A New Scheme for Compensation of Unwanted Components of Instantaneous Load Power

Man-Chung WONG Ying-Duo HAN Heng-San LEONG Hon-Pan SIO
FST, University of Macau , Macau .
Tel : (853)3974290 Fax : (853)831694

Abstract – In practice, not only the load current but also the load voltage may contain asymmetric and harmonic components. Instantaneous power using p-q theory is analyzed to have compensation of reactive power, harmonics and asymmetry at the same time. In this paper, the limitation of p-q theory by using only shunt or series active filter is analyzed. A new scheme is proposed to solve the above issues.

I. Introduction

In a power system, the p-q theory is widely used to analyze the compensation of the harmonics and reactive power at the same time. Recent research can verify the above issues. But normally the system will operate under asymmetry where the compensation by using p-q theory may meet problems. However, p-q theory (Real and Imaginary Power, Park Transformation) is widely used as the compensated strategy to improve the power flow [1][2][3].

To reduce the power loss is the main focus in this paper, i.e. the generator should only give the active power to the system. The unwanted components of instantaneous load power in p-q theory are: the average part of imaginary power, the oscillating parts of real power and imaginary power, and the zero power.

In a shunt or series compensator, the 3[rd] harmonic component will be generated by p-q compensated strategy. The reason will be explained in section III. To solve this problem, moving average method [4] is employed. Nevertheless, according to the power flow analysis in section II, the above method [4] cannot optimize the power flow although the power factor on each individual phase is 1.

A combination of series and shunt active filter can overcome the above issues and compensate the harmonics, reactive power and asymmetry together. The simulation using PSCAD/EMTDC [7] verify the conclusion.

II. Power Flow of Asymmetric System

Power Flow of asymmetric system without harmonics is investigated in this section. It shows that the system can be further improved when power factor on each phase is 1. The generator should only give the average real power (active power) to the load so that the transmission loss can be minimized.

- *Symmetric Voltage Sources with Asymmetric Current*

Recently, *Equivalent Apparent Power* is reported [5][6] to investigate the power flow in the power network. The voltage sources are assumed to be symmetric so that only positive sequence component exists. However, there are positive, negative and zero sequences in the current. Equivalent voltage and equivalent current can be expressed as (1) and (2) respectively.

$$V_e = \sqrt{\frac{V_a^2 + V_b^2 + V_c^2}{3}} = \sqrt{V_-^2 - V_-^2 + V_0^2} \qquad (1)$$

$$I_e = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2}{3}} = \sqrt{I_+^2 + I_-^2 + I_0^2} \qquad (2)$$

, where V_a is the that r.m.s. voltage in phase "a" , and "+" ,"-" and "0" are the positive, negative and zero sequence components respectively.

The Equivalent Apparent Power is:

$$S_e = 3V_eI_e \qquad (3)$$

It also can be expressed as (4).

$$S_{3\phi} = 3V\sqrt{(I_+^2 + I_-^2 + I_0^2)} = \sqrt{(P_{3\phi}^{++})^2 + (Q_{3\phi}^{++})^2 + O_u^2} \qquad (4)$$

,where $P_{3\phi}^{++}$, $Q_{3\phi}^{++}$ and O_u are the active power, reactive power and unbalanced oscillating power for 3-phase system

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respectively. The instantaneous power in time domain also can be expressed as (5).

$$p_{3\phi}(t) = 3VI^{+}\cos\phi_{+} - 3VI^{-}\cos(2\omega t + \phi_{-}) \qquad (5)$$

From (5), it is clear that unbalanced oscillating power O_u increases transmission loss. Fig. 1 shows a power tetrahedron indicating the relationship among the apparent power, active power, reactive and unbalanced oscillating power.

