Improve Power Quality with High Power UPQC

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1. Introduction

An ideal AC power transmission is pure sinusoidal, both its voltage and its current. With the increasing production of modern industry, more and more power electronic equipments are used and cause serious current distortion because of open and close of power electronic devices. Harmonic, a measurement of distorted degree of voltage or current, reflects the deviation from sinusoidal wave. Another cause of harmonic is nonlinear loads such as Arc furnaces and transformers. The widely using of nonlinear load brings much harmonic current to transmission lines. The harmonic current passes through transmission lines and causes harmonic voltage exert on the loads in other place(Terciyanli et al. 2011). As a result, the loss of power transmission is increased and the safety of power grid is seriously weakened.

With the fast development of modern production, the harmonic in power grid become more and more serious and people pay more attention to how to eliminate harmonic(wen et al. 2010). Active Power Filter (APF) is a promising tool to cut down the influence of harmonics, shunt APF for harmonic current, series APF for harmonic voltage. Unified Power Quality Conditioner (UPQC), consisted of shunt APF and series APF, is effective to reduce both harmonic voltage and harmonic current. Now, UPQC is mainly used in low-voltage low-capacity applications. But with the development of power system, more and more high-power nonlinear loads are connected to higher voltage grid and the demand of high voltage and high capacity keeps being enlarged. The paper discussed a high power UPQC for high power nonlinear loads. In this UPQC, shunt APF uses a hybrid APF which includes a Passive Power Filter (PPF) and an APF. Shunt APF is connected to a series LC resonance circuit in grid fundamental frequency so as to make shunt APF in lower voltage and lower power. The series LC resonance circuit is connected to grid with a capacitor. DC linker of PPF is connected to DC link of APF. This type of UPQC is fit for high voltage high power application because the voltage and capacity of its active device is much lower than those of the whole UPQC. The paper discussed the principle and control method of this UPQC.

2. Fundamental knowledge

To show better about the principle and the theory about the high power UPQC, some fundamental knowledge about harmonic and harmonic elimination equipments are list below.

2.1 Series active power filter

In power system, voltage out from turbine is promising to be sinusoidal. So if there is no nonlinear load connects to power grid between generator and the nonlinear load in question, a shunt APF is enough to keep both the voltage and the current of transmission line sinusoidal because the transmission line is composed of linear components such as resistances, inductions and capacitors. But in modern power system, power is transmitted for a long distance before delivery to the nonlinear load and power is distributed to many nonlinear loads in many difference places along the transmission line. The transmission of harmonic current causes harmonic voltage in transmission lines which increases possibility of damage to some critical loads such as storage devices and some micromachining devices. Shunt APF can do little with the damage caused by harmonic voltage in transmission line. A series APF is installed between power source and critical load so as to insulate voltage harmonic from the critical load(Kim et al. 2004). It is also promising to eliminate damages to load caused by some other supply quality issues such as voltage sage, instant voltage interrupts, flicks and over voltage.

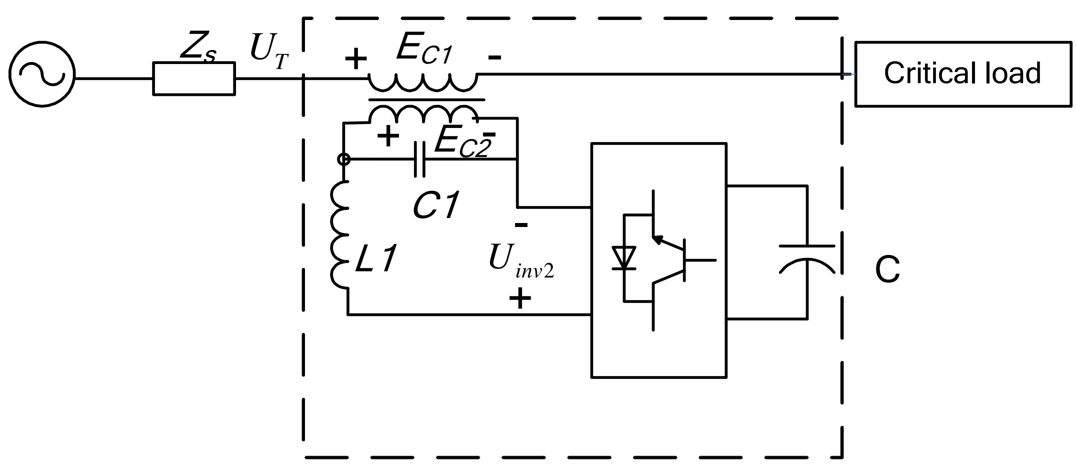


Fig. 1. Configuration of series APF

2.2 Shunt active power filter

The distortion of current not only brings serious loss of power transmission, but also endangers power grid and power equipments. Harmonic current increases the current flowed through transmission lines and as a result power transmission loss is increased and power grid has to take a risk of higher temperature which threatens the safety of power grid. Harmonic current in transformers will make them magnetic saturated and seriously heated. Much noise is generated because of harmonics in equipments. Besides, harmonics make some instruments indicate or display wrong values, and sometimes make they work wrong.

To eliminate harmonic current produced by nonlinear loads, a shunt Active Power Filter (APF) is expected to connect parallel to power grid(Ahmed et al. 2010). Shunt APF draws energy from power grid and makes it to be harmonic current that is equal to the harmonic current produced by nonlinear load so that harmonic current doesn't go to transmission line but goes between nonlinear load and APF. Usually an inverter is employed to realize this function.

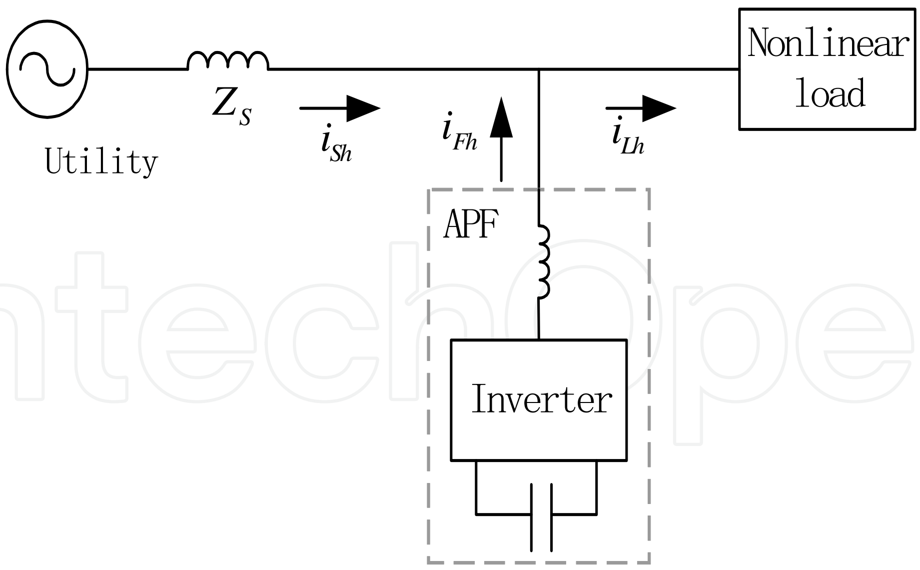


Fig. 2. Configuration of shunt APF

Fig.2 shows Configuration of shunt APF, where Z_s is impedance of transmission line, i_{sh} is harmonic current trough transmission line, i_{Lh} is load harmonic current and i_{Fh} is harmonic current from APF. APF employs an inverter to generator a harmonic current that always keeps equal to load harmonic current, that is:

$$i_{Fh} \equiv i_{Lh} \tag{1}$$

Then load harmonic current is intercepted by APF and will not pass through transmission line.

$$i_{sh} \equiv 0 \tag{2}$$

Usually a voltage source inverter which uses a high capacity capacitor to store energy in DC linker is used.

Under some conditions, nonlinear load not only produces harmonic current but also produces much more reactive current. In order to avoid reactive current going to transmission line, the shunt equipment needs to compensate also the reactive current. Passive Power Filter (PPF) is usually added to APF to compensate most of reactive current and a part of harmonic current so as to decrease the cost. This hybrid system of APF and PF is called Hybrid Active Power Filter (HAPF) (Wu et al. 2007). In HAPF, APF and PPF are connected in different forms and form many types of HAPF. Because of its low cost, HAPF attracts more and more eyes and has been developing very quickly.

