeder3 is subjected to the voltage sag / swell etc., the feeder1 source current can be expressed as:

$$\begin{aligned} I_{S1} = \frac{I_{L1}}{\left(1+x_1\right)}\cos\varphi_{L1} - \frac{x_2 V_{L2} I_{L2}}{\left(1+x_1\right)V_{L1}}\cos\varphi_{L2} \\ - \frac{x_3 V_{L3} I_{L3}}{\left(1+x_1\right)V_{L1}}\cos\varphi_{L3} \end{aligned} \tag{8}$$

Based on Fig. 1(b), the compensation current by the shunt compensator which includes active and reactive current components can be expressed by (9):

$$\bar{i}_{C1} = I_{S1} - I_{L1}\angle -\varphi_{L1} = \left(I_{S1} - I_{L1}\cos\varphi_{L1}\right) + j\left(I_{L1}\sin\varphi_{L1}\right) \tag{9}$$

Then, the complex power of the shunt compensator is:

$$\begin{aligned} S_{VSC_1} &= \bar{v}_{L1}\bar{i}_{C1} \\ &= V_{L1}\left(I_{S1} - I_{L1}\cos\varphi_{L1}\right) + jV_{L1}I_{L1}\sin\varphi_{L1} \end{aligned} \tag{10}$$

$$P_{VSC_1} = V_{L1}\left(I_{S1} - I_{L1}\cos\varphi_{L1}\right) \tag{11}$$

$$Q_{VSC_1} = V_{L1}I_{L1}\sin\varphi_{L1} \tag{12}$$

Similarly, the complex power absorbed by each of the series compensators can be expressed as:

$$\begin{aligned} S_{VSC_{2,3}} &= \bar{v}_{Cn}\bar{i}_{Ln}\angle -\varphi_{Ln} \\ &= -x_n V_{Ln} I_{Ln}\cos\varphi_{Ln} + jx_n V_{Ln} I_{Ln}\sin\varphi_{Ln} \end{aligned} \tag{13}$$

Feeder2 compensator, VSC_2, active and reactive powers:

$$P_{VSC_2} = -\,x_2 V_{L2} I_{L2}\cos\varphi_{L2} \tag{14}$$

$$Q_{VSC_2} = x_2 V_{L2} I_{L2}\sin\varphi_{L2} \tag{15}$$

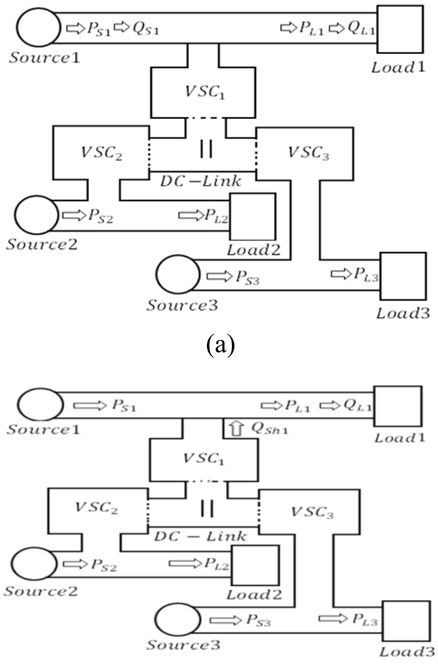
Feeder3 compensator, VSC_3, active and reactive powers:

$$P_{VSC_3} = -x_3 V_{L3} I_{L3}\cos\varphi_{L3} \tag{16}$$

$$Q_{VSC_3} = x_3 V_{L3} I_{L3}\sin\varphi_{L3} \tag{17}$$

Based on the above active and reactive power equations, the power flow in the three feeders an analysis was carried out in the following case studies to show the ability of the GUPQC to maintaining the overall power balance in a multi-bus/three-feeder distribution system.

Case 1: In the normal operation condition of most of the distribution systems, the utility supplied the load active and reactive power demand, which puts an extra burden on the source to supply the load reactive power as seen in Fig. 2(a). As the GUPQC comes into the operation, and under assumption of, $x_2 = x_3 = 0$, i.e. $V_{Sn} = V_{Ln}$ based on (12), (14) and (16), $Q_{VSC_1} = Q_{L1} = Q_{sh1}$ and $P_{VSC_2} = P_{VSC_3} = 0$ which means that the reactive power required by sensitive nonlinear load1, is supplied by the shunt compensator such that no extra reactive power burden is put on the source1 during the voltage imperfections in feeder2 or feeder3. Fig. 2(b) shows the power flow in this case.