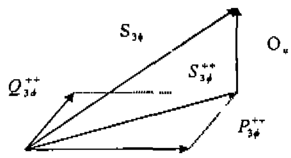

Fig. 1

- *Asymmetric Voltage Sources with Asymmetric Current*

The equivalent apparent power is:

$$S_{3\phi} = 3\sqrt{V_+^2 + V_-^2 + V_0^2}\sqrt{I_+^2 + I_-^2 + I_0^2}, \qquad (6)$$

and it can also be expressed as (7):

$$S_{3\phi}{}^2 = (P_{3\phi}^{++})^2 + (P_{3\phi}^{--})^2 + (P_{3\phi}^{00})^2 + (Q_{3\phi}^{++})^2 + (Q_{3\phi}^{--})^2 + (Q_{3\phi}^{00})^2 + (O_u^{+})^2 + (O_u^{-})^2 + (O_u^{0})^2 \qquad (7)$$

The asymmetric voltage sources can be considered as positive, negative and zero sequence voltage sources which supply power to the load respectively.

III. Third Harmonic Generation Using p-q Theory Compensation Strategy with one shunt or series structure

The p-q theory is widely employed as the compensated strategy to control the operation of active filter. However, this paper focuses on the investigation of compensation of harmonics, reactive power and asymmetry problems at the same time. It seems to work well in a balanced system to compensate harmonics and reactive power together. But, the system may work under unbalance. The third harmonic will be generated in the line current. The reason is investigated in this section for a shunt or series structure compensator.

The instantaneous average part of real power (8) is :

$$\bar{p} = \sum_{n=1}^{\infty} 3V_{+n}I_{+n}\cos\left(\phi_{V_{+n}} - \phi_{I_{+n}}\right) + \sum_{n=1}^{\infty} 3V_{-n}I_{-n}\cos\left(\phi_{V_{-n}} - \phi_{I_{-n}}\right) \qquad (8)$$

The instantaneous alternating part of real power (9) is :

$$\tilde{p} = \left\{\sum_{n=1}^{\infty} -3V_{+n}I_{-n}\cos\left(2\omega_n t + \phi_{V_{+n}} + \phi_{I_{-n}}\right)\right. + \sum_{n=1}^{\infty} -3V_{-n}I_{+n}\cos\left(2\omega_n t + \phi_{V_{-n}} + \phi_{I_{+n}}\right)$$
$$+ \sum_{\substack{m=1\\ m\neq n}}^{\infty}\left[\sum_{n=1}^{\infty} 3V_{+m}I_{+n}\cos\left((\omega_m - \omega_n)t + \phi_{V_{+m}} - \phi_{I_{+n}}\right)\right]$$
$$+ \sum_{\substack{m=1\\ m\neq n}}^{\infty}\left[\sum_{n=1}^{\infty} 3V_{-m}I_{-n}\cos\left((\omega_m - \omega_n)t + \phi_{V_{-m}} - \phi_{I_{-n}}\right)\right]$$
$$+ \sum_{\substack{m=1\\ m\neq n}}^{\infty}\left[\sum_{n=1}^{\infty} -3V_{+m}I_{-n}\cos\left((\omega_m + \omega_n)t + \phi_{V_{+m}} + \phi_{I_{-n}}\right)\right]$$
$$\left. + \sum_{\substack{m=1\\ m\neq n}}^{\infty}\left[\sum_{n=1}^{\infty} -3V_{-m}I_{+n}\cos\left((\omega_m + \omega_n)t + \phi_{V_{-m}} + \phi_{I_{+n}}\right)\right]\right\} \qquad (9)$$

The instantaneous average part of imaginary power (10) is :

$$\bar{q} = \sum_{n=1}^{\infty} -3V_{+n}I_{+n}\sin\left(\phi_{V_{+n}} - \phi_{I_{+n}}\right) + \sum_{n=1}^{\infty} 3V_{-n}I_{-n}\sin\left(\phi_{V_{-n}} - \phi_{I_{-n}}\right) \qquad (10)$$

