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A New Control Scheme for Unified Power Quality Compensator-Q with Minimum Power Injection

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ABSTRACT

Voltage sags are one of the most frequently occurring power quality problems challenging power systems today. The Unified Power Quality Conditioner (UPQC) is one of the major custom power solutions that are capable of mitigating the effect of supply voltage sags at the load or Point of Common Coupling (PCC). A UPQC-Q employs a control method in which the series compensator injects a voltage that leads the supply current by 90° so that the series compensator at steady state consumes no active power. However, the UPQC-Q has the disadvantage that its series compensator needs to be overrated. Thus it cannot offer effective compensation. This paper proposes a new control scheme for the UPQC-Q that offers minimum power injection. The proposed minimum power injection method takes into consideration the limits on the rated voltage capacity of the series compensator and its control scheme. The validity of the proposed control scheme is investigated through simulation and experimental results.

Keywords: voltage sag, reactive power, UPQC-Q, minimum power injection, voltage capacity

1. Introduction

Due to the wide spread automation of critical processes throughout the energy industry, the importance of precise control and stability has increased dramatically. Sensitive loads are greatly affected by power quality disturbances in the system. Many non-linear loads used are the main cause of harmonic currents that decrease power quality.

The harmonic currents flowing through the finite source impedance of the utility supply can cause voltage distortion at the Point of Common Coupling (PCC). It results in malfunction of control, protection and metering equipment used in other loads and system monitoring devices. Harmonic currents can also cause unwanted system resonance, overloading of capacitors, decrease in efficiency due to increased losses, interference with communication and control signals, saturation and overheating of distribution transformers and lines. Loads that operate with poor power factor show ineffective use of the volt-ampere rating of the utility equipment such as transformers, distribution lines and generators.

This places a restriction on the total equipment load that can be connected to a typical home or office wall plug with a specified maximum rms current rating. To solve these problems, passive power filters have been widely used for a long time [1]. Passive power filters consist of a combination of inductors and capacitors tuned to a certain frequency. Although they are simple in structure and have a relatively low investment cost, they can cause unwanted

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resonance and amplify harmonic currents.

To overcome the disadvantage of passive power filters and restrictions on their performance, research in active power filters has been carried out actively. Active power filters can be classified as series or parallel by their system configuration. The combination of series and parallel active power filters is called the Unified Power Quality Compensator (UPQC).

Although its main drawback is its high cost and complexity of control, interest in UPQCs is growing due to its superior performance. UPQCs offer not only elimination of harmonics but also compensation for reactive power, load current unbalance, source voltage sags, source voltage unbalance and power factor correction [2]. The UPQC-Q, employs a quadrature injection method which controls voltage sags and offers economical compensation using reactive power instead of active power [3]. The "Q" of UPQC-Q refers to reactive power.

Although compensation can be achieved by using a voltage with small magnitude if the voltage is injected in phase with the source current, this is not a method which offers compensation with minimum power.

The required energy for compensation can be reduced when the reactive power is used to inject a voltage that has an adequate phase difference with the source current.

The rating of the series active compensator must be sufficiently large when only the reactive power is used. This paper proposes a minimum power injection method that can overcome limitations on the conventional UPQC-Q scheme such as not being able to offer compensation due to limitations on the rating of the series active filter and configuration of an economical system.

The proposed method allows the rating of series compensator injecting the voltage to be reduced which allows economical compensation.

If voltage sags cannot be compensated by reactive power because of limits on the series compensator rating, economical compensation would be possible by using minimum active power. Simulation and experimental results show the validity of the minimum power injection method proposed in this paper.