(a)

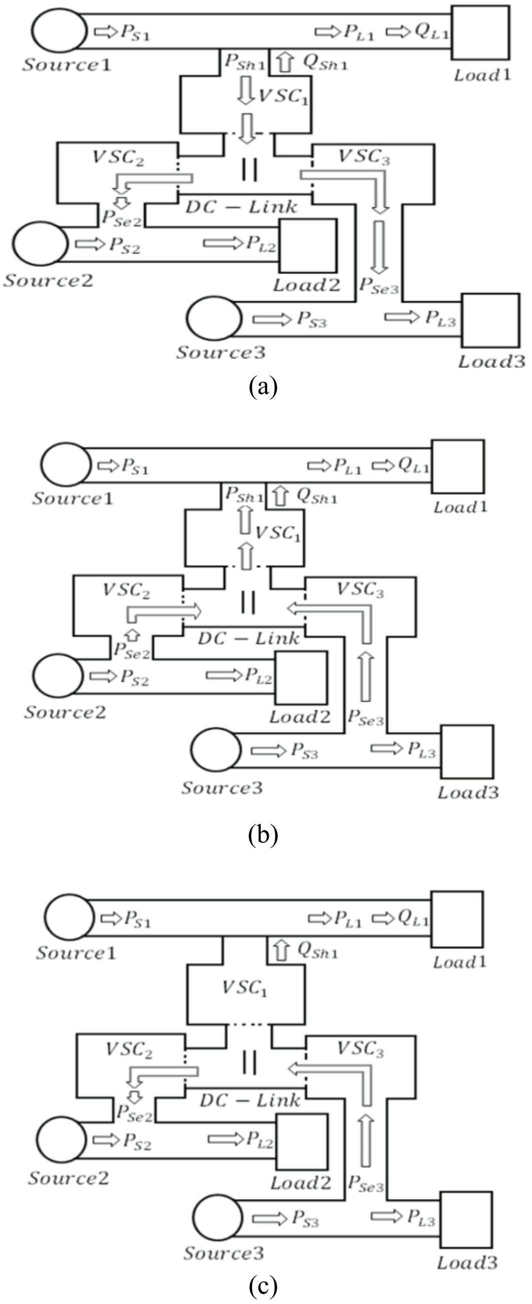
(b)

Fig. 2. Normal operation condition: (a) GUPQC-OFF; (b) GUPQC-ON

Case 2: In this case, the power required by the load2 and load3 are assumed to be higher than the source capacities, such that, $x_2 < 0; x_3 < 0$, i.e. $V_{S2} < V_{L2}$; $V_{S3} < V_{L3}$. These conditions are possible during the supply system2 and supply system3 voltage sag. The active powers of feeder2 and feeder3 based on (14) and (16) become, $P_{VSC_2} > 0$; $P_{VSC_3} > 0$, this means that each of the series compensators is required to supply additional active power to the corresponding load to compensate for the source side voltage sag. It can be observed from (8) that, the feeder1 source side current increased above the normal rated current to maintain the DC-link voltage at the desired level or to maintain a power balance in the system. Fig. 3(a) represents the power flow in this case.

Case 3: In this case, the power supplied by the source2 and source3 to the sensitive load2 and sensitive load3, respectively, are assumed to be higher than the power demanded by two the loads such that, $x_2 > 0$; $x_3 > 0$ i.e. $V_{S2} > V_{L2}$; $V_{S3} > V_{L3}$. These conditions are possible during the supply voltage swell. The active power of feeder2 and feeder3 based on (14) and (16) becomes, $P_{VSC_2} < 0$; $P_{VSC_3} < 0$, which means that the series compensators in feeder2 and feeder3 absorbed the extra active power from the source sides to compensate for the voltage swells. It can be observed from (8) that the feeder1 source side current decreased below the normal rated current to maintain the DC-link voltage at the desired level or to maintain a power balance. Fig. 3(b) shows the power flow in this case.

