A CONTROL STRATEGY FOR SHUNT ACTIVE POWER FILTER UNDER THE DISTORTED SOURCE VOLTAGES CONDITION

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ABSTRACT

The shunt active power filter (APF) is a useful device to eliminate the harmonic currents and to compensate reactive power. This paper proposes a useful approach to determine the reference compensation currents when the source voltages are severely distorted and imbalanced. The approach is simulated by *PSCAD/EMTDC* .The simulation results show that this strategy can be applied for such situations with acceptable results.

I. INTRODUCTION

Due to the recent advancements device technology that makes high-speed high-power switching devices such as power MOSFETs, MCTs, IGBTs, IEGTs and etc. the use of shunt active power filters (APF) to eliminate harmonic currents and to compensate reactive power has attracted much attention, in the last years [1]. APFs basically work by detecting the harmonic components from the distorted signals and injecting the right amount of counter harmonic compensating currents to the coupling point of the load. Fig.1 shows the schematic diagram of a three-phase four-wire shunt APF, where APF senses the source voltages and load currents to determine the reference compensation currents.

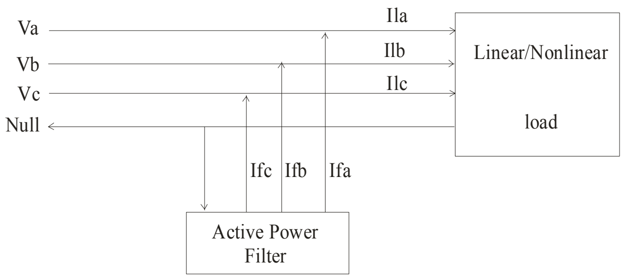

Fig.1.Schematic diagram of a three-phase four-wire shunt active filter.

Many approaches to determine the reference compensation currents are being developed. One of them is the instantaneous reactive power theory (i.e. p-q theory) introduced by Akagi [2]. This method requires transmission of both source voltages and load currents from the a-b-c reference frame to the α-β reference frame to determine the APF reference compensation currents in the three-phase three-wire systems. p-q theory is not suitable for three-phase four-wire systems in its primary form. Peng extended the p-q theory to apply for three-phase four-wire systems by handling the zero-sequence power compensation [4]. p-q theory has caused many works dealing with active filter compensation strategies. One of them is that APF can be designed without active energy source units, such as batteries or in other forms in its compensation machines. In other words, an ideal APF does not consume any average real power supplied by the source.

Another one is the synchronous reference frame (SRF) method [5]. SRF con not compensate for reactive power.

Reference [6] proposed an algorithm in the a-b-c reference frame for maintaining ideal three-phase source currents when the source voltages are amplitude-imbalanced. This method works very well on harmonic and/or reactive power compensation for nonlinear loads under ideal source voltages. This theory did not work under the imbalanced and/or distorted source voltages conditions.

The methods mentioned above, do not use the strategies to apply under the imbalanced and/or distorted source voltages conditions. To achieve full compensation of both reactive power and harmonic/neutral currents of the load, this paper presents an approach to determine the shunt APF reference compensation currents, even if the source voltages and load currents are both imbalanced and distorted. The proposed method is somehow similar to that presented in [6].

This paper, reviews the p-q theory as an example of the methods that don't work under the unbalanced and/or distorted source voltages conditions. Next the proposed method is explained analytically and the *PSCAD/EMTDC* simulation results are followed to compare the proposed method with p-q theory.

II. p-q THEORY

This theory introduced by Akagi. In this theory both source voltages and load currents transfer from the *a-b-c* reference frame to α-β reference frame. Then the load voltages and load currents are:

$$\begin{bmatrix} v_{l\alpha} \\ v_{l\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_{la} \\ v_{lb} \\ v_{lc} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \quad (2)$$

