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Simplified method for protecting the power capacitor from over-voltage/over-current

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Abstract

A simplified method for protecting the power capacitor from over-voltage/over-current is proposed. The proposed method retrieves the voltage across the power capacitor to calculate the root mean square (RMS) values of the power capacitor voltage and the power capacitor current. The salient point of the proposed method is this method can protect the power capacitor from over-voltage/over-current caused by harmonic or power resonance only sensing the power capacitor voltage. The control circuit generates a trigger signal to actuate the electromagnetic switch to switch off the power capacitor from the power system or adjust the impedance characteristic of inductor/power capacitor for protecting the power capacitor from over-voltage/over-current if an abnormal voltage or current is detected. The proposed method has the advantages of simplified control circuit, easy installation and low implementation cost. A prototype is implemented to verify its performance. The test results show that the proposed method has the expected performance.

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Keywords: Power capacitor; Harmonic; Power resonance

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1. Introduction

Most of loads in the electric power system have the characteristic of inductance. The phase of inductive load current lags with that of the utility voltage. This results in that the current in the transmission or distribution power system contains not only the active current component but also the reactive current component. Therefore, it has the disadvantages that the power efficiency of the transmission or distribution power system is reduced and the voltage regulation in the load side is poor. In order to solve the above problems, utilities or electric power users use the power capacitor set or the automatic power factor regulator (APFR) to improve the power factor [1–3]. The capacity of power capacitor sets used in the power system is about 25–35% of the total capacity of the power system even so much as about 50% in some power systems. Evidently, the power capacitor is widely used in the power system [4].

Power electronic facilities such as the Uninterruptible Power Supply (UPS), the rectifier, the motor driver and the switching power supply are widely applied in the distribution power system. These power electronic facilities have the characteristic of non-linear input current and the poor input power factor. In general, the voltage and current waveforms of transmission and distribution power systems are designed to operate under the sinusoidal waveform with constant frequency. The voltage waveform of the power system is distorted due to the harmonic current pollution, and the distorted voltage waveform results in the degradation of power quality. Since the impedance of the power capacitor is inversely proportional to the frequency, the effect of harmonic pollution for power capacitor is very serious. In general, an inductor is usually serially connected to a power capacitor to filter harmonic current and limit the inrush current of power capacitor [5–7]. However, the inductor and power capacitor may be damaged as the harmonic resonance occurs [8].

The investigation of harmonic events in Japan shows that the event of the inductor caused by harmonic is 65% and that of the power capacitor is 26% in the power system [9]. Significantly, the damage of the inductor and the power capacitor caused by harmonics is a very serious problem. The damage of inductor/power capacitor caused by harmonic

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resonance includes over-voltage resulting in the insulation damage, or over-current resulting in the thermal damage [10]. The voltage/current rating of inductor/power capacitor set is designed under the normal operation condition. However, the over-voltage/over-current of the inductor/power capacitor set occurs frequently due to the power resonant phenomenon between the system impedance and its branch impedance. When the distribution power system or the nonlinear load contain the harmonic whose frequency is near the resonant frequency, the harmonic voltage/current may be amplified over 10 times of its rated voltage that results in over-voltage/over-current and thus the inductor/power capacitor set is damaged.

In order to prevent the power inductor/power capacitor set from over-voltage/over-current caused by harmonic resonance in a power factor improvement system or a passive power filter system, the voltage/current rating of power capacitor was risen up conventionally. This solution not only increases overall cost but also fails to protect the inductor/power capacitor set from the damage caused by the harmonic resonance. If the current rating of inductor does not increase in the design of this solution, the inductor may be damaged due to the over-current caused by the resonant phenomenon. This may be the reason that the inductor damage (65%) is higher than the power capacitor damage (26%) [9]. Consequently, the conventional solution is ineffective.

