

# Chapter 6

## Synchronverter based Multifunctional UPQC for Distributed Generation Applications

### 6.1 Introduction

Maintaining supply power quality is a big concern with the ever-growing renewable energy sources based on power electronic converters. Due to non-linear nature of the power electronic devices, grid faces serious power quality problems [107, 108]. In addition, non-linear loads have increased recently. Hence, the compensation of PQ problems is a big task for the grid operators. Emerging trends, such as microgrids, are also demanding power quality improvements [112]. Power quality problems are categorized as voltage- and current-related problems. Voltage-related PQ problems are mostly on the grid side, such as voltage sag, swell, flicker, harmonics, etc. Current-related PQ problems involves load-side issues such as current harmonics generated by the non-linear-load. To compensate for both current and voltage PQ problems simultaneously, the combination of DVR and STATCOM called UPQC [119–124] is employed.

UPQC can solve PQ issues like harmonics, sag and swell, but they are not capable of inertial response because they lack rotating mass or inertia. Inertia is necessary for the stability of the power system. Absence of physical inertia creates a variety of problems, like instability, large frequency deviations, etc. Conventional synchronous machines have the property to regulate the frequency and voltage and improve system stability since

they have a physical rotor. Hence, the reduction in grid inertia can be sorted out by implementing the synchronous generator characteristics in the voltage source inverters.

Till now, no efforts have been made to incorporate the current harmonic compensation with the virtual synchronous generator concept. In this chapter, the shunt converter control algorithm of UPQC is developed by integrating virtual synchronous machine characteristics with current harmonic compensation and the modified UPQC is termed as multifunctional UPQC (MUPQC). This proposed MUPQC's shunt converter control technique was created by modelling the functional attributes of a synchronous machine. Beside its ability to enhance power quality, this MUPQC can also adjust active power, reactive power, and frequency. The major contributions to this chapter are:

- The proposed MUPQC has the advantages of a synchronous generator for increasing stability, as well as the advantages of UPQC for compensating voltage and current harmonics.
- The proposed MUPQC performs voltage sag mitigation, voltage swell mitigation, voltage harmonics mitigation, and load current harmonics compensation, in addition to active and reactive power management and frequency regulation services.
- Additionally, the suggested MUPQC may operate in both grid-tied and isolated modes without any issues.

The proposed MUPQC is implemented in MATLAB/Simulink environment to validate the performance of the system in various scenarios. The performance of the proposed MUPQC controller under various cases is presented through simulation results. A brief outline of the chapter is as follows:

- Section 6.2 describes the MUPQC architecture.
- The design of the various components of MUPQC is discussed in Section 6.3.
- The proposed control algorithm for MUPQC is presented in Section 6.4.
- Simulation results of the MUPQC with the proposed controller using MATLAB/Simulink platform is discussed in Section 6.5.
- Conclusion is made in Section 6.6.

## 6.2 MUPQC Architecture

Figure 6.1 illustrates the structure of the UPQC interfaced with DG system. This DG may consist of several renewable energy sources such as fuel cell, solar and wind along with the DC loads and the battery energy storage system (BESS). However, the whole DG system is considered as a basic BESS integrated with the DC link of a back to back connected converters. The circuit parameters of the considered MUPQC are presented in the Appendix.

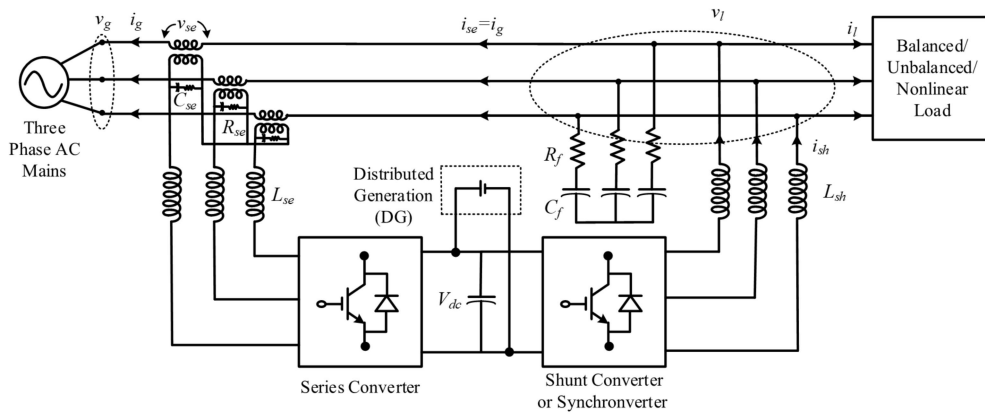


Figure 6.1: Schematic representation of the Synchronverter based MUPQC interfaced with DG.