2. UPQC-Q

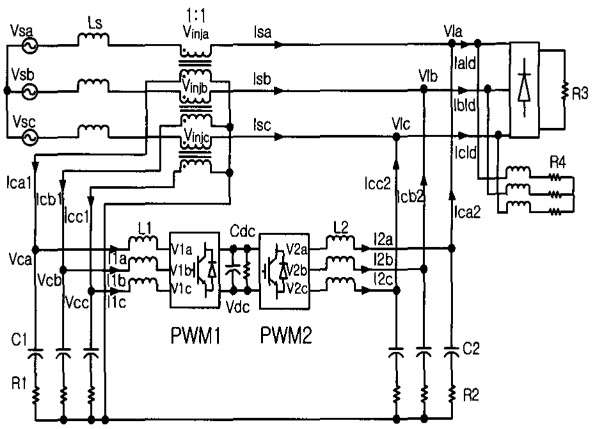


Fig. 1 Configuration of UPQC-Q

Fig.1 shows a simple configuration of the UPQC-Q. In Fig.1, the series compensator controls voltage sags by injecting V_{inj}, which leads the source current by 90°. The parallel compensator performs power factor correction through reactive power compensation, harmonic elimination, and DC link charging

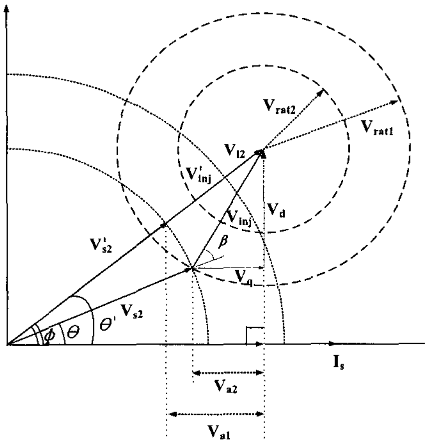


Fig. 2 Voltage compensation of reactive power without parallel compensator

Fig.2 shows the energy saving of voltage compensation using reactive power without a parallel compensator. Each of the abbreviations refers to the following:

V_s: Source voltage phasor
V_{inj}: Injected voltage
V_l : Load side voltage phasor
V_{rat} : Voltage injection limit of series compensator
I_s : Load current phasor

V_{a1} : Active power component of in-phase injection voltage V_{inj}

V_{a2}: Active power component of V_{inj}, injected by a phase advance of β with respect to source side voltage.

β: Phase advance angle of V_{inj}, with respect to V_s

θ: Phase angle difference between V_s and I_s without a parallel compensator

(Phase angle difference between V_s and V_l with a parallel compensator)

ϕ: Load power factor

The phasor diagram shows that voltage compensation is possible, when β increases, the needed active power decreases with minimum power[4][5]. Active power $V_{a1}I_s$ is required when V'_{inj} is injected in phase with load voltage V_{l2}. If a voltage that leads the source voltage by β is injected, only V_{a2} I_s which is smaller than $V_{a1}I_s$ is consumed. V_{s2} *and* V'_{s2} are source voltages according to the two cases.

The most ideal case is a UPQC-Q of β=90° control scheme and for a given voltage sag, the corresponding reactive power generated internally by the inverter increases. Voltage restoration by injecting voltage with a leading phase decreases the demand of energy injection from energy storage devices such as capacitors or batteries.

However, there is a phase difference between the input and output voltages, a transient state will occur when the source voltage decreases or returns to a normal value. The magnitude of the injected voltage must be larger than that used for in-phase injection.

Therefore, considering the limits of series compensator as shown in Fig.2, voltage compensation is possible V_{inj} which leads the source voltage by β with minimum energy consumption. In this case the problem of a phase difference between input and output voltage will be overcome because β is calculated, and the time to reach a calculated value can be controlled. In Fig. 2 when β increases, θ decreases and the injected active power decreases. β depends on the level of voltage sag and the limits of the series compensator, but the power factor θ can be controlled by a parallel compensator. Therefore, if the parallel compensator controls the power factor, the effective power can be reduced.