For protecting the inductor/power capacitor from harmonic resonance, a simplified protection method is proposed. The control circuit generates a trigger signal to actuate the electromagnetic switch to switch off the power capacitor from the power system or adjust the impedance characteristic of inductor/power capacitor for protecting the power capacitor from over-voltage/over-current if an abnormal voltage or current is detected. The proposed method has the advantages of simplified control circuit, easy installation and low implementation cost. Finally, a prototype is developed and tested to verify its performance.

2. Basic theory

In general, an inductor is usually serially connected to a power capacitor to filter the harmonic current and limit the inrush current in the industrial power system. Hence, both the reactive power compensator and passive power filter contain a power capacitor and an inductor connected in series. Fig. 1(a) shows a simplified industrial power system with a L–C circuit. The L–C circuit may be a tuned power filter or a reactive power compensated power capacitor with a serial inductor. The power facility in the load side is a nonlinear load, which is named as the un-compensated nonlinear load. The neighboring power facilities may also contain nonlinear loads, which names as the un-compensated neighboring nonlinear load. Hence, Fig. 1(a) may contain two harmonic sources, an un-compensated nonlinear load and an un-compensated neighboring nonlinear load. To simplify the analysis, both nonlinear loads are simplified as the harmonic current sources (I_{Lh}, I_{nh}). Fig. 1(b) shows the harmonic equivalent circuit of Fig. 1(a).

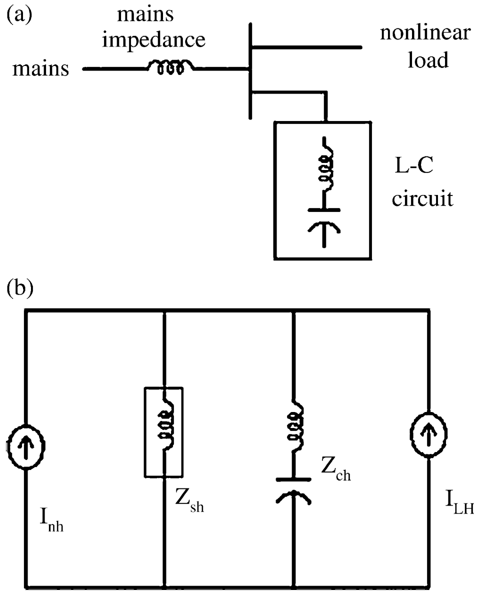

Fig. 1. The simplified industrial system with power capacitor/passive power filter, (a) circuit diagram, (b) equivalent circuit.

From Fig. 1(b), it can be found that the harmonic current injected into the L–C circuit (I_{ch}) can be derived as:

$$I_{\mathrm{ch}} = \frac{Z_{\mathrm{sh}}}{Z_{\mathrm{ch}} + Z_{\mathrm{sh}}}(I_{\mathrm{Lh}} + I_{\mathrm{nh}}) \tag{1}$$

where h is the index for representing the harmonic order. The parallel resonance occurs when the denominator of Eq. (1) is near zero. It will result in a large harmonic current injected into the L–C circuit. The amplitude of injected harmonic current may be several times amplitude of harmonic current source. In the same time, the harmonic voltage across the power capacitor will also be amplified. Hence, the power resonance may result in over-voltage/over-current and cause the damage of L–C circuit. From Eq. (1), it can be found that the L–C circuit cannot distinguish the harmonic currents generated by the un-compensated nonlinear load or the un-compensated neighboring nonlinear load. It means that the L–C circuit supplies a low impedance path of harmonic current not only for the un-compensated nonlinear load but also for the un-compensated neighboring nonlinear load. It shows that the harmonic current of the un-compensated neighboring nonlinear loads will inject into the power capacitor/passive power filter and result in over-current in the practical industrial distribution power system. The frequency of parallel resonance can be derived as:

$$\omega_{\mathrm{r}} = \frac{1}{\sqrt{(L + L_{\mathrm{s}})C}} \tag{2}$$

where L and C are the inductance and capacitance of L–C circuit and L_{s} is the inductance of system impedance. From Eq. (2), it can be found that the resonant frequency will be shifted after adjusting the inductance of L–C circuit. The basic operation theory of the proposed method is to change the inductance of the inductor in the power capacitor/passive power filter to avoid the parallel resonance between the system