## 6.3 Design of the MUPQC

The design procedure for MUPQC involves the proper sizing of dc-link capacitor, dc-link voltage level, interfacing inductors of series and shunt compensators and series injection transformer of the series compensator.

### 6.3.1 DC Voltage level

Voltage Magnitude of DC-Link: The magnitude of dc-link voltage  $V_{dc}$  depends on the depth of modulation used and per-phase voltage of the system. The dc-link voltage magnitude should be more than double the peak of per-phase voltage of the three-phase

system [147] and is given as

$$V_{dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}m} \quad (6.1)$$

where modulation index ( $m$ ) is taken as 1 and  $V_{LL}$  is the grid line voltage. For a line voltage of 400 V, the required minimum value dc-bus voltage is 653.2 V. The dc-bus voltage is set at 700 V (approx).

### 6.3.2 DC-Bus Capacitor Selection

The dc-link capacitor is sized based on power requirement as well as dc-bus voltage level. The energy balance equation for the dc-bus capacitor is given as follows [147]:

$$C_{dc} = \frac{3kxV_{ph}I_{sh}t}{0.5 * (V_{dc}^2 - V_{dc1}^2)} \quad (6.2)$$

where  $V_{dc}$  is the average dc-bus voltage,  $V_{dc1}$  is the lowest required value of dc-bus voltage,  $x$  is the overloading factor,  $V_{ph}$  is per-phase voltage,  $t$  is the minimum time required for attaining steady value after a disturbance,  $I_{sh}$  is per-phase current of shunt compensator, and  $k$  factor considers variation in energy during dynamics. The minimum required dc-link voltage is  $V_{dc1} = 653.2$  as obtained from (6.2),  $V_{dc} = 700$  V,  $V_{ph} = 230.94$  V,  $I_{sh} = 14.43$  A,  $t = 30$  ms,  $x = 1.2$ , and for dynamic energy change = 10%,  $k = 0.1$ , the value of  $C_{dc}$  is obtained as 1600  $\mu F$ .

### 6.3.3 Interfacing Inductor for Shunt Compensator

The interfacing inductor rating of the shunt compensator depends on the ripple current, the switching frequency, and dc-link voltage. The expression for the interfacing inductor is

$$L_f = \frac{\sqrt{3}mV_{dc}}{12xf_{sh}(I_{c,pp})} \quad (6.3)$$

where  $m$  is depth of modulation,  $x$  is the p.u. value of maximum overload,  $f_{sh}$  is the switching frequency, and  $I_{c,pp}$  is the inductor ripple current which is taken as 10% of rms phase current of a shunt compensator. Here,  $m = 1$ ,  $x = 1.2$ ,  $f_{sh} = 10$  kHz,  $V_{dc} = 700$  V, one gets 3.8 mH as value. The value chosen is approximated to 4 mH.

### 6.3.4 Series Injection Transformer

UPQC is designed to compensate for a sag/swell of 0.3 p.u., i.e., 69.28 V. Hence, the required voltage to be injection is only 69.28 V which results in low modulation index for the series compensator when the dc link voltage is 700 V. In order to operate the series compensator with minimum harmonics, one keeps modulation index of the series compensator near to unity. Hence, a series transformer is used with a turns ratio

$$K_{SE} = \frac{V_{VSC}}{V_{SE}} \quad (6.4)$$

The value obtained for  $K_{SE}$  is 3.33. The value selected is 3. The rating of series injection transformer is given as

$$S_{SE} = 3VI_{SEsag} \quad (6.5)$$

The current through series voltage source converter (VSC) is the same as the grid current. The supply current under sag condition of 0.3 p.u. is 30 A and hence the VA rating of an injection transformer achieved is 7 kVA.

### 6.3.5 Interfacing Inductor of Series Compensator

The rating of interfacing inductor of the series compensator depends on ripple current at swell condition, switching frequency, and dclink voltage. Its value is expressed as

$$L_r = \frac{\sqrt{3}mV_{dc}k_{SE}}{12xf_{se}I_r} \quad (6.6)$$

where  $m$  is the depth of modulation,  $x$  is the p.u. value of maximum overload,  $f_{se}$  is the switching frequency,  $I_r$  is the inductor current ripple, which is taken to be 10% of the grid current. Here,  $m = 1$ ,  $x = 1.5$ ,  $f_{se} = 10 \text{ kHz}$ ,  $V_{dc} = 700 \text{ V}$ , and 10% ripple current, one gets 3.6 mH. Hence, 4 mH is selected.