2.1 Phasor diagram

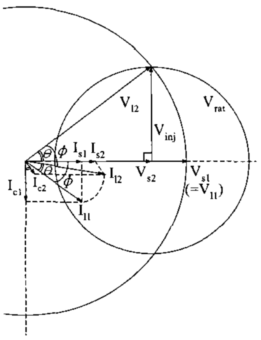


Fig. 3 Phasor diagram of UPQC-Q

Fig.3 is a phasor diagram showing the UPQC-Q performance. When the source voltage is the rated voltage V_{s1}, load voltage V_{l1} equals V_{s1}. The load current I_{l1} flows with power factor ϕ with respect to the output voltage V_{l1}. This current is supplied by the parallel compensator current I_{c1}, and source current I_{s1}.

When voltage sag occurs, V_{s1} becomes V_{s2} and V_{inj} injected from the series compensator compensates output voltage which has the same amplitude as V_{s1}. At this moment V_{l1}, the load voltage before the voltage sag, has a phase difference of θ with V_{l2}, the load voltage after compensation. The load current I_{l2} is also supplied by the parallel compensator current I_{c2}, and source current I_{s2}.

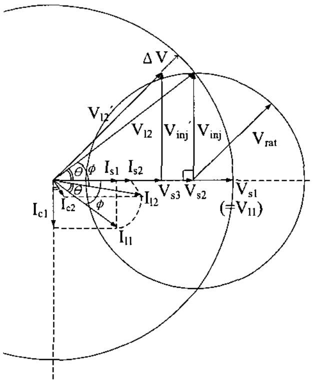


Fig. 4 Phasor diagram of UPQC-Q (compensation not possible)

If the maximum value of V_{inj} injected by the series compensator is limited as a specific value and a more severe voltage sag occurs ($|V_{s3}| < |V_{s2}|$) as shown in Fig. 4, compensation is not possible only with reactive power because the compensated voltage V_{l2}' is less than V_{l1}. Voltage sag is only compensated with reactive power and the voltage sag of ΔV is not compensated in this condition.

Therefore, if it is compensated with minimum active power and maximum reactive power, voltage compensation is possible with minimum energy.

3. The Proposed Method

3.1 Compensation with active power

As shown in Fig.4, when compensation of voltage sag is not possible using only reactive power, boundary condition can be found in the following figures.

The series compensator voltage rating V_{rat} and voltage sag V_{s2} determine whether active power will be used or not. In the case of $V_{rat} \geq V_l$ compensation of all boundaries is possible only with reactive power, but in the case of $V_{rat} < V_l$ there is a condition to need active power with a limit of series compensator rating. In Fig. 5 $V_{rat} \geq V_l$, sags of all ranges can be compensated using only reactive power. In this case β=90°, injected voltage from series compensator V_{inj} is

$$V_{inj} = \sqrt{V_{l2}^2 - V_{s2}^2} \tag{1}$$

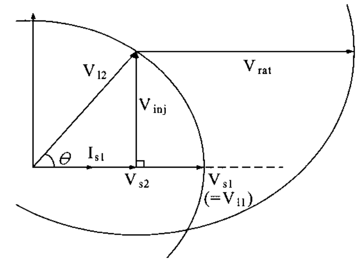
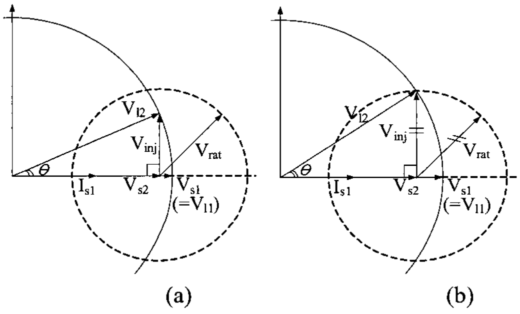


Fig. 5 Phasor diagram when V_{rat} is bigger than V_l($V_{rat} > V_l$, all V_{sag})

If $\sqrt{V_{l2}^2 - V_{s2}^2} \leq V_{rat} < V_{l2}$, compensation of all boundaries is possible only with reactive power as shown in Fig. 6.



