Chapter 6

PQ Compensation using Unified Power Quality Conditioner

Introduction

The major power quality problems in the MG are mainly based on voltage quality and current quality. These problems include the voltage sag/swell, flicker, unbalance, reactive power flow, harmonics in currents and voltages, and an flow of neutral current as discussed previously. The existing survey offers the solution to a few among the fore mentioned PQ problems either related particularly to voltage or current. However, the increase in the sensitivity of the distribution system equipment demands a fast-acting multitasking device that offers compensation considering both simultaneously. The device, unified power quality conditioner (UPQC) is identified as a single solution to multiple PQ issues mentioned above. The UPQC, a combination of shunt and series APFs provides compensation to both current and voltage related issues. The series compensator of UPQC deals with all voltage related issues whereas shunt compensator takes care of current related issues. The series and shunt APFs are replaced by enhanced DVR and DSTATCOM as discussed in the previous chapter. Hence, this chapter presents a detailed analysis and design of enhanced UPQC in providing power quality compensation.

6.0.1 State of the Art on Unified Power Quality Conditioner

A UPQC, which is a combination of shunt and series active power filters, is proposed as a single solution for many PQ issues. The concept of hybrid active filtering was introduced by Akagi [158, 167, 168]. UPQC, a hybrid filter is the upgraded configuration of APF technology and hence termes as universal active filter [169–173]. UPQC is a multifunction power conditioner that can be used to compensate various voltage disturbances of the power supply. The device, UPQC consists of two VSCs joined back to back by a common DC link and designed for single-phase, three-phase three-wire, or three-phase four-wire configurations. UPQC provides current and voltage compensation by means of its shunt and series APFs. All the PQ issues mitigated by the two CPDs are compensated together by using a single multitasking device. The series and shunt APF of UPQC provide compensation based on the control objective(s) and provide multiple problem compensations. They are controlled separately for PQ enhancement in the current by shunt APF and voltage by series APF. There different control techniques and topologies of UPQCs in conventional distribution systems are mentioned in [174, 175]. UPQC employed with energy storage is discussed in [158]. The instantaneous reactive power theory [158], SRF theory [171], and instantaneous symmetrical component theory [176], are the few control techniques presented in the literature. The 3P4W systems require a neutral current compensation in addition to other PQ issues compensation. A novel structure for a 3P4W distribution system utilizing a UPQC is presented in the literature [177] and the control approaches are mentioned in the [178]. The single-phase p-q theory for single-phase loads compensation is proposed in [161] with both direct and indirect current control techniques to mitigate current harmonics in the conventional distribution system. A comprehensive overview of a UPQC for enhancing electric power quality has been presented in [179]. Extraction of fundamental and/or harmonic components present in the nonlinear load currents for shunt APF using advanced ANN techniques is presented in [113]. A scheme to compensate for the load reactive power, current harmonics, unbalances, and neutral current in a three-phase four wire (3P4W) system using shunt active power filter (APF) is presented in [162]. This scheme consists of three H-bridge single-phase voltage source inverters (VSI) supported by a common DC bus voltage. A method of controlling a shunt APF to mitigate current harmonics under distorted supply condition is outlined in [114]. A single-phase active power filter in a distorted power system environment is used with improved harmonic suppression efficiency with self-tuning filter (STF) algorithm [117]. To enhance the capacity and to ensure operational flexibility, employing multiple and parallel APF units (in distributed mode) with a common DC link is proposed in [118]. This scheme is also capable of limiting the circulating currents flow using hysteresis current controller in load sharing mode. The design of a shunt APF for a 3 phase 3 wire system, pertaining to system parameters and the compensation capability is presented in [116]. UPQC acting as an emergency power supply to compensate for power interruptions in an electric vehicle charging is discussed in [180]. Current control with modified double hysteresis loop for optimal operation of UPQC is presented in [181]. All these techniques are implemented effectively in the conventional distribution system.

In MGs, the application of customized power devices in a DG system to enhance the power quality is presented in [115]. Ghanizadeh [182] et.al present voltage harmonic compensation in islanded microgrids for non-linear loads. Control of single-phase shunt filter under weak grid condition is discussed in [117]. In this, the MG based compensation towards grid is discussed. Similarly, MG to enhance power quality to the grid is discussed for harmonics power compensation in [116]. From the literature, it is observed that the multifunction compensating device application widely in the conventional distribution system to mitigate all voltage and current problems. However, UPQC in MG application is limited in providing support to the main grid. In all the applications of MG-UPQC, the MG is used to provide DC link support according to the requirement from the main grid. The individual application of UPQC to solve MG PQ issues is not focused. However, based on the discussion from Chapter 3, there exists many PQ issues in MG based on voltage and current and requires a compensating device. From the Chapter 4 and 5, the two CPDs, DVR and DSTATCOM are proved to be providing effective compensation for voltage and current problems respectively. It is recommended to have a multitasking device that comprises the functions of both the CPDs. The conventional distribution system literature strengthens this kind of implementation in dealing grid problems. Hence, the implementation of the device is considered in MG and designed to fit the requirement. The chapters 4 and 5 presented the ability of enhanced DVR and DSTATCOM to replace the series and shunt APFs. Hence UPQC which is a combination of series and shunt APFs is replaced with a combination of DVR and DSTATCOM and turned into enhanced UPQC is considered in this work. On the other hand, DVR operates to supply active power for most of the time and it is recommended to have a DC link support at its DC side. This can be obtained by using shunt APF. Hence a combination of DSTATCOM and DVR is envisaged for both load and supply side PQ issues in terms of voltages and currents. In addition, if the DVR and DSTATCOM are connected back to back such that DVR provides required energy during compensation whereas DSTATCOM provides DC link control. The structure, operation, control and classification of UPQC are discussed in the next sections.

6.1 Unified Power Quality Conditioner

UPQC is an optimal compensation device that ensures to maintain standards and specifications of the system by maintaining power balance. The UPQC, consists of the combination of a series converter to inject series voltage v_C), a shunt converter to inject shunt current i_C), and a common DC link (connected to a DC capacitor) as shown in the Figure 6.1.

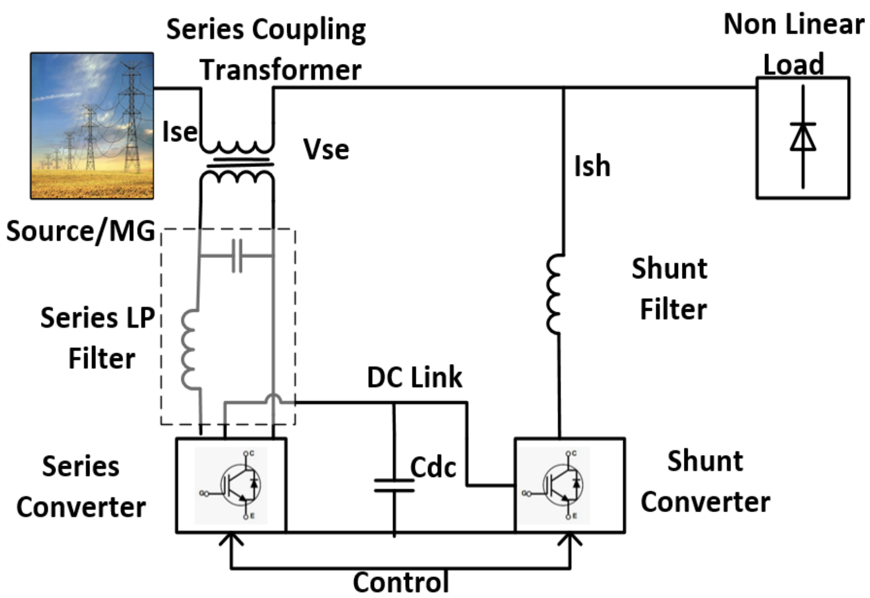


Figure 6.1: Block diagram of UPQC

The major elements of UPQC include series and shunt VSCs, DC capacitive link, low-pass and high-pass filters, series and shunt injection transformers. The detailed schematic diagram of UPQC is shown in Figure 6.2.

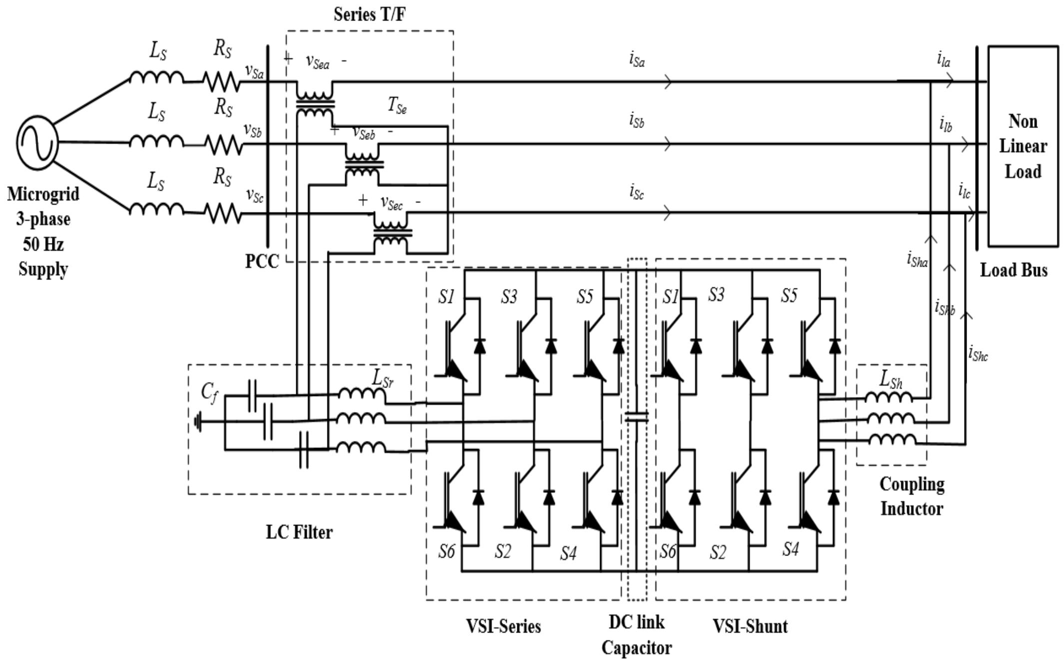


FIGURE 6.2: Schematic diagram of UPQC

- **Series Converter** is a voltage source converter connected in series with the AC line and acts as a voltage source to mitigate distortions. It eliminates supply voltage flickers, sags/swells from the load terminal voltage and forces the shunt branch to absorb current harmonics generated by the nonlinear load. Control of the series converter output voltage is usually performed using pulse width modulation (PWM) signals for the gate circuit of VSC that are generated by the comparison of a fundamental voltage reference signal with actual voltage.

- **Shunt Converter** is a VSC connected in shunt with the same AC line and acts as a current source to cancel out current distortions to compensate reactive current of the load, and to improve the power factor. It also performs the DC link voltage regulations, resulting in a significant reduction of the DC capacitor rating. The VSC of the shunt converter is controlled such that output current follows the reference signal and remains in a predetermined reference value.