## 6.4 Control Algorithm

The main functionalities of the shunt converter are active power transfer, reactive power transfer, load current harmonic compensation, frequency regulation and compensation of load current unbalance. The series converter is used to compensate the voltage related power quality issues, for example swell, sag and harmonics. This section discusses the

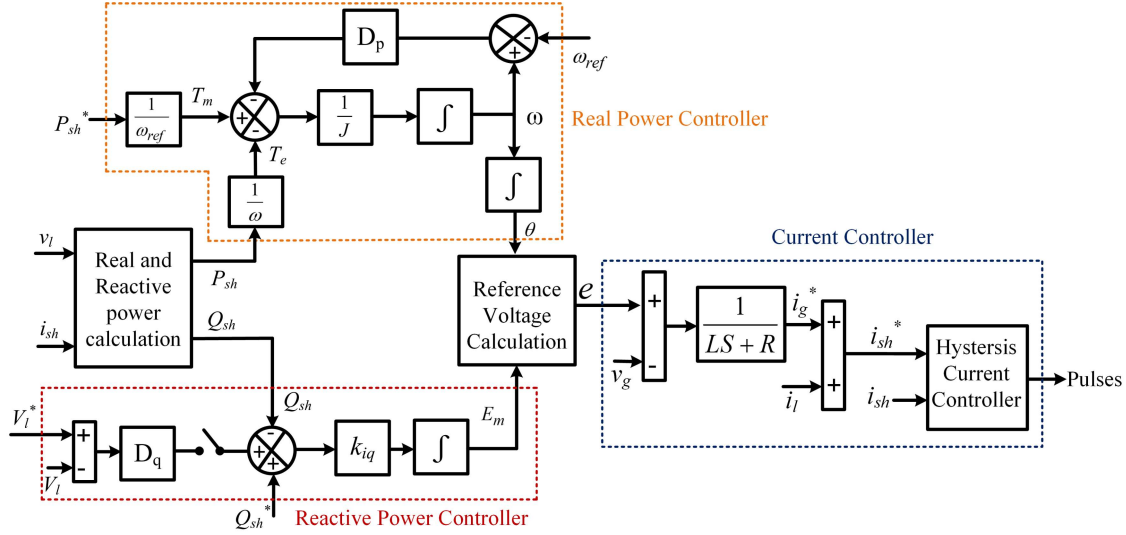


Figure 6.2: Control technique of the shunt converter acting as a synchronverter.

design and development of shunt and series converters for achieving the above-mentioned functionalities.

### 6.4.1 Synchronverter Control Algorithm

The synchronverter/shunt converter's complete control layout is shown in Figure 6.2. An inner current loop and an outer power loop forms the control structure of the shunt converter. Equations for controlling the virtual synchronous machine are applied to prepare the outer power loops. These power loops are used to estimate the reference voltage ( $e$ ) across the load ends. An impedance ( $Z = R + j\omega L$ ) is used to transform the estimated load voltage into current values. The pulses are produced to the synchronverter by employing the hysteresis controller.

The reference load voltage's magnitude ( $E_m$ ) and phase angle ( $\theta$ ) are determined by the reactive power and real power control loops respectively. Applying this real power loop, frequency control ( $\omega_{ref}$ ) and active power ( $P_{sh}^*$ ) control are realized. While the reactive power loop performs the load voltage regulation ( $v_l^*$ ) and reactive power ( $Q_{sh}^*$ ) control.

The synchronverter's active power loop is formed through the integration of virtual inertia to accommodate in the events of grid frequency transients. A cylindrical rotor synchronous machine's mathematical model is used to derive the algorithm for the shunt

converter controller. The dynamic equation of the synchronous machine [148] are,

$$\frac{d^2\theta}{dt^2} = \frac{1}{J}[T_m - T_e - D_p \frac{d\theta}{dt}] \quad (6.7)$$

Rearranging (6.7),

$$\omega = \int \frac{d\omega}{dt} = \frac{1}{J} \int [T_m - T_e - D_p(\omega - \omega_{ref})] dt \quad (6.8)$$