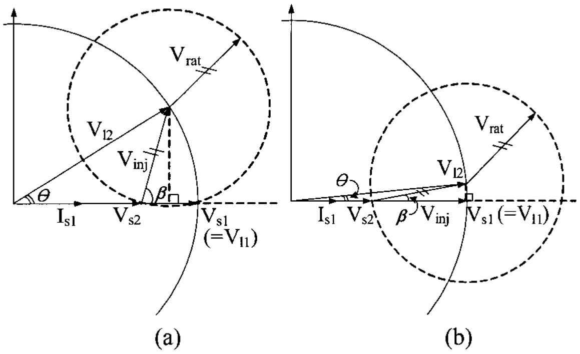
(a) (b)

Fig. 6 Phasor diagram when V_{rat} is bigger than $\sqrt{V_{l2}^2 - V_{s2}^2}$, and smaller than V_{l2}

(a) $\sqrt{V_{l2}^2 - V_{s2}^2} < V_{rat} < V_{l2}$ (b) $\sqrt{V_{l2}^2 - V_{s2}^2} = V_{rat} < V_{l2}$

If $V_{rat} < \sqrt{V_{l2}^2 - V_{s2}^2}$ the level of voltage sag V_{s2} must be considered, and there are three possible cases.

First, $V_{s2} + V_{rat} > V_{l2}$



(a) (b)

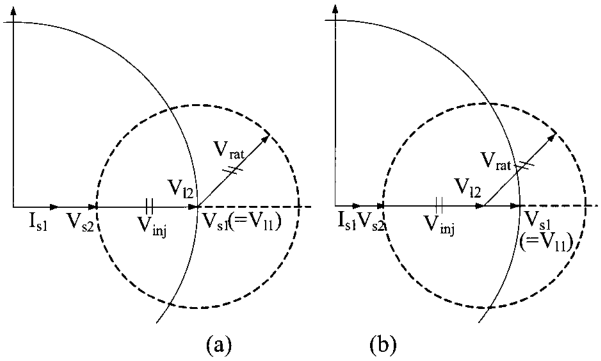
Fig. 7 Phasor diagram when V_{rat} is smaller than $\sqrt{V_{l2}^2 - V_{s2}^2}$

(a) Voltage drop is slight ($V_{s2} + V_{rat} > V_{l2}$) (b) Voltage drop is serious ($V_{s2} + V_{rat} > V_{l2}$)

As shown in Fig. 7, injected voltage V_{inj} and angle β from series compensator are

$$V_{inj} = V_{rat} \tag{2}$$

$$\beta = \pi - \arccos((V_{s2}^2 + V_{inj}^2 - V_l^2) / 2V_{s2}V_{inj}) \tag{3}$$



(a) (b)

Fig. 8 Phasor diagram when V_{rat} is smaller than $\sqrt{V_{l2}^2 - V_{s2}^2}$

(a) $V_{s2} + V_{rat} = V_{l2}$ (b) $V_{s2} + V_{rat} < V_{l1}$

Second, $V_{s2} + V_{rat} = V_{l2}$

It is possible to compensate for the voltage drop by using only active power as shown in Fig. 8(a).

Third, $V_{s2}+V_{rat}<V_{l1}$

Even though active power is used, it is impossible to compensate for the voltage drop as shown in Fig. 8(b).