- **DC link Capacitor** The two VSIs are connected back to back with each other through this DC link Capacitor. The voltage across this capacitor provides the self-supporting DC voltage for proper operation of both the inverters. With proper control, the DC link voltage acts as a source of active as well as reactive power and thus eliminates the need for external DC source.

- **Low-pass Filters/LC Filters** are used to filter high-frequency switching harmonics of the injected voltage generated from the series VSC.

- **High-pass Filter/Coupling inductors** are used to filter current ripples generated from the shunt VSC.

- **Injection transformers** are used to inject voltage and current required for compensation.

The UPQC is mainly operated to maintain the desired load voltage and the line current at the point of its installation and does not (need not) check the power quality status of the entire system every time. It is mentioned in Chapter 4.1 and Chapter 5.1 that DVR and DSTATCOM can be represented as series and shunt compensators of UPQC to provide overall power quality to the MG. Hence, the UPQC as a combination of DVR and DSTATCOM connected to MG (AC mains) is shown in the Figure. 6.3.

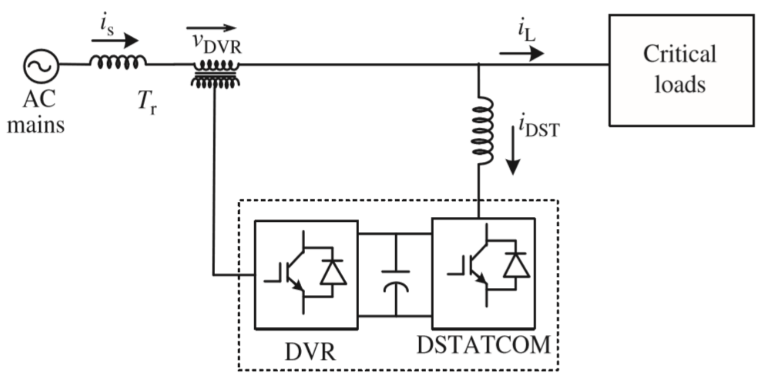


FIGURE 6.3: DVR and DSTATCOM connected UPQC

6.2 Classification of UPQC

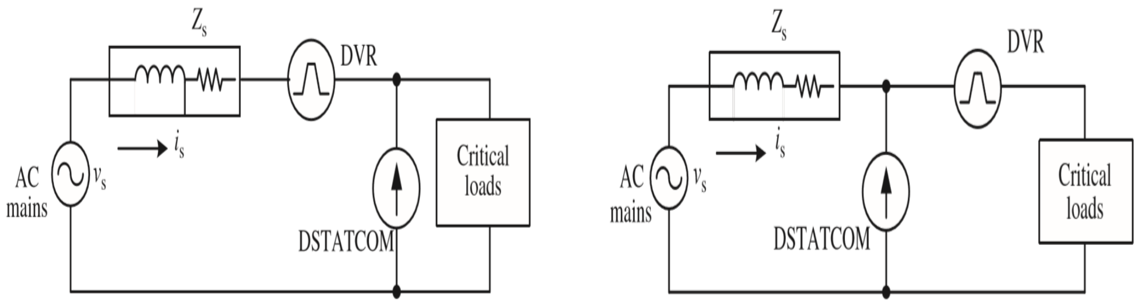
UPQC classification is based on the type of converter, topology, supply type, and method of control.

6.2.1 Converter-Based Classification of UPQC

Like DVR and DSTATCOM, UPQC is also classified based on converter. The two converters that are used are CSC and VSC. However, VSC based UPQC is preferred to CSC due to its easy adaptability for multilevel configuration.

6.2.2 Topology-Based Classification of UPQC

UPQC based on topology can be categorised into right shunt and left shunt UPQC. The right shunt UPQC is named as its shunt APF, i.e DSTATCOM is connected just before the load and series APF, i.e., DVR is connected in series with the MG reference (AC mains) as shown in Figure 6.4(a). This topology requires lower rating converters with a simple control and hence more preferrable. Figure 6.4(b) shows a left shunt UPQC. The left shunt UPQC provides clean



(a) A right shunt UPQC (b) A left shunt UPQC

Figure 6.4: UQPC topologies

power to critical and sensitive loads as it balances and regulates the terminal voltage. However, due to high cost and complex circuitry, this topology is inferior to right shunt UPQC. The overall characteristics of the right shunt UPQC are superior and are considered as a better option in this work. The same for UPQC is assumed and analyzed in further sections.

6.2.3 Supply System-Based Classification of UPQCs

Similarly, based on a number of supply phases the UPQCs are classified into: 3-phase 3-wire, and 3-phase 4-wire. The 3P4W supply systems are generally employed with neutral currents due to unbalanced loads. To mitigate these concerned issues, 3P4W UPQCs are used as shown in Figure. 6.5.

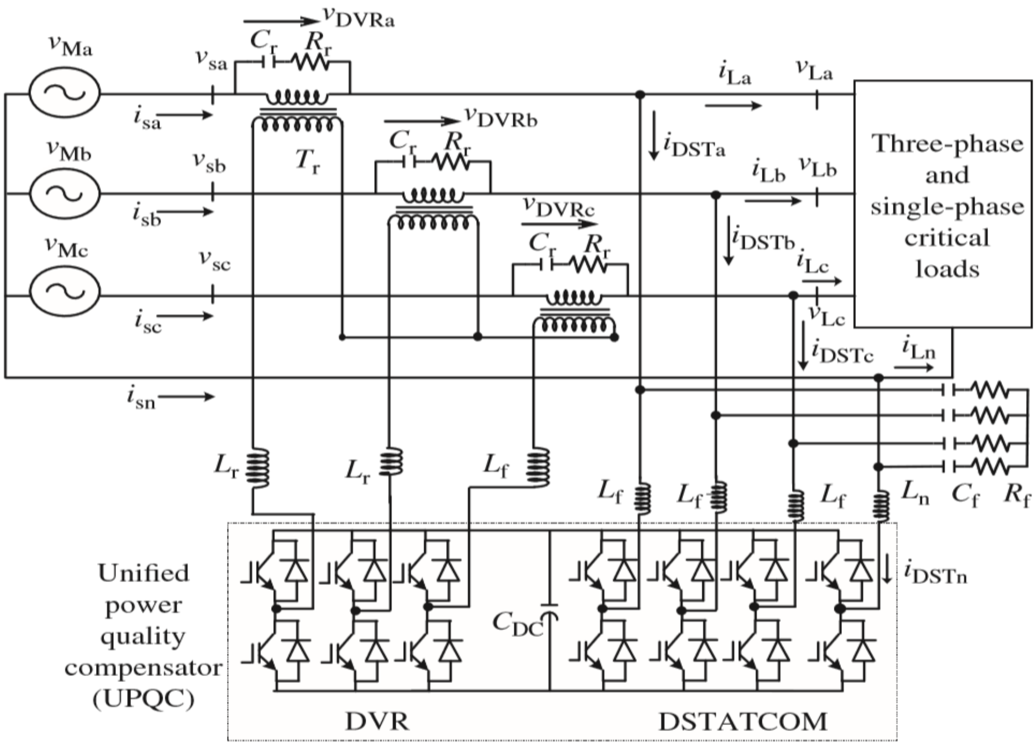


FIGURE 6.5: Schematic diagram of DVR and DSTATCOM connected UPQC

6.2.4 Rating-Based classification of UPQCs

The device, UPQC is classified based on rating in 3 ways: UPQC-P, UPQC-Q, UPQC-S. This classification is based on the type of voltage compensation method adapted for its series APF i.e, DVR. The different voltage compensation methods are discussed in 4.3. If the DVR is injecting the voltage in quadrature with the supply current, it is known as UPQC- Q. The sag and swell compensation using this type are shown in (a) of Figure 6.6 and in (b) of Figure 6.6. In this approach, DVR provides reactive power to the system that reduces the VAR requirement of the system. However, in case of swell compensation, the quadrature injected component is not intersected with the locus of the rated voltage. It is more predominant in case of right-shunt configuration. Hence, it can not be used for swell compensation. If the DVR injects the voltage in-phase with supply current, then it forms UPQC- P. Similarly, (c) and (d) of Figure 6.6 represents the sag/swell compensation using UPQC-P approach. The DVR can provide compensation effectively in both the condition. As the DVR has to transfer active power in this condition, the rating of the DVR should be high in general. However, in case of LV level MGs, this type is considerable.

If the DVR injects the voltage at minimum/suitable phase angle with supply current, then it is known as UPQC-S type. The sag/swell mitigation in this control are represented in (e) and (f) of Figure 6.6. In this condition, the DVR can be of low rating, i.e with minimum/optimal KVA rating. This is method is very optimal compared to other two methods to achieve the required objectives. However, the application is a bit complex and mainly for large-scale distribution system especially in case of the conventional distribution system. In case of MG level distribution systems, UPQC-P is more suitable and the same is considered to mitigate all kinds of PQ issues.

6.3 Operation and Control of UPQC

The device, UPQC is used for the voltage compensation by injecting voltage in series and mitigates all kinds of voltage quality issues using its DVR. Similarly, the shunt element, DSTATCOM is used for current quality compensation by providing harmonic, reactive power, neutral current and unbalance compensations respectively. The device is capable of mitigating the problems from both the supply and load sides. In case of voltage compensation, if the DVR requires active power, DSTATCOM supports the DVR in addition to its DC link. The operation of the UPQC is based on the required control objective(s) that are summarized below:

6.3.1 Control Objectives of UPQC

The control objectives of shunt converter are:

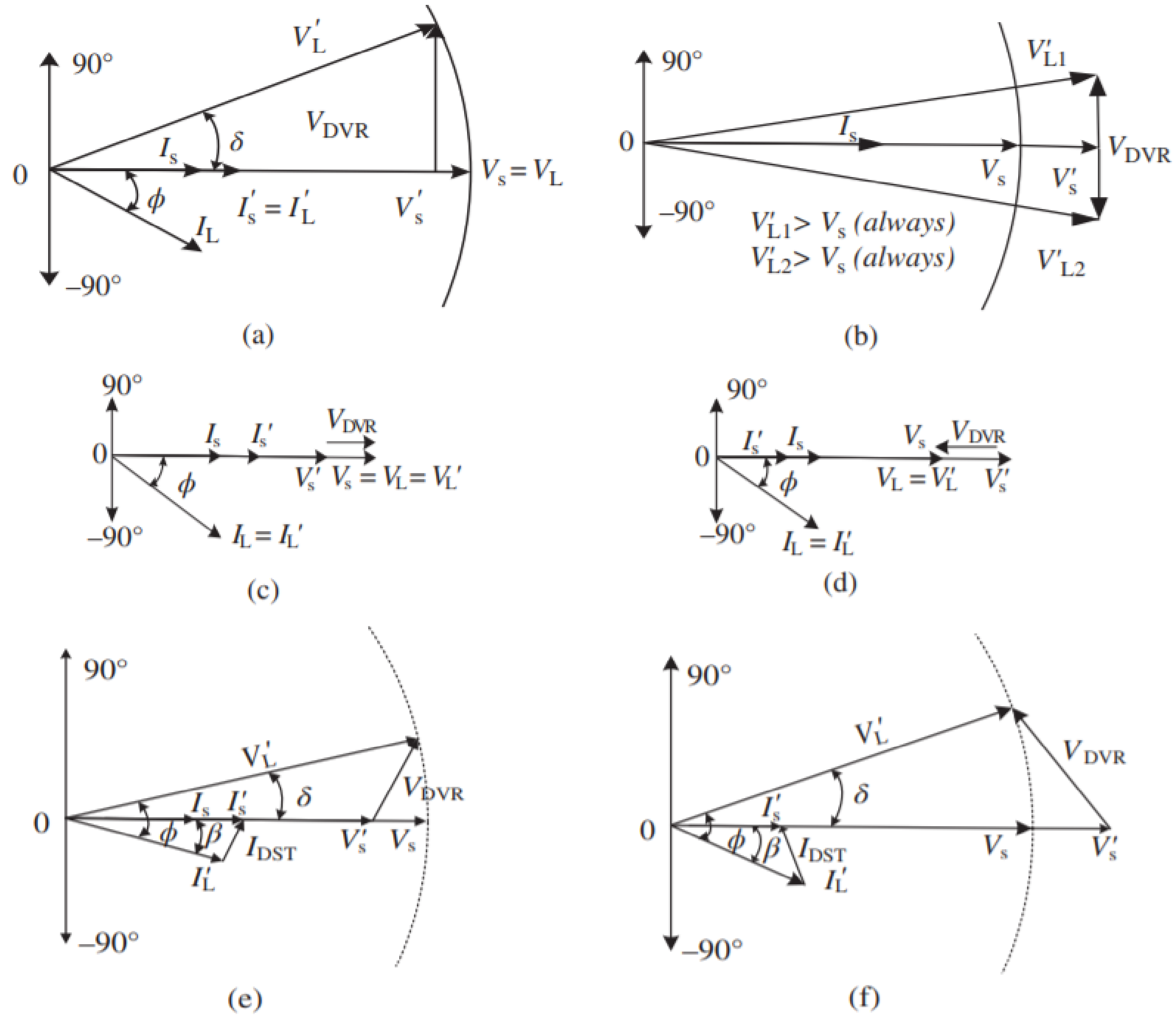


Figure 6.6: (a) Phasor diagram of a UPQC-Q for voltage sag compensation. (b) Phasor diagram of a UPQC-Q for voltage swell compensation.(c) Phasor diagram of a UPQC-P for voltage sag compensation.(d) Phasor diagram of a UPQC-P for voltage swell compensation.(e) Phasor diagram of a UPQC-S for voltage sag compensation.(f) Phasor diagram of a UPQC-S for voltage swell compensation.

1. Unbalance compensation by providing compensation to negative and zero sequence current components to the load
2. Source current harmonic compensation due to load current harmonics
3. p.f control obtained by providing RPC at the fundamental frequency
4. DC link control.

The series connected converter has the following control objectives:

1. Compensation of negative and zero sequence voltages to the load
2. Load voltage harmonic compensation
3. sag/swell compensation by injecting required active and reactive components

In meeting these objectives, the power flow control during different operating conditions is explained in the next subsection.

6.3.2 Power Flow Control in UPQC

To solve voltage based PQ issues, the difference between the reference and actual voltages is to be injected from the series converter. The magnitude of injected voltage may be positive or negative that implies supply or absorption of real power. Considering reference phasor as the load voltage v_L (6.1) and the load with lagging power factor cos ϕ_L (6.1)

$$v_L = V_L \angle 0^{\circ} \tag{6.1}$$

$$i_L = I_L \angle -\phi_L \tag{6.2}$$

$$v_S = V_L(1+s_f)\angle 0^{\circ} \tag{6.3}$$

Instantaenous values are indicated by lower case letters whereas upper case letters represent peak values. s_f in eq. (6.3) is the ratio of actual voltage to reference and is defined in (6.4),

$$s_f = \frac{V_S - V_L}{V_L} \tag{6.4}$$

The voltage injected by the series inverter is given by (5)

$$v_{se} = v_L - v_S = -s_f V_L \angle 0^{\circ} \tag{6.5}$$

The UPQC is supposed to be lossless and load active power demand (P_L) is equal to the input active power at PCC (P_S). UPQC delivers a source current with unity power factor, for a specified load condition the input active power can be expressed as

$$P_s = P_L \tag{6.6}$$

$$V_S I_S = V_L I_L \cos\phi_L \tag{6.7}$$

$$V_L(1+s_f)I_S = V_L I_L \cos\phi_L \tag{6.8}$$

and thus

$$I_S = \frac{I_L}{1+s_f}\cos\phi_L \tag{6.9}$$

From the equation (6.9), it is observed that the factor s_f influences the source current I_S. ϕ_L, I_L are constant based on the particular load connected. The series APF mainatains the active (P_{se}) and reactive power (Q_{se}) as given by (6.10), (6.11) & (6.12).

$$P_{se} = V_{se} I_S \cos\phi_S \tag{6.10}$$

$$P_{se} = -s_f V_L I_S \cos\phi_S \tag{6.11}$$

$$Q_{se} = V_{se} I_S \sin\phi_S \tag{6.12}$$

For $\phi_S = 0$, and UPQC power factor is maintained as unity, then active (P_{se}) and reactive power (Q_{se}) of series inverter can be expressed as

$$P_{se} = V_{se} I_S = -s_f V_L I_S \tag{6.13}$$

$$Q_{se} = 0 \tag{6.14}$$

Thus the series inverter of UPQC controls the active power whereas the shunt inverter produces the current (i_{sh}). i_{sh} represents the compensation current provided by shunt APF to meet the difference between the source current and load current with harmonic/reactive load connected. Thus i_{sh} is defined as

$$i_{sh} = i_S - I_L \tag{6.15}$$

$$i_{sh} = I_S\angle 0^{\circ} - I_L\angle\phi_L \tag{6.16}$$

$$i_{sh} = I_S - I_L\,(\cos\phi_L - j\sin\phi_L) \tag{6.17}$$

$$i_{sh} = (I_S - I_L\,\cos\phi_L) + j\sin\phi_L) = I_{sh}\angle\phi_{sh} \tag{6.18}$$

ϕ_{sh} represents the phase angle of i_{sh} w.r.to v_S (6.18). P_{sh} (6.19) and Q_{sh} (6.20) due to shunt APF are given by,

$$P_{sh} = V_L I_{sh}\cos\phi_{sh} = V_L(I_S - I_L\cos\phi_L) \tag{6.19}$$

$$P_{sh} = V_L I_{sh}\sin\phi_{sh} = V_L I_L\sin\phi_L \tag{6.20}$$

The P, Q flows among source, load and UPQC under different situations of MG are explained below in detail.

6.3.2.1 Active, Reactive Power Flows During Normal Operating Condition

In this condition, $V_S = V_L$, $s_f = 0$. There is no exchange of power in the MG. UPQC does not exchange any active power in this condition. Without UPQC and shunt APF, Q_L is provided by the source. When UPQC is connected, Q_L is provided by Q_{sh} from its shunt APF. This makes the VAR burden on the source as zero. However, there is no action required from series APF in this case. The P & Q flow during the normal operating condition is shown in Figure 6.7.

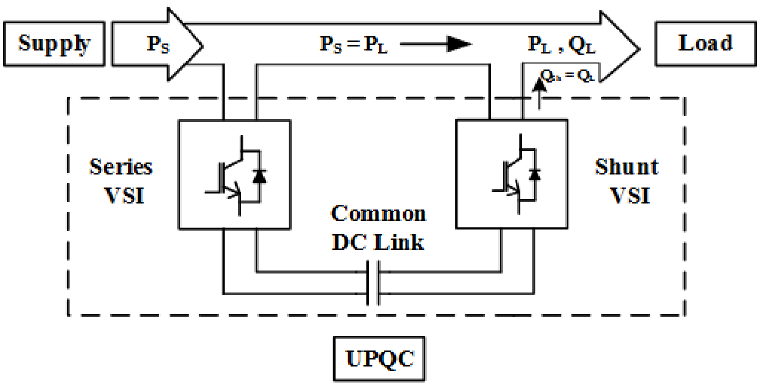


FIGURE 6.7: Active, reactive power flows during normal operating condition

6.3.2.2 Active, Reactive Power Flows During Voltage Sag

During voltage sag, $s_f < 0$, i.e. $V_S < V_L$. P_{se} will become positive as per (6.4) and (6.13). The series APF has to provide the required active power to the load as $I_S > I_L$. The flow of P is as follows: source to shunt APF, shunt APF to series APF via DC link, series APF to load. In such cases P'_{sh} absorbed (6.21) is equal to P'_{se} (6.22) to keep DC link voltage constant. The active and reactive power flow during sag is shown in Figure 6.8. P'_s is the power supplied by the source to the load voltage, P'_{sh} is the power absorbed by the shunt inverter, P'_{se} is the power injected by the series inverter during voltage sag condition.

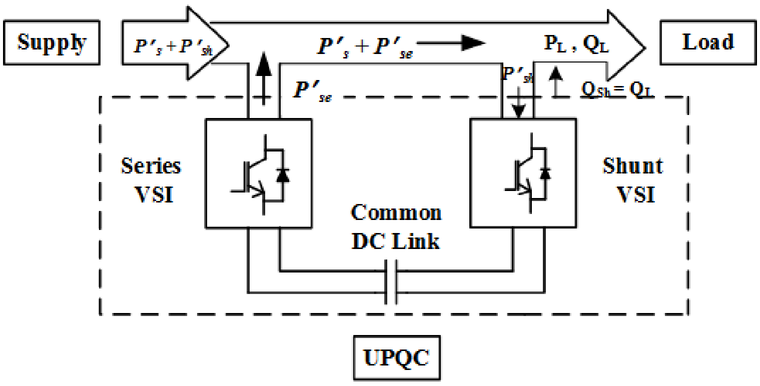


FIGURE 6.8: Active, reactive power flows during voltage sag

$$P'_{sh} = P'_{se} \tag{6.21}$$

$$P_s = P'_s + P'_{se} = P_L \tag{6.22}$$

6.3.2.3 Active, Reactive Power Flows During Voltage Swell

During voltage swell, $s_f > 0$, i.e. $V_S > V_L$. P_{se} will become negative which implies that series APF has to absorb excess real power from the source as per (6.24) i.e, $I_S < I_L$. i.e, UPQC is giving power back to the MG supply. The P-Q flow during swell is shown in Figure 6.9. The power delivered by MG source to load is P''_s, the power from series and shunt APFs are given by P''_{se} and P''_{sh} in swell condition as given by (6.23) and (6.24).