Case 4: In this case, the power required by the sensitive load2 is assumed to be higher than the source capacity $x_2 < 0$, i.e. $V_{S2} < V_{L2}$ (voltage sag), and the power supplied by the source3 to the sensitive load3 is higher than the power demanded by the load (voltage swell), $x_3 > 0$, i.e. $V_{S3} > V_{L3}$. Based on (14) and (16), the active powers of the two feeders become, $P_{VSC_2} > 0$; $P_{VSC_3} < 0$, which means that the series compensator of feeder2, in this case, supplied active power to the load2 to compensate for the voltage sag whereas the series compensator of feeder3 absorbed the source extra active power to compensate for the voltage swell. It can be observed from (8) that, the feeder1 source side current did not change and the power required by the load2 is supplied by the series compensator of feeder3 through the DC-link capacitor, such that the overall power is balanced. Fig. 3(c) shows the power flow in this case.



(a)

(b)

(c)

Fig. 3. GUPQC-ON: (a) Voltage Sag condition; (b) Voltage swell condition; (C) Voltage Sag/swell condition

4. Control OF GUPQC

Different controller strategies to control the series and shunt compensators of the UPQC have been proposed as presented in [10-13]. Most of the proposed controllers are used to detect voltage or current disturbances under steady state conditions. However, under dynamic operation conditions, a few of them showed good response but too complex to implement. This is because a significant computing time is required to implement. In this paper, the estimation of the reference signals for the series compensator of GUPQC has been calculated based on the synchronous reference frame transformation. While for the shunt compensator, the generalized non-active power theory (GNPT) [14, 15] has been used to estimate the reference compensation currents.

The reference compensation signals to control the GUPQC series compensators were derived by using the proposed method based on the synchronous reference frame. The proposed series compensator controller was used to control the GUPQC in order to inject in-phase voltage with the source side current. This was done to ensure that the sensitive loads (load 2 and load 3) received pure sinusoidal voltage with constant amplitude and frequency even when the supply side voltage of the two feeders was either completely distorted or subjected to the voltage sag/swell or interruptions. To realize the proposed series compensator controller algorithm, only the *d*-axis voltage in the synchronous rotating frame was considered, and given a unity value. Both *q* and *0* axis components were equalized to zero. By applying *d-q-0* to *a-b-c* transformation under this assumption, three-phase balanced unity sinusoidal voltages were generated as shown in (18).

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(\omega t) & \cos(\omega t) & 1 \\ \sin\left(\omega t - 120^\circ\right) & \cos\left(\omega t - 120^\circ\right) & 1 \\ \sin\left(\omega t + 120^\circ\right) & \cos\left(\omega t + 120^\circ\right) & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \tag{18}$$

From the generated sinusoidal voltages in (18), and by using the maximum voltages of load2 or load3, the desired load2 or load3 voltages were derived as shown (19) to (21).

$$v_{La}^{*} = u_a \cdot V_{L\max} = V_{L\max}\sin\left(\omega t\right) \tag{19}$$

$$v_{Lb}^{*} = u_b \cdot V_{L\max} = V_{L\max}\sin\left(\omega t - 120^{\circ}\right) \tag{20}$$

$$v_{Lc}^{*} = u_c \cdot V_{L\max} = V_{L\max}\sin\left(\omega t + 120^{\circ}\right) \tag{21}$$

The reference compensation voltages were obtained by comparing the measured distorted feeder2 and feeder3 source side voltages with the desired load side voltages as:

$$v_{Ca}^{*} = v_{Sa} - v_{La}^{*} \tag{22}$$

$$v_{Cb}^{*} = v_{Sb} - v_{Lb}^{*} \tag{23}$$

$$v_{Cc}^{*} = v_{Sc} - v_{Lc}^{*} \tag{24}$$

In order to generate adequate gating patterns to activate the IGBT switches of the GUPQC series compensators, the calculated reference voltages (22) to (24) were compared with the measured actual series compensator output voltages while the error signal was processed using the improved sinusoidal pulse width modulation (SPWM) technique as shown in Fig. 4(a). The implementation of this controller scheme in the MATLAB/SIMULINK platform is shown in Fig. 4(b).