Here,  $\theta$  denotes the virtual angle of synchronverter;  $\omega$  is the virtual angular frequency and  $\omega_{ref}$  is the grid frequency in rad/sec.  $T_e$  and  $T_m$  stands for electrical torque and mechanical torque respectively.  $D_p$  is the damping coefficient and  $J$  is the moment of inertia. Number of poles are taken as 2. So, the mechanical speed and the electrical speed are same. Reference real power ( $P_{sh}^*$ ) and the reference frequency ( $\omega_{ref}$ ) are used to determine the mechanical torque ( $T_m$ ) which is given as,

$$T_m = \frac{P_{sh}^*}{\omega_{ref}} \quad (6.9)$$

The output torque ( $T_e$ ) of synchronverter is determined from the real power ( $P_{sh}$ ) and the virtual frequency ( $\omega$ ) as,

$$T_e = \frac{P_{sh}}{\omega} \quad (6.10)$$

Load voltage ( $v_l$ ) and shunt converter current ( $i_{sh}$ ) are used to get the virtual synchronous machine output power.

Solving equation (6.8) gives the virtual angular frequency ( $\omega$ ) and angle ( $\theta$ ) by further integrating angular frequency ( $\omega$ ).

The reactive power controller adjusts the load voltage and shunt converter reactive power. Droop coefficient ( $D_q$ ) of reactive power controller regulates the load voltage ( $v_l$ ) to the reference value. But in this present case, the series converter takes care of the voltage regulation. However, this voltage regulation loop comes in the picture during the initial synchronization process. The actual reactive power generated from the shunt converter ( $Q_{sh}$ ) is calculated using the load voltage ( $v_l$ ) and shunt converter current ( $i_{sh}$ ).  $Q/V$  droop characteristics is used to determine the value of  $k_{iq}$  to take part in the adjustment of grid voltage. Reactive power controller gives the amplitude ( $E_m$ ) of reference voltage ( $e$ ).

Rotor angle ( $\theta$ ) and reference voltage amplitude ( $E_m$ ) are used to determine the reference voltages at the load terminals as,

$$e_a = E_m \sin(\theta) \quad (6.11)$$

$$e_b = E_m \sin(\theta - 120^\circ) \quad (6.12)$$

$$e_c = E_m \sin(\theta - 240^\circ) \quad (6.13)$$

The current controller of the shunt converter is shown in Figure 6.2, for harmonic compensation of the load current. The grid current reference ( $i_g^*$ ) is derived from the grid voltage ( $v_g$ ) and the reference load voltage ( $e$ ) using the impedance ( $Z = R + j\omega L$ ) of the grid as,

$$i_g = \frac{e - v_g}{Ls + R} \quad (6.14)$$

The grid current ( $i_g$ ) and nonlinear load currents ( $i_l$ ) are added to estimate the reference currents ( $i_{sh}^*$ ) of shunt converter. Shunt converter current ( $i_{sh}^*$ ) comprises of fundamental as well as harmonic components required by the nonlinear load. Gating signals to the synchronverter are produced by comparing the shunt current reference ( $i_{sh}^*$ ) and actual shunt converter current ( $i_{sh}$ ) with the hysteresis controller.

### 6.4.2 Series Converter Controller

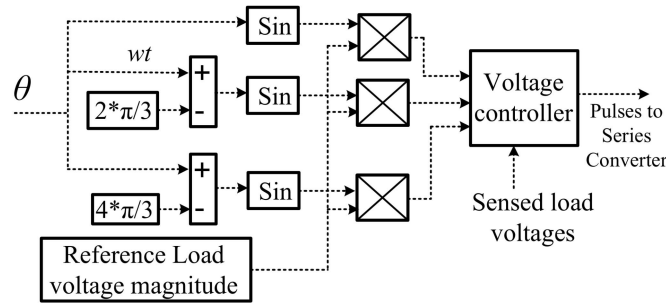


Figure 6.3: Series converter control diagram.

The series converter's primary function is to keep the load safe from grid voltage power quality issues. This series converter is able to mitigate the voltage sag, swell and harmonics. Here, the indirect voltage control is adapted. So, the reference voltage is selected as the load voltage instead of the series transformer injection voltage. Figure 6.3 shows the control algorithm for the series converter. The angle of the load voltage ( $\theta$ ) is

obtained from the virtual synchronous machine used in the case of shunt converter control algorithm. The phase angle and rated reference voltage magnitudes are used to compute the reference load voltages as expressed in (6.15)-(6.17).

$$v_{la} = V_{lm} \sin(\theta) \quad (6.15)$$

$$v_{lb} = V_{lm} \sin(\theta - 2 * \pi/3) \quad (6.16)$$

$$v_{lc} = V_{lm} \sin(\theta - 4 * \pi/3) \quad (6.17)$$

The reference load voltages are compared with the actual load voltages and passed through the voltage controller for generating PWM pulses to the series converter.