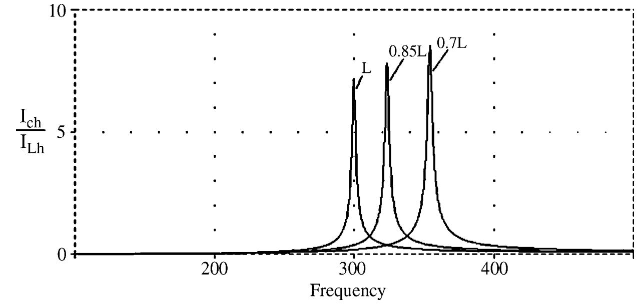

Fig. 2. The frequency spectrum for the L–C circuit under different inductor.

impedance and power capacitor/passive power filter path, and then it can protect the power capacitor from the damage of over-voltage/over-current. Fig. 2 shows the frequency response of L–C circuit current under different inductance. In this figure, the parallel resonant frequency between the system impedance and L–C circuit is assumed to be fifth order harmonic frequency (300 Hz), and L is the value of inductance in the L–C circuit under this resonance frequency. It shows that the 5th order harmonic will be amplified more than seven times. If the inductance of L–C circuit is reduced to 0.85 times ($0.85L$), the fifth order harmonic is suppressed to 0.38 times. If the inductance of L–C circuit is further reduced to 0.7 times ($0.7L$), the fifth order harmonic can be further suppressed to 0.19 times. The simulation result proves that the harmonic resonance can be suppressed effectively by adjusting the inductance of L–C circuit.

In the other hand, the change of inductance of the serial inductor will result in the change of the fundamental voltage across the power capacitor. The amplitude of the fundamental voltage across the power capacitor can be derived as:

$$V_{c1} = \frac{1/\omega C}{1/\omega C - \omega L} V_{s1} \tag{3}$$

where V_{s1} is the fundamental amplitude of the utility voltage where the power capacitor/passive power filter is connected to. From Eq. (3), it shows that if the inductance of serial inductor is reduced, the amplitude of fundamental voltage across the power capacitor is also reduced. Then, the fundamental current of the power capacitor is also reduced. Hence, it shows that the proposed method can suppress the harmonic amplification in the specific harmonic frequency and reduce the fundamental voltage and current when the power capacitor is over-voltage/over-current by changing the inductance of serial inductor.

3. Operation principle

Most of power capacitor damage in the power system can be divided into the insulation damage and the thermal damage. Over-voltage will result in insulation damage, and over-current will result in the thermal damage. For protecting the power capacitor, the real mean square (RMS) values of power capacitor voltage and current must be calculated firstly. If the power capacitor voltage with harmonic is represented as:

$$v_c(t) = \sum_{n=1}^{\infty} V_{cn} \sin(n\omega t + \theta_n) \tag{4}$$

Then, the power capacitor current can be represented as:

$$i_c(t) = \sum_{n=1}^{\infty} {}^{j}\omega C V_{cn} \cos(n\omega t + \theta_n) \tag{5}$$

where ω is the fundamental angular frequency. From above equations, it can be found that the power capacitor current can be directly calculated from the power capacitor voltage if the frequency spectrum of power capacitor voltage is pre-known. In an industry application example, the per-unit theory can be used, then, the power capacitor current can be directly calculated from the spectrum of power capacitor voltage.

The RMS values of power capacitor voltage and current can be represented as:

$$V_c\ (\text{p. u.}) = \frac{1}{\sqrt{2}} \sqrt{\sum_{n=1}^{\infty} V_{n,\text{pu}}^2} \tag{6}$$

$$I_c\ (\text{p. u.}) = \frac{1}{\sqrt{2}} \sqrt{\sum_{n=1}^{\infty} (nV_{n,\text{pu}})^2} \tag{7}$$

where $V_{n,\text{pu}}$ is the p.u. value of the nth order component of power capacitor voltage.