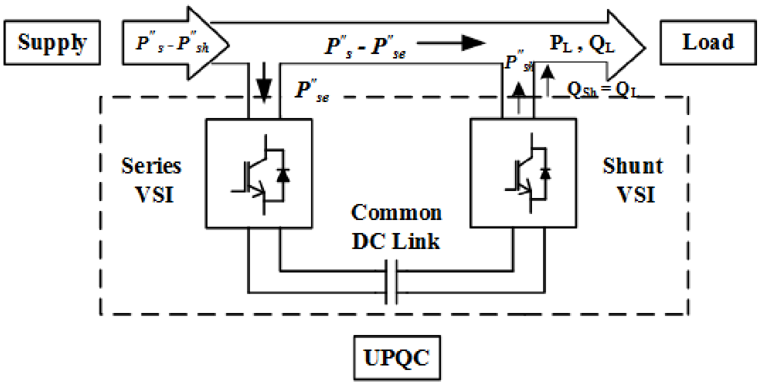


FIGURE 6.9: Active, reactive power flows during voltage swell

$$P_{sh}^{''} = P_{se}^{''} \tag{6.23}$$

$$P_s = P_s^{''} - P_{se}^{''} = P_L \tag{6.24}$$

The detailed schematic diagram of UPQC is given in Figure 6.10. The phasor representation of the above cases are shown in Figure 6.10 (a) to Figure 6.10 (f) represents the loads with inductive and capacitive nature. Figure 6.10 (a) gives the normal operating condition, with the source voltage V_S acting as a reference. ϕ_L is angle of load angle. Without UPQC, $I_S = I_L$. Phasor in Figure 6.10 (b) gives the normal working condition at with leading power factor of the load. The phasor representation of supply voltage sag and swell for different load conditions are represented from Figure 6.10 (c) to Figure 6.10 (f) respectively.

6.4 Control Techniques

The UPQC considered in this chapter as a combination of enhanced DVR and DSTATCOM based on discussions in previous chapters 4 and 5. Hence the control techniques that are proven effective in the case of both the devices are considered i.e, IVTG control for DVR and 1-phase p-q theory for DSTATCOM. The corresponding techniques are implemented as control techniques for series and shunt APFs of the UPQC.

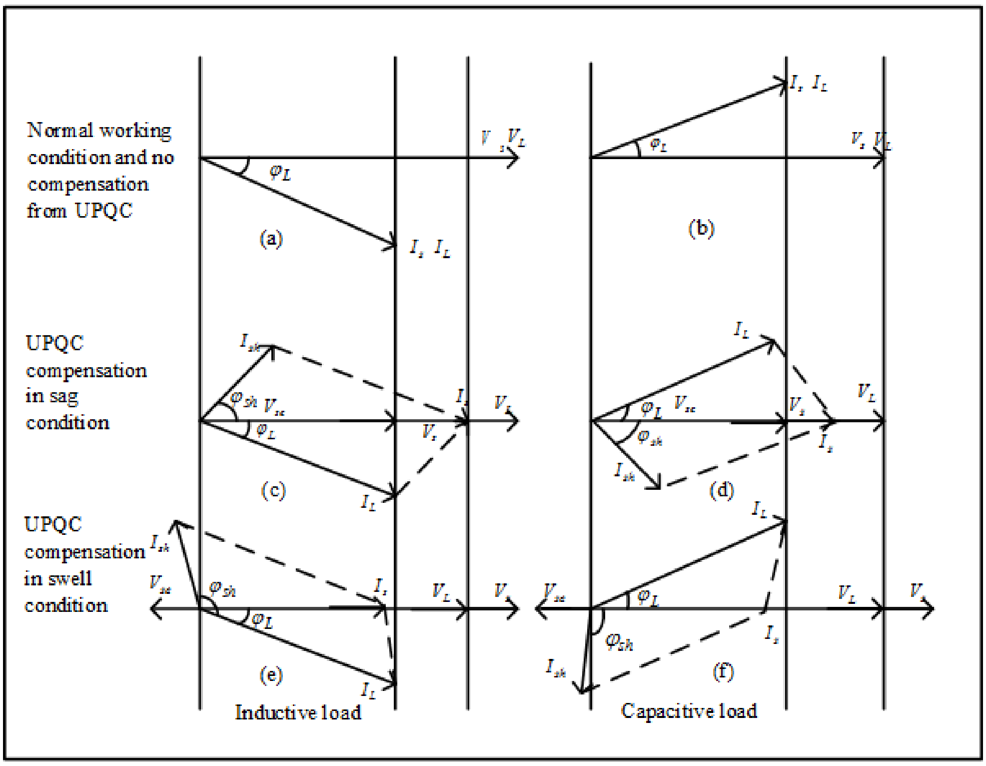


FIGURE 6.10: Phasor representation of UPQC working in normal, sag and swell conditions

6.4.1 Voltage and Current Compensation using UPQC

The voltage and current deviations due to MG source and load currents are distinguished and mitigated by using UPQC. It can correct both the problems at PCC during the same instant of time and improves the PQ of supply current and load voltage simultaneously by using its back-back connected series and shunt APFs. The system voltages and load currents of a resultant three-phase system of MG are mostly not balanced and comprise harmonics of higher order and UPQC can provide compensation for both types of distortions. The equivalent circuit of UPQC is shown in Figure 6.11. The unbalanced three-phase system consists positive, negative, and zero sequence fundamental and harmonic components. The system voltage can be expressed as in (6.25).

$$v_S(t) = v_{S+}(t) + v_{S-}(t) + v_{S0}(t) + \sum v_{sh}(t) \tag{6.25}$$

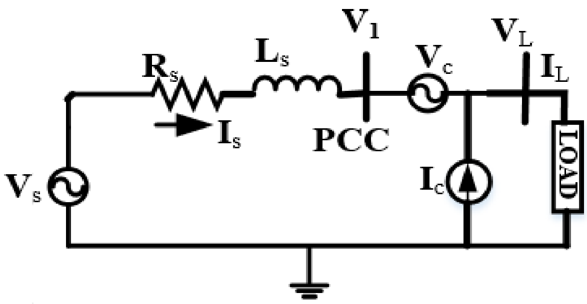


FIGURE 6.11: Equivalent circuit of UPQC

where subscripts +,-, and 0 represents positive, negative and zero sequence fundamental components respectively; The function of series converter is to compensate voltage (6.26)

$$v_C(t) = v_L(t) - v_S(t) \tag{6.26}$$

The series converter is controlled by the control system designed to generate $v_C(t)$. The nonlinear load current (6.27) with distortion can be expressed as

$$i_L(t) = i_{L+}(t) + i_{L-}(t) + i_{S0}(t) + \sum i_{sh}(t) \tag{6.27}$$

The shunt converter provides compensation for load current including harmonics and unbalance by separating harmonic and sequence components. Later the control is designed for shunt APF such that harmonic and negative, zero sequence components are cancelled. The current component to be compensated by the shunt converter is given by (6.28)

$$i_S(t) = i_L(t) - i_C(t) \tag{6.28}$$

Equations. (6.26) and (6.28) establish the principles of an ideal UPQC. By implementing all the above, UPQC can ensure that the system voltages and currents can be maintained to their references which are balanced and sinusoidal. UPQC as a combination of DVR and DSTATCOM has been mentioned in 6.2.3. The different control algorithms based on two approaches, one is based on PARKS transformation and the second is IRPT, to achieve corresponding control objectives 6.3.1 for DVR and DSTATCOM are discussed in 4.6 and 5.4. Hence based on the control objectives, respective control algorithms are selected from 4.6 and 5.4 for the individual control of DVR and DSTATCOM of the combined UPQC. Based on real-time control techniques for the generation of reference signals for the control of VSCs of the UPQC for a 3-phase 4-wire system, the overall control diagram of UPQC is shown in Figure 6.5.

6.5 Design of UPQC for Power Quality Compensation

To achieve multiple PQ problem mitigations using both series and shunt converters, the design of UPQC includes the design of series APF(enhanced DVR) and shunt APF(DSTATCOM).

6.5.1 Design of Series APF

A three-phase series APF (represented as SAPF in this chapter) consisting VSC and a DC bus to provide (i) voltage sag/swell mitigation and reactive power compensation (ii) harmonic compensation for a 3-phase microgrid with an operating voltage of 415V, 50Hz. The following subsection provides the complete design of SAPF to compensate for the aforementioned power quality problems using its active power filter technology. The microgrid with an operating voltage of 415V, 50Hz and feeding a critical linear load of 50 kVA with 0.8 lagging power factor is considered. A voltage dip and rise of ±21 % is considered in microgrid which is assumed as supply sag/swell at PCC. The operation of SAPF under normal operating condition is as follows: Under normal operating condition, the SAPF of the UPQC injects zero voltage. However the shunt APF injects current in quadrature with the load voltage for compensation of the reactive power of the load. The phase volatge(s) of supply and load V_{Sp}, V_{Lp} are given by,

$$V_{sp} = V_{s1}/\sqrt{3} = V_{L1}/\sqrt{3} = V_{Lp}. \tag{6.29}$$

The active power of the load is

$$P_L = 3V_{Lp}I_{Lp} * PF. \tag{6.30}$$

The reactive power of the load is

$$Q_L = 3V_{Lp}I_{Lp} * \sqrt{1 - PF^2}. \tag{6.31}$$

The supply current before any voltage sag is

$$I_S = I_{APF,se} = P_L/3V_{Sp}. \tag{6.32}$$

6.5.2 Voltage Sag Compensation by Series APF

There is a voltage sag of -X (%) in microgrid output voltage. Therefore the series APF of the UPQC must inject in quadrature with the supply (MG) voltage to provide the required voltage at the load end.

Due to sag, the MG voltage is

$$V_{S1} = V_S * (1 - X) \& V_{sp} = V_{s1}/\sqrt{3} \tag{6.33}$$

At the time of compensation, the supply current is

$$I_S^{'} = P_L/3V_{Sp} \tag{6.34}$$

The voltage rating of the series APF is

$$V_{APF,se} = \sqrt{V_L^2 - V_s^2} \tag{6.35}$$

The current rating of the series APF must be the same as supply current. $I_{APF,se}$= The load current is $I_S^{'} = P_L/3V_{Sp}$ The VA rating of the series APF of the UPQC is computed as follows:

$$Q_{APF,se} = 3 * V_{APF,se} * I_{APF,se} \tag{6.36}$$

$P_{APF,se} = 0$, as the voltgae of the series APF is injected in quadrature with its current.

$$S_{APF,se} = \sqrt{P_{APF,se}^2 + Q_{APF,se}^2} = Q_{APF,se} \tag{6.37}$$

The voltage rating of the shunt APF of the UPQC is equal to the AC load voltage $V_{APF,sh}$ since it is connected across the load.