The estimation of the reference compensation signals for the GUPQC shunt compensator was based on the GNPT as illustrated in Fig. 5. The voltage and current vectors in *m*-phase systems can be define by (25) and (26):

$$i\left(t\right) = \left[i_1\left(t\right), i_2\left(t\right), \ldots i_m\left(t\right)\right]^T \tag{25}$$

$$v\left(t\right) = \left[v_1\left(t\right), v_2\left(t\right), \ldots v_m\left(t\right)\right]^T \tag{26}$$

Based on GNAPT theory, the instantaneous power, *p(t),*and the average power *P(t),* over the averaging interval [*t-T*$_C$*, t*] could be calculated as:

$$p\left(t\right) = v^T\left(t\right) i\left(t\right) = \sum_{k=1}^{m} v_k\left(t\right) i_k\left(t\right) \tag{27}$$

$$P\left(t\right) = \frac{1}{T_C}\int_{t-T_C}^{t} p\left(\tau\right) d\tau \tag{28}$$

The selection procedure of the averaging interval, (T_c) was based on the application of GNPT as explained in [14, 15]. Based on the GAPT, the current component that carries the active power and in-phase with the voltage is known as the active current, $i_a(t)$. Both the instantaneous active current and non-active current, $i_n(t)$, are defined as:

$$i_a\left(t\right) = \frac{P\left(t\right)}{V_a^2\left(t\right)} v_a\left(t\right) \tag{29}$$

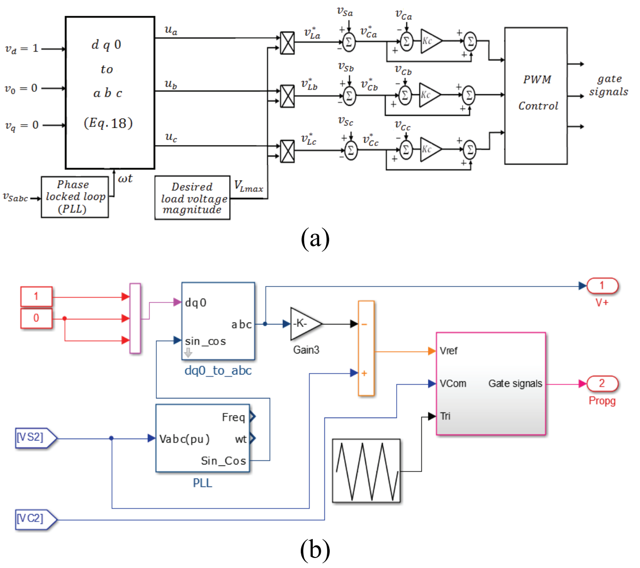
$$i_n\left(t\right) = i\left(t\right) - i_a\left(t\right) \tag{30}$$

Thus, the instantaneous active power, $p_a(t)$ and instantaneous non-active power, $p_n(t)$ could be defined as:

$$p_a\left(t\right) = v^T\left(t\right) i_a\left(t\right) = \sum_{k=1}^{m} v_k\left(t\right) i_{ak}\left(t\right) \tag{31}$$

$$p_n\left(t\right) = v^T\left(t\right) i_n\left(t\right) = \sum_{k=1}^{m} v_k\left(t\right) i_{nk}\left(t\right) \tag{32}$$

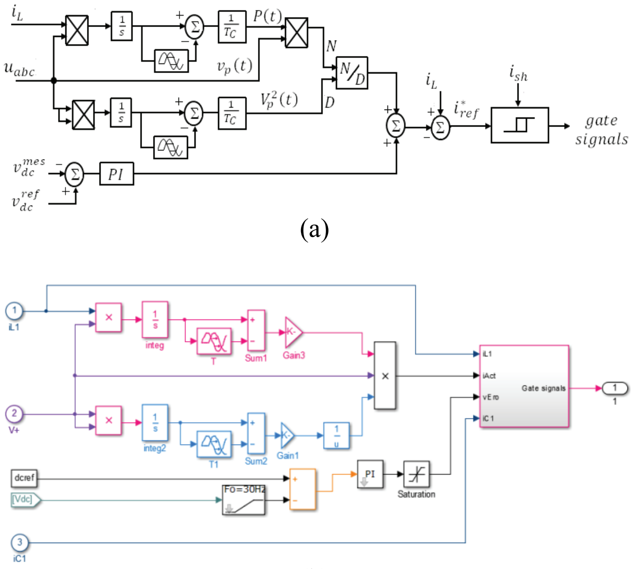
Similarly, the corresponding average active power, $P_a(t)$, and the average non-active power, $P_n(t)$, over an averaging interval [*t-T*$_C$*, t*] are calculated as:



(a)

(b)