2.3 UPQC: Combined shunt APF and series APF

Unified Power Quality Conditioner (UPQC) is composed of series APF and shunt APF(Yang & Ren, 2008). It not only protects the critical load from voltage quality problems but also eliminates the harmonic current produced by load. In UPQC, the series APF (usually called its series device) and shunt APF (usually called its shunt device) usually share the energy storage so as to simplify the structure and reduce the cost of UPQC.

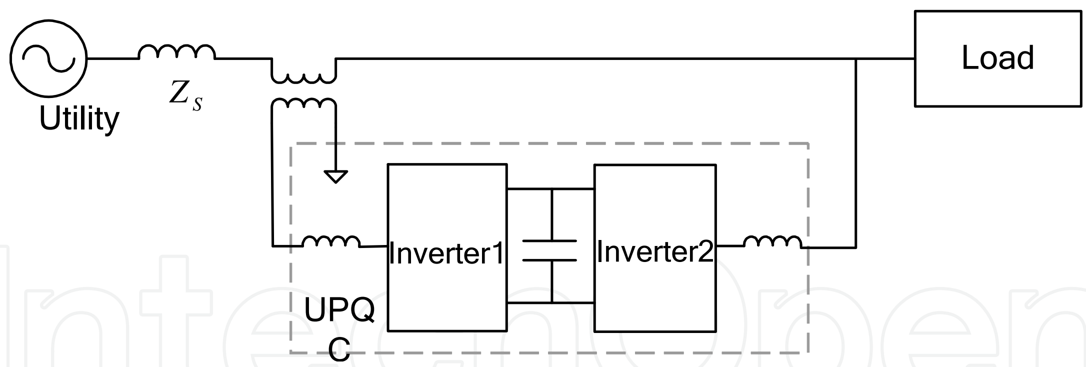


Fig. 3. Unified Power Quality Conditioner

3. An UPQC in high power application

In many mid-voltage or high-voltage applications, nonlinear load not only produces heavy harmonic current but also is sensitive to harmonic voltage. An UPQC combined a series APF and a HAPF is much suitable for these applications(Khadkikar et al.,2005). Fig.4 shows the detailed system configuration of the high power UPQC, where e_{sa}, e_{sb} and e_{sc} are three phase voltages of generator, e_{ca}, e_{cb} and e_{cc} are the voltages compensated by series APF, I_s is utility current, I_L is load current, I_F is compensating current output from shunt device, Z_s is impedance of transmission line, C is a big capacitor for DC linker.

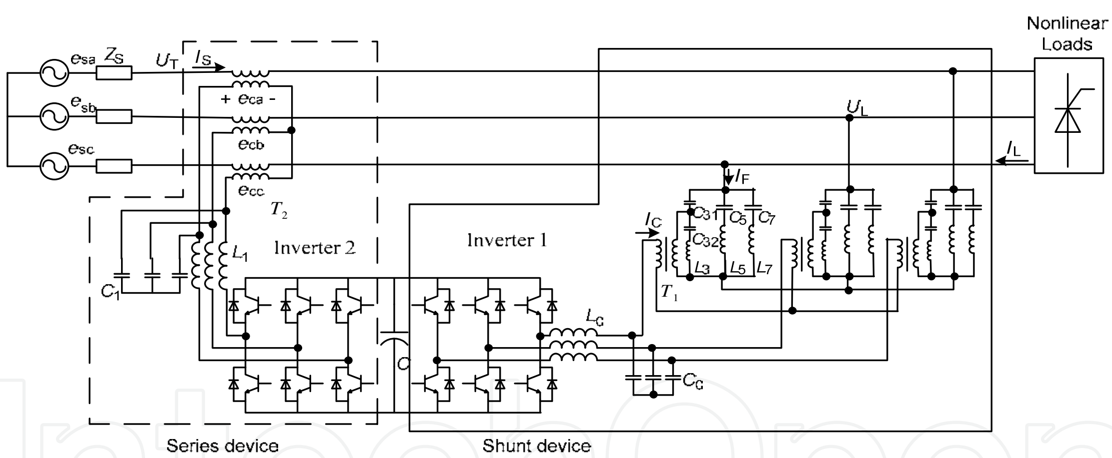


Fig. 4. Configuration of high power UPQC

The high power UPQC is composed of series device and shunt device. The series device is mainly for insulating the source voltage interference, adjusting loads voltage etc. The shunt device is mainly for eliminating harmonic current produced by nonlinear load. In series device, L_1 and C_1 make low-pass filter (LPF) to filter output voltage of Inverter 2 because power electronics devices in Inverter 2 open and close in high frequency and generate high frequency disturbances exerted on expected sinusoidal output voltage of Inverter 2. In series device, transformer T_2 not only insulates Inverter 2 from utility but also makes output voltage of Inverter 2 (after LPF) satisfy maximum utility harmonic voltage. In shunt device, L_0 and C_0 make a LPF to filter output voltage of Inverter 1. The shunt device and series device share the DC capacitor. The shunt device is consisted of an inverter and a PPF. PPF is consisted of 3 L-C resonance branches. One is consisted of L_5 and C_5 for 5th harmonic current elimination, the other is consisted of L_7 and C_7 for 7th harmonic current elimination, and the third is consisted of L_3, C_{31}, C_{32} for 3rd harmonic current elimination. The resonance frequency of L_3 and C_{32} is set to be the same as the frequency of fundamental component so that most of fundamental reactive current in this series resonance branch goes through L_3 and C_{32} and little goes through inverter through transformer T_1. As a result Inverter 1 suffers little fundamental voltage which helps to cut down its cost and improve its safety. Transformer T1 connects Inverter 1 with the series fundamental resonant branch L_3 and C_{32} to insulate them and fit the difference between maximum output voltage of Inverter 1 and maximum voltage that L3 and C_{32} needed to generate the maximum compensating current. The 3rd, 5th, 7th harmonic currents can be eliminated by the 3 L-C resonance branches, and Inverter 1 can also inject harmonic current into utility to give a fine compensation to every order harmonic current except 3rd harmonic current.

3.1 Series device of high power UPQC

Series device of UPQC is mainly to filter utility voltage and adjust voltage exerted on load so as to eliminate harmonic current produced by utility harmonic voltage and provide load a good sinusoidal voltage(Brenna et al. 2009; Zhou et al. 2009).

Series device of high power UPQC has the same topology as series APF whose Configuration is shown in Fig.1. Fig.1shows the single phase equivalent circuit of the series device, where Z_s is impedance of transmission line. The main circuit and control circuit of the active part are in the dashed box.

From the sigle-pahse system, the voltage of the transformer can be expressed as

$$E_{C2} = U_{inv2} \cdot \frac{Z_{C1}}{Z_{L1} + Z_{C1}} \tag{3}$$

Suppose $E_{C1} = n \bullet E_{C2}$, then the voltage of the Inverter 2 can be calculated as

$$\begin{aligned} U_{inv2} &= E_{C2} \cdot \frac{Z_{L1} + Z_{C1}}{Z_{C1}} \\ &= \frac{Z_{L1} + Z_{C1}}{nZ_{C1}}(U_T - U_L) \end{aligned} \tag{4}$$

The voltage of Inverter 2 can be written at another way as

$$U_{inv2} = K_V \cdot U_{DC} \cdot B(s) \tag{5}$$

Where K_V is amplitude ratio between U_{inv2} and U_{DC}, $B(s)$ is phase shift between input control signal and output voltage of Inverter 2.

$$\begin{aligned} U_L &= U_T - E_{C1} \\ &= U_T - n \cdot K_V \cdot B(s) \cdot \frac{Z_{C1}}{Z_{L1} + Z_{C1}} \cdot U_{DC} \\ &= U_T - K_{CL} U_{DC} \end{aligned} \tag{6}$$

Where
$$K_{CL} = n \cdot K_V \cdot B(S) \cdot \frac{Z_{C1}}{Z_{L1} + Z_{C1}} \tag{7}$$