Fig. 3 shows the system diagram of the proposed method for protecting the power capacitor. The power circuit contains two electromagnetic switches (MC 1 and MC 2) and a serial inductor with center-tap. The electromagnetic switch M.C. 1 is used to switch on/off the power capacitor path, and the electromagnetic switch MC 2 is used to change the inductance of serial inductor. The control circuit includes a DSP chip, a voltage detection circuit and two relays. The DSP chip is used to calculate the RMS values of the power capacitor voltage and current, and then determines the states of two electromagnetic switches. The voltage detection circuit is used to detect the power capacitor voltage. Two relays are used to actuate two electromagnetic switches. The voltage detection circuit senses the power capacitor voltage and then sent to the A/D converter module of the DSP chip. The DSP chip calculates the fundamental and every order harmonic components of power capacitor voltage by the Fast Fourier Transformation (FFT) algorithm, then, it calculates the RMS values of power

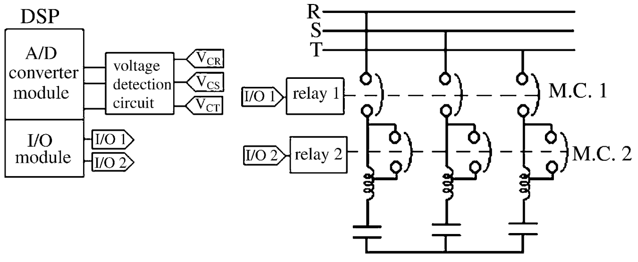

Fig. 3. System configuration of the proposed method.

capacitor voltage and current according as Eqs. (6) and (7). The calculated results are used to determine the states of two electromagnetic switches.

Under normal condition, the electromagnetic switch MC 1 is closed and the electromagnetic switch MC 2 is opened. The power capacitor path performs as reactive power compensation or the harmonic filter. If over-voltage/over-current of the power capacitor occurs, the electromagnetic switch MC 2 is closed firstly to shift the resonant frequency and then avoid the resonant frequency near the domain harmonic frequency. The harmonic amplification due to the resonance near the domain harmonic frequency will be suppressed effectively in theory. The inductance of the serial inductor is reduced when the electromagnetic switch MC 2 is closed, and the fundamental voltage and the fundamental current of power capacitor can also be reduced. Hence, it may protect the power capacitor away from over-voltage/over-current. In this time, the power capacitor path is still worked. If the over-voltage/over-current is still existed after the electromagnetic switch MC 2 is closed, the electromagnetic switch MC 1 will be opened, and the power capacitor path is switched away from a power system under this condition. Hence, the proposed method can protect the power capacitor from over-voltage/over-current effectively.

4. Design specifications

The over-voltage/over-current tolerance of the power capacitor is based on the standards of IEC 831 and IEC 871 [11]. The major rules used in this paper are described as following:

(1) the power capacitor over-voltage sustained time is shown in Table 1. The operation voltage must below 110% RMS of the normal rated voltage, including the fundamental voltage and the harmonic voltages (excluding system temporary state) under the normal operation;
(2) the power capacitor is capable of allowing over-current in a short time (transient state) according to IEC standard;
(3) the operation current is set as 130% RMS of the normal rated current, including the fundamental current and harmonic currents under the normal operation.

This paper intends to propose a method for the power system that judge the over-voltage/over-current of power capacitor according to IEC standard, so as to switch off the power capacitor from the power system or change the impedance characteristic of inductor/power capacitor path within the tolerance time to protect the power capacitor. The over-voltage protection used in the proposed method is according to IEC 831 standard. The allowable over-voltage sustain time in the proposed method is shown in Table 2. The allowable over-voltage sustain time is smaller than that of IEC standard in order to avoid abnormal operation or ineffective protection. The over-current protection used in the proposed method is also according to IEC 831 standard. The allowable over-current sustain time in the proposed method is shown in Table 3. The allowable over-current sustain time is also smaller than that of IEC standard in order to avoid abnormal operation or ineffective protection.