3.2 Minimum power injection

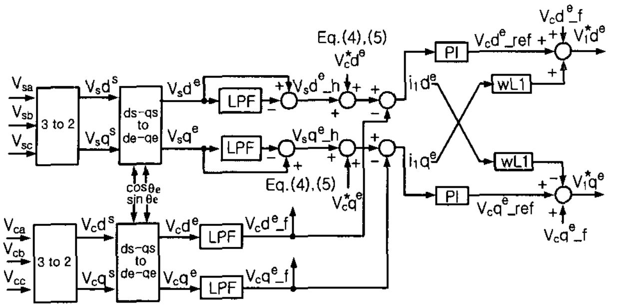


Fig. 9 Synchronous reference frame controller for a series active compensator

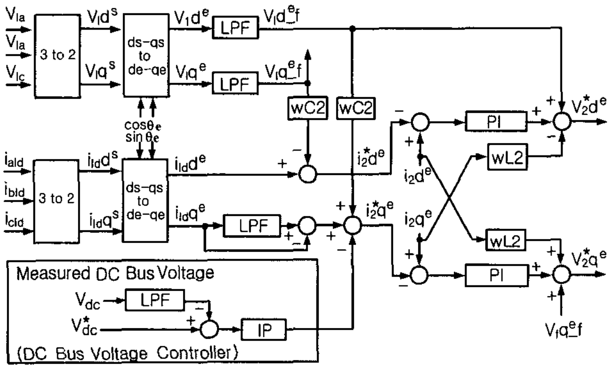


Fig. 10 Synchronous reference frame controller for a parallel active compensator

Fig.9 and 10 show the control block diagram of the series compensator and parallel compensator in synchronous reference frame. Series compensator is the implemented voltage control scheme that receives three phase input and output voltage and supplies reference [6][7]. Three phase input voltage is transformed to a stationary reference frame, and to the synchronous reference frame, which is through HPF (1-LPF). Harmonics are separated, and a reference for harmonics compensation is provided.

Through PI control of reference of compensation of input voltage harmonics and EQ (4), (5) controlling portion of reactive and active power and feedback of output voltage, reference of series compensator is provided.

$$V_c^*d^e=V_{rat}\sin\beta \tag{4}$$

$$V_c^*q^e=V_{rat}\cos\beta \tag{5}$$

$$V_{inj}^{\ 2}=(V_c^*d^e)^2+(V_c^*q^e)^2 \tag{6}$$

$$\beta=\arctan(\,V_c^*d^e/V_c^*q^e) \tag{7}$$

Cut-off frequency of source voltage and output voltage of serial converter are 5Hz, and 100Hz, respectively. PI gains are 1, 150.

Parallel compensators are implemented using a current control scheme that receives load voltage, current and supply reference [8]. The load current is transformed to the stationary reference frame, the synchronous reference frame, which is through the HPF (1-LPF). Harmonics are separated, and a reference for harmonics compensation is provided.

Cut-off frequency of load voltage and current are 100Hz, and 100Hz, respectively. PI gains are 1.23, 150. Additionally, through the feed-forward term of *wL2* and *wC2*, decoupling between d axis and q axis is possible. The IP controller for DC voltage control is used.

Fig. 11 shows the flow chart of series compensator control

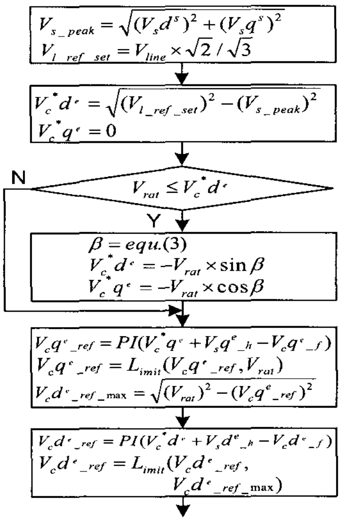


Fig. 11 Flow chart of series compensator control

4. Simulation and experimental result

4.1 Simulation Results

The proposed algorithms were studied by simulation tools ACSL (Advanced Continuous Simulation Language). System parameters are shown in Table. 1.

Table. 1 SYSTEM PARAMETERS

Parameters	Value
Source Voltage (V_{sa}, V_{sb}, V_{sc})	220[V], 60[Hz]
Line Impedance (L_s)	0[μH]
DC-link Capacitor(C_{dc})	6800[μF]
DC-link Voltage(V_{dc})	400[V]
L_1	0.35[mH]
L_2	1.3[mH]
R_3	25[Ω]
R_4, R_5	10[Ω], 5mH
C_1, R_1	50[μF], 1[Ω]
C_2,R_2	50[μF], 1[Ω]

Fig. 12, 13 and 14 show the simulation results of the UPQC-Q. In the first simulation, shown in Fig.12, V_{sa} is the input voltage, V_{inja} is the injected voltage by the series compensator, V_{la} is the output voltage, I_{sa} is the source current, and I_{ald} is load current.