To make load voltage sinusoidal, load voltage U_L is usually sampled for control. Control scheme for series device is:

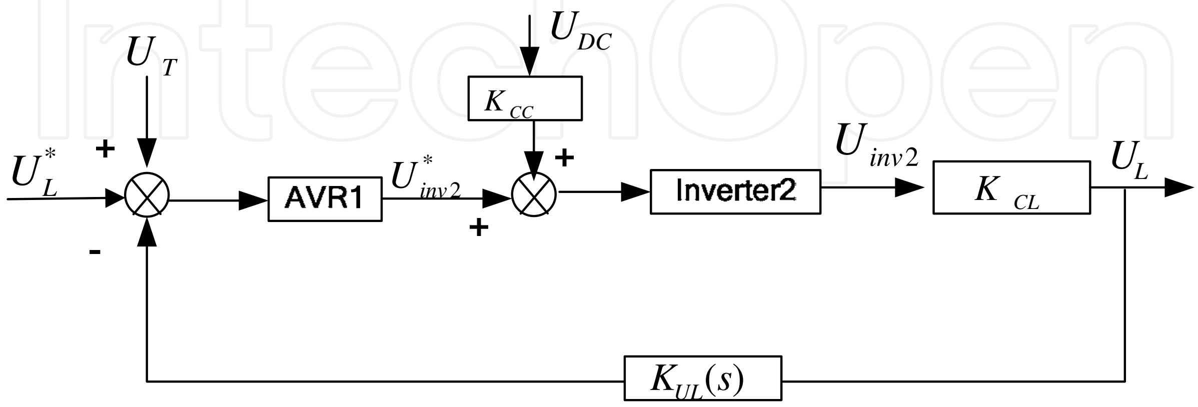


Fig. 5. Control scheme for series device of high power UPQC

Where AVR1 is automatic voltage regulator for U_L control and AVR2 is for U_C control. U_{DC} is voltage of DC-linker. $K_{UC}(S)$ is transform function of detecting circuit of U_C which is consisted of a proportion segment and a delay segment. $K_{UL}(S)$ is transform function of detecting circuit of U_L. U^*_L is reference voltage for load voltage U_L, when a certain harmonic component is concerned, it is set to zero. AVR1 is automatic voltage regulator for U_L and it can be divided to 3 parts, one is harmonic extraction, another is PI adjustor and the third is delay array. Control scheme of AVR1 is depicted in Fig.6. A selective harmonic extraction is adopted to extract the main order harmonics. Abc_dq0 is described as equation (8-10) for a certain k order harmonic and transformation dq0_abc is described as equation (11-13). LPF is low pass filter that only let DC component pass through.

$$U_d = \frac{2}{3}(V_a \sin(k\omega_0) + V_b \sin[k(\omega_0 - \frac{2\pi}{3})] + V_c \sin[k(\omega_0 + \frac{2\pi}{3})] \tag{8}$$

$$U_q = \frac{2}{3}(V_a \cos(k\omega_0) + V_b \cos[k(\omega_0 - \frac{2\pi}{3})] + V_c \cos[k(\omega_0 + \frac{2\pi}{3})] \tag{9}$$

$$U_0 = \frac{1}{3}(V_a + V_b + V_c) \tag{10}$$

$$V_a = U_d \sin(k\omega_0) + U_q \cos(k\omega_0) + U_0 \tag{11}$$

$$V_b = U_d \sin[k(\omega_0 - \frac{2\pi}{3})] + U_q \cos[k(\omega_0 - \frac{2\pi}{3})] + U_0 \tag{12}$$

$$V_c = U_d \sin[k(\omega_0 + \frac{2\pi}{3})] + U_q \cos[k(\omega_0 + \frac{2\pi}{3})] + U_0 \quad (13)$$

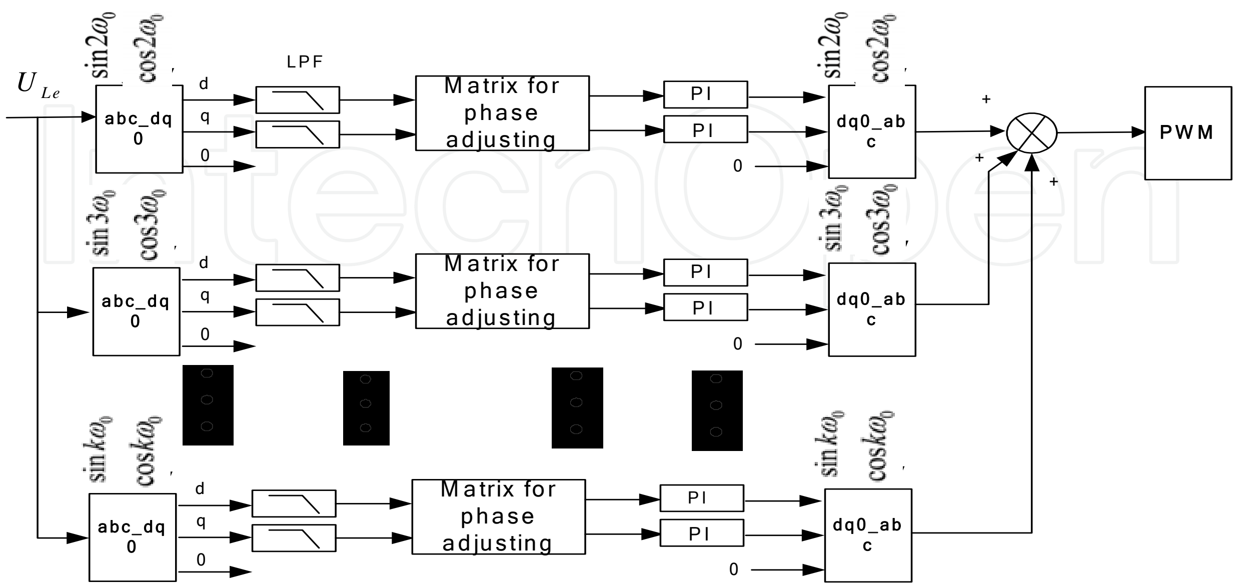


Fig. 6. Control scheme of AVR1

Because a delay will unavoidably happen during detecting and controlling, a matrix is used to adjust the phase shift of the certain order harmonic. The matrix is described as:

$$\begin{bmatrix} U_d^{'} \\ U_q^{'} \end{bmatrix} = \begin{bmatrix} \cos(k\omega_0 + \theta) & -\sin(k\omega_0 + \theta) \\ \sin(k\omega_0 + \theta) & \cos(k\omega_0 + \theta) \end{bmatrix} \begin{bmatrix} U_d \\ U_q \end{bmatrix} \quad (14)$$

Where θ is phase angle for delay.

To check the effect of series device of high power UPQC to harmonic voltage, with MATLAB, a 3-phase 10KV utility supplied to capacitors is set up. Suppose the initial load is a 3-phase capacitor group, a resister valued 0.2 ohm series with a capacitor valued 100uF in each phase. When t=0.04s, series device switches to run. Tab.1 shows the parameters of power source and series device. Comparing the main harmonic voltages and harmonic currents after series run with those before series run, we know that series device reduce much harmonic of load voltage and so load harmonic current is much reduced. Fig.7 shows waveform of load voltage before and after series device run. In Fig.8, the spectrums of load voltage are compared through FFT. Fig.9 shows load current waveform and Fig.11 shows the spectrums of load current before and after series device run. With transformer T_2, fundamental voltage produced by Inverter 2 can be added to power source, so it can also compensate voltage sags. When it is concerned, U_L^* in Fig.6 is set to be expected fundament component of source voltage. Fig.12 and Fig.13 shows this function of series device. At 0.1s, utility voltage suddenly goes below to be 80 percents of previous voltage, as is shown in Fig.12. If series device keep running before voltage sag happen, utility voltage will keep almost const, as is shown in Fig.13.