Table 1
The power capacitor over-voltage sustained time

Continuous allow time	Maximum allowable RMS of the normal rated voltage (%)
1 min	130 (1.3 times of the rated voltage)
5 min	120 (1.2 times of the rated voltage)
30 min	115 (1.15 times of the rated voltage)
12 h	110 (1.1 times of the rated voltage)

Table 2
The allowable over-voltage sustained time in the proposed method

Rated voltage times of the rated voltage	1.1	1.15	1.2	1.3
IEC allow time	12 hr	30 min	5 min	1 min
Allow time	1 hr	15 min	3 min	30 sec

Table 3
The allowable over-voltage sustained time in the proposed method

Rated current times of the rated voltage	1.3	2.0
Allow time	30 sec	0 sec

5. Experimental results

A prototype is developed to verify the performance of the proposed protection method for over-voltage/over-current of the power capacitor. Table 4 is the system parameters of the developed prototype. For observing the effect of the proposed

Table 4
The system parameters for the developed prototype

Utility voltage	Power capacitor	Serial inductor	System inductor
220 V	17 μF	4.9 mH	0.54 mH

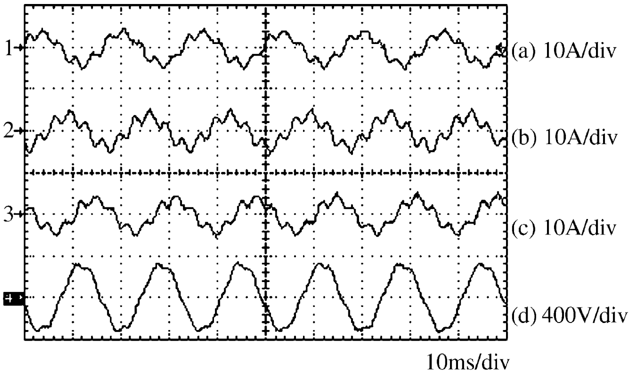

Fig. 4. The test result under the distorted utility voltage before applying the nonlinear load, (a) R phase power capacitor current, (b) S phase power capacitor current, (c) T phase power capacitor current, (d) utility voltage.

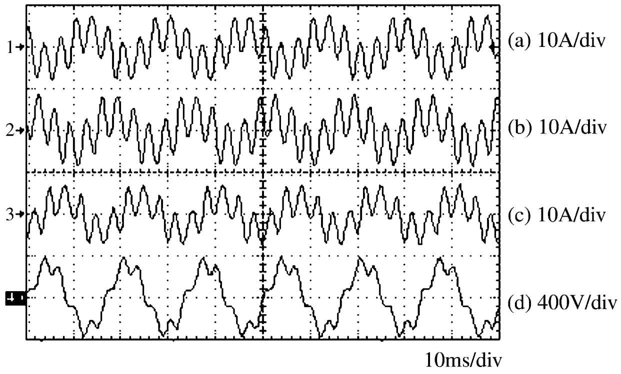

Fig. 5. The test result under the distorted utility voltage after applying the nonlinear load, (a) R phase power capacitor current, (b) S phase power capacitor current, (c) T phase power capacitor current, (d) utility voltage.

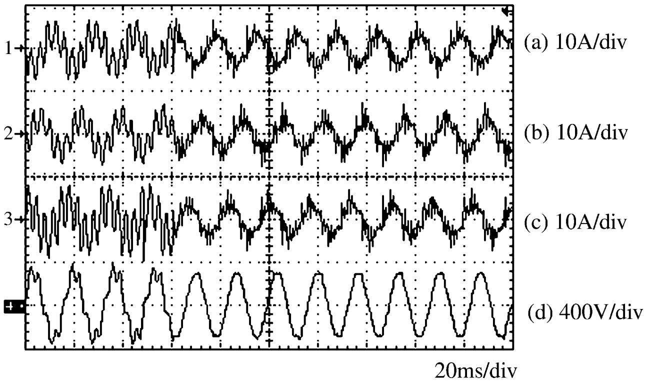

Fig. 7. The test result under the transient of closing MC 2, (a) R phase power capacitor current, (b) S phase power capacitor current, (c) T-phase power capacitor current, (d) utility voltage.

protection method clearly, a 0.54 mH inductor is inserted into the utility to enlarge the mains impedance.