Where v_{la}, v_{lb}, v_{lc}, i_{la}, i_{lb}, i_{lc} load voltages and currents in the *a-b-c* reference frame and $i_{l\alpha}$, $i_{l\beta}$ are the load voltages and currents in α-β reference frame, respectively.
The active power and reactive power are as follow:

$$p=v_{l\alpha}\, i_{l\alpha} + v_{l\beta}\, i_{l\beta} \quad (3)$$

$$q=v_{l\alpha}\, i_{l\beta} - v_{l\beta}\, i_{l\alpha} \quad (4)$$

Therefore $i_{l\alpha}$ and $i_{l\beta}$ are

$$\begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix} = \begin{bmatrix} v_{l\alpha} & v_{l\beta} \\ -v_{l\beta} & v_{l\alpha} \end{bmatrix}^{-1} \begin{bmatrix} p \\ q \end{bmatrix} \quad (5)$$

we can also write

$$p = \overline{p} + \widetilde{p} \quad (6)$$
$$q = \overline{q} + \widetilde{q} \quad (7)$$

Where $\overline{p}$, $\overline{q}$ and $\widetilde{p}$, $\widetilde{q}$ are the DC and AC components of instantaneous active power and reactive power, respectively.
Similarly, for APF

$$\begin{bmatrix} i_{f\alpha} \\ i_{f\beta} \end{bmatrix} = \begin{bmatrix} v_{l\alpha} & v_{l\beta} \\ -v_{l\beta} & v_{l\alpha} \end{bmatrix} \begin{bmatrix} \widetilde{p} + p_c \\ q_l \end{bmatrix} \quad (10)$$

where p_c is switching losses and q_l is the load required reactive power. $i_{f\alpha}$ *and* $i_{f\beta}$ are the desired reference compensation currents.

III. PROPOSED APPROACH FOR DETERMINING THE REFERENCE COMPENSATION CURRENTS

This method is based on the requirement of the source currents need to be balanced, undistorted, and in phase with the positive-sequence source voltages. The goals of this approach are: harmonic and neutral current compensation, unity power factor at positive-sequence fundamental frequency and minimum average real power consumed or supplied by the APF. The approach provides a full compensation for the non-linear load. Therefore the source currents and the positive-sequence source voltages at the fundamental frequency must be:

$$i_{sa}=I_s \sin(\omega t+\theta_p) \quad (11)$$
$$i_{sa}=I_s \sin(\omega t-120+\theta_p) \quad (12)$$
$$i_{sa}=I_s \sin(\omega t+120+\theta_p) \quad (13)$$

and

$$v_{pfa}=V_{mp} \sin(\omega t+\theta_p) \quad (14)$$
$$v_{pfb}= V_{mp} \sin(\omega t-120+\theta_p) \quad (15)$$
$$v_{pfc}= V_{mp} \sin(\omega t+120+\theta_p) \quad (16)$$

Where V_{mp} and θ_p are voltage magnitude and phase angle of the positive-sequence components at the fundamental frequency, respectively. The load average real power should be supplied by the source and the APF dos not provide or consume any average real power. This requires that I_s-current amplitude- expressed as a function of the sequential instantaneous voltage and real power components. According to the symmetrical components transformation of (17) for the three-phase root-mean-square (rms) voltages at each harmonic order $h=1,2,3,\ldots$ the three phase instantaneous voltages can be expressed by equations (18) to (20).

$$\begin{bmatrix} V_{zh} \\ V_{ph} \\ V_{nh} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} V_{ah} \\ V_{bh} \\ V_{ch} \end{bmatrix} \quad (17)$$

$$v_a = \sum_{h=1}^{\infty} v_{pha} + \sum_{h=1}^{\infty} v_{nha} + \sum_{h=1}^{\infty} v_{zha} \quad (18)$$

$$v_b = \sum_{h=1}^{\infty} v_{phb} + \sum_{h=1}^{\infty} v_{nhb} + \sum_{h=1}^{\infty} v_{zhb} \quad (19)$$

$$v_c = \sum_{h=1}^{\infty} v_{phc} + \sum_{h=1}^{\infty} v_{nhc} + \sum_{h=1}^{\infty} v_{zhc} \quad (20)$$