Items	Parameters
Utility fundamental voltage	3-phase in positive sequence; line to line voltage: 10KV; Initial phase: 0 deg.
Utility 2nd harmonic voltage	3-phase in negative sequence; line to line voltage: 250V; Initial phase: 0 deg.
Utility 3rd harmonic voltage	3-phase in zero sequence; line to line voltage: 600V; Initial phase: 0 deg.
Utility 5th harmonic voltage	3-phase in negative sequence; line to line voltage: 1500V; Initial phase: 0 deg.
Utility 7th harmonic voltage	3-phase in positive sequence; line to line voltage: 1300V; Initial phase: 0 deg.
Impedance of transmission line	Resister: 0.04 ohm; Inductor : 1uH;
Low Pass filter	L_1: 4mH; C_1: 15uF
Transformer T2	n=10
Load	3-phase series resister and capacitor Resister: 0.2 ohm; capacitor: 100uF

Table 1. Parameters for series device

	2nd (%)	3rd (%)	5th (%)	7th (%)	THD(%)
Voltage before run	3.07	7.35	12.24	9.79	17.58
Voltage after run	0.88	1.55	3.55	2.37	4.66
current before run	6.09	21.93	60.48	66.96	93.05
current after run	1.99	4.86	17.72	16.44	25.67

Table 2. Harmonics before and after series device run

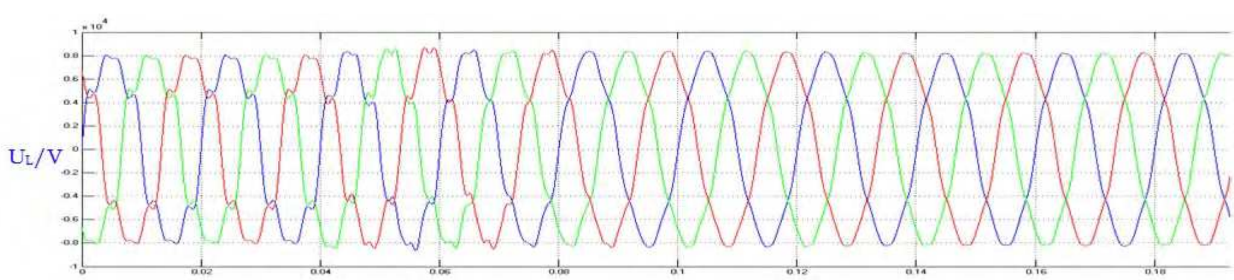
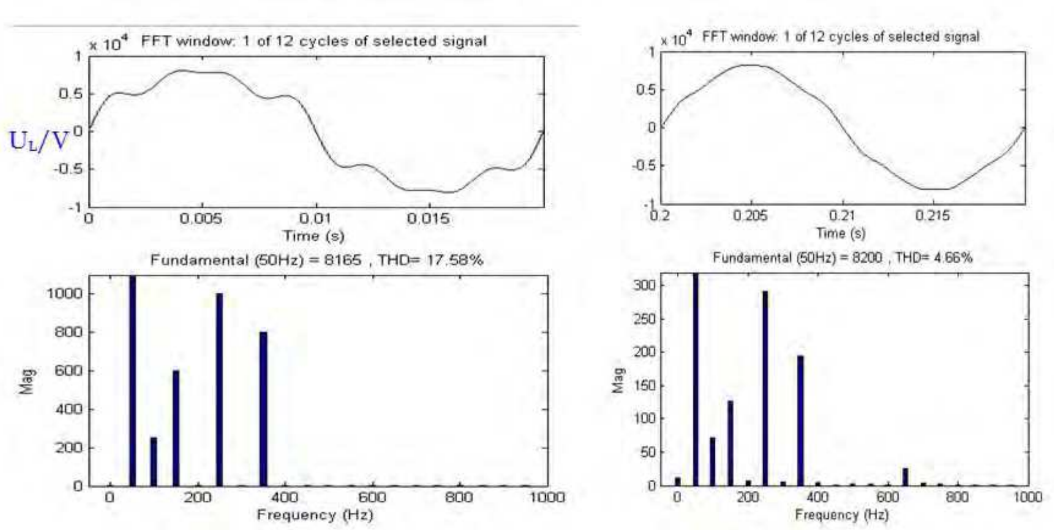


Fig. 7. Waveform of load voltage



(a) Before series device run (b) After series device run

Fig. 8. FFT analysis for load voltage

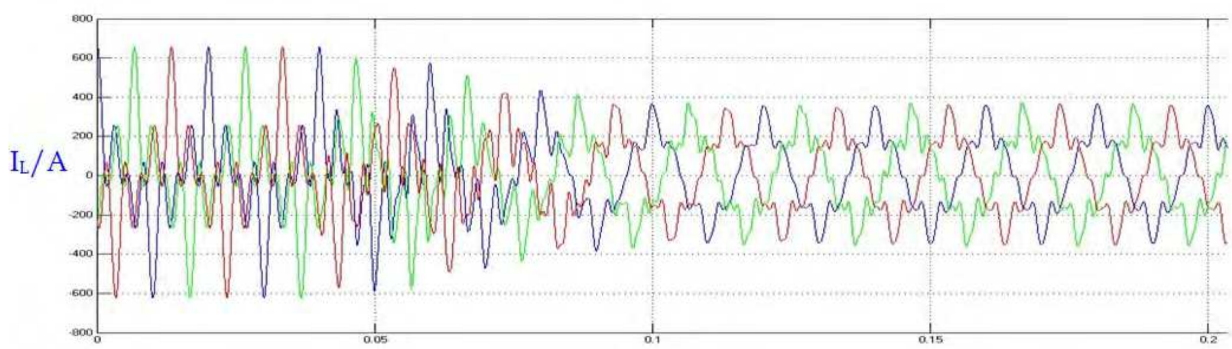
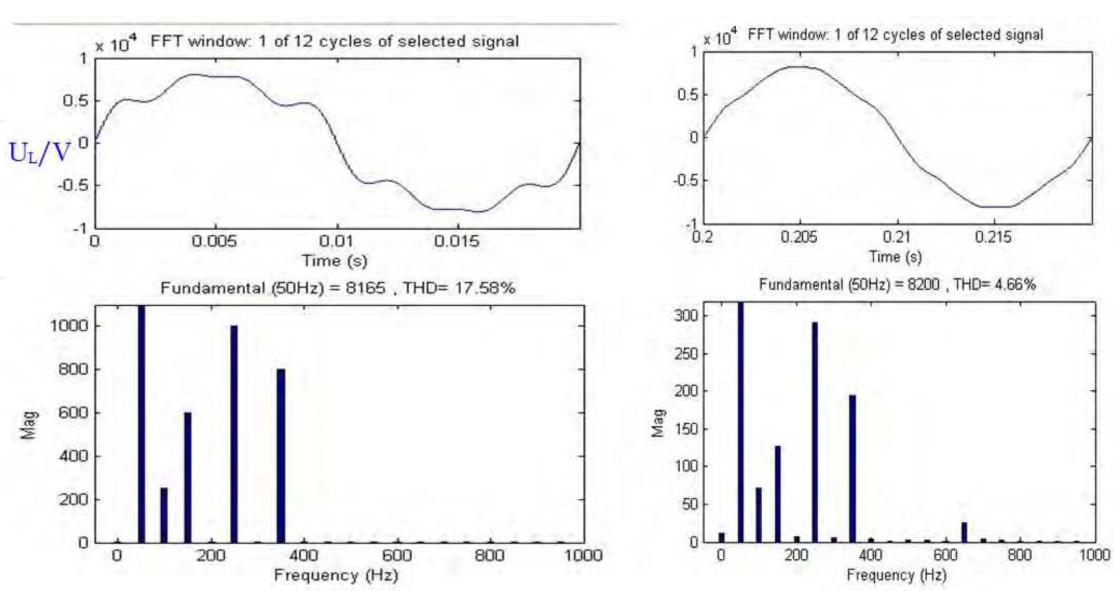