The instantaneous alternating part of imaginary power (11) is:

$$\tilde{q} = \left\{\sum_{n=1}^{\infty} -3V_{+n}I_{-n}\sin\left(2\omega_n t + \phi_{V_{+n}} + \phi_{I_{-n}}\right)\right. + \sum_{n=1}^{\infty} -3V_{-n}I_{+n}\sin\left(2\omega_n t + \phi_{V_{-n}} + \phi_{I_{+n}}\right)$$
$$+ \sum_{\substack{m=1\\ m\neq n}}^{\infty}\left[\sum_{n=1}^{\infty} 3V_{+m}I_{+n}\sin\left((\omega_m - \omega_n)t + \phi_{V_{+m}} - \phi_{I_{+n}}\right)\right]$$
$$+ \sum_{\substack{m=1\\ m\neq n}}^{\infty}\left[\sum_{n=1}^{\infty} 3V_{-m}I_{-n}\sin\left((\omega_m - \omega_n)t + \phi_{V_{-m}} - \phi_{I_{-n}}\right)\right]$$
$$+ \sum_{\substack{m=1\\ m\neq n}}^{\infty}\left[\sum_{n=1}^{\infty} -3V_{+m}I_{-n}\sin\left((\omega_m + \omega_n)t + \phi_{V_{+m}} + \phi_{I_{-n}}\right)\right]$$
$$\left. + \sum_{\substack{m=1\\ m\neq n}}^{\infty}\left[\sum_{n=1}^{\infty} -3V_{-m}I_{+n}\sin\left((\omega_m + \omega_n)t + \phi_{V_{-m}} + \phi_{I_{+n}}\right)\right]\right\} \qquad (11)$$

For simplification only, 3-phase 3-wires system is under discussion.

- Balanced Voltage Sources with Unbalanced Current

The equations from (8) to (11) can be re-written as the following.

$$\bar{p} = \sum \bar{p}_{nn++} \qquad (12)$$

$$\tilde{p} = \sum(\tilde{p}_{nn+-} + \tilde{p}_{mn++} + \tilde{p}_{mn+-}) \qquad (13)$$

$$\bar{q} = \sum \bar{q}_{nn++} \qquad (14)$$

$$\tilde{q} = \sum(\tilde{q}_{nn+-} + \tilde{q}_{mn++} + \tilde{q}_{mn+-}) \qquad (15)$$

, where m and n are the harmonic orders , and the subscript "-+" means that negative sequence of voltage is composed of the positive sequence of current.

- Unbalanced Voltage Source with Unbalanced Current

The equations from (8) to (11) can be re-written as follows for general case.

$$\bar{p} = \sum (\bar{p}_{nn++} + \bar{p}_{nn--}) \qquad (16)$$

$$\tilde{p} = \sum (\tilde{p}_{m+-} + \tilde{p}_{m-+} + \tilde{p}_{mn++} + \tilde{p}_{mn--} + \tilde{p}_{mn+-} + \tilde{p}_{mn-+}) \qquad (17)$$

$$\bar{q} = \sum (\bar{q}_{nn++} + \bar{q}_{nn--}) \qquad (18)$$

$$\tilde{q} = \sum (\tilde{q}_{m+-} + \tilde{q}_{m-+} + \tilde{q}_{mn++} + \tilde{q}_{mn--} + \tilde{q}_{mn+-} + \tilde{q}_{mn-+}) \qquad (19)$$

Compensation by using Shunt Active Filter :

Fig. 2 shows the compensated strategy for shunt structure of active filter for 3-phase 3-wires system.

After getting $i_{c\alpha}$ and $i_{c\beta}$ by using (20) to compensate the unwanted components ($\tilde{p}, q$), the actual current on each phase can be obtained according to (21).

