ANALYSIS OF THE IMPACT ON THE SURROUNDING LOADS FOR THE APPLICATION OF SHUNT ACTIVE POWER FILTER

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ABSTRACT

The industrial field not only includes diode rectifier with smoothing inductor, thyristor rectifier, and diode rectifier with smoothing dc capacitor loads, but also contains reactive compensation capacitors and passive filters. The application of Shunt Active Power Filter (SAPF) in this field may cause significant harmonic pollution to the systems. This paper analyzes the harmonic characteristics before and after SAPF put into operation for a given nonlinear load, reveals the series and parallel resonance between the equivalent capacitance (the voltage-type harmonic source, reactive compensation capacitors and passive filters) and system inductance(line inductors and the leakage inductors of transformers or motors) may be excited for the frequency conversion effect, and analyzes the harmonic voltage propagation and the harmonic voltage and current magnification by using transmission line theory. Then, two-type methods are proposed to deal with the problems by this paper, i.e. to modify the topology/parameters so as to change the resonant frequency of the system; while the other is to improve and change SAPF's compensation bandwidth to be a selective or limited one. Furthermore, a virtual-harmonic-resistance based active damping method is also proposed for the harmonic-resonance suppression. They all can suppress the harmonic current effectively, while guarantee the load-side current without significant enlargement. Simulation results validate the feasibility of the schemes proposed by this paper.

Ⅰ. INTRODUCTION

In recent years, there is an increasing use of switching power supplies, uninterruptible power supply, voltage source inverter (VSI)-fed motor drives, especially in industrial applications of the range of low-to medium-horsepower levels. Most of these devices have a similar input power conversion part, i.e. a three-phase diode-bridge rectifier with a large smoothing dc capacitor that converts the ac supply voltage to an unregulated dc voltage. The large dc-link capacitor determines an appreciable pulsating component in the dc current. Consequently, the harmonic levels of the line current are considerably different and higher than those caused by a choker smoothed rectifier. This so-called capacitive-/voltage-type harmonic source has become an important type in practice.

The Shunt Active Power Filter (SAPF) with its easy installation and maintenance, etc., has been studied and used widely [1]. However, SAPF is suitable for compensation current-type harmonics but not appropriate for eliminating voltage-type/capacitive ones [2][3]. In the case of application SAPF for compensation current-type harmonics, it also may increase the voltage ripple of the diode rectifier bridge DC side and the peak current of the surrounding loads, even cause significant harmonic pollution to the systems. This paper analyzes the harmonic characteristics before and after SAPF put into operation for a given nonlinear load, reveals the series and parallel resonance. Then, three-type methods are proposed to deal with the problems by this paper.

Ⅱ. ANALYSIS OF THYRISTOR NONLINEAR LOAD

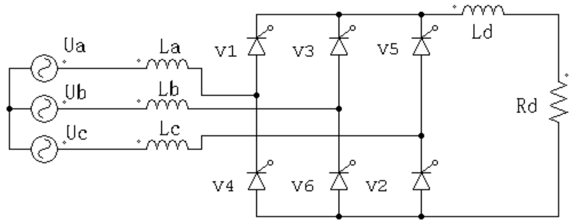


Fig.1.Basic principle of thyristor rectifier

The three-phase thyristor bridge rectifier with a large smoothing reactor L_d is shown in Fig. 1.Consider the system voltage u_a, u_b, u_c contain harmonic, we have Eqs:

$$u_a = \sum_{k=-1,0,1} \sum_{i=1}^{\infty} U_{km} \cos(\omega_x t + \alpha_{kx}) \quad (1)$$

$$u_b = \sum_{k=-1,0,1} \sum_{i=1}^{\infty} U_{km} \cos(\omega_x t + \alpha_{kx} - \frac{2\pi}{3}) \quad (2)$$

$$u_c = \sum_{k=-1,0,1} \sum_{i=1}^{\infty} U_{km} \cos(\omega_x t + \alpha_{kx} + \frac{2\pi}{3}) \quad (3)$$

Then, with the switching function and Fourier decomposition, we could get the direct voltage u_d shown in equations (4) and (5).