Fig. 9. Waveform of load current



(a) Before series device run (b) After series device run

Fig. 10. FFT analysis for load current

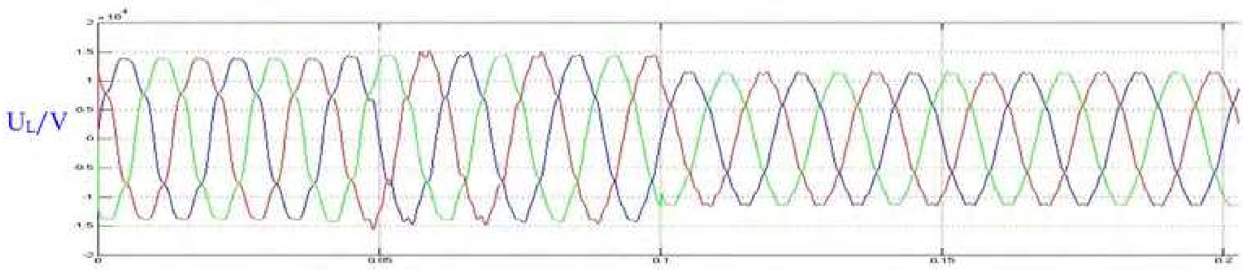


Fig. 11. Voltage sag at 0.1s

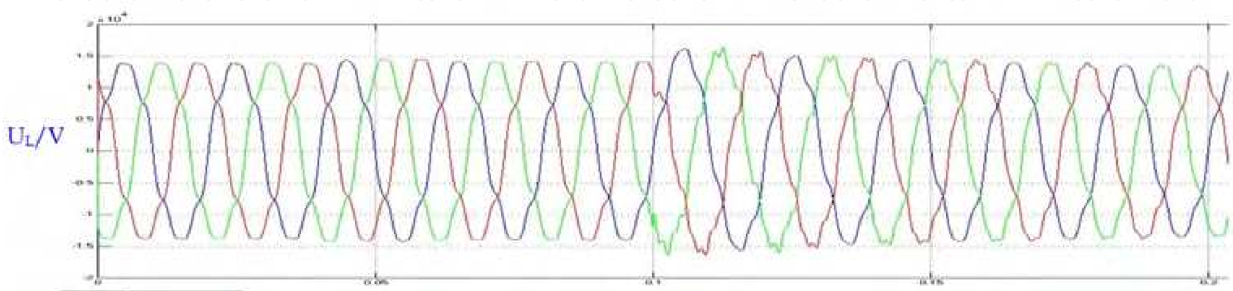


Fig. 12. Load voltage when series device run

3.2 Shunt device of high power UPQC

Fig.13 shows the single phase equivalent circuit of the shunt device of high power UPQC. The active part of the shunt device could be considered as an ideal controlled voltage source U_{inv1}, the Load harmonic source is equivalent to a current source I_L. The impedance of the output filter L_0 and C_0 are Z_{L0} and Z_{C0}.

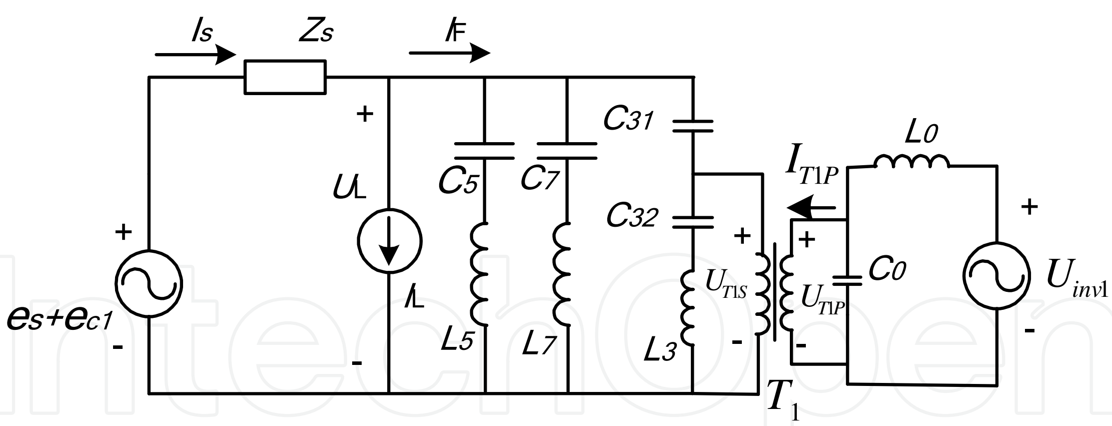


Fig. 13. The single phase equivalent circuit of the shunt device of UPQC

Suppose $\frac{U_{T1S}}{U_{T1P}} = n_1$ and transformer T_1 is a ideal transformer, we can learn

$$\begin{aligned} U_{inv1} &= U_{T1P} + Z_{L0}(I_{T1P} + \frac{U_{T1P}}{Z_{C0}}) \\ &= U_{T1P}(1 + \frac{Z_{L0}}{Z_{C0}}) + Z_{L0} I_{T1P} \end{aligned} \tag{15}$$

And

$$I_{T1P} = n_1 (I_F - \frac{U_L}{Z_{57}} - \frac{n_1 \cdot U_{T1P}}{Z_{332}}) \tag{16}$$

Where

$$Z_{57} = \frac{(Z_{L5} + Z_{C5})(Z_{L7} + Z_{C7})}{Z_{L5} + Z_{C5} + Z_{L7} + Z_{C7}}, \tag{17}$$

$$Z_{332} = Z_{L3} + Z_{C32} \tag{18}$$

Besides

$$U_{L1} - n_1 U_{T1P} = (I_F - \frac{U_L}{Z_{57}}) Z_{C31} \tag{19}$$

So

$$U_{T1P} = \frac{Z_{57} + Z_{C31}}{n_1 Z_{57}} U_L - \frac{Z_{C31}}{n_1} I_F \tag{20}$$

From equation (16) and (20), we get

$$I_{T1P} = (1 + \frac{Z_{C31}}{Z_{332}}) I_F - n_1 (\frac{1}{Z_{57}} + n_1 \cdot \frac{Z_{57} + Z_{C31}}{n_1 Z_{57} Z_{332}}) U_L \tag{21}$$

Where

$$Z_{57} = \frac{(Z_{C5} + Z_{L5})(Z_{C7} + Z_{L7})}{Z_{C5} + Z_{L5} + Z_{C7} + Z_{L7}} \tag{22}$$

$$Z_{332} = Z_{C32} + Z_{L3} \tag{23}$$

For completely compensating load harmonic current, I_F is controlled to be the same as I_L, so

$$I_{T1P} = (1 + \frac{Z_{C31}}{Z_{332}}) I_L - n_1 (\frac{1}{Z_{57}} + n_1 \cdot \frac{Z_{57} + Z_{C31}}{n_1 Z_{57} Z_{332}}) U_L \tag{24}$$

From equation (24), we can find control rule for shunt device of UPQC. If Inverter 1 is controlled to work as a current source, we can make it linear to load harmonic current and a fore-feed controller of load harmonic voltage is expected to add to the harmonic current controller. Control scheme for shunt device of high power UPQC is shown in Fig.14. To support DC linker voltage, shunt device should absorb enough energy from utility. Because it is easier for shunt device to absorb energy from utility, the DC linker voltage controller is placed in control scheme of shunt device. A PI conditioner is used here to adjust fundamental active current so as to keep DC-linker voltage const. ACR1 and ACR2 are the same as that of series device. Current out of active part is detected and form a close-loop controller. ACR3 is a hysteresis controller which makes Inverter 1 work as a current source. U_L is also added to control scheme as a fore-feed controller.

Fig.15 shows the effect of this control scheme for shunt device of UPQC. The simulation parameters are shown in Tab.3. Suppose at 0.04s, passive part of shunt device is switched on and at 0.1s active part is started. Fig.15 shows waveform of utility current during shunt device is switched on. Fig.16 shows spectrums of utility current. Before shunt device switched on, THD of utility current is 28.53%. after passive part is switched on, it is cut down to be 18.25% and after active part is also switched on it is further cut down to be 11.97%.