Fig. 12 shows the conventional UPQC-Q without limitation of rating of series compensator using only reactive power when the source voltage decreases 20 % at 0.4 [sec], respectively. At T=0.4 [sec] a voltage sag occurred and the output voltage was controlled constantly. That was because the injected voltage from series compensator, V_{inja}, was enough to maintain the output voltage. We can see that rms value of output voltage, V_{la}, was recovered at T=0.456[sec].

However, I_{sa} was increased and I_{ald} maintained its normal values because the output voltage was maintained constantly.

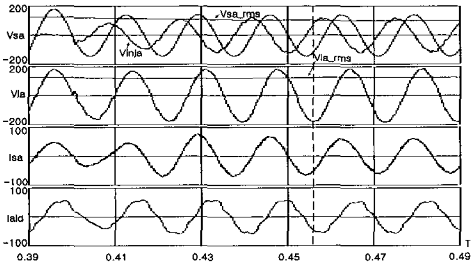


Fig. 12 Conventional UPQC-Q without limitation on the series compensator rating(V_{sa} : source voltage, V_{inja}: injected voltage, V_{la} : output voltage, I_{sa} : source current, I_{ald} : load current)

Fig.13 shows the conventional UPQC-Q with limitation of rating of series compensator using only reactive power when the source voltage decreases 20 % at 0.4 [sec], respectively. At T=0.4 [sec] a voltage sag occurred and the output voltage was not compensated fully. That was because the injected voltage from the series compensator, V_{inja}, was not enough to maintain the output voltage.

We can see that rms value of the output voltage, V_{la}, was not recovered fully, and the load current, I_{ald}, was decreased according to the decrease of the output voltage.

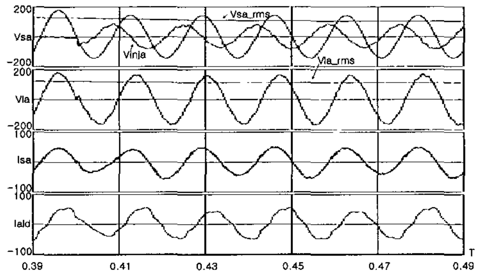


Fig. 13 Conventional UPQC-Q with limitation on the series compensator rating

Fig.14 shows the proposed UPQC-Q with limitation of rating of series compensator using reactive and active power when the source voltage decreases 20 % at 0.4 [sec], respectively. At T=0.4 [sec] a sag occurred and the output voltage was fully compensated. That was because even though there are limitations on the rating of the series compensator, the injected voltage from series compensator, V_{inja}, included not only reactive power but also effective power.

However, the effective power was minimized according to the proposed minimum power injection algorithm. We can see that rms value of the output voltage, V_{la}, was recovered at T=0.452[sec]. This is faster than that of Fig.12, and I_{ald} maintained its normal values because of constant output voltage. At this time, the β *is* 1.13[radian/sec].

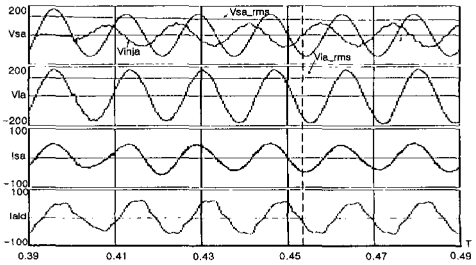


Fig. 14 Proposed UPQC-Q with minimum power injection

4.2 Experimental Results

In order to verify the proposed strategy, a control system was implemented using a digital signal processor (TMS320C31). A single 32-bit floating-point DSP with the single-cycle execution time of 40 *nsec* was used to implement all algorithms. The switching period for PWM was 125μsec.