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} \\ -\bar{q} - \tilde{q} \end{bmatrix} \qquad (20)$$

$$\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} -i_0 \\ i_{c\alpha} \\ i_{c\beta} \end{bmatrix} \qquad (21)$$

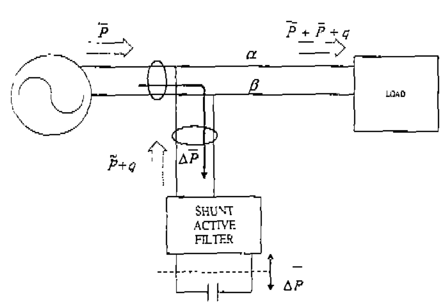

Fig. 2

In 3-phase 3-wires system, i_0 is zero. For simplification, only fundamental component is considered. According to (16)~(19), the average real power and average imaginary power cannot exist along. It means that positive and negative sequence components composed together generate twice of fundamental frequency component in the real and imaginary power respectively.

$$p = \bar{p} + \tilde{p}_{2\omega} = \bar{p}_{++} + \bar{p}_{--} + \tilde{p}_{2\omega}^{--} \qquad (22)$$

$$q = \bar{q} + \tilde{q}_{2\omega} = \bar{q}_{++} + \bar{q}_{--} + \tilde{q}_{2\omega}^{--} \qquad (23)$$

The two time fundamental components of real power and imaginary power will exist with the average components due to the negative sequence. The component current in α-axis is shown in (24).

$$i_{c\alpha}^{*} = \frac{v_\alpha}{v_\alpha^2 + v_\beta^2}\bar{p} + \frac{v_\alpha}{v_\alpha^2 + v_\beta^2}\tilde{p}_{2\omega} - \frac{v_\beta}{v_\alpha^2 + v_\beta^2}\bar{q} - \frac{v_\beta}{v_\alpha^2 + v_\beta^2}\tilde{q}_{2\omega} \qquad (24)$$

The third harmonic will be generated in the line current after compensation when originally the voltage and current are both asymmetric. The similar reason to generate the 3rd harmonic component can also be verified for the series active filter compensation using p-q theory.

IV. Proposed Method

A system is being developed for compensation of the reactive power, harmonics and asymmetry at the same time. Using the average moving method [4], although the power factor in each phase can be 1, there is still unbalance oscillating power existed in the system to increase the loss as explained in section II. The power flow in this case cannot be optimized. Harmonics and reactive power can be compensated together using only a shunt or series structure under symmetry, but not for asymmetry.

Only series or shunt structure of active filter cannot solve the above problems. The combination of series and shunt structure is suggested to compensate all the above problems at the same time and it is shown in Fig. 3.

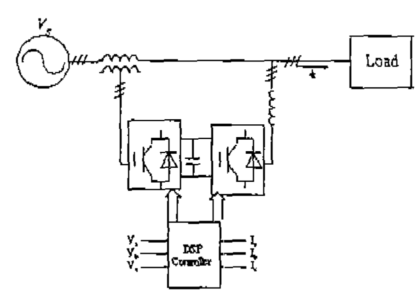

Fig. 3

The purpose of series one is to compensate the negative sequence component of the voltage so that the last term of equation (22) and (23) can be minimized. The second term and the fourth term in equation (24) can be cancelled so that there is no third harmonic component generated in line current.

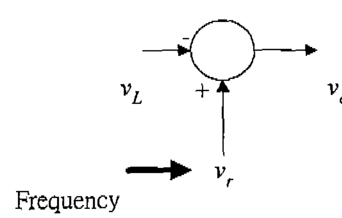

Fig.4

The Digital Signal Processor should determine the compensated voltage V_c^* if the voltage contains asymmetry and harmonics in Fig. 4. V_L is the input voltage signal and V_r is the reference voltage. The amplitude of reference voltage V_r can be easily determined. However, the synchronization of the phase angle change is very important in this control strategy. The measured frequency of the power network may be changed due to the unbalance input and output electrical power. However, the synchronization of phase angle change is out of the discussion in this paper.

