

# Unified Power Quality Conditioner with Electric Double Layer Capacitor

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**Abstract.** This paper proposes a new configuration of UPQC (Unified Power Quality Conditioner) that consists of the DC/DC converter and the electric double layer capacitors for compensating the voltage interruption. The proposed UPQC can compensate the reactive power, harmonic current, voltage sag and swell, voltage unbalance, and the voltage interruption. The performance of proposed system was verified through experimental works with a prototype. The proposed system can improve the power quality at the common connection point of the non-linear load and the sensitive load.

## Key words

Voltage interruption, DC/DC Converter, Electric Double Layer Capacitor, super-capacitor, UPQC (Unified Power Quality Conditioner)

## 1. Introduction

As more sensitive loads, such as computers, automation equipments, and communication equipments, have come into wide use, the power quality is a big issue in both customer and utility company. Since these equipments are very sensitive for the input voltage disturbances, the inadequate operation or the fault of these loads brings about huge losses [1]-[3]. The elimination or mitigation of disturbances propagated from the source side and the other loads interconnected is critical for improving the operational reliability of these critical loads.

UPQC has been widely studied to eliminate or mitigate the disturbances propagated from the source side and the other loads interconnected [4]-[6]. UPQC has two voltage-source inverters of three-phase four-wire or three-phase three-wire configuration. One inverter called the series inverter is connected through transformers between the source and the common connection point. The other inverter called the shunt inverter is connected in parallel with the load. The series inverter operates as a voltage source, while the shunt inverter operates as a current source.

UPQC can simultaneously mitigate the voltage disturbance in source side and the current disturbance in load side. UPQC can compensate voltage sag, voltage swell, harmonic current, and harmonic voltage, and

control the power flow and the reactive power. However, it cannot compensate the voltage interruption because it has no energy storage in the dc link.

This paper proposes a new configuration of UPQC that consists of the DC/DC converter and the electric double layer capacitors for compensating the voltage interruption. The operation of proposed system was verified through experimental works with a prototype of 20kVA rating.

## 2. Configuration of proposed UPQC

Fig. 1 shows the configuration of proposed UPQC, which additionally has a DC/DC converter and super-capacitors for compensating the voltage interruption. The energy in the DC link charges the electric double layer capacitors through the bi-directional DC/DC converter when the system is in normal operation. The energy in the electric double layer capacitors is released to the DC link through the bi-directional DC/DC converter when the voltage interruption occurs.

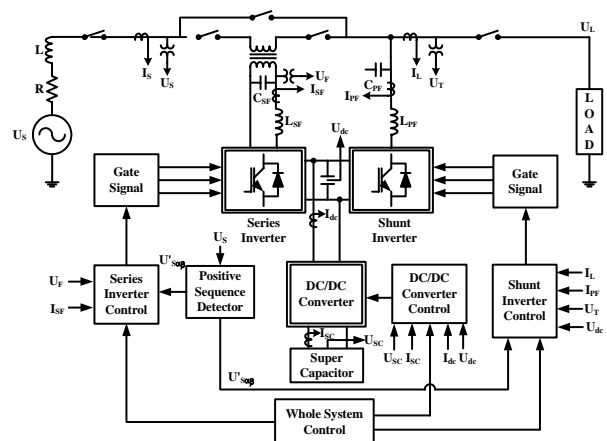


Fig. 1. UPQC system interconnected with energy storage

The control system has five major elements, which are system manager, positive sequence detector, shunt inverter control, series inverter control, and DC/DC converter control. The first four elements were implemented using a digital signal processor, while the last element was implemented using analog circuit.



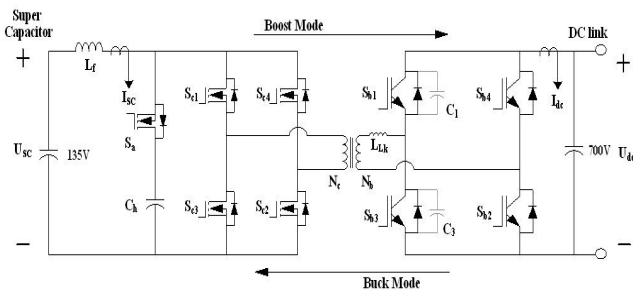


Fig. 4. DC/DC converter structure

A filter reactor is inserted between the bank and the full-bridge to reduce the ripple of charging and discharging current, which can reduce the lifetime of super-capacitors due to unwanted heat generation. The full-bridge in bank side works as a current-fed type, while the full-bridge in dc link side works as voltage-fed type.