## 6.5 Simulation Results

The performance of the proposed MUPQC is presented in this section by MATLAB simulation results. The proposed MUPQC is validated for different test cases by changing the grid frequency, real and reactive power commands. Further, the transition from grid-connected to standalone mode, harmonics compensation of the load current, and grid voltage variation are also examined for MUPQC. MUPQC parameters are shown in the Table 6.1, Table 6.2 and Table 6.3.

Table 6.1: System Parameters

S.No.	Parameter	Values
1	Input power supply	3- $\phi$ 400 V (rms)
2	Frequency	50 Hz
3	DC bus: Capacitor rating	1600 $\mu F$ /800 V
4	reference dc link voltage	700 V

### 6.5.1 Grid Frequency Variation

By changing the grid frequency, the proposed MUPQC's frequency regulation is validated. By decreasing or increasing its real power generation in accordance with the rise or decline in frequency respectively, synchronverter based shunt converter helps in maintaining the

Table 6.2: UPQC Parameters

S.No.	Parameter	Values
1	Synchronverter filter inductance ( $L_{sh}$ )	4 mH
2	Synchronverter ripple filter resistance ( $R_f$ )	5 $\Omega$
3	Synchronverter ripple filter capacitance ( $C_f$ )	10 $\mu F$
4	Series converter filter inductance ( $L_{sc}$ )	4 mH
5	Series converter ripple filter resistance ( $R_{se}$ )	5 $\Omega$
6	Series converter ripple filter capacitance ( $C_{sc}$ )	10 $\mu F$
7	Transformer turn ratio	1:3

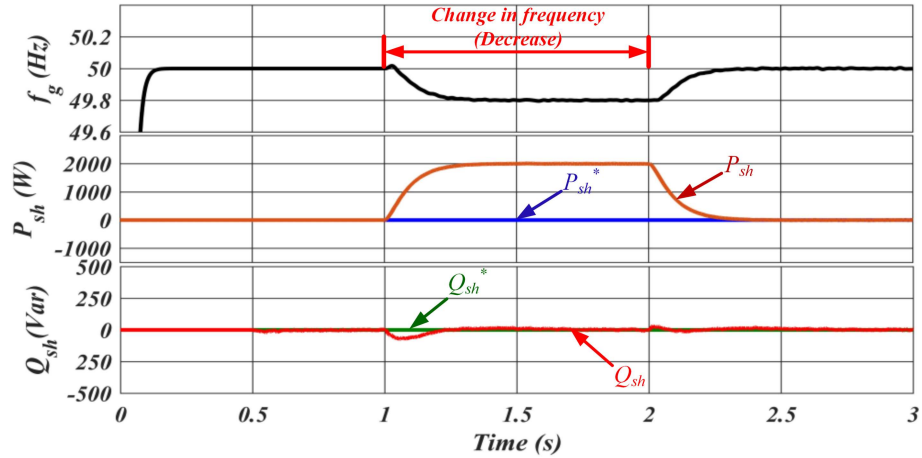
Table 6.3: Synchronverter Control Parameters

S.No.	Parameter	Values
1	Virtual damping $D_p$	500
2	Virtual inertia $J$	0.06
3	$D_q$	321
4	$k_{iq}$	0.045

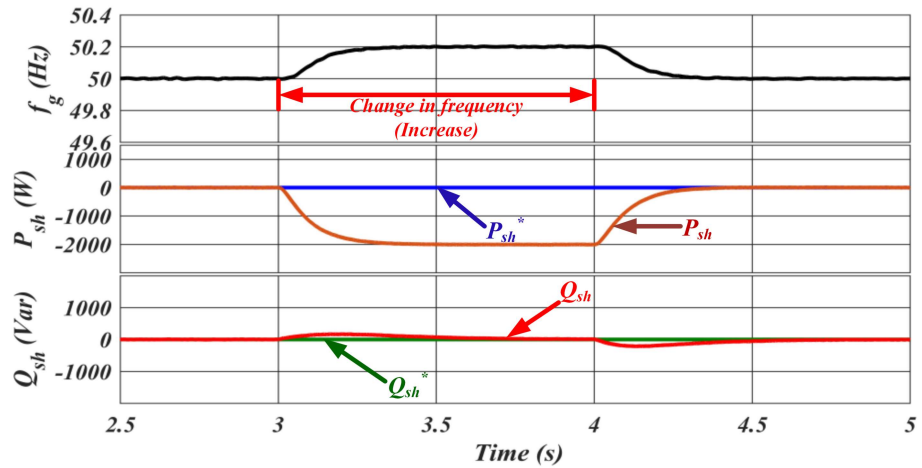
system frequency. In accordance with the frequency disturbance in the utility grid, the variation in the output powers ( $P_{sh}$  &  $Q_{sh}$ ) of the synchronverter is shown in Figure 6.4.