$$u_d^{+} = \sum_{m=1}^{\infty} \sum_{k=0}^{\infty} \frac{3u_m^{+}}{2} \begin{Bmatrix} A_{(6k\text{-}1)} \cos\{[\omega_x + (6k\text{-}1)\omega_0]t + \alpha_m^{+}\} \\ + A_{(6k+1)} \cos\{[\omega_x \text{-} (6k+1)\omega_0]t + \alpha_m^{+}\} \end{Bmatrix} \quad (4)$$

$$u_d^{-} = \sum_{m=1}^{\infty} \sum_{k=0}^{\infty} \frac{3u_m^{-}}{2} \begin{Bmatrix} A_{(6k+1)} \cos\{[\omega_x + (6k+1)\omega_0]t + \alpha_m^{-}\} \\ + A_{(6k+1)} \cos\{[\omega_x \text{-} (6k\text{-}1)\omega_0]t + \alpha_m^{-}\} \end{Bmatrix} \quad (5)$$

Equations (4) and (5) indicate the disturbance of harmonic voltage with frequency f_x will produce the voltage harmonic with frequency $f_d = f_x \pm (6k \pm 1) f_0$ in dc side, where, f_0 is the system normal frequency.

Consider the small disturbance of DC current，e.g. SAPF bringing in, there is

$$i_d = I_{dm}\cos(\omega_d t + \varphi_d) \quad (6)$$

Where, I_{dm} is the amplitude of id， ω_d is the disturbance frequency and φ_d is the initial angel. Then, it could get the AC current shown in equations (7), (8) and (9):

$$i_a = \frac{2\sqrt{3}\sin\frac{\mu}{2}}{\pi v} I_{dm}\{\cos[(\omega_d+\omega_0)t+\varphi_d]+\cos[(\omega_d-\omega_0)t+\varphi_d]\} \quad (7)$$

$$i_b = \frac{2\sqrt{3}\sin\frac{\mu}{2}}{\pi v} I_{dm}\left\{\cos\left[(\omega_d+\omega_0)t+\varphi_d-\frac{2\pi}{3}\right]+\cos\left[(\omega_d-\omega_0)t+\varphi_d-\frac{2\pi}{3}\right]\right\} \quad (8)$$

$$i_c = \frac{2\sqrt{3}\sin\frac{\mu}{2}}{\pi v} I_{dm}\left\{\cos\left[(\omega_d+\omega_0)t+\varphi_d+\frac{2\pi}{3}\right]+\cos\left[(\omega_d-\omega_0)t+\varphi_d+\frac{2\pi}{3}\right]\right\} \quad (9)$$

The disturbance of harmonic current with frequency f_d will produce two type current harmonic, one for positive sequence with frequency $f_d + f_0$, another for negative sequence with frequency $f_d - f_0$.

Ⅲ. ANALYSIS OF THE IMPACT FOR SAPF COMPENSATION HARMONIC

SAPF is suitable for compensation current harmonic, but for a harmonic voltage source installed nearby, shown in Fig.2, it maybe bring disaster, where, U_L represents the harmonic voltage, Z_{L1}, Z_{L2}represents harmonic impedance. I_{Lh} represents the harmonic current, U_S is system voltage, Zs is system impedance, G and I_C represents the SAPF.

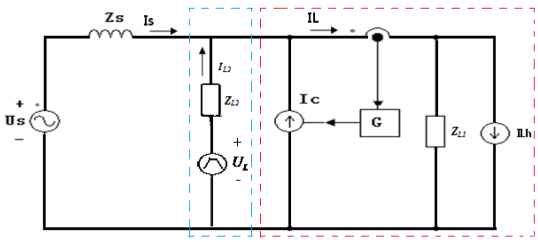


Fig.2.Basic principle of SAPF compensation current-type harmonic load with a voltage-type harmonic source nearby

From Fig. 2, there can get equations (10) - (12):

$$I_c = GI_L \quad (10)$$

$$I_s = \frac{(1-G)U_s Z_{L2} + (U_s - U_L)Z_{L1} + (1-G)Z_{L1}Z_{L2}I_{Lh}}{(1-G)Z_s Z_{L2} + Z_{L1}Z_s + Z_{L1}Z_{L2}} \quad (11)$$

$$I_{L2h} = \frac{U_L(1-G)Z_s + U_L Z_{L1} + (1-G)I_{Lh}Z_{L1}Z_s}{(1-G)Z_s Z_{L2} + Z_{L1}Z_s + Z_{L1}Z_{L2}} \quad (12)$$