The current rating of the shunt APF is computed as follows:

The shunt APF of the UPQC needs to correct the power factor of the source to unity. Hence, the required reactive power by the shunt APF is now lower than the load reactive power as the angle between the supply voltage and the load current is reduced to

$$\beta = \phi - \delta \tag{6.38}$$

where $\cos\phi$ is the load power factor and δ is the angle between the load voltage and the PCC voltage after compensation. The angle δ is computed as follows:

$$tan\delta = \frac{V_{APF,se}}{V_S^{'}} \tag{6.39}$$

The current rating of the shunt APF is given by $I_{APF,sh}$,

$$= \frac{I_L\sqrt{(1-X)^2 + \cos^2\phi - 2\ cos\phi\cos(\phi-\delta)(1-X)}}{1-X} \tag{6.40}$$

The VA rating of shunt APF is computed as follows.

$$Q_{APF,sh} = 3 * V_{APF,sh} * I_{APF,sh} \tag{6.41}$$

Since the voltage of the shunt APF is injected in quadrature with its current $P_{APF,sh} = 0$,.

$$S_{APF,sh} = \sqrt{P_{APF,sh}^2 + Q_{APF,sh}^2} = Q_{APF,sh} \tag{6.42}$$

The VA rating of the UPQC during voltage sag is

$$S_{UPQC,undersag} = S_{APF,se} + S_{APF,sh} \tag{6.43}$$

Under normal operating conditiions, shunt. APF provides the reactive power required by the load. In this case the reactive power rating of Sh.APF is 30 kVAR. When there is a sag in supply voltage, the series APF of the UPQC injects in quadrature to provide the required voltage at the load end. In this situation, the VA rating of the SAPF which is computed using the above set of equations is 19.373 kVA. The voltage rating of the shunt APF of UPQC is equal to the AC load voltage since it is connected to the load. The VA rating of the shunt APF using above set of equations is computed as 30.003 kVA. (The computed parameters are $V_{Sh.APF} = 239.6V, I_{Sh.APF} = 41.73A, S_{Sh.APF} = 3V_{Sh.APF} * I_{Sh.APF} = 30.0003kVA$. Similarly $V_{SAPF} = 104.44V, I_{SAPF} = 61.83A, S_{SAPF} = 3V_{SAPF} * I_{SAPF} = 19.373kVA$. The VA rating of the UPQC is $S_{UPQC} = S_{SAPF} + S_{Sh.APF} = 49.373kVA$)

6.5.3 Design of Shunt APF

The 3-phase shunt APF is employed for harmonic current compensation for a 3-phase microgrid o/p voltage of 415V, 50 Hz. The MG is connected to a nonlinear load with diode bridge converter drawing 60 A of constant DC current. The switching frequency is considered as 20 kHz. It is assumed that the DC bus voltage has to be controlled within 8 % range and ripple current in the inductor is 5 %. The supply voltage i.e. MG o/p voltage is assumed to be stiff enough so that the distortion in o/p voltage at the point of common coupling is negligible. With these conditions applied, the design of shunt APF is as follows:

6.5.4 Harmonic Compensation by Shunt APF

The MG o/p RMS phase voltage $V_{MG} = 415/\sqrt{3}$

The frequency of the supply (f) = 50 Hz.

The load current drawn by non linear diode bridge converter = I_{DC}.

However in a 3-phase diode bridge converter (load) , the waveform of the supply current $(I_{MG} or I_s)$ is a quasi-square wave with the amplitude of the DC link current I_{DC}.

Hence, the RMS of the quasi-square wave load current is

$$(I_{MG} or I_s) = I_{DC}\sqrt{\frac{2}{3}} \tag{6.44}$$

Moreover, the RMS value of the fundamental component of the quasi square wave is

$$I_{MG1} or I_{s1} = \frac{\sqrt{6}}{\pi} * I_{DC} \tag{6.45}$$

The active power drawn by the load is P

$$P = 3V_{MG} I_{MG1} \cos\theta 1 \tag{6.46}$$

Current rating of the shunt APF = The total RMS harmonic current.

$$I_{APf,sh} = I_f = I_h = \sqrt{I_{MG}^2 - I_{MG1}^2} \tag{6.47}$$

Voltage rating of the shunt APF = Voltage across the filter = $V_f = V_s$.

The VA rating of the shunt APF = $3 * V_f * I_f$.

The VA rating of the DC bus voltage of the APF is

$$V_{DC,APF} = \frac{2\sqrt{2}V_f}{m_a} \tag{6.48}$$

where m_a is modulation index.

The value of the minimum DC bus voltage required (split capacitor type arrangement is given by

$$V_{DC,min} = \frac{\sqrt{3} * \sqrt{2}}{0.87} * V_{s,rms} \tag{6.49}$$

The interfacing inductance of the shunt APF is

$$L_{f,interface} = \frac{\sqrt{3} m_a V_{DC,APF}}{2 * 6 * a f_s * \Delta I_f} \tag{6.50}$$

where ΔI_f is $= 0.05 * I_{APF}$ as 5% ripple current for inductor is considered.) , a is overload factor =1.2, f_s is switching frequency = 20 kHz.

The DC bus capacitance of the APF is computed from the change in stored energy during dynamics.

The change in stored energy during dynamics is given by

$$\Delta E = \frac{1}{2}C_{DC}(V_{DC,APF}^2 - V_{DC,minAPF}^2) = 2 * 3V_f I_f \Delta t \tag{6.51}$$

The DC bus capacitance of the APF is computed as

$$C_{DC} = \frac{2\Delta E}{(V_{DC,APF}^2 - V_{DC,minAPF}^2)} = \frac{3V_f I_f \Delta t}{(V_{DC,APF}^2 - V_{DC,minAPF}^2)} \tag{6.52}$$

Based on these filter and DC link parameters calculated, UPQC has been designed. The designed parameters are listed in Table. 6.1. The next section presents the simulation results that are obtained.

TABLE 6.1: Design parameters of UPQC

Electrical Parameters	Value in Units
Microgrid Reference Voltage $V_s or V_{MG}$	415V
Fundamental Frequency f	50Hz
Source Inductance L_s	0.5 mH
Ref. DC bus voltage V_{DC}	680V
DC bus capacitor C_{DC}	2000μF
Inverter Coupling L_{Sh}	5.583mH

6.6 Simulation of UPQC in MG for Power Quality Compensation

A microgrid configuration developed in Chapter 3 is developed initially with 2 DERS, a PV generator, and a wind generator. The developed model and simulations in Simulink/MATLAB environment are presented in the previous Chapter 3. It is designed to deliver an output voltage of 415V RMS, at common AC bus as shown in Figure. 6.12. This 3 phase, 415 V(RMS) is the reference source voltage. The power quality behavior of the MG for various operating

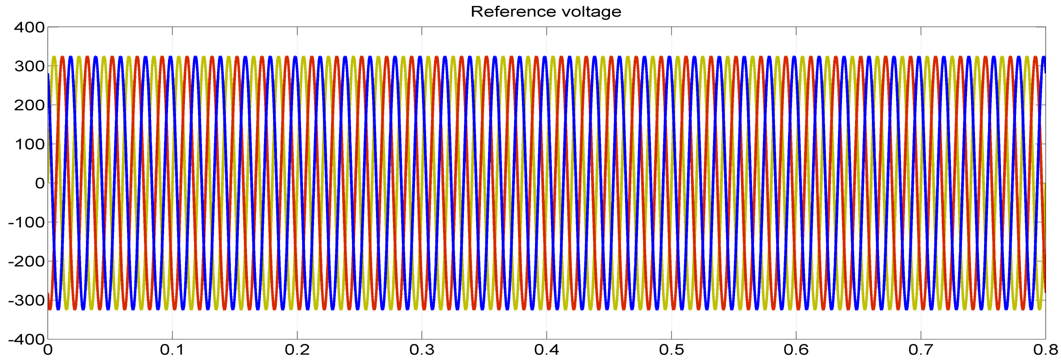


FIGURE 6.12: MG output voltage or reference source voltage

conditions is also studied in Chapter 3. The different operating conditions considered are sag, swell, simultaneous sag and swell in supply and load voltages, fault ride through switching of loads creating voltage harmonics, circulating currents due to unbalanced loads, current harmonics, and connection of various reactive loads into the system. The above-specified power quality problems are developed and simulated in the considered MG. All these problems are categorized into two types: 1. Voltage quality 2. Current quality. The performance of series(DVR) and shunt (DSTATCOM) devices to mitigate these issues are discussed in Chapter 4 and 5. Later the enhanced DVR and DSTATCOM are recommended to replace the series and shunt elements of the UPQC. Thus the enhanced UPQC with its selected control techniques (based on control techniques discussed in Chapter 4 and 5) is incorporated into the same MG to mitigate all the aforementioned power quality issues. In this regard, Initially, the performance of the device is verified for simultaneous sag/swell condition in supply voltage in MG.

A supply disturbance to reduce and increase its peak value by 87.5V (X = 21%) to create both sag and swell within a short time span is created and observed for the duration from 0.0 to 0.4 sec, (sag from 0.05 to 0.15 sec, swell from 0.25 to 0.35sec). The reference voltage is depicted in Figure. 6.12 for comparison. For clear analysis, the phase 'a' components are considered. The sag in supply voltage (3-phase) without switching on UPQC, sag in supply voltage (1-phase) without switching on UPQC, injected voltage by using UPQC, Load voltage (1-phase) with switching ON UPQC, Load voltage (3-phase) with switching ON UPQC are shown in Figure. 6.13. The responses to the swell condition in supply voltage is shown in Figure. 6.14 respectively. Similarly, the effectiveness of UPQC is also verified for simultaneous sag and the swell condition is shown in Figure. 6.15. From all this, it is found that the UPQC is able to compensate for all abnormal conditions in supply voltage very effectively and recovers the MG load voltage without much delay. Significant voltage fluctuations can cause equipment to shut down or fail. Hence the

