Simulation Research on Unified Power Quality Compensator for Distribution System

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Abstract—The paper analyzed the defects and causes of shunt APF and serial APF when they are used to suppress the distortion in load current or in source voltage separately. It also introduced the operation principle of Unified Power Quality Compensator (UPQC), which is able to compensate for both the source voltage and load current at the same time. The paper proposed the reference criteria comparison detection method for voltage distortion, dq0 detection method for current distortion and PI control strategy for stabilizing the voltage of DC capacitors. Simulation result verified the correctness of analysis and the effectiveness of UPQC design.

Keywords- Custom Power, Unified Power Quality Compensator, Simulation

I. INTRODUCTION

Since all kinds of nonlinear loads are increasing, especially in the area of power electronic devices, the power quality in the distribution system becomes worse. On the other hand, with rapid development of computer and modern industrial technology, electrical equipments become more sensitive to power quality, since poor power supply quality leads to poor product quality. Particularly in those critical industrial production process, short-time voltage outrage, impulse, surge, sags will all cause enormous economic losses.

In 1988, Dr. N. G. Hingorani of the US proposed the concept of Customer Power, which represents a new type of integrated technology targeting at improving power supply reliability and power quality by using high and new technologies, such as power electronics technology, microprocessor technology and control technology in mid and low voltage power supply and distribution system, to reduce harmonic distortion, eliminate voltage fluctuation, voltage flicker, voltage imbalance and short-time interruption of power supply. The idea of Customer Power offers a new way to settle the power quality problem in distribution system.

There is a kind of compensator devices in the custom power mechanism family that can be used to improve the power quality—Active Power Filter (APF). Based on differences in its structure and function, it can be divided into two categories: Shunt/parallel APF and Serial APF. According to present industrial application practices, Shunt APF is mainly used to reduce harmonic current of nonlinear loads, to ensure sine wave current to the grid, while Serial APF is mainly used to compensate various component distortions in power supply, to ensure regular sine wave power supply to the customer. Unified Power Quality Compensator/ Conditioner, UPQC, is such a well-performing compensation device developed recently. It integrates the functions of Shunt APF and Serial APF, that is, can both reduce harmonic current of nonlinear loads, and compensate component distortions in power supply.

II. SHUNT APF AND SERIAL APF

For today, great progresses have been made in Shunt APF and Serial APF study. However, the limitations of both are obvious, which will be analyzed later. (For convenience of analysis, all the wave shapes below take Phase A of a three-phase system as example).

A. Limitation of Shunt APF

The principle of how Shunt APF compensates for current distortion of nonlinear loads is showed in figure 1. Countless research paper and data have stated that when the power supply is in regular sine wave, Shunt APF can filter successfully the harmonic current of nonlinear loads and reactive power. But in real case, there is always a distortion in power supply, Shunt APF cannot work that well as expected.

Fig.1 Shunt APF Compensates for current distortion

Assume that the nonlinear load in Figure 1 is a rectifier device. Figure 2 shows the waveform of current compensated by Shunt APF, when there is no distortion in power supply. Figure 3 shows the waveform of the current compensated by Shunt APF, when there is a distortion in power supply, for example, has a 10% of the fifth harmonic current.

Fig.2 Compensated waveform of source current without voltage distortion
According to the simulation, with compensation of Shunt APR, the THD of power supply, which is 53.6%, can be reduced to 4.2%, when there is no distortion. However, when distortion does exist in power supply, the THD of the current will still be as high as 17.7% ever after compensation. The main cause for that is: no matter which method is used by Shunt APF to detect voltage distortion, p, q method or \(i_p, i_q\) method, power supply voltage is a key figure in the calculation process. If there is a distortion on it, most possibly, there will be a variation in detected current distortion, so Shunt APF can not make good compensation.

B. Limitation of Serial APF

The principle of how Serial APF compensates for voltage distortion is showed in figure 4.

Assume that there is a harmonic distortion in power supply, 10% each for the third, fifth and seventh harmonic. Figure 5 shows the waveform of the compensated load side voltage when the load is linear, it can be seen that Serial APF compensates the distortion perfectly in power supply voltage. The waveform in Figure 6 shows that when the load is nonlinear, even with compensation of Serial APF, obvious distortion still exists.

The explanation of why Serial APF performs not so well when there is a nonlinear load is that: even if the Serial APF can detect all the distortion in power supply and compensate, since the load is nonlinear, there are still some distortion in the current, which will create a voltage drop on the two sides of the serial transformer (voltage distortion caused by nonlinear load). Serial APF could hardly detect and compensate such distortion because it is on power supply side of Serial APF.

From the analysis above, it is easy to conclude that, both Shunt APF and Serial APF has its own demerits when compensate current with load and distortion of power supply. In some cases, some nonlinear loads on one hand generate huge harmonic current, but on the other hand, demand high power supply quality. Then the only way is to use UPQC to compensate both current and voltage distortions.

III. THE STRUCTURE AND PRINCIPLE OF UPQC

The structure of UPQC is shown in Figure 7. It includes a serial converter and a parallel converter coupled by a DC capacitor, which composes an “AC-DC-AC” structure. Serial converter will offer a voltage to compensate the distortion through the transformer in the power grid. While the parallel converter will offer a harmonic component to reduce the harmonic current, that is caused by the nonlinear loads, through the inductor in the grid. Another function of the parallel converter is to provide active current to DC capacitor to compensate the power loss of UPQC. As the two converters are controlled by the PWM control signals, high harmonics will be generated on the output side. So some passive filters are needed to prevent the high harmonics into the power grid. L1, C and L2, C in Figure 7 play the role of filters.