Therefore if the equation

$$\left|\frac{Z_{L1}}{1-G}\right|_h >> |Z_s|_h \quad (13)$$

is met, we have the below equations(14)-(16):

$$I_C = I_{Lh} \quad (14)$$

$$I_{sh} \approx \frac{U_{sh}Z_{L2} + (U_{sh} - U_L)\frac{Z_{L1}}{1-G} + Z_{L1}Z_{L2}I_{Lh}}{\frac{Z_{L1}}{1-G}(Z_s + Z_{L2})} \quad (15)$$

$$I_{L2h} \approx \frac{U_L Z_s + U_L\frac{Z_{L1}}{1-G} + I_{Lh}Z_{L1}Z_s}{\frac{Z_{L1}}{1-G}(Z_s + Z_{L2})} \quad (16)$$

Therefore, when the equation $|Z_s + Z_{L2}|_h \approx 0$ is met at some frequency to be introduced by SAPF, the source current will become non-sinusoidal, even worse the source current $I_{sh} \approx \infty$, and the surrounding load current $I_{L2h} \approx \infty$. A harmonic voltage source usually presents very low internal impedance Z_{L2}. For example, considering a diode rectifier with a large smoothing electrolytic dc capacitor, we have $|Z_{L2}|_h \approx 0$ as long as no series reactor is inserted on the ac side of the rectifier. Further, the capacitance load installed nearby will make the total equivalent impedance become smaller, which makes harmonic current I_{L2} increased obviously, because Z_{L2} is also very low in this case.

A. Lumped Parameter Model

Fig. 3 gives a lumped parameter model of the distributed system. Where, R_s, X_s represents the system harmonic impedance, X_c is condensance. I_{Lh} represents the harmonic current. From Fig.3, we get Eqs. (17) and (18):

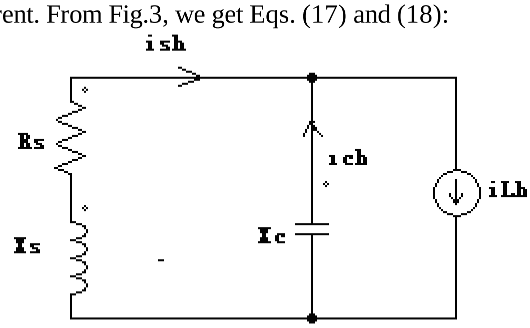


Fig.3.System harmonic equivalent circuit with shunt capacitors

$$i_{sh} = \frac{-X_c/n^2}{X_s - X_c/n^2} i_{lh} \quad (17)$$

$$i_{ch} = \frac{X_s}{X_s - X_c/n^2} i_{lh} \quad (18)$$

When equation $i_{ch} = 2 i_{lh}$ is satisfied，the source harmonic current begin to enlarge，where the resonance point is $n_{k1} = \sqrt{\frac{2X_c}{Xs}}$;When equation $i_{sh} = 2\ i_{lh}$ is met， the capacitance harmonic current begin to enlarge， where the resonance point is $n_{k2}=\sqrt{\frac{X_c}{2Xs}}$;

B. Distributed Parameter Model

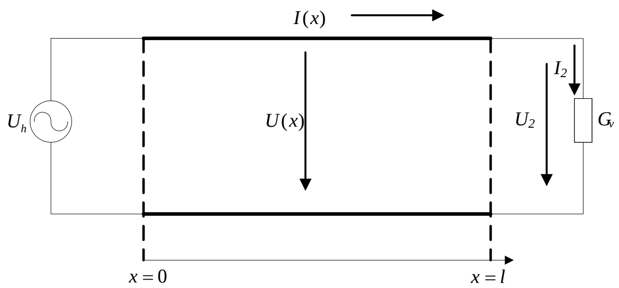


Fig.4 Distributed-parameter model with a virtual admittance Gv in the terminal

Fig. 4 depicts a distributed parameter model of the feeder, where l is the feeder length, and x is the distance from transformer. According to the transmission line theory, we get:

$$\dot{U}=\dot{U}_2\cosh[\gamma(l-x)]+Z_c\dot{I}_2\sinh[\gamma(l-x)] \quad (19)$$

$$\dot{I}=\dot{I}_2\cosh[\gamma(l-x)]+\frac{\dot{U}_2}{Z_c}\sinh[\gamma(l-x)] \quad (20)$$

Where Z_c is the characteristic impedance of the distribution line

$$Z_c=\sqrt{\frac{Z_0}{\gamma_0}}=\sqrt{\frac{R_0+j\omega L_0}{G_0+j\omega C_0}} \quad (21)$$