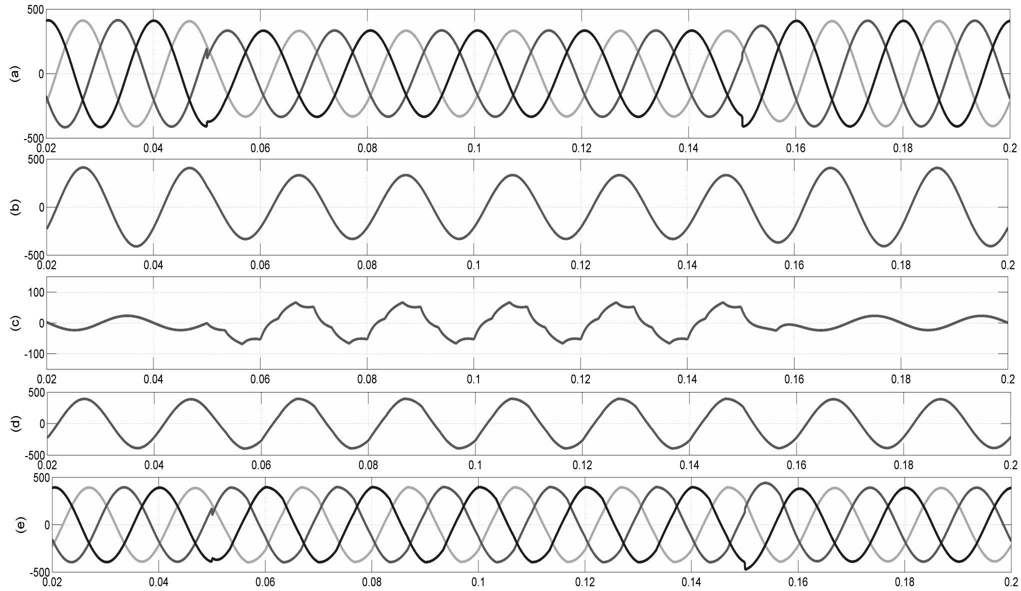


Figure 6.13: Mitigation of sag in supply voltage

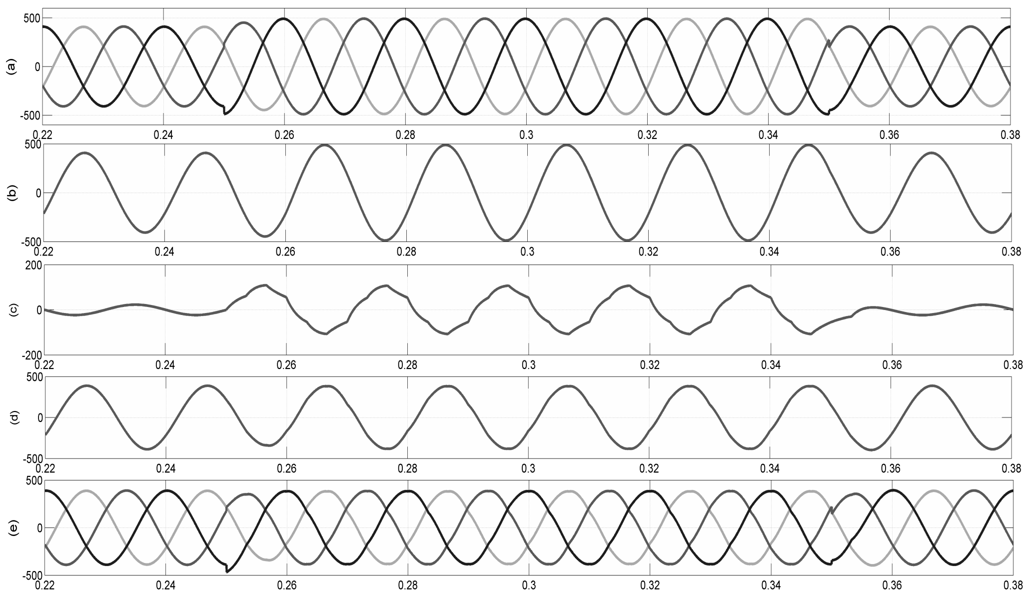


Figure 6.14: Mitigation of swell in supply voltage

changes in the supply voltage of MG due to environmental disturbances and other load changes that can cause a flicker in MG output voltage is also analyzed. It occurs typically due to voltage variation due to supply changes and phase shifting harmonics, resulting from frequent motor

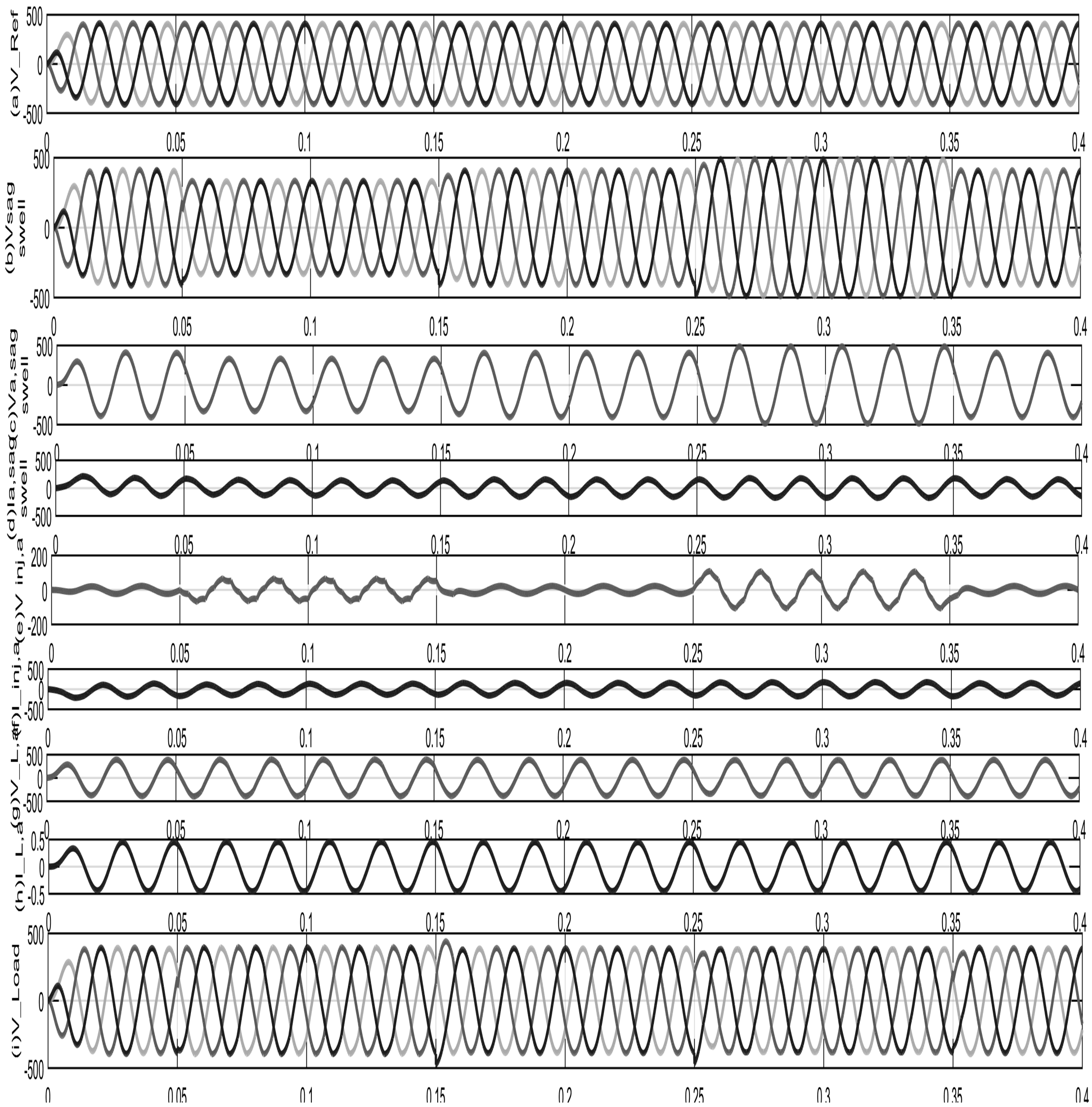


FIGURE 6.15: Mitigation of simultaneous sag and swell in supply voltage

starts, switching of capacitors or other load changes at the customer site or at other sites on the same line, or from momentary high impedance faults like trees brushing the line. Rapid voltage deviations could produce extremely annoying fluctuations in the output of lights, especially if the frequency of repetitive deviations is 5-15 Hz. The effect of flicker on the MG source voltage is shown in Figure. 6.16 The term flicker index is defined as follows:

$$\text{Flicker index} = \frac{\Delta V}{V} \tag{6.53}$$

$$\Delta V = V_{max} - V_{min} \tag{6.54}$$

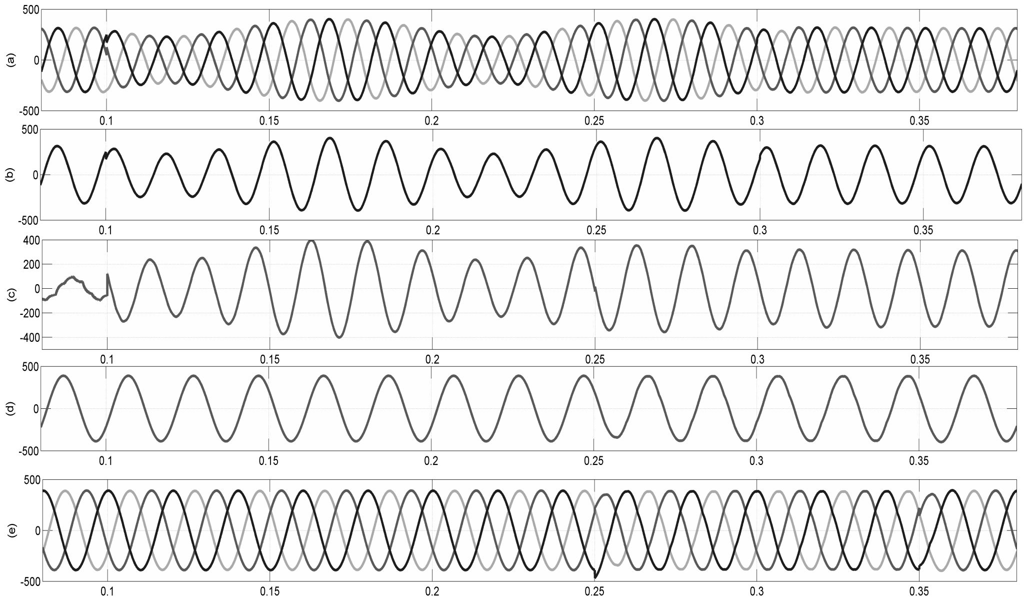


FIGURE 6.16: Mitigation of flicker in supply voltage

where V_{max} and V_{min} are peaks of maximum and minimum of positive peaks (or negative peaks) V is peak amplitude of rated voltage. The flicker index in this condition for the MG source output voltage is given by; V_{max} = 402.5, V_{min} = 229.5, V= 317.85,

$$\text{Flicker index} = \frac{402.5 - 229.5}{317.85} = 0.54 \tag{6.55}$$

The UPQC using its series APF effectively compensated this flicker condition shown in Figure. 6.16. (a) on the system by injecting appropriate voltage through series inverter. The voltage injected by series inverter to compensate the flicker effect is shown in Figure. 6.16 .(c) Whereas the compensated load voltage is shown in Figure. 6.16. (e).

The flicker index for the compensated load voltage is; V_{max} = 338.5, V_{min} = 326.8, V= 317.85,

$$\text{Flicker index} = \frac{338.5 - 326.8}{317.85} = 0.0368 \tag{6.56}$$

Similarly, the harmonic compensation is provided by using UPQC and the results in terms of % THD are shown in Figure. 6.17,Figure. 6.18 & Figure. 6.19. Two nonlinear loads that create harmonics in load voltage with 32.82% THD and 24.48 % THD are connected. The % THD in both cases is improved to 0.94% &, % 0.99 respectively, with the switching ON UPQC. Similarly, the nonlinear load mentioned in 5 that creates harmonics with a 150.84% THD in source current is connected. When UPQC is connected, the % THD is reduced to a value of 23.99. From all this, the UPQC is able to mitigate both the harmonics using its series APF (enhanced DVR) and shunt APF (enhanced DSTATCOM) similar to that of respective individual operating conditions.