Fig. 4 shows the waveforms of the power capacitor current and voltage under the distorted utility voltage before applying the nonlinear load. The RMS and the total harmonic distortion (THD) of the power capacitor current are 2.702 A and 35.8%, and the RMS and THD of power capacitor voltage are 224 V and 7.4%. Because the current rating of power capacitor is 2.8 A, both current and voltage are still below the power rating of power capacitor. The power capacitor is operated normally. Fig. 5 shows the waveforms of power capacitor current and voltage under the distorted utility voltage after applying the nonlinear load. The RMS and THD of power capacitor current are 4.466 A and 85.6%, and the RMS and THD of power capacitor voltage are 227.1 V and 21.2%. The current of power capacitor increases to 1.6 times of its rating current. This current value is over the allowable current rating of power capacitor, and the power capacitor may be damaged. Fig. 6 shows the waveforms of power capacitor current and voltage under the distorted utility voltage after applying the nonlinear load and closing MC 2. The inductance of serial inductor is changed to a half of its original value. The RMS and THD of power capacitor current are 2.827 A and 52.3%, and the RMS and THD of power capacitor voltage are 213 V and 5.9%. The current of power capacitor is 1.01 times of its rating current. Because the power capacitor allows 1.3 times of the rating current, the power capacitor can operate without interruption. The above tested results show that the resonant frequency has been deviated after closing MC 2. Hence, the current of power capacitor decreases significantly. Table 5 shows the summary for the voltage and current of power capacitor in the test of Figs. 4–6. Fig. 7 shows the test result under the transient of closing MC 2. It can be found that the power capacitor current is reduced evidently after closing MC 2.

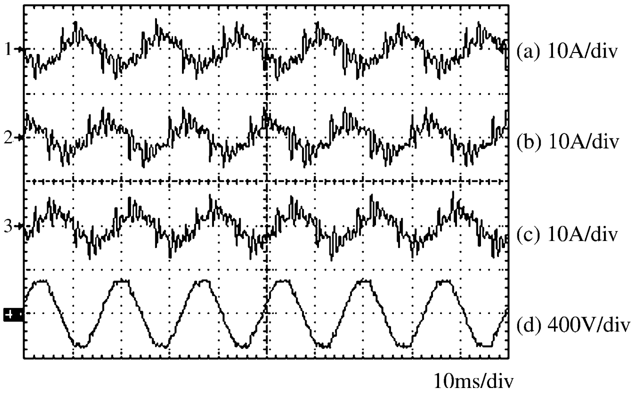

Fig. 6. The test result under the distorted utility voltage after applying the nonlinear load and closing M.C. 2, (a) R phase power capacitor current, (b) S phase power capacitor current, (c) T phase power capacitor current, (d) utility voltage.

Table 5
The summary of power capacitor current and voltage

	Before applying the nonlinear load	After applying the nonlinear load	After closing MC 2
Power capacitor current, THD%	2.702 A, 35.8%	4.466 A, 85.6%	2.827 A, 51.2%
Power capacitor voltage, THD%	224 V, 7.4%	227.1 V, 21.2%	213 V, 5.7%

6. Conclusions

A simplified method for protecting the power capacitor from over-voltage/over-current is proposed in this paper. The proposed method actuated the electromagnetic switches to switch the power capacitor away from a power system or to adjust the impedance characteristic of power capacitor for protecting the power capacitor from over-voltage/over-current if the abnormal voltage or current is detected. The salient point of this method is that it can detect and protect the power capacitor from over-current without using current sensor. The proposed method has the advantages that

(1) simplified control circuit,
(2) easy installation,
(3) low implementation cost.

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