Although, the reference active power command ( $P_{sh}^*$ ) of the shunt converter is not changed, the output power of the shunt converter rises as the grid frequency drops, as shown in Figure 6.4(a). So, frequency regulation capability of the proposed MUPQC is verified. The shunt converter active power eventually reaches the specified reference value as the grid frequency returns to its rated value. The reactive power output of shunt converter is not affected by frequency disturbances of the grid.

Active and reactive power flow between the synchronverter and grid as the grid frequency rises is shown in Figure 6.4(b). In the steady state condition, the real power generated from the MUPQC synchronverter is 2 kW. With the increase in grid frequency, the active power should be sent back to the DG (or BESS) through the synchronverter. So, the power through the synchronverter becomes negative as shown in Figure 6.4(b). Active and reactive power of shunt converter eventually returns back to the reference



(a)



(b)

Figure 6.4: Real power ( $P_{sh}$ ) and reactive power ( $Q_{sh}$ ) response with the (a) decrease in frequency, (b) increase in frequency.

value as the frequency is restored again.

### 6.5.2 Real and Reactive Power Control

In this case, real and reactive power regulation abilities of shunt converter is examined while making sure that there is no disturbance in grid frequency and grid voltage. Amount of real and reactive powers supplied to the grid is decided based on the requirement of the grid operator. Real and reactive power flow ( $P_{sh}$  &  $Q_{sh}$ ) between the converter and grid with the reference real power ( $P_{sh}^*$ ) and reference reactive power ( $Q_{sh}^*$ ) commands are presented in Figure 6.5. At first, power references ( $P_{sh}^*$ ) & ( $Q_{sh}^*$ ) are kept to zero. As soon

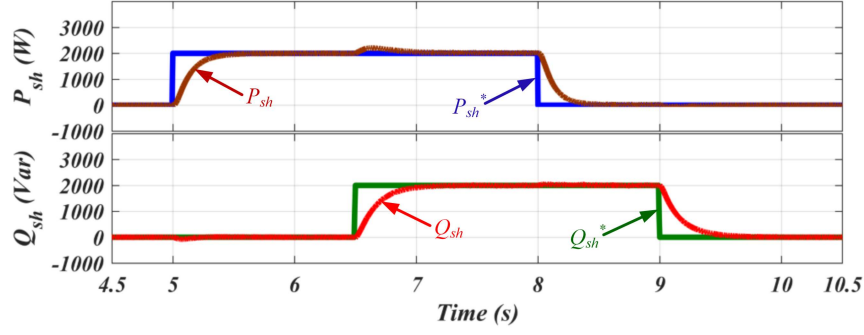


Figure 6.5: Response of real power ( $P_{sh}$ ) and reactive power ( $Q_{sh}$ ) with the change in reference real power ( $P_{sh}^*$ ) and reactive power ( $Q_{sh}^*$ ).

as  $P_{sh}^*$  is changed from 0 to 2 kW, the shunt converter supplies 2 kW real power ( $P_{sh}$ ). Afterwards,  $Q_{sh}^*$  is changed from 0 to 2 kVar. Hence, the shunt converter supplies the same amount of reactive power ( $Q_{sh}$ ) to the grid. As soon as, the real and reactive power references restored to initial values i.e. zero, there will be no power flowing from shunt converter to the grid. Hence, real and reactive power regulation of MUPQC is validated.

### 6.5.3 Harmonics Compensation

Here, Synchronverter (shunt converter) is examined for compensation of current harmonics caused by the non-linear loads.