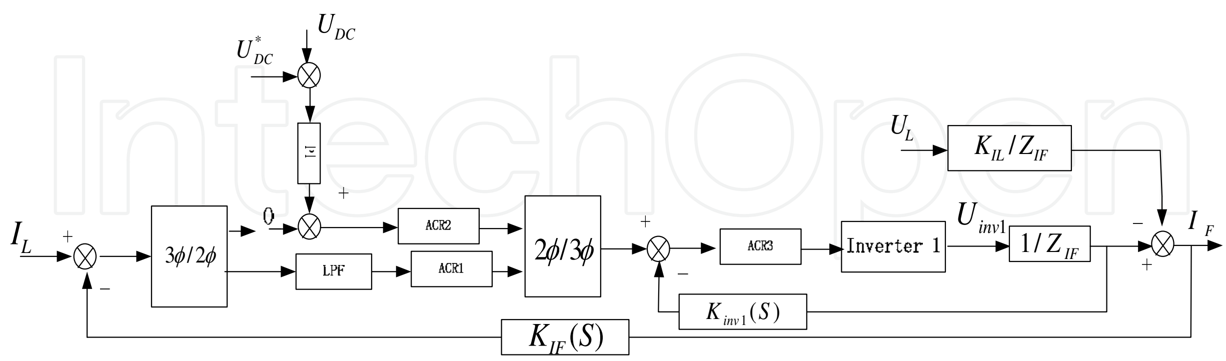


Fig. 14. Control scheme for shunt device of UPQC

Items	Description
Power source	3-phase; line to line voltage:10KV;
Impedance of transmission line	Resister: 0.04 ohm; Inductor : 1uH;
Load	Rectifier with series reactor and resister; Reactor: 1mH; resister: 10 ohm;
Shunt device of UPQC	3rd $L_3 = 15\,mH$ $C_{31} = 334\,\mu F$ $C_{32} = 669\,\mu F$ 5th $L_5 = 3.4mH$ $C_5 = 120\,\mu F$ 7th $L_7 = 1.5mH$ $C_7 = 140\,\mu F$ T_1 $n_1 = 10$ LPF $L_0 = 4mH$ $C_0 = 15uF$

Table 3. Parameters for shunt device

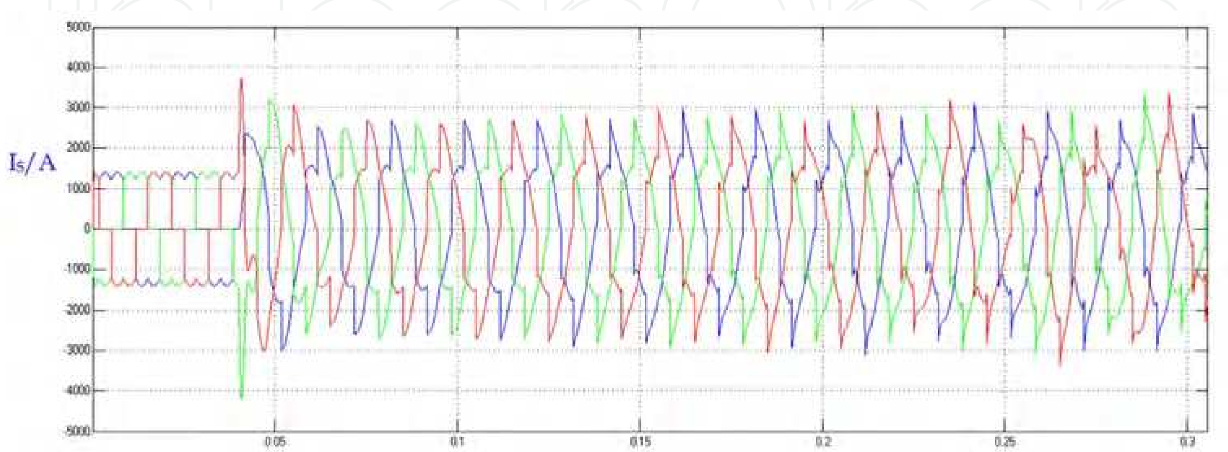
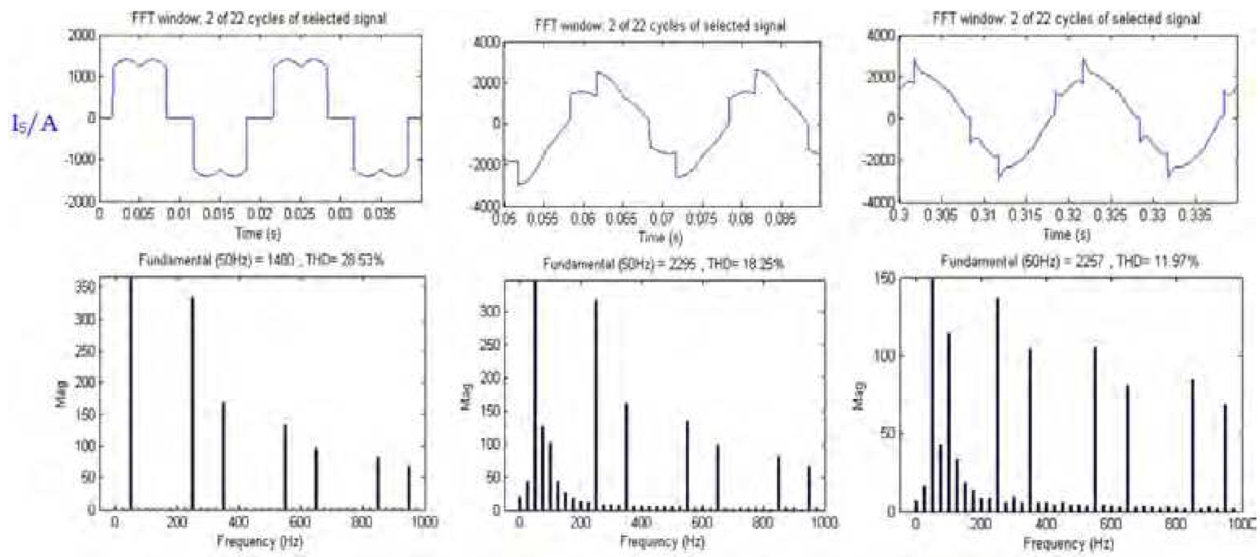


Fig. 15. Utility current waveform



(a) Before shunt device run (b) After PPF switched on (c) After APF switched on

Fig. 16. Spectrums of utility current

3.3 Entire control of high power UPQC

High power UPQC is composed of series device and shunt device. Its control scheme combined control of series device and shunt device, as is shown in Fig.17. From above discussion, we know that load harmonic current is a bad disturb to series device controller because it influences load harmonic voltage. With shunt device, utility harmonic current is cut down and it does help to series device controller. On the other hand, load harmonic voltage is also a bad disturb to shunt device controller which will produce additional harmonic current and influence effect of shunt device. With series device, load harmonic voltage is cut down and it does help to shunt device controller. Cycling like this, effects of shunt device and series device are both improved. Tab.4 shows parameters for high power UPQC.