In (17), the operator α equals $e^{j2\Pi/3}$ and *p, n* and *z* represents the positive-, negative- and zero-sequence components, respectively. In equations (18) to (20), the voltage components for $h=1,2,3,\ldots$ are defined as

$$v_{pha}=V_{mph} \sin(h(\omega t+\theta_{ph}) \quad (21)$$
$$v_{phb}=V_{mph} \sin(h(\omega t-120)+\theta_{ph}) \quad (22)$$
$$v_{phc}=V_{mph} \sin(h(\omega t+120)+\theta_{ph}) \quad (23)$$
$$v_{nha}=V_{mph} \sin(h(\omega t+\theta_{nh})) \quad (24)$$
$$v_{nhb}=V_{mph} \sin(h(\omega t+120)+\theta_{nh}) \quad (25)$$
$$v_{nhc}=V_{mph} \sin((\omega t-120)+\theta_{nh}) \quad (26)$$
$$v_{zha}=v_{zhb}=v_{zhc}=V_{mzh} \sin(h\omega t+\theta_{zh}) \quad (27)$$

The average real power consumed by the load over the one period of time *T* should be supplied by the source and the APF should not consumes or supplies any average real power. Then:

$$p_s = p_l + p_s \tag{28}$$

$$\overline{p}_s = \frac{1}{T}\int_0^T (v_a i_{sa} + v_b i_{sb} + v_c i_{sc})dt \tag{29}$$

$$\overline{p}_l = \frac{1}{T}\int_0^T (v_a i_{la} + v_b i_{lb} + v_c i_{lc})dt \tag{30}$$

$$\overline{p}_f = 0 \tag{31}$$

$$\overline{p}_s = \overline{p}_l \tag{32}$$

Where $\overline{p}_l$ includes the average fundamental and har real power. Substituting (18)-(20) into (29) yields

$$\overline{p}_s = \overline{p}_{spf} + \overline{p}_{snf} + \overline{p}_{szf} + \overline{p}_{sph} + \overline{p}_{snh} + \overline{p}_{szh} \tag{33}$$

Where the positive-, negative-, and zero-sequence average real power components at the fundamental frequency and at harmonic frequencies are given in (34) to (39), respectively.

$$\overline{p}_{spf} = \frac{1}{T}\int_0^T (v_{pfa} i_{sa} + v_{pfb} i_{sb} + v_{pfc} i_{sc})dt \tag{34}$$

$$\overline{p}_{snf} = \frac{1}{T}\int_0^T (v_{nfa} i_{sa} + v_{nfb} i_{sb} + v_{nfc} i_{sc})dt \tag{35}$$

$$\overline{p}_{szf} = \frac{1}{T}\int_0^T (v_{zfa} i_{sa} + v_{zfb} i_{sb} + v_{zfc} i_{sc})dt \tag{36}$$

$$\overline{p}_{sph} = \sum_{h=2}^{\infty} \{\frac{1}{T}\int_0^T (v_{pha} i_{sa} + v_{phb} i_{sb} + v_{phc} i_{sc})dt\} \tag{37}$$

$$\overline{p}_{snh} = \sum_{h=2}^{\infty} \{\frac{1}{T}\int_0^T (v_{nha} i_{sa} + v_{nhb} i_{sb} + v_{nhc} i_{sc})dt\} \tag{38}$$

$$\overline{p}_{szh} = \sum_{h=2}^{\infty} \{\frac{1}{T}\int_0^T (v_{zha} i_{sa} + v_{zhb} i_{sb} + v_{zhc} i_{sc})dt\} \tag{39}$$

Substituting the desired source currents of (11) to (13) and fundamental positive-sequence voltages of (14) to (16) into (34), results

$$\overline{p}_{spf} = \frac{3V_{mp} I_s}{2} \tag{40}$$

Similarly, it can be shown that all other average real power compensation satisfy (41) after substituting (11) to (13) and (21) to (27) into (35) to (39)

$$\overline{p}_{snf} = \overline{p}_{szf} = \overline{p}_{sph} = \overline{p}_{snh} = \overline{p}_{szh} = 0 \tag{41}$$

(32) and (33) must satisfy:

$$\overline{p}_s = \overline{p}_{spf} = \overline{p}_l \tag{42}$$

Then according to (40) and (42), the desired source current amplitude at each phase is determined as follow

$$I_s = \frac{2\overline{p}_l}{3V_{mp}} \tag{43}$$

and the source currents are expressed by

$$i_{sk} = I_s \frac{v_{pfk}}{V_{mp}} = \frac{2\overline{p}_l}{3(V_{mp})^2} v_{pfk} \text{ T} \qquad K=a,b,c. \tag{44}$$