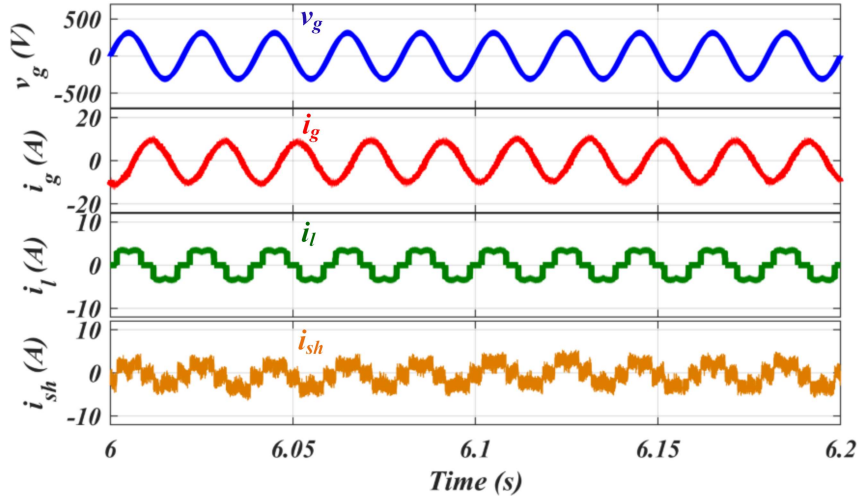


Figure 6.6: Load current harmonics compensation.

It is observed that Synchronverter is capable of fulfilling the requirement of load current harmonics in addition to supply/absorb the real and reactive power. Waveforms

of grid current ( $i_g$ ), shunt converter current ( $i_{sh}$ ), load current ( $i_l$ ) and grid voltage ( $v_g$ ) is shown in Figure 6.6. In spite of the harmonics current ( $i_l$ ) drawn by the non-linear load, the grid current ( $i_g$ ) remains sinusoidal as seen in Figure 6.6. Hence, shunt converter of proposed MUPQC supplies the harmonics component of the load current without disturbing the grid current quality.

### 6.5.4 Smooth Transition between Modes

Seamless switching of MUPQC shunt converter between grid-tied and standalone mode is validated under this case. Synchronverter of the proposed MUPQC works efficiently in both the modes i.e. grid connected and standalone mode due to the grid forming capability or the voltage controlled mode operation of synchronverter (shunt converter). The grid current ( $i_g$ ) goes to zero when the MUPQC shunt converter is deliberately isolated from the grid, as illustrated in Figure 6.7. Still, the load voltage ( $v_l$ ) is maintained without any problem, i.e. MUPQC synchronverter is supplying the power requirement of the load during standalone mode.

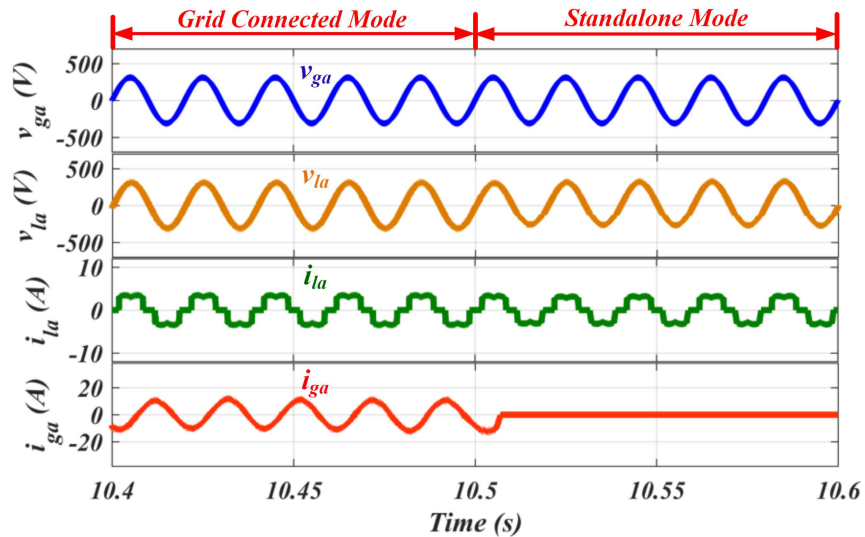
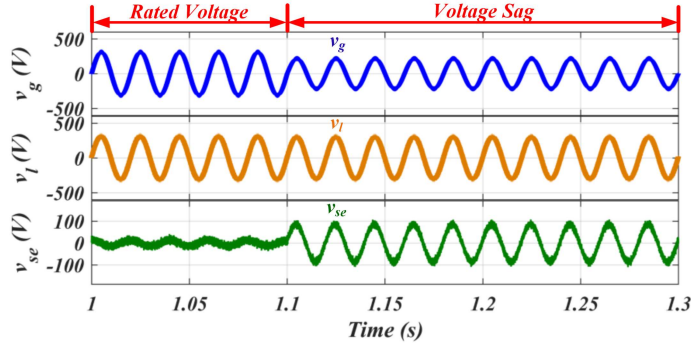