Fig. 4. Proposed control scheme of the series compensator: (a) block diagram; (b) MATLAB/SIMULINK model



(a)

(b)

Fig. 5. Control scheme of the shunt compensator: (a) block diagram; (b) MATLAB/SIMULINK model

$$P_a(t)=\frac{1}{T_C}\int_{t-T_C}^{t} p_a(\tau)\,d\tau \tag{33}$$

$$P_n(t)=\frac{1}{T_C}\int_{t-T_C}^{t} p_n(\tau)\,d\tau \tag{34}$$

The *RMS* values of the voltage, $v_a(t)$, as well as the active current, $i_a(t)$, and the non-active current, $i_n(t)$, have been defined, respectively, as:

$$V_a(t)=\sqrt{\frac{1}{T_C}\int_{t-T_C}^{t} v_a^T(\tau)v_a(\tau)\,d\tau} \tag{35}$$

$$I_a(t)=\sqrt{\frac{1}{T_C}\int_{t-T_C}^{t} i_a^T(\tau)i_a(\tau)\,d\tau} \tag{36}$$

$$I_n(t)=\sqrt{\frac{1}{T_C}\int_{t-T_C}^{t} i_n^T(\tau)i_n(\tau)\,d\tau} \tag{37}$$

In proposed controller of GUPQC shunt compensator as shown in Fig. 5, firstly, the average power is calculated using (28) with the help of the unity voltages (u_a, u_b, u_c) which are generated from the series compensator control as in (18). The calculated average power, together with the *RMS* value of the load voltage (35) are used to calculated the active current component, $i_a(t)$, based on (29). The shunt compensator is employed to compensate for current distortions, provide the reactive power required by the load1, support the real power required by the series compensators and to maintain the DC-link capacitor voltage at a desired level. To achieve these objectives, the voltage of the DC-link capacitor was measured and compared with the reference value while the error signal was processed by using *PI* controller. The output of the *PI* controller alongside with the estimated active current component was used to calculate the non-active currents components $i_n(t)$, based on (30) which representing the reference compensating currents for the shunt compensator.

The calculated reference compensating currents together with the measured actual shunt compensator output current were then processed by using the hysteresis band PWM controller to generate the gating signals for the shunt compensator IGBTs switches. The implementation of this controller scheme in the MATLAB/SIMULINK platform is depicted as in Fig. 5(b).

5. Simulation Results

In order to verify the performance and the effectiveness of the proposed series compensator controller beside the power flow through the GUPQC a comprehensive simulations studies have been carried out with the help of MATLAB/SIMULINK. The simulation model of GUPQC test model in MATLAB/SIMULINK platform is illustrated as in Fig. 6. The system parameters considered for the simulation is listed in the Table. 1.

Figs. 7(a) to 7(c) represented the load, compensation and the source side currents of feeder1. As the sensitive nonlinear load1 is a combination of linear and non-linear loads, initially the linear part was connected to the system. The shunt compensator was put into the operation at t_1= 0.10*s* as seen in Fig. 7(b) and immediately started injecting the compensation currents, i.e., non-active current component. As a result of this, the source side current as seen in Fig. 7(c) decreased because certain parts of the load