Φ. THE DETECTION METHOD OF UPQC

Detection of voltage and current distortion is crucial in the operation of UPQC, its accuracy and immediateness directly affects the compensation of UPQC. In recent years, many detection methods were proposed, such as: active and reactive separation method, self-adapting testing method based on the instantaneous reactive theory, p, q detection method, \(i_p, i_q\) method based on the instantaneous reactive power theory and so on. Though they all have their distinctive advantages, still could hardly be used in UPQC since UPCQ has a high requirement on accuracy and immediateness of detection. A detection method based on broad instantaneous reactive power theory in dq0 coordinate system was developed, such method, better than others, can be applied to non-sine, asymmetrical circuit.
A. The Detection Method of Parallel Part in UPQC

The principle of dq0 transformation detection method on current distortion is: after the transformation of dq0, the n\textsuperscript{th} positive-phase-sequence component of three-phase current, will become the (n-1)\textsuperscript{th} component in the dq0 ordinate system. And the n\textsuperscript{th} negative-phase-sequence component will become the (n+1)\textsuperscript{th} component in the dq0 ordinate system. Only the components by id, iq which have been transformed from i_{a1}, i_{b1} and i_{c1} (Figure 8 shows the low pass filter and the subtraction link), the current distortions in dq0 ordinate system, i_d' and iq' come out. Counter-transform L', i_{a'} and zero component i_0, we get i_{ac}, i_{bc} and i_{cc} of three-phase load current a, b and c. These components are the ones which are needed to be compensated. Send them to the parallel converter, we will realize compensation to the load current.

B. The Detection Method of Serial Part in UPQC

One of the functions of UPQC is to ensure standard sine voltage to customer, i.e., the harmonic component, the asymmetric component, and the fundamental component which is higher or lower than standard in power supply will all be filtered out. Thus, when detecting voltage distortion component, the difference between original power supply voltage and standard load voltage can be looked as the voltage component to be compensated, it is named as reference index comparison detection method, the process of which is shown in Figure 9. When the a-phase voltage passes the low pass filter BPF, and goes into PLL, it will provide anti-dq0 transformation module a real time synchronization signal. The input to the anti-dq0 transformation module is standard d-axis voltage, standard q-axis voltage and standard 0-axis voltage (in the 380 V low-voltage system, the three components would be 380, 0 and 0), and the output will be three-phase symmetrical sine voltage wave. Minus the power supply voltage of the three-phase u_{as}, u_{bs} and u_{cs} by the standard voltage requested by load, it will get voltage distortions u_{ac}, u_{bc} and u_{cc} to be compensated by the UPQC serial side.

V. CONTROL STRATEGY OF UPQC

Control of UPQC serial part is relatively simple. Take the detected voltage quantity to be compensated as modulation signal, modulate it with triangle wave carrier, PWM control signals then can be got. Use PWM control signals to control switches of the serial converter, the power supply voltage will be compensated.

Control of UPQC parallel part is more complicated, since it has to compensate the load current distortion component, and to maintain a constant voltage level of DC capacitor. Adopt PI adjustment to control this part, the principle of which is shown in Figure 10.

VI. SIMULATION RESULT OF UPCQ

Assume that the normal amplitude of the three-phase rectifier load voltage is 311 V standard sine wave, while the actual amplitude of the supply voltage has both low harmonic and fundamental asymmetric component, and the fundamental symmetry components is only 290 V. So the serial part of UPQC has to both compensate the distortion component of power supply voltage, and the under-voltage power supply. See the equations below:

u_s = 290 \sin(\omega t)+31.1 \sin(3 \omega t)+31.1 \sin(5 \omega t)+31.1 \sin(7 \omega t)+10 \sin(\omega t+120°)

u_s = 290 \sin(\omega t+120°)+31.1 \sin(3 \omega t)+31.1 \sin(5 \omega t+120°)+31.1 \sin(7 \omega t+120°)+10 \sin(\omega t)

Figure 11 shows the waveforms of the supply voltage Us and the compensated load voltage Ul with UPQC. Figure 12
shows the waveforms of the load current $I_l$ and the compensated current $I_s$ with UPQC.

From the simulation results, we can see UPQC compensates both the 21 V under difference of power supply, and the negative sequence fundamental component and low harmonic components for the power supply. According to the calculation, the supply voltage THD is 16.6%, and the load voltage $U_l$ THD is reduced to 1.49%; UPQC also reduces greatly the nonlinear load current THD, from 77.5% on the load side to 4.58% on the supply-side. The compensation is successful.

VII. CONCLUSION

Since power quality of distribution grid is deteriorating, the research on various active compensation devices based on power electronics technology is going farther. Parallel active filter can reduce the nonlinear load current distortion, but when there is a supply voltage distortion, it is difficult to achieve expected results; serial active filter can filter out the power supply voltage distortion, but with nonlinear load, the compensation device can not offer satisfied results. The analysis has been given before.

Using reference index comparison testing method to detect the serial part, and dq0 detection method to detect parallel part of the UPQC, the distortion component in load current and supply voltage can be detected with high accuracy. The PI control strategy can maintain the DC capacitor voltage stability by compensating the power loss. The simulation results show that, UPQC can compensate the distortion of the supply voltage to ensure an ideal sine voltage, and control the nonlinear distortion of the load current, to avoid the power grid being contaminated by the harmonic. It is believed that UPQC devices provide a practical way to settle the power quality problems in the power distribution grid.

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