The required compensation current that should be injected to network is obtained by subtracting the desired source current from the load current as given in (45)

$$i^*_{fk} = i_{lk} - \frac{2\overline{p}_l}{3(V_{mp})^2} v_{pfk} \qquad K=a,b,c. \tag{45}$$

The average real power consumed or supplied by the APF is expressed as

$$\overline{p}_f = \frac{1}{T}\int_0^T (v_a i_{fa} + v_b i_{fb} + v_c i_{fc})dt \tag{46}$$

By substituting (45) into (46)

$$\overline{p}_f = \frac{1}{T}\int_0^T (v_a i_{fa} + v_b i_{fb} + v_c i_{fc})dt - \frac{2\overline{p}_l}{3(V_{mp})^2} \cdot \frac{1}{T}\int_0^T (v_a v_{pfa} + v_b v_{pfb} + v_c v_{pfc})dt = 0 \tag{47}$$

Then, the APF does not consume or supply average real power.

Fig.2 shows the block diagram of the control circuit for proposed approach.

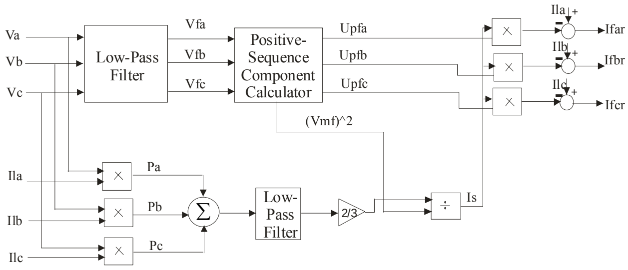

Fig.2. Block diagram of the control circuit for proposed approach..

The *SPWM* current controller is used to control the APF inverter switching.

IV. SIMULATION RESULTS

To verify the performance of the proposed compensation strategy for the APF, results obtained by using *PSCAD/EMTDC* are given. First the results for p-q theory are given, as an example of the strategies that do not apply when the source voltages are imbalanced and distorted. Next the results for the proposed approach are given.

In both p-q theory and the proposed approach, the magnitude imbalance for source voltages is ٪10 and the distortion with 5th harmonic is ٪7. Also a single phase breaker, breaks phase 'a' at t=0.8 sec to show that how the APF follows the reference currents to compensate the harmonic currents and reactive power.

A)simulation results for p-q theory

Fig.3 shows the simulation results for p-q theory.

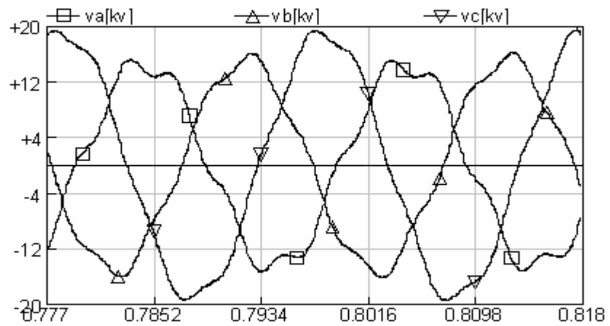

Fig.3)a. Imbalanced and distorted source voltages.

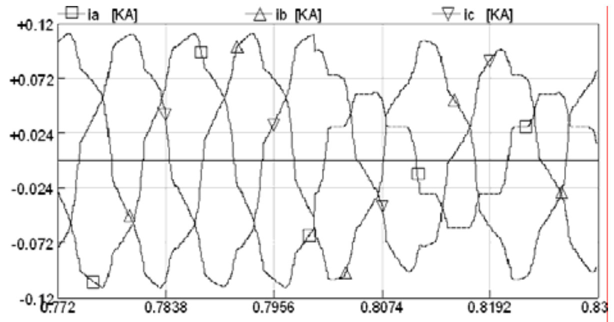

Fig.3)b. Distorted load currents.