The DC/DC converter boosts the super-capacitor voltage up to the nominal dc link voltage in discharge mode. The super-capacitor voltage is controlled between 115-135V, while the dc link voltage increases up to 700V. The switches  $S_{c1}$  and  $S_{c2}$  operate with a duty ratio of higher than 0.5. The current through the inductor  $L_f$  increases as all the switches are on conduction-state. The voltage overshoot can be suppressed by turning on auxiliary switch  $S_a$  when two switches in face with diagonal opposition are on conduction state. The current through transformer rises linearly and its peak value becomes larger than the current through the boost inductor. The magnetic energy stored in the leakage inductance of transformer flows through the back-connection diode of off-state switch when the auxiliary switch turns off. So, the zero-voltage turn-on condition is provided.

The DC/DC converter decreases the nominal dc-link voltage down to the level of super-capacitor voltage in charge mode. When switch  $S_{b1}$  and  $S_{b2}$  turns on, the input voltage applied to the leakage inductance of transformer  $L_{Lk}$  increases the input current. The power in the primary side is transferred to the secondary side. The secondary voltage charges the capacitor Ch through the reverse-connected diode of auxiliary switch  $S_a$ . If the charging voltage is high enough to make the charging current zero, switch  $S_{b1}$  turns off. Switch  $S_{b3}$  turns on with zero-voltage scheme while the capacitor C1 is charged and the capacitor C3 is discharged. When auxiliary  $S_a$  turns on, the voltage across the auxiliary capacitor affects the primary voltage of the coupling transformer. This voltage is applied to the leakage inductance  $L_{Lk}$  with reverse polarity. This makes the primary current zero and switch  $S_{b2}$  turns off with zero-current scheme.

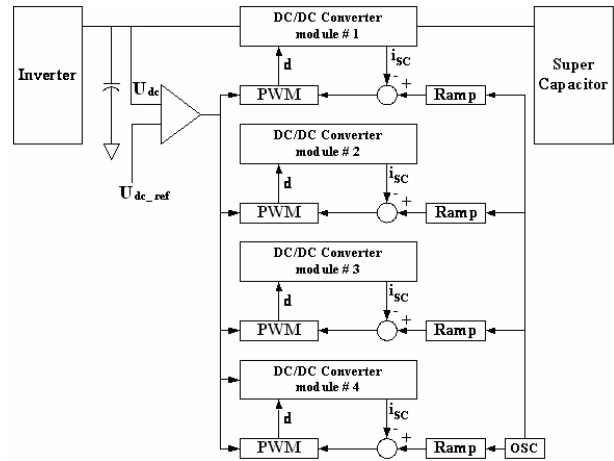


Fig.5. Four module parallel operation and PWM pulse interleaving

In design point of view it is not effective to build a 20kW DC/DC converter in a single module due to the restriction in power rating of switching unit. Since super-capacitors operate at low-voltage large-current, the switching frequency is limited by the critical value of di/dt which depends on the leakage inductance of the coupling transformer. So, when the converter is designed in a single module, the switching ripple of charging or discharging current is high. Therefore, the proposed DC/DC converter has four modules of 5kW converter connected in parallel as shown in Fig. 5. When the multi-module is used, it is possible to expand the system rating and to increase the operation reliability. Also, the switching ripple of the charging or discharging current can be extremely reduced using the interleaving scheme of PWM switching.

### B. Controller Design

The controller of DC/DC converter is comprised of main control, charging control, and discharging control as shown in Fig. 6. One function of main control is to select the charge mode and discharge mode according to the command from the system manager. The other function of main control is to monitor the operation of each converter module and to remove the module in fault. The main control also monitors the maximum and minimum charge or discharge voltage.

The DC/DC converter control was designed using OP amps and passive elements because the DC/DC converter requires higher switching speed in PWM than the shunt and series inverters.