The system configuration is shown in Fig. 15. A 5kVA laboratory prototype using IGBT modules was used. A three phase diode rectifier is included to show the characteristics of harmonic load current elimination. The parameters used in the experiment are shown in Table 2. To avoid serious problems, the input voltage was reduced to 70 (V). When the system and control algorithms are stabilized, the input voltage is returned to 220 (V) instead of 70 (V). Source voltage sags were implemented by increasing the output voltage due to the lack of power equipment.

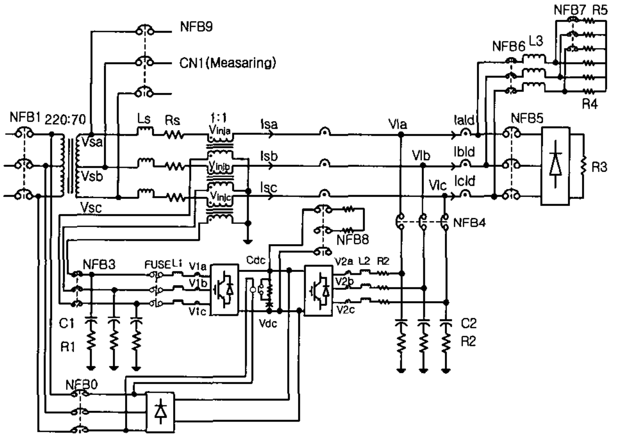


Fig. 15 Prototype system configuration

Table. 2 SYSTEM PARAMETERS

Parameters	Value
Source Voltage (V_{sa}, V_{sb}, V_{sc})	70[V], 60[Hz]
Line Impedance (R_s, L_s)	0[Ω], 0[μH]
DC-link Capacitor(C_{dc})	6800[μF]
DC-link Voltage(V_{dc})	150[V]
L_1	1.35[mH]
L_2	1.3[mH]
C_1, R_1	50[μF], 1[Ω]
C_2, R_2	50[μF], 1[Ω]
R_3	25[Ω]
L_3	5[mH]
R_4, R_5	10[Ω]

Fig. 16 shows the experimental results for UPQC-Q without limitation of rating of series compensator when the source voltage sag occurred from 85 (V) to 70 (V). As mentioned previously, the voltage sag was modeled by raising the output voltage from 70 (V) to 85 (V).

When the voltage sag occurred, the series compensator injected the voltage, V_{inja}, which has a 90° leading phase with respect to the source voltage, V_{sa}. There was no limitation on the rating and the voltage sag was fully compensated, but there existed a phase difference between the source voltage and the output voltage and a distortion when the voltage drop happened. The source current was controlled as having a high power factor, because of the parallel compensator.

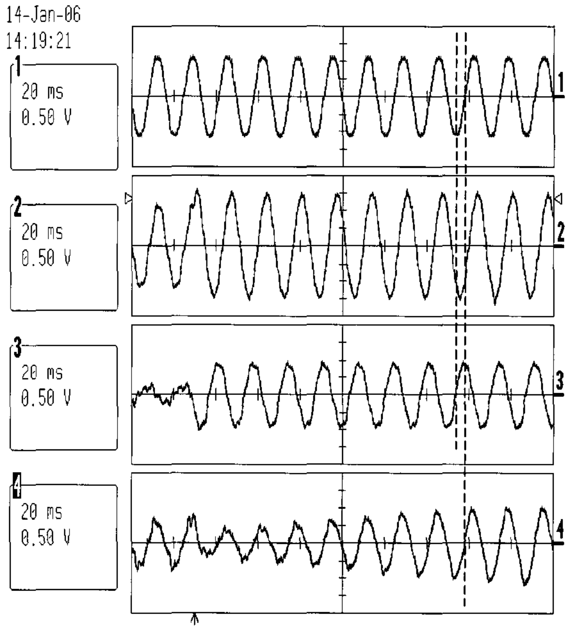


Fig. 16 Experimental results for conventional UPQC-Q without limitation on the series compensator rating (1.V_{sa} : source voltage(25V/div), 2.V_{la} : output voltage(25V/div),3.V_{inja}: injected voltage(25V/div), 4. I_{sa} : source current(5A/div))