V. Simulation Results and Discussion

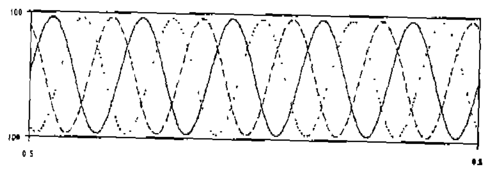

Fig. 5.a

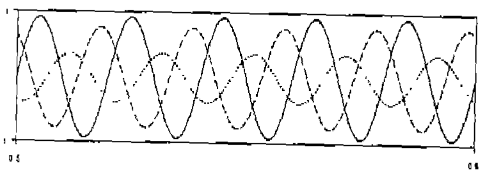

Fig. 5.b

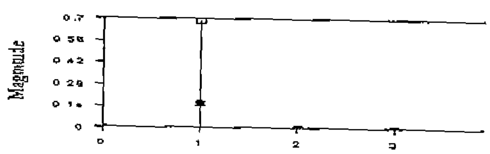

Fig. 5.c

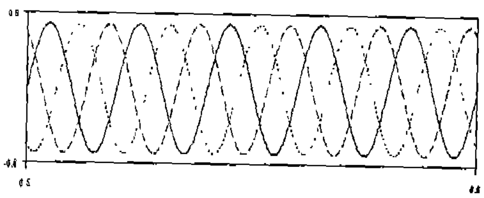

Fig. 5.d

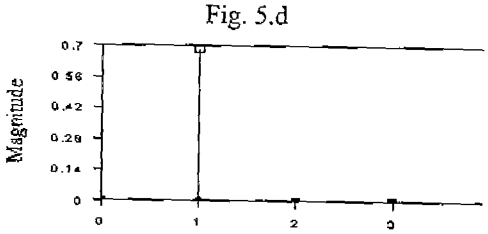

Fig. 5.e

PSCAD/EMTDC [7] software is used as the simulation program. For simplification and obvious outcome, the waveforms of the simulation results given in this paper do not include the harmonics.

Fig. 5 is the case in which voltage sources are symmetric and load current are asymmetric. It shows the identical results as the discussion (12)~(15) in section III. After compensation with only shunt active filter, the generator will give only the active power (average real power) to the load. Fig. 5.a , Fig. 5.b and Fig. 5.c are the voltage waveforms , current waveforms and frequency spectrum of current respectively before compensation. Fig. 5.d and Fig. 5.e are the current waveform and frequency spectrum of current respectively after compensation. It works well under symmetric voltage sources and asymmetric current.