The propagation constant γ and the wavelength λin Fig. 4 are given by:

$$\gamma=\sqrt{(R_0+j\omega L_0)(G_0+j\omega C_0)}=\alpha+j\beta \quad (22)$$

$$\lambda=\frac{2\pi}{\beta} \quad (23)$$

The voltage along the line is the sum of the incident wave and the reflected wave, and the terminal of the feeder determines the amplitude and the phase of the reflected wave, if the phase of the reflected wave and the phase of the incident wave are the same, the voltage distortion in distribution line could be serious resulting from total reflection. The condition for total reflection is defined as follows, where n is a random positive number:

$$l=\frac{(2n+1)\lambda}{4} \quad (24)$$

The harmonic voltage standing wave $U_h(x)$ at position x can be expressed in equation (25):

$$\dot{U}_h(x)=\frac{\cosh[\gamma(l-x)]+Z_c\dot{G}_v\sinh[\gamma(l-x)]}{\cosh(\gamma l)+Z_c\dot{G}_v\sinh(\gamma l)}\dot{U}_h \quad (25)$$

Where, G_v is the virtual terminal admittance of the feeder. Neglect the line equivalent resistance R_0 and conductance G_0; the equation (25) can be simplified to Eq. (27).

$$Gv=\frac{\dot{I}_2{}^h}{\dot{U}_2{}^h} \quad (26)$$

$$U_h(\mathrm{x})=\frac{\cos(\beta l-\beta x)}{\cos\beta l}U_h \quad (27)$$

According Eq. (27), if the feeder length is integral multiples of half-length of the harmonic voltage wavelength, the harmonic voltage on x=0 will not propagate along feeder. But if the feeder length $l=\frac{(2n+1)\lambda}{4}$ is odd multiples of 1/4 length of the harmonic voltage wavelength, then a large harmonic voltage will appear throughout the feeder because the denominator in (27) would be equal to zero.

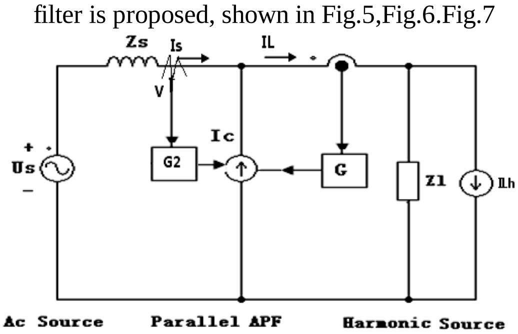
Ⅳ. SOLUTIONS FOR SAPF APPLICATION NEARBY CAPACITIVE LOADS

With the above analysis, there is a series/parallel resonance between transformer leakage inductance, line inductance and the dc capacitor in the rectifier conduction period. The shunt active power filter will easily excite the resonance and cause harmonic amplification and the peak load current increase. Three methods are proposed to avoid this happen.

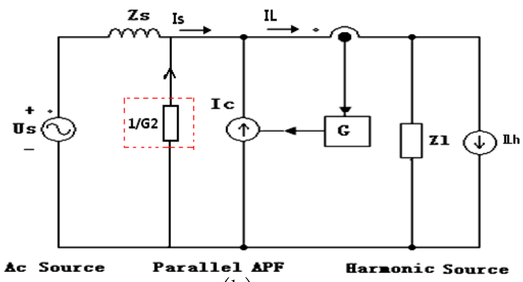
(1) Modifying the main circuit nature frequency characteristics using a small series inductance or a small parallel capacitance or the both

(2) To change the control of the SAPF itself into a selective harmonics compensator to avoid the resonant amplification.

(3) A novel control method in which the grid voltage, grid current and load current are detected to control the output current of shunt active power filter is proposed, shown in Fig.5,Fig.6.Fig.7



(a)



(b)

Fig.5 Principle of SAPF with both detection grid voltage and load current

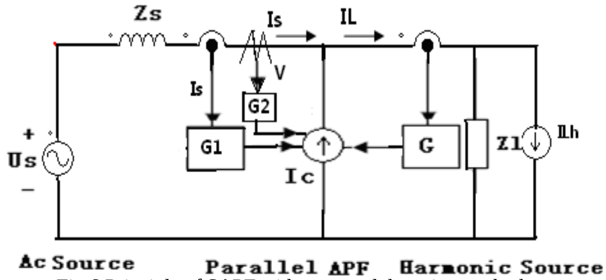


Fig.6 Principle of SAPF with proposed detection method

From Fig.6, the equations (28) and (29) can get:

$$I_c = GI_L + G_1 I_s + G_2 U_s \quad (28)$$

$$I_s = \frac{(1-G-G_2 Z_L)U_s + (1-G)Z_L I_{Lh}}{(1+G_1)Z_L + (1-G-G_2 Z_L)Z_s} \quad (29)$$