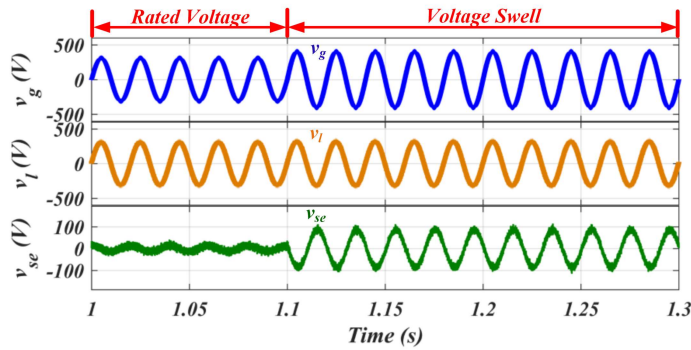
Figure 6.7: Different quantities during transition from grid connected mode to standalone mode.

### 6.5.5 Grid Voltage Variation

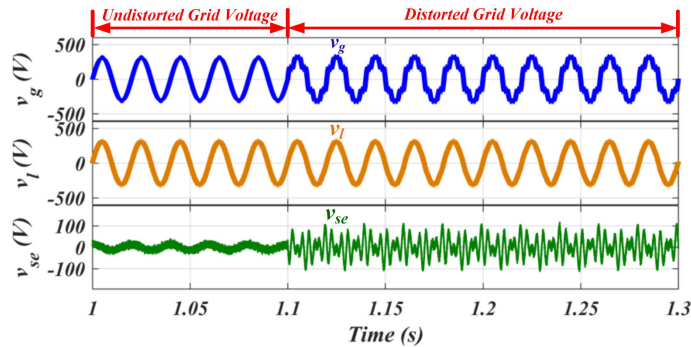
Operation of the series converter for mitigating the grid voltage power quality issues such as voltage sag, swell and harmonics are illustrated in this subsection. Figure 6.8(a)-6.8(c) shows the grid voltage ( $v_g$ ), load voltage ( $v_l$ ) and series converter voltage ( $v_{se}$ ) for voltage sag, swell and harmonics condition respectively.



(a)



(b)



(c)

Figure 6.8: Variation in the grid voltage ( $v_g$ ), load voltage ( $v_l$ ) and series converter voltage ( $v_{se}$ ) under (a) voltage sag condition, (b) voltage swell condition and (c) voltage harmonics condition.

As shown in Figure 6.8(a), during the voltage sag phenomena in the grid voltage ( $v_g$ ), the load voltage ( $v_l$ ) is still maintained at the rated value by injecting the voltage through the series transformer.

Figure 6.8(b) presents the case for the voltage swell condition. For the voltage swell condition, the series MUPQC converter injects the voltage in opposite phase to decrease the load voltage. Hence, the load voltage is maintained to the rated value regardless of the voltage swell in the grid voltage. Figure 6.8(c) presents the test case for the harmonics distortion in the grid voltage. The series converter injects the harmonics in the opposite phase. So, the load voltage ( $v_l$ ) is observed to be sinusoidal as shown in Figure 6.8(c).

## 6.6 Conclusion

A multifunctional unified power quality conditioner (MUPQC) for DG application to emulate the behaviour of a synchronous generator has been presented in this chapter. The synchronous machine characteristics are integrated into the shunt converter control algorithm, so that this MUPQC can add virtual inertia to the grid to regulate the frequency. Implementation of the virtual synchronous machine in MUPQC provides a reliable and simpler control method and completely removes the synchronizing element like phase locked loop (PLL). In addition, the proposed MUPQC synchronverter control is capable of working in standalone as well as grid-tied mode. This feature of the proposed MUPQC makes it a viable choice for the micro grid applications. The proposed MUPQC has been implemented in MATLAB/Simulink platform and validated for voltage sag, swell, harmonics compensation for load current and frequency disturbance conditions. The proposed MUPQC is very much suitable to work in future grid connected systems comprising large number of power electronics devices.