Fig. 17 shows the waveforms with the limitation on the rating of the series compensator. Even though the injected voltage has a phase leading 90° with respect to the source voltage, the voltage sag was not fully compensated because of the limitation on the injected voltage. The source current was controlled as having a high power factor.

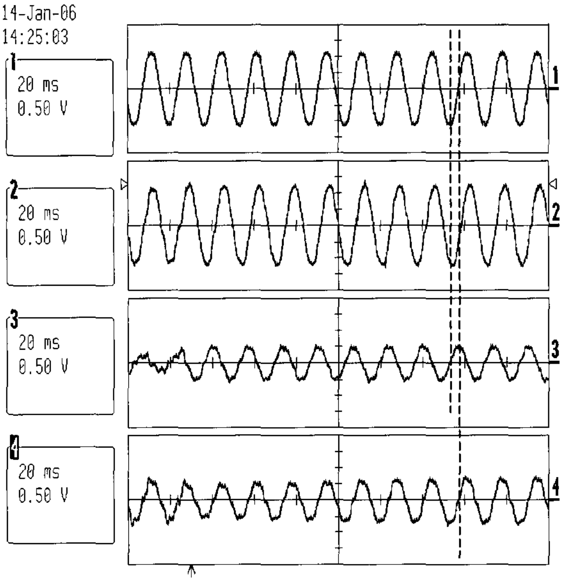


Fig. 17 Experimental results for conventional UPQC-Q with limitation on the series compensator

Fig. 18 shows the proposed minimum energy injection. When the voltage sag occurred, the voltage sag was fully compensated in spite of the limitation on the rating. However, as mentioned in the introduction there existed a phase difference between the source voltage and the injected voltage exceeding 90°. As with former experiments, the input power factor was controlled to unity.

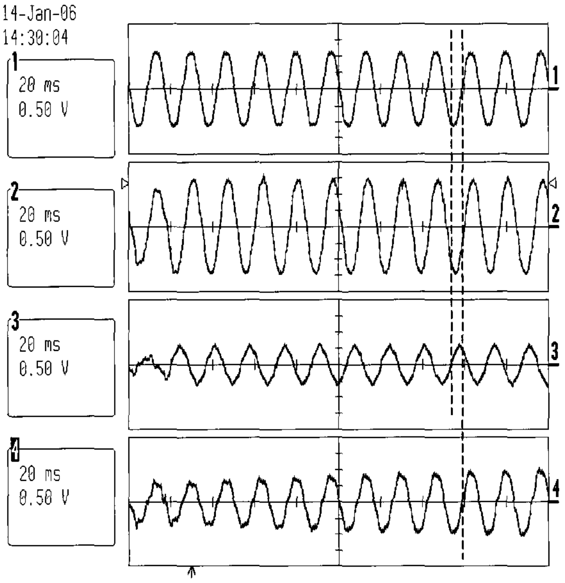


Fig. 18 Experimental results for proposed UPQC-Q with minimum power injection

5. Conclusions

This paper discussed the control methods for a UPQC-Q using a minimum power injection algorithm. The conventional UPQC-Q cannot compensate for the voltage sag effectively with limitations on the rating of the series compensator.

When there are limitations on the rating, the proposed control scheme can compensate for the voltage sag effectively and economically while using minimum effective power. The control algorithm and mathematical models were proposed, and then simulation and experimental results were presented to verify the performance of the proposed control strategy.

Although satisfactory results were obtained, further research will be done regarding 1) the input voltage returned to 220V instead of 70V, and 2) the imbalance of load current and source voltage.

Acknowledgment

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