Power quality conditioning using UPQC when reactive loads that require compensation are

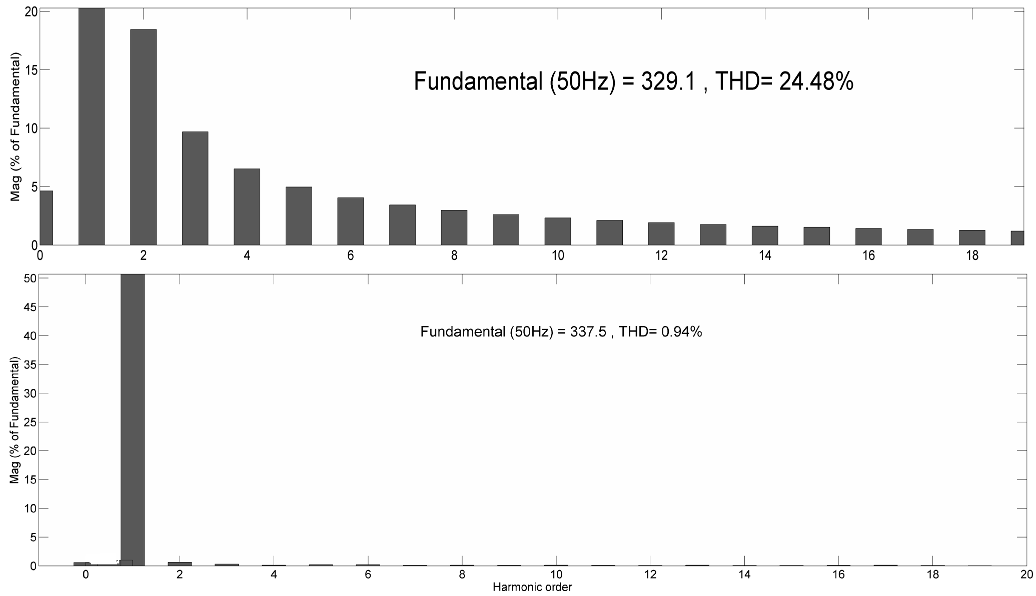


FIGURE 6.17: Voltage harmonic compensation for load1

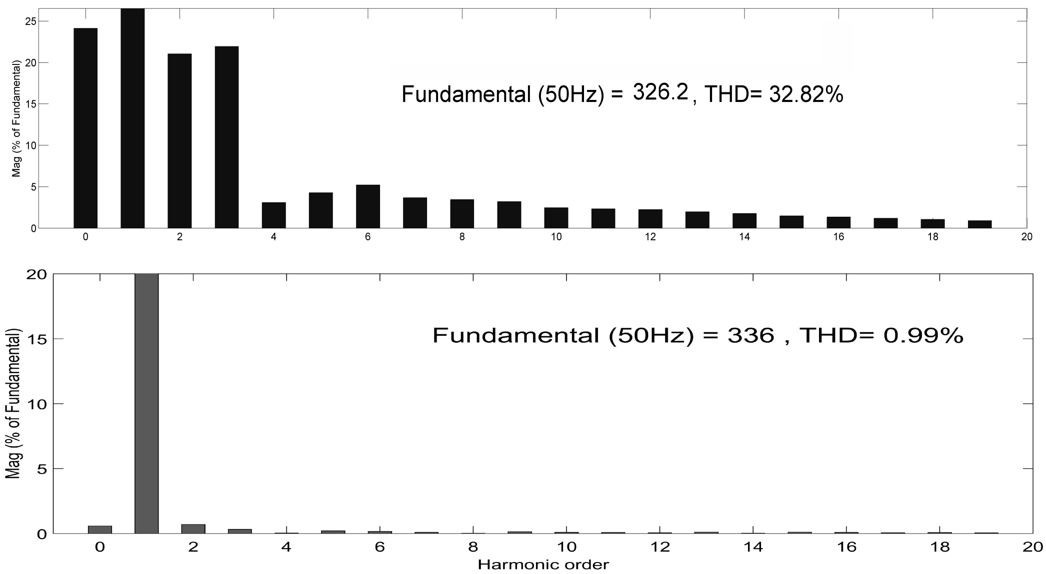


FIGURE 6.18: Voltage harmonic compensation for load2

connected on the distribution side of MG is also analyzed in this paper. In this regard, inductive

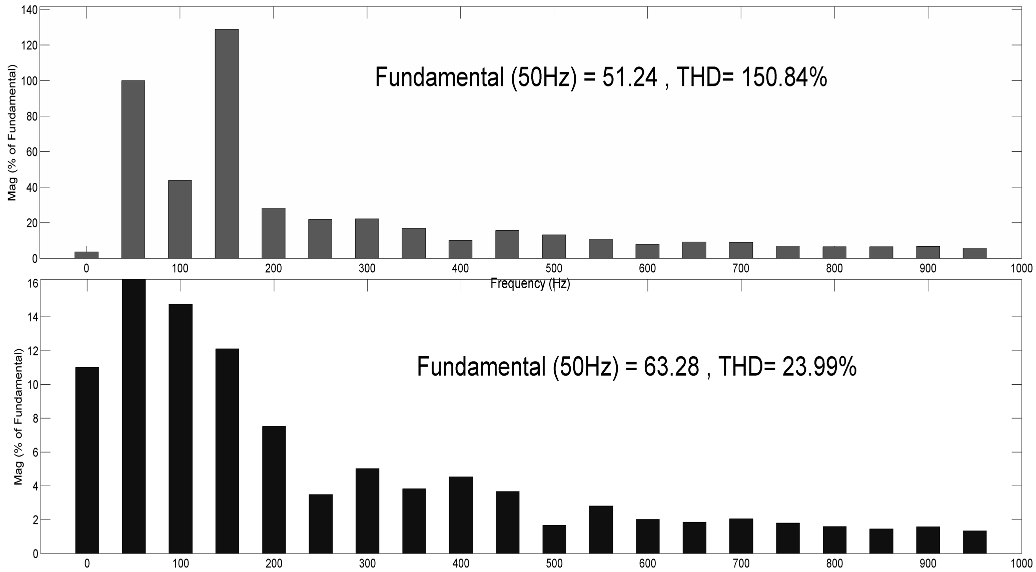


FIGURE 6.19: Current harmonic compensation

and capacitive loads that require reactive power are connected and the performance of the MG is assessed. Now the MG with an actual reference voltage generated and represented as in Figure. 6.12 is connected to deliver the reactive loads. Both sag and swell conditions are observed due to sudden switching of these loads in the MG for the duration from 0.0 to 0.4 sec when UPQC is not connected in the system, whereas by using UPQC, the reactive power compensation is provided to the load. For clear analysis, the phase 'a' components are considered. The sag in load voltage (3-phase) without switching on UPQC, sag in load voltage (1-phase) without switching on UPQC, injected voltage by using UPQC, Load voltage (1-phase) with switching ON UPQC, Load voltage (3-phase) with switching ON UPQC are shown in Figure. 6.20. The responses for swell and simultaneous sag/ swell conditions in supply voltage are shown in Figure. 6.21 & Figure. 6.22 respectively. The simulation results prove that sag, swell and simultaneous sag/ swell conditions in load voltage caused by reactive loads are compensated well with the help of UPQC and is able to maintain its load voltage near to reference voltage in MG. The power flows & p.f in case of a supply disturbance are shown in Figure. 6.23, Figure. 6.24, Figure. 6.25. Figure. 6.23 represents the reference power which is flowing in the MG when there is no disturbance in the source voltage. The negative sign indicates the active power transfer (delivery) from the source (MG) to the load. However, due to the sag/swell in supply, the active power transfer capacity

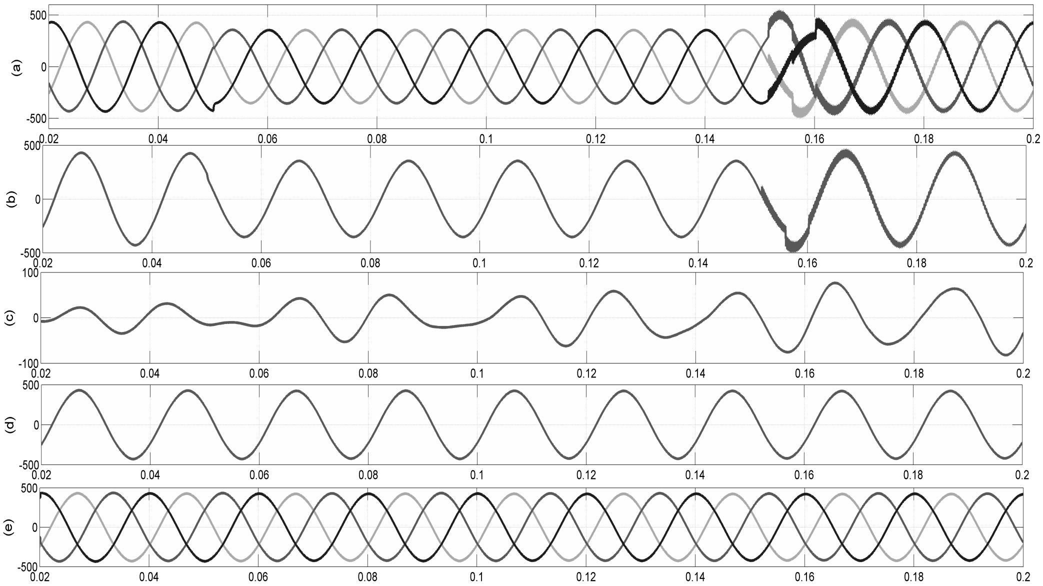


FIGURE 6.20: Mitigation of sag in load voltage

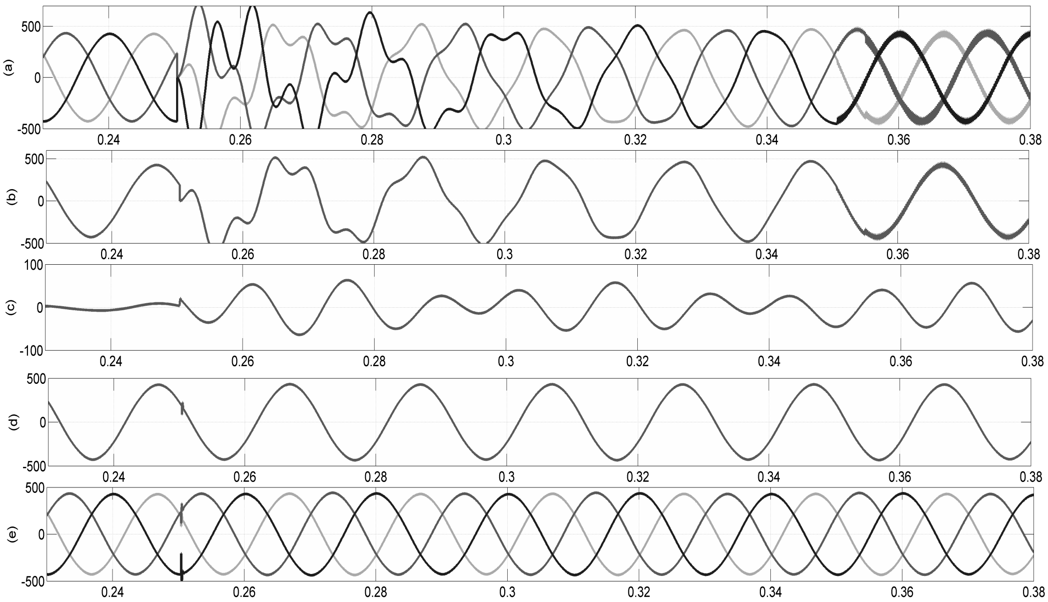


FIGURE 6.21: Mitigation of swell in load voltage

of the source is immediately changed. The active power consumed/delivered by the load from MG source is also represented. Due to the sag/swell in the source voltage, the active power is varied by the load based on the change in the source. However, when UPQC is connected, the source active power is maintained in balance condition. Similarly, Figure. 6.24 represents the reactive power that flows in the MG when there is no disturbance in the source voltage. Due to the sag/swell in supply, the reactive power flow from source and load connected to MG source are