The discharge control was designed to discharge the super-capacitors when the voltage interruption occurs in ac side. The discharge control consists of two control loops, which are the outer loop of voltage control and the inner loop of current control as shown in Fig. 7(a) and 7(b).

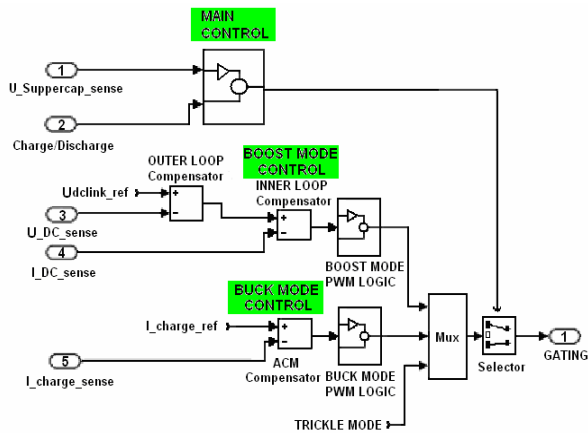


Fig.6. DC/DC Converter controller

The voltage control loop measures the DC link voltage and compares it with the reference voltage. The error passes through the RC circuit to calculate the reference current for the inner-loop current control. The inner-loop current control measures the discharge current in bank side and compares it with the reference current obtained from the outer-loop voltage control. The error passes through the RC circuit to calculate the duty ratio for the DC/DC converter module.

The charge control was designed to charge the super-capacitor in a slow speed in order not to make the DC link voltage change in normal operation. The charging operation is performed with 2kW power rating for each module and stops when the bank voltage reaches 135V. The operation of charge control has the same configuration as that of the current control shown in Fig. 7(b).

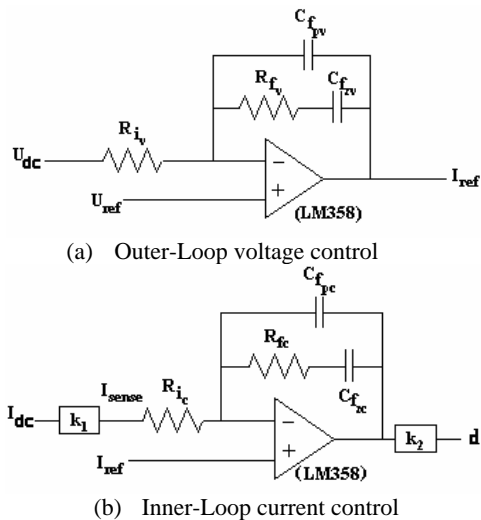


Fig.7. Discharge control circuit

### C. Energy Storage Design

The size of electric double layer capacitors is determined depending on the duration of voltage interruption and the size of load connected. It is assumed that the voltage interruption has duration of 2 sec and the load has a power rating of 20kW. Therefore, total energy to be released during the voltage interruption is 40kJ.

The bank of electric double layer capacitors is

designed considering three criteria, the expandability of storage capacity, the unbalance of unit voltage, and the current rating of each unit. HP1700P-0027A manufactured by Ness Company was selected as a basic unit for the energy storage bank. Table 1 shows the specification of selected electric double layer capacitor.

TABLE I  
SPECIFICATION OF ELECTRIC DOUBLE LAYER CAPACITOR

Parameters	Specification
Capacitance	1700 F
ESR @25°C DC (100A)	0.7 M ohms
AC (100Hz)	0.7 M ohms
Continuous operation voltage	2.7 V
Peak operation voltage	2.85 V
Current rating	360 A

The bank is designed so as to utilize the upper 25% of maximum storage capacity, considering the expandability of operation capacity by adding more capacitors. The maximum current flows through the capacitor bank, when it discharges the maximum power. The minimum voltage across the capacitor bank can be determined with the maximum discharge power and the current rating as the following.

$$U_{bank\_min} = 40kW / 360A = 111 V \quad (1)$$

It is assumed that the capacitor is charged by 2.43V, which is 90% to the maximum charging voltage of 2.7V, for consideration of 10% margin. The lowest discharged voltage is determined to be 2.1V using the following.

$$U_{unit\_min} = \sqrt{3/4} \times U_{unit\_max} = 2.1 V \quad (2)$$

Therefore, the lowest discharge voltage and the minimum unit voltage determine the number of units to be connected in series as the following.

$$N = U_{bank\_min} / U_{unit\_min} = 53 \quad (3)$$

However, the bank was designed using total 56 units of capacitors for the purpose of safety margin.