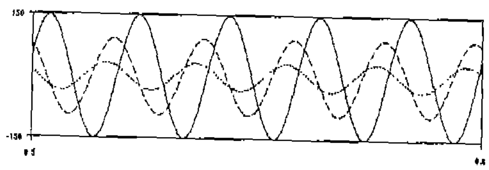

Fig. 6.a

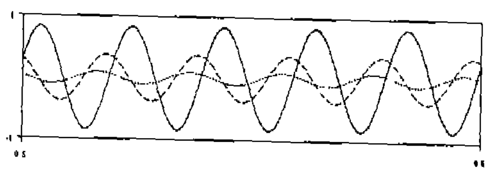

Fig. 6.b

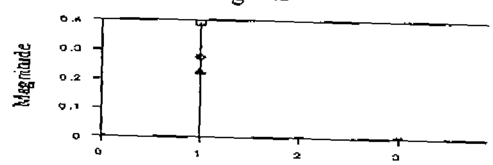

Fig. 6.c

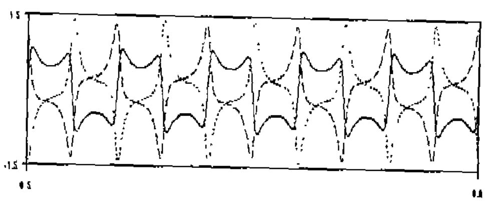

Fig. 6.d

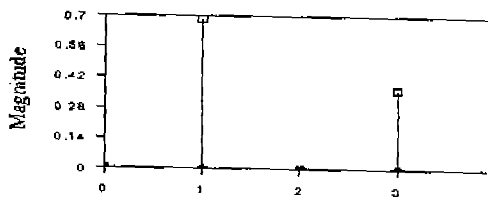

Fig. 6.e

Another consideration is the case that both voltage and current are asymmetric. The load current can be predicted that they will contain the 3rd harmonic component according to the analysis in (16)~(24), especially in (24). In this case, only shunt or series compensator cannot fulfill the jobs to compensate the reactive power and harmonics. After compensation, the system may be worse than before compensation. Fig. 6 are the simulation results for this case. Fig. 6.a , Fig. 6.b and Fig. 6.c are the voltage waveforms , current waveforms and frequency spectrum of current respectively before compensation. Fig. 6.d and Fig. 6.e are the current waveform and frequency spectrum of current respectively after compensation with only shunt compensator. It is obvious that the 3rd harmonic component is generated in the line current.

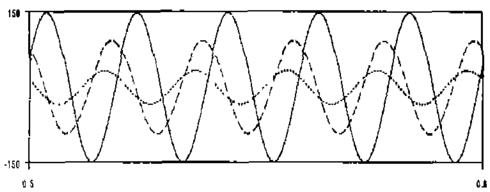

Fig. 7.a

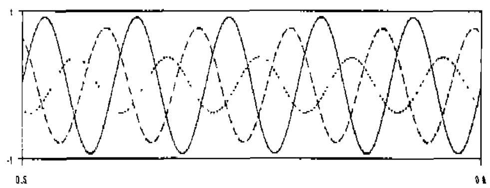

Fig. 7.b

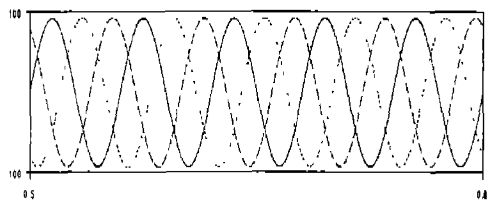

Fig. 7.c

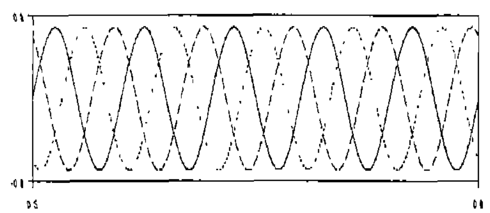

Fig. 7.d

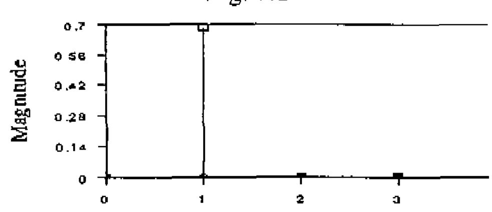

Fig. 7.e

Case	Voltage Sources	Load Current	Harmonic Components
1	Symmetry	Balance	1st.
2	Symmetry	Unbalance	1st.
3	Asymmetry	Balance	1st. + 3rd.
4	Asymmetry	Unbalance	1st. + 3rd.

Table 1

Table 1 summarizes the simulation results using a shunt compensator only. It is obvious that the line current contains the 3rd harmonic component using p-q control strategy in those cases.

Fig. 7 shows the simulation results using the combination of shunt and series combined structure for voltage and current are both asymmetric. No 3rd harmonic component exists in the line current. Fig. 7.a and Fig. 7.b are the voltage and current waveforms respectively before compensation. Fig. 7.c and Fig. 7.d are the waveforms of voltage and current after compensation with the scheme in Fig. 3. Fig. 7.e is the frequency spectrum of load current after compensation.

VI. Conclusion

The p-q theory is widely used in control strategy for compensation. However, the 3rd harmonic component will be generated using only a shunt or series structure of compensator. Moving average method [4] cannot optimize the power flow although the power factor on each phase is 1. A combination of series and shunt structure of the compensator using p-q theory can compensate the reactive power, harmonics and asymmetry at the same time.

VII. References

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