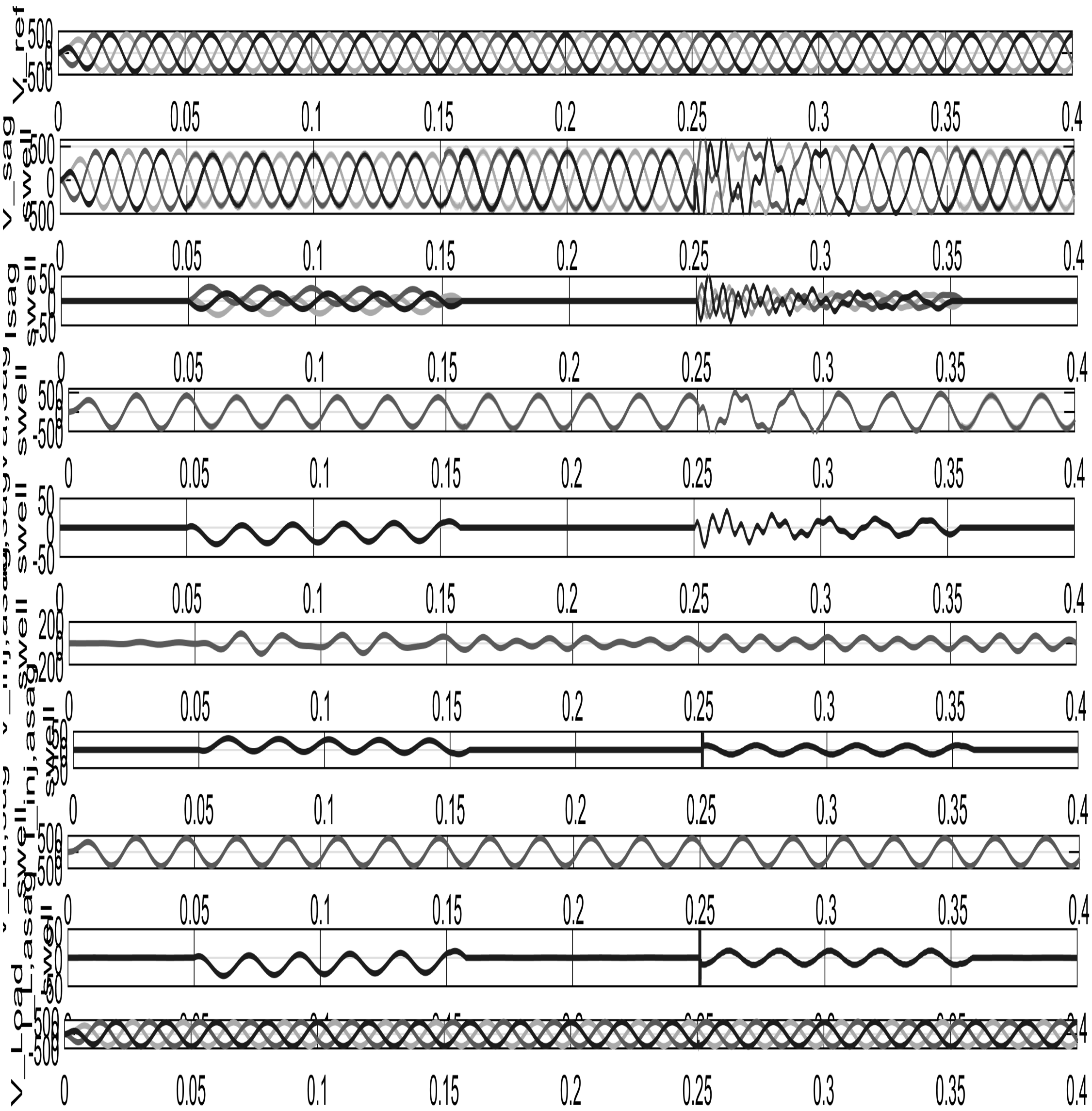


FIGURE 6.22: Mitigation of simultaneous sag/swell in load voltage

indicated. However, the UPQC provides the required reactive power to maintain power balance. Similarly, power factor variation for sag/swell condition is shown in Figure. 6.25. From the above results, the effectiveness of UPQC in providing harmonic, reactive power compensation, and improvement in p.f is verified.

6.7 Conclusion

MG PQ problems are categorized in terms of current and voltage quality issues. These problems are separately addressed by enhanced DVR and DSTATCOM in the previous chapters 4 and 5.

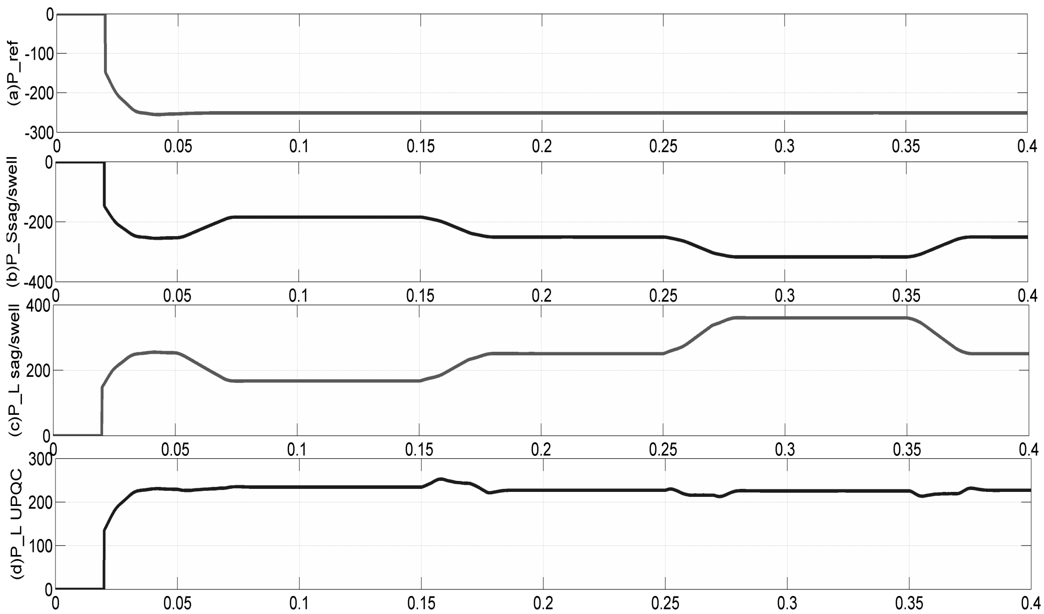


FIGURE 6.23: Active power flow in MG for simultanoeus sag/swell

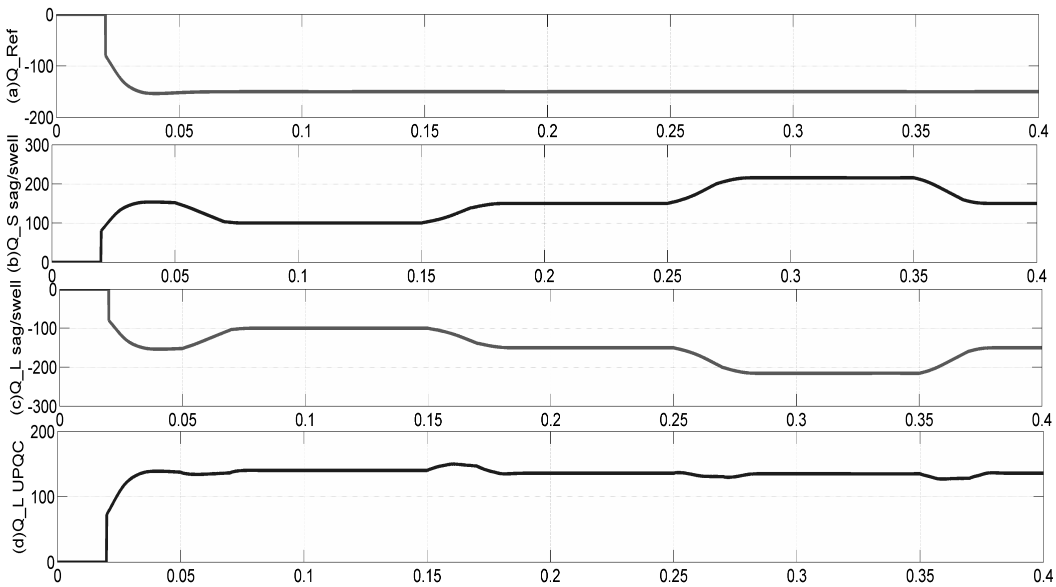


FIGURE 6.24: Reactive power flow in MG for simultanoeus sag/swell

However, both the applications are combined and developed using a multitasking device UPQC. The UPQC constituting series and shunt APFs is enhanced by replacing both the APFs with enhanced DVR and DSTATCOM and presented as enhanced UPQC in this chapter. To overcome all the PQ problems, the device has been systematically designed along with different control strategies applied depending upon the control objective selected. Thus the designed UPQC with the modified topology has been proposed is used to compensate for reactive power, unbalance

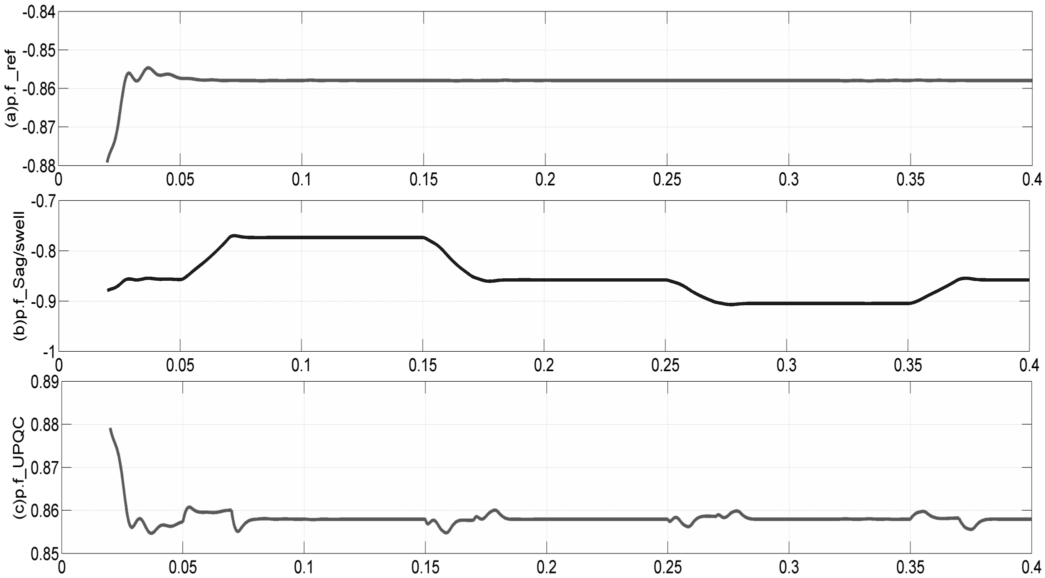


FIGURE 6.25: p.f variation in MG for simultaneous sag/swell

and harmonic components. It is found that for different types of disturbances like voltage sag, swell and nonlinear load conditions, the system could function satisfactorily in the presence of enhanced UPQC keeping current and voltage quality at the grid side/ load and within the norms. In all, the novel control strategy (series APF with IVTG and shunt APF with modified three-phase (or) single-phase PQ theory) for the UPQC has been proposed and it is found to work effectively in maintaining the overall power quality of the DG based AC microgrid.