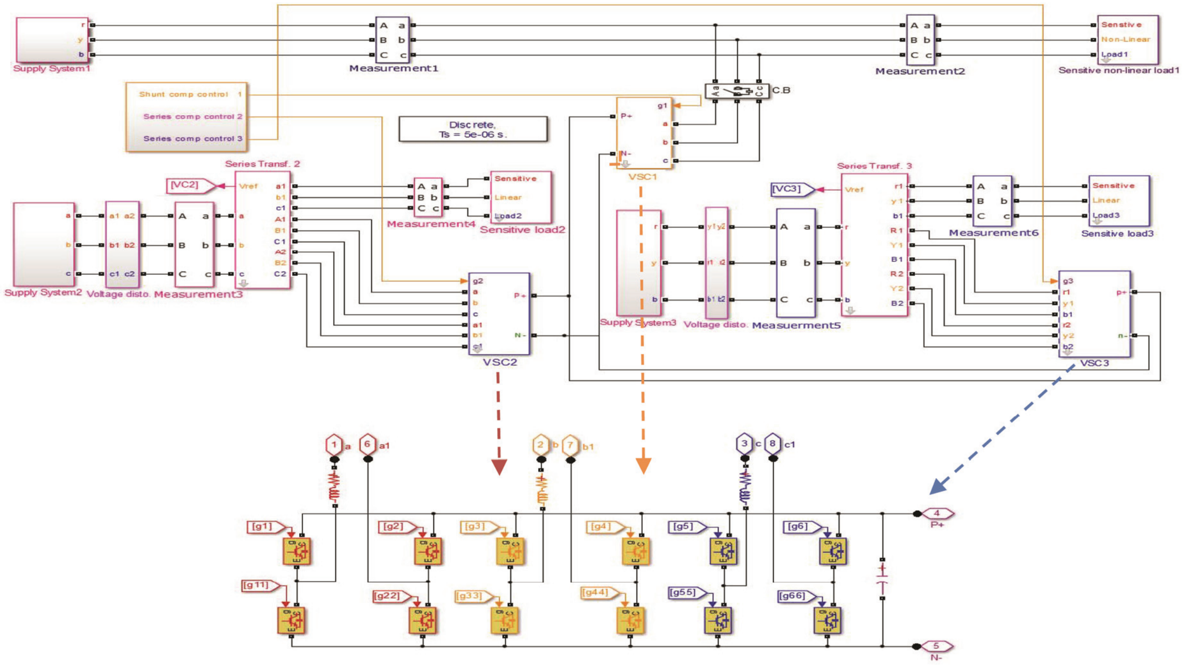
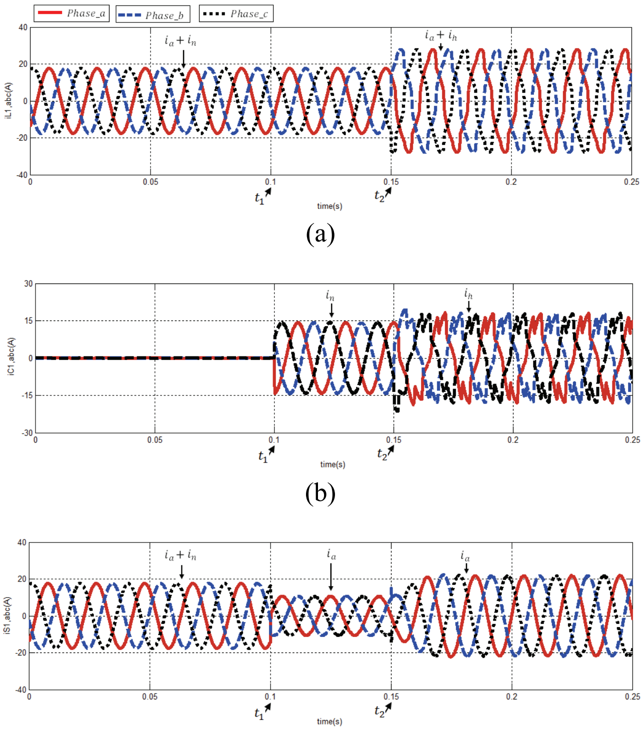


Fig. 6. Simulation model of GUPQC connected to three-feeder/multi-bus system in MATLAB/SIMULINK platform

Table 1. GUPQC Simulation parameters

Parameter		Value
Supply voltage of the three feeders		380 V (L-L) 50 Hz
Feeder1 load	linear load	R_{L11} = 10.50 Ω L_{L11} = 88.1 mH
	Non-linear load (diode bridge rectifier followed by R-L load)	R_{L12} = 55.00 Ω L_{L12} = 12.5 mH
Feeder2, sensitive load2		R_{L2} = 45.00 Ω L_{L2} = 10.0 mH
Feeder3, sensitive load3		R_{L3} = 26.00 Ω L_{L3} = 98.0 mH
DC-link capacitor		C_{DC} = 2540 μf 750.00 V



(a)

(b)

(c)