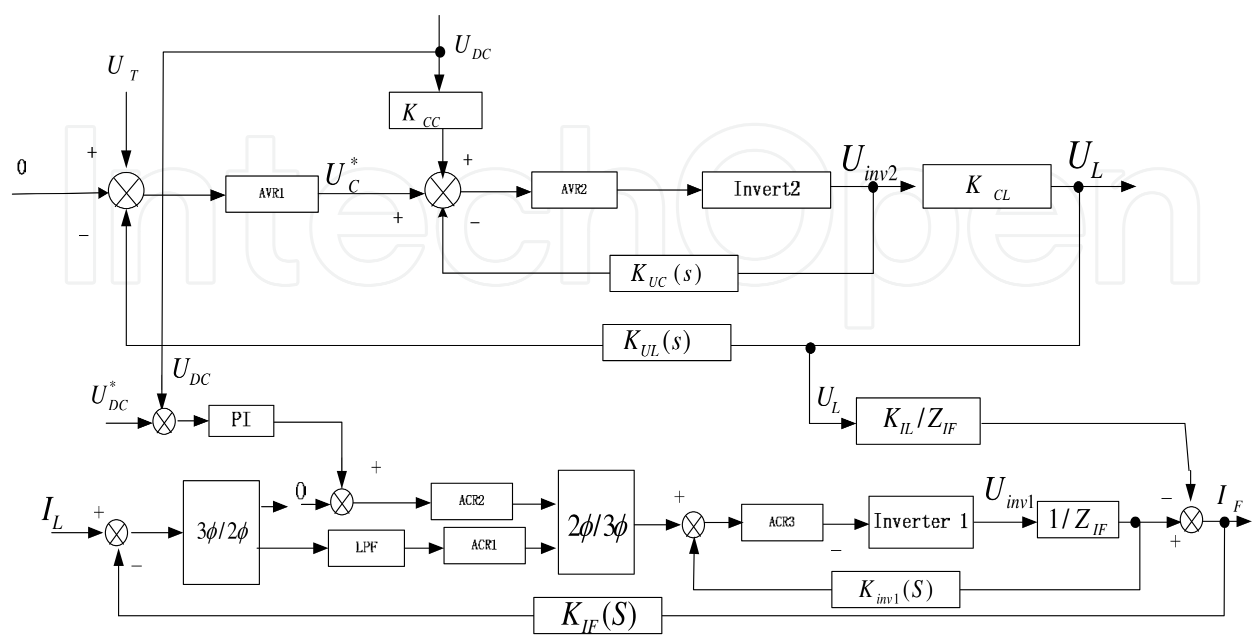


Fig. 17. Control scheme for high power UPQC

Items	Description
Power source	3-phase; line to line voltage:10KV; 2nd, 3rd, 5th, 7th harmonic voltage listed in Tab.1
Impedance of transmission line	Resister: 0.04 ohm; Inductor : 1uH;
Load	Rectifier load in Tab.3 paralleled with 3-phase series resister and capacitor listed in Tab.1
Shunt device	Same as Tab.3
Series device	Same as Tab.1

Table 4. Parameters for high power UPQC.

Suppose at 0.04s, series device is switched on, at 0.1s passive part of shunt device is switched on and finally at 0.16s active part of shunt device is also switched on. Fig.18 shows the utility current waveform and Fig.19 shows its spectrums. Fig.20 shows the utility voltage waveform and Fig.21 shows its spectrums. The harmonics during switching on the whole UPQC are shown in Tab.5. We can see that power quality is improved step by step.

THD(%)	Before UPQC run	Series device only	Switch on passive part	Switch on active part
Utility voltage	17.7	8.26	4.78	4.77
Utility current	40.36	31.10	11.97	8.90

Table 5. THD comparison during switching on UPQC

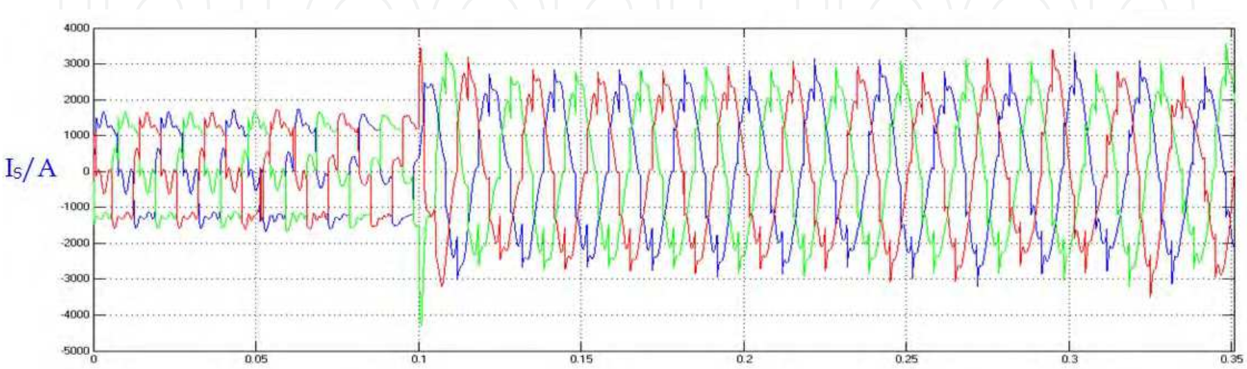
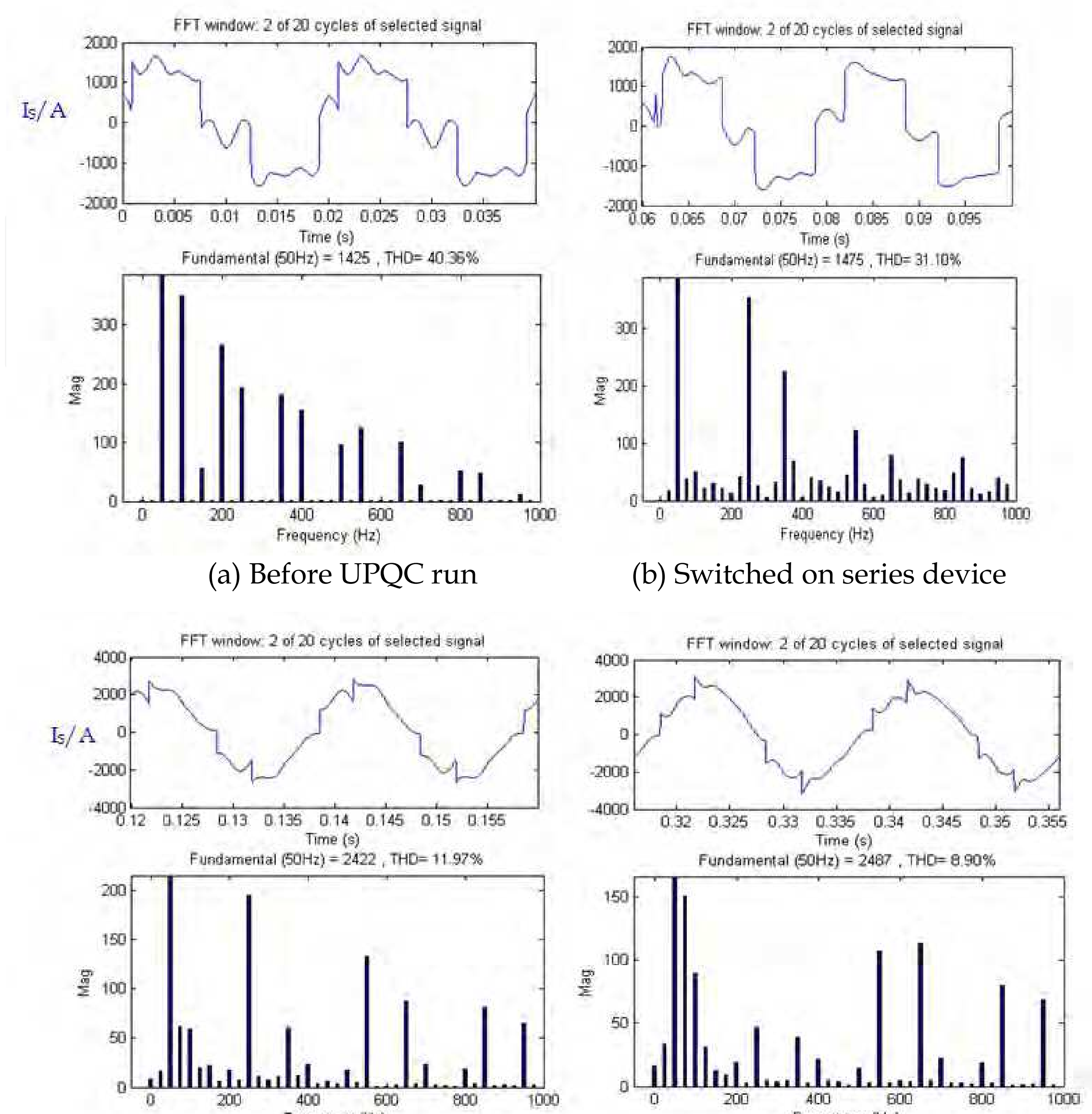