## 4. Experiment Result

A prototype was built and tested to confirm the feasibility of actual hardware implementation. In order to simulate various fault cases, a source simulator using two inverters with DSP processor was built in a separate cabinet, which can generate the voltage sag, the voltage swell, and the voltage interruption for simulating all kinds of voltage disturbance in distribution system. UPQC was also built in a cabinet using two inverters with one solid-state switch and DSP processor. A 20kW

DC/DC converter with super-capacitors was built in a separate cabinet as shown in Fig. 8. There are four 5kW DC/DC converter modules and four racks of super-capacitor banks, where each module is connected with each super-capacitor rack in one by one manner. Both linear and non-linear loads are built for experimental work. Each load is designed for simulating the various load conditions.

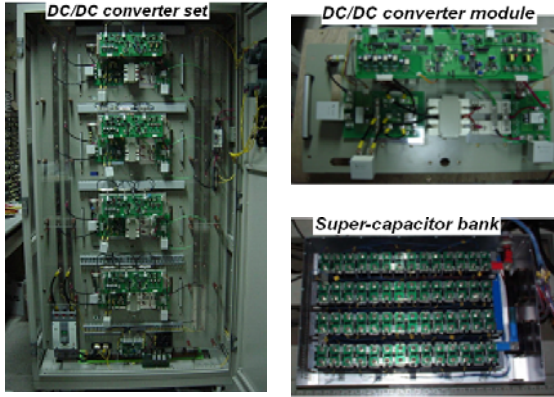


Fig.8. Hardware structure of DC/DC converter and super-capacitor bank

All the circuit parameters are exactly same as those used in computer simulation. All the experimental conditions are set up exactly same as the simulation conditions. Fig. 9 shows the compensation of harmonic current in the shunt inverter. Although there are some high-frequency harmonics, the experimental result is very close to the simulation result.

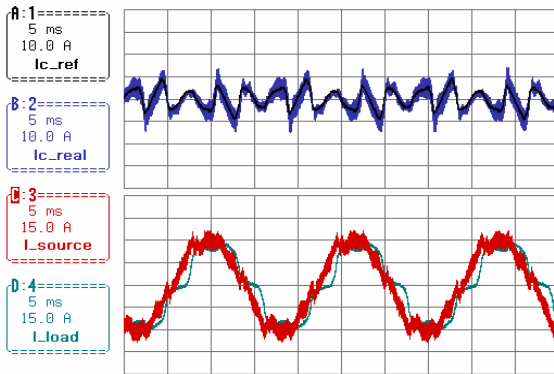


Fig.9. Active-Power Filter operation

Fig. 10 shows the experimental results when the unbalanced sag and swell occur. Both results are very close to the simulation results shown in Fig. 9 and 10.