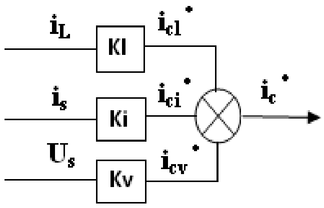


Fig.7 Proposed detection method

Therefore, if the equations

$$\left|\frac{1+G_1}{1-G-G_2 Z_L} Z_L\right| >> |Z_s| \quad (30)$$

$$\left|\frac{1-G}{1+G_1}\right| << 1 \; p.u \quad (31)$$

is met, it will damp the harmonic resonance and compensate the current harmonic effectively.

Fig.8 shows the simulation waveforms of SAPF for compensation current-type harmonics with normal method, where, i_s is grid current; i_{apf} is the compensation current and i_L is load current, i_c is the current of the shunt capacitor branch (the same below), At 0.04s when SAPF starts to operation, the resonance is beginning and the load peak current began to enlarge, which is increased by 535A from original 500A.

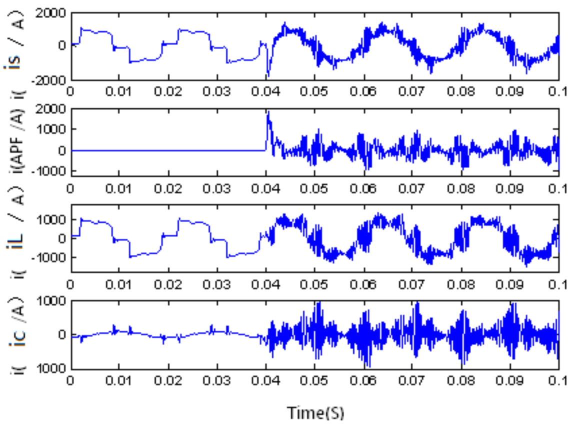


Fig.8 Simulation results with the normal method

Fig.9 shows the simulation waveforms of SAPF for compensation current-type harmonics with the proposed method. The SAPF has good harmonic suppression and no load-side current enlargement or resonance happen. Further, the source current THD is 4.13%, as shown in Fig.10.

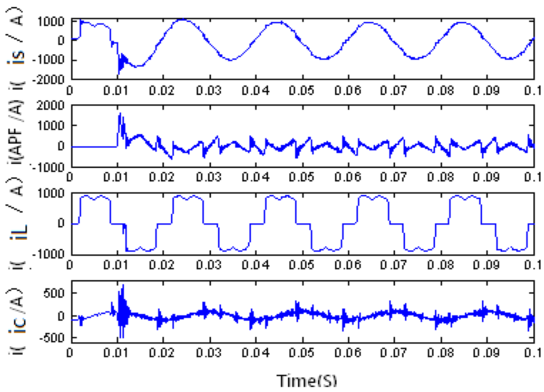


Fig.9 Simulation results with the proposed method

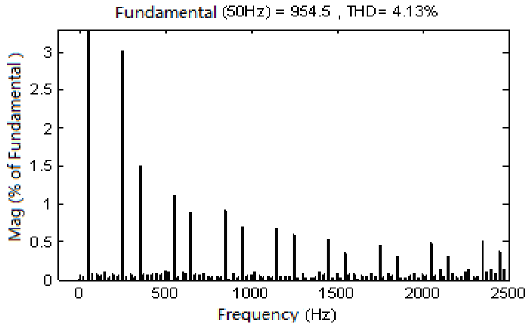


Fig.10 FFT analysis of grid current with the proposed method

Ⅴ. CONCLUTION

Shunt Active Power Filter (SAPF) application is generally not suitable for the environment of capacitive-type harmonic existence. This paper reveals load current amplifying risks by the equivalent circuit analysis of lumped and distributed parameter modes.

Two essential approaches are proposed to avoid the risks i.e. (1) Modifying the main circuit nature frequency characteristics using a small series inductance or a small parallel capacitance or the both , (2) To change the control of the SAPF itself into a selective harmonics compensator to avoid the resonant amplification..

A novel control method in which the grid voltage, grid current and load current are detected to control the output current of shunt active power filter is also proposed. Simulation results validate that the proposed methods are effective, analysis is correct, and the SAPF could suppress harmonic effectively and no load-side current enlargement or resonance happen.

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