Fig. 7. Feeder 1 currents: (a) load side; (b) compensation; (c) source side

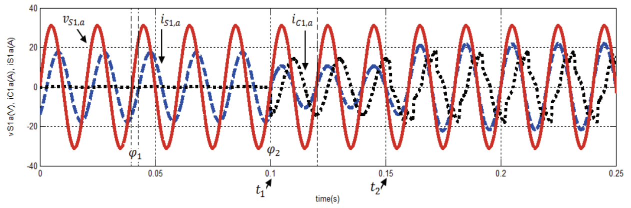
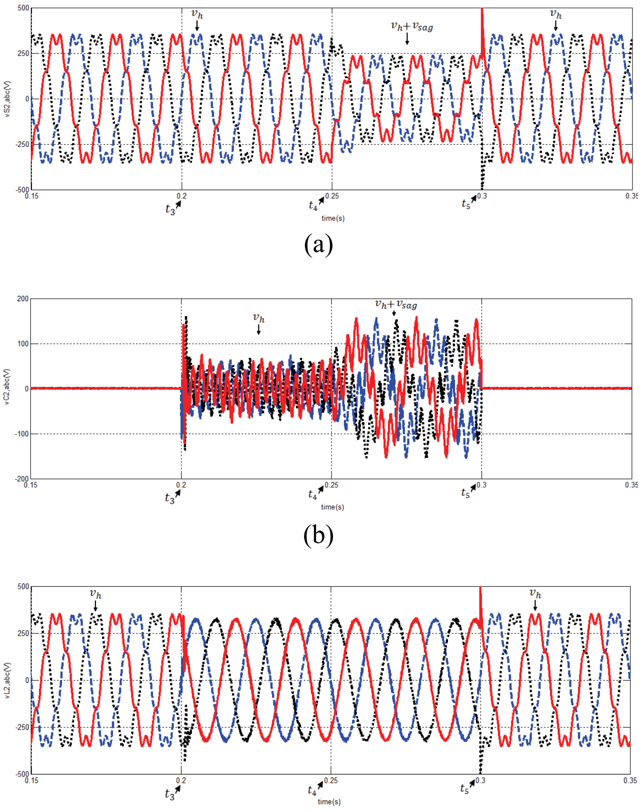


Fig. 8. Feeder 1 source voltage, source side current and compensation current



(a)

(b)

(c)

Fig. 9. Feeder 2 voltages: (a) source; (b) compensation; (c) load

non-active currents component were supplied by the shunt compensator. It can be seen from Fig. 8 that the load power factor was improved to unity from $t_1 \geq 0.10s$.

To compensate for current harmonics, the non-linear part of the sensitive nonlinear load1 was connected at $t_2 = 0.15s$. The shunt compensator, in this case injected the required compensating current components i.e. the non-active current component (i_n) plus harmonic components (i_h). The resultant source side current profile was transferred to sinusoidal from and balanced as seen in Fig. 7(c).

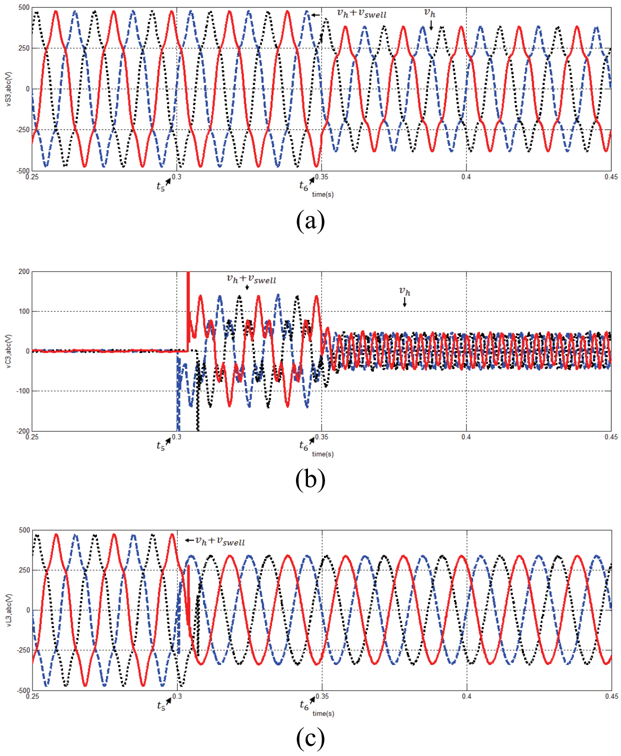
The total harmonic distortion (THD) of the load side currents before compensation was observed to be 26.54 %. After the compensation process was started, the source side current THD was significantly reduced to 1.65 %. It is to be noted that the shunt compensator of GUPQC have an appreciable effect as a harmonic filter, which prevented the sensitive nonlinear load1 harmonics from flowing into the supply side of the distribution feeder. This in turn protected the other consumers connected to the same feeder from the load side current distortions.