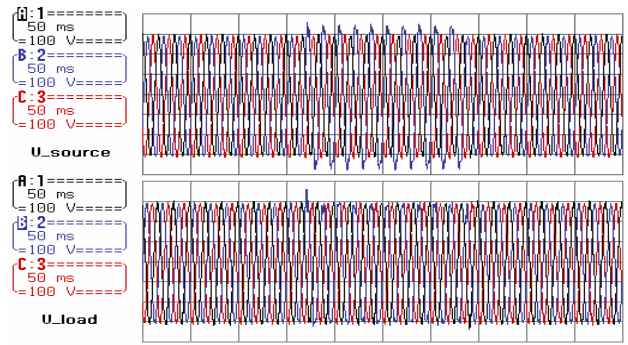
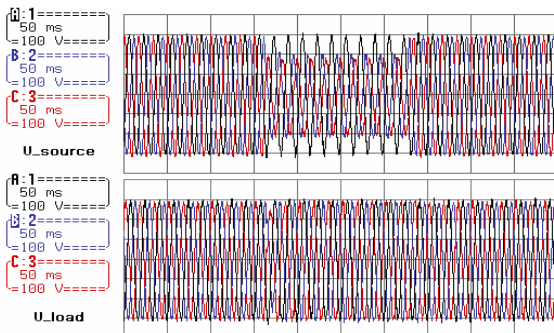
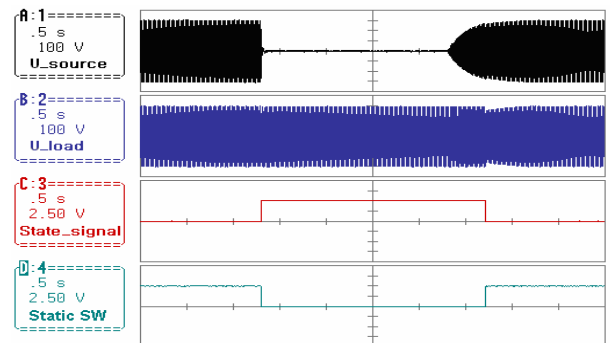


Fig.10. UPQC operation during sag or swell

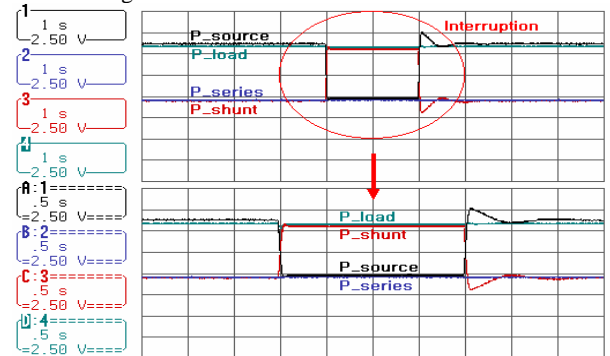
Fig. 11 shows the experimental results when the voltage interruption occurs. The 1st and 2nd graph in Fig. 11(a) shows the source voltage and the load voltage in the voltage interruption for 2 seconds. The load voltage can be maintained as a constant value as expected. The 3rd and last graph shows the state signal for activating the solid-state breaker to isolate the source side.

Fig. 11(b) shows the active power variations during voltage interruption, which explains the power required in the load is provided by the shunt inverter of UPQC during the voltage interruption.

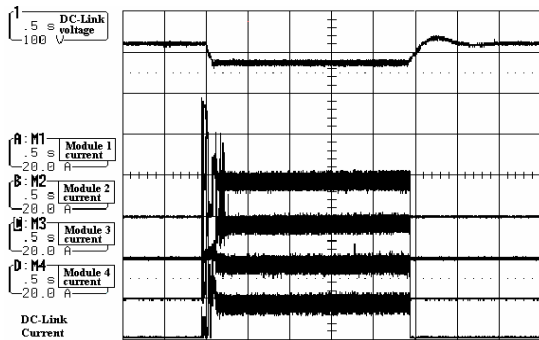
The 1st graph in Fig. 11(c) shows the voltage in the dc link, which is maintained at 680V less than the normal DC link voltage 720V. But the control system increases the modulation index to maintain the output voltage properly. The 2nd, 3rd, 4th, and last graph shows the dc link current from each DC/DC converter module, which confirms that each module provides balanced constant current



(a) Source voltage and load voltage, static switch gate signal



(b) Active power variation during voltage interruption



(c) DC-Link voltage and converter module output current

Fig. 11. UPQC operation during interruption

## 5. Conclusion

This paper proposes a new configuration of UPQC that consists of the DC/DC converter and the super-capacitors for compensating the voltage interruption. The proposed UPQC can compensate the reactive power, harmonic current, voltage sag and swell, voltage unbalance, and the voltage interruption.

The control strategy for the proposed UPQC was derived based on the instantaneous power method. The operation of proposed system was verified through experimental works with a prototype of 20kVA rating.

The proposed UPQC has the ultimate capability of improving the power quality at the installation point in the distribution system. The proposed system can replace the UPS, which is effective for the long duration of voltage interruption, because the long duration of voltage interruption is very rare in the present power system.

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