Fig. 18. Utility current waveform



(a) Before UPQC run (b) Switched on series device

(c) Switched on passive part (d) Switched on active part

Fig. 19. Spectrums of utility current

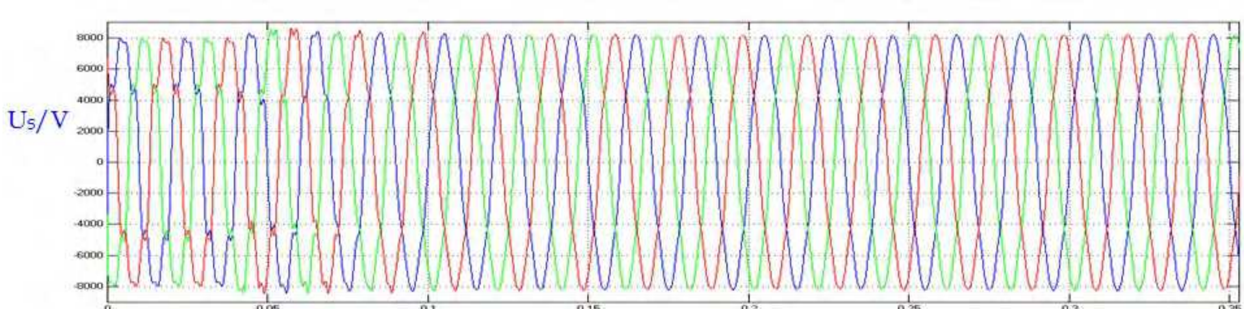
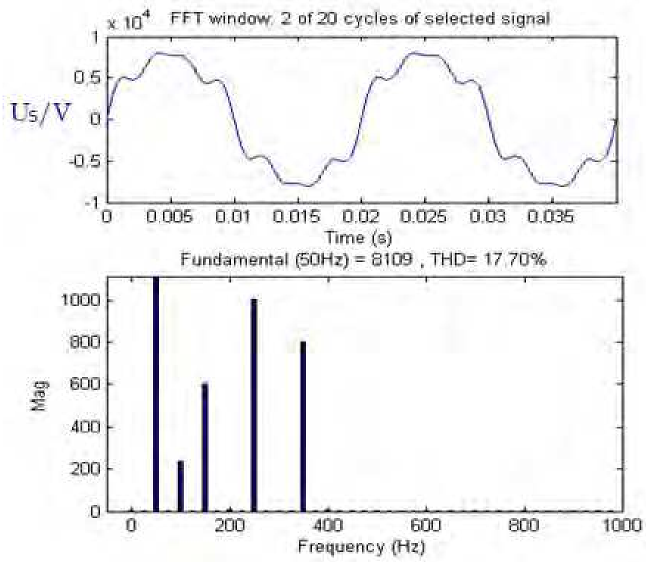
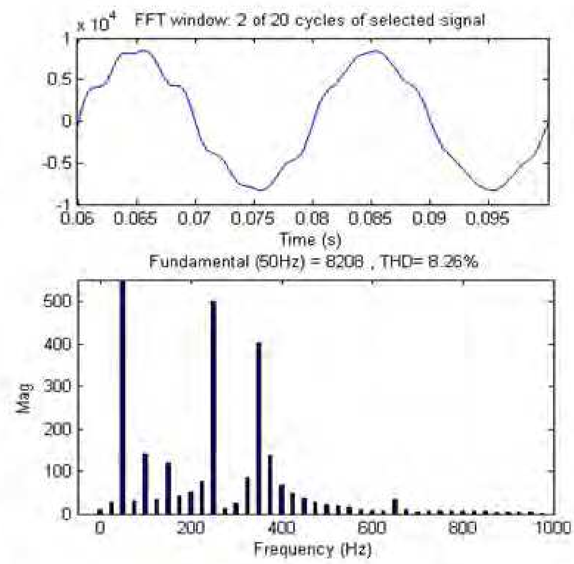


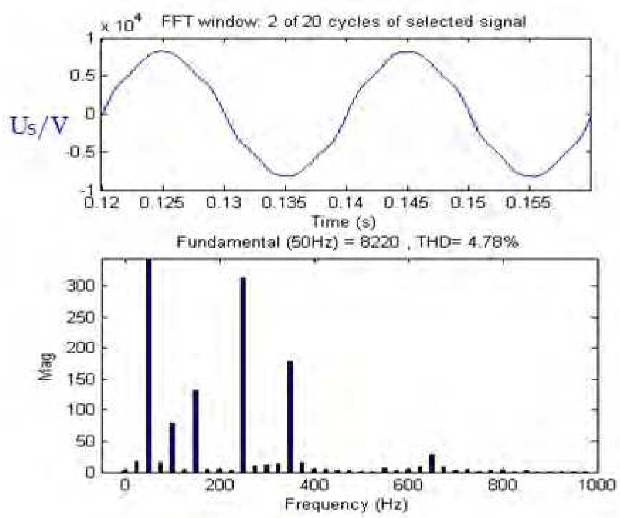
Fig. 20. Utility voltage waveform



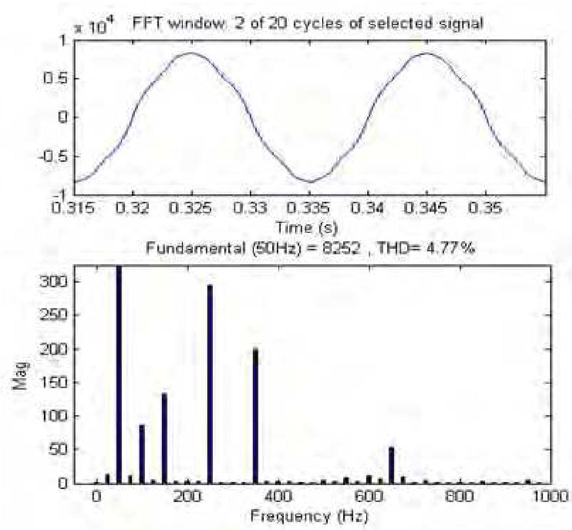
(a) Before UPQC run



(b) Switched on series device



(c) Switched on passive part



(d) Switched on active part

Fig. 21. Spectrums of utility voltage

4. Conclusions

To eliminate harmonics in power system, series APF and shunt APF are adopted. Series APF mainly eliminate harmonic voltage and avoid voltage sag or swell so as to protect critical load. It also helps to eliminate harmonic current if power source voltage is distorted. Shunt APF is to eliminate harmonic current avoiding it flowing through transmission line. UPQC combined series APF and shunt APF can not only eliminate harmonic current but also guarantee a good supply voltage.

In some applications, the equipment needs to compensate high power reactive power produced by load. In this case, An UPQC with current-injection shunt APF is expected to be installed. This chapter discussed the principle of UPQC, including that of its shunt device and series device, and mainly discussed a scheme and control of UPQC with current-injection shunt APF which can protect load from almost all supply problems of voltage quality and eliminate harmonic current transferred to power grid.

In high power UPQC, load harmonic current is a bad disturb to series device controller. Shunt device cuts down utility harmonic current and does help to series device controller. On the other hand, load harmonic voltage is also a bad disturb to shunt device controller and series device does much help to cut it down. With the combined action of series device and shunt device, high power can eliminate evidently load harmonic current and harmonic voltage and improve power quality efficiently.

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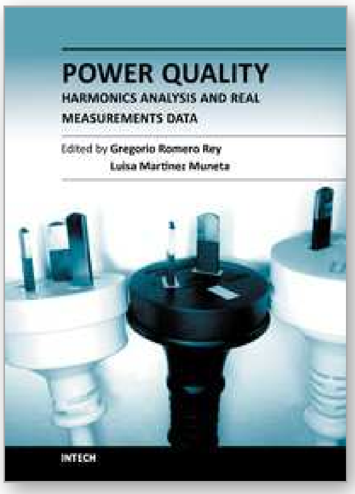

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Nowadays, the increasing use of power electronics equipment origins important distortions. The perfect AC power systems are a pure sinusoidal wave, both voltage and current, but the ever-increasing existence of non-linear loads modify the characteristics of voltage and current from the ideal sinusoidal wave. This deviation from the ideal wave is reflected by the harmonics and, although its effects vary depending on the type of load, it affects the efficiency of an electrical system and can cause considerable damage to the systems and infrastructures. Ensuring optimal power quality after a good design and devices means productivity, efficiency, competitiveness and profitability. Nevertheless, nobody can assure the optimal power quality when there is a good design if the correct testing and working process from the obtained data is not properly assured at every instant; this entails processing the real data correctly. In this book the reader will be introduced to the harmonics analysis from the real measurement data and to the study of different industrial environments and electronic devices.