In order to show the effectiveness of the proposed controller scheme of the series compensator under distorted supply voltage conditions, the source side voltage of feeder2 was distorted by introducing a 7th harmonic voltage source beside a 20 % voltage sag during time interval from $t_4 = 0.25s$ to $t_5 = 0.30$ s, as seen in Figs. 9(a) to 9(c). The corresponding load and source side voltages of feeder2 were distorted completely. As the series compensator of GUPQC injected the desired compensating voltage at $t_3 = 0.20$s, the bus voltage of the sensitive load2 resulted in being nearly sinusoidal. At the initiation of the voltage sag the series compensator injected the harmonic as well as the voltage sag components, such that the bus voltage of the sensitive load2 was restored to the desired value as seen in Fig. 9(c). The THD level of the source and load voltages was recorded to be 12.23 % and 1.253 %, respectively.

Similarly, a simulation was carried out for feeder3 by introducing a 5th harmonic voltage source and voltage swell. The feeder was under 30 % voltage swell before $t_6 = 0.35s$, Figs. 10(a) to 10(c) represented the corresponding source side voltage, injected and load side voltage of feeder3. The series compensator of GUPQC response rapidly and injected the swell compensation voltage, first, and then, the harmonic component as seen in Fig. 10(b). Due to the injection voltage, the bus voltage of the sensitive load3 was effectively maintained harmonic free and at the desired level as seen in Fig. 10(c). Thus, the effectiveness of the series compensator to detect the voltage swell and to inject the compensating voltages is clearly demonstrated. The THD of the load side voltage was reduced from 26.50 % to 0.7756 % by the series compensator of feeder3.

It is interesting to note that the distortion of the supply voltages besides the voltage sag/swell was compensated with excellent compensating characteristics of the GUPQC based on the proposed controller. The response of the shunt compensaor to the changes in the system voltages (power flow) was presented as in Figs. 11 and 12 in terms of the source side current of feeder1 and DC-link capcitor voltage.

Based on Figs. 11 and 12 before $t_1 = 0.10s$ the load1 active and reactive powers were supplied by the source which puts an extra burden to the source to supply reactive power. From $t_1 = 0.10s$ the reactive power required by the load1 was supplied by the shunt compensator such that no reactive power burden was put on the source. From $t_4 = 0.25s$ to $t_5 = 0.30s$ the series compensator in feeder2 supplied the active power to the load2 to compensate for voltage sag. The source side current of feeder1 increased to more than the normal rated current to maintain the DC-link voltage at the desired level. From $t_5 = 0.30s$ to $t_6 = 0.35s$ the series compensator of feeder3 absorbed the extra active power of the source3 to compensate for the voltage swell. The shunt compensator decreased the source current of feeder2 in this case to less than the normal rated current to maintain the DC-link voltage at the desired level or to maintain the power balance in the system.



(a)

(b)

(c)

Fig. 10. Feeder 3 voltages: (a) supply; (b) compensation; (c) load

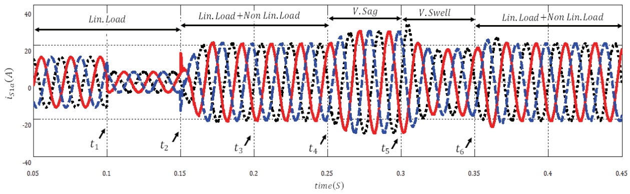


Fig. 11. Supply side current of feeder1

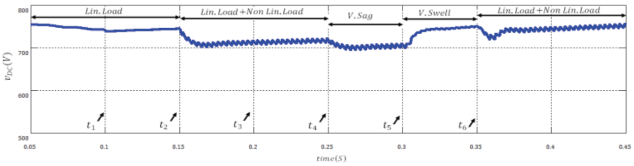


Fig. 12. DC-link capacitor voltage

6. Conclusion

In this paper the power flow analysis through the GUPQC connected to the multi-bus/three-feeder distribution systems was carried out. A new controller scheme for the series compensator of GUPQC based on the *d-q* theory to compensate for the source side voltage harmonics, voltage sag/swell and interruption was presented. The application of the proposed controller to compensate for voltage imperfections of the network and for the improvement of the power quality of the customer loads was validated by the simulation results. It has also been demonstrated that the shunt compensator based on the developed controller effectively maintained the power balanced beside the DC-link capacitor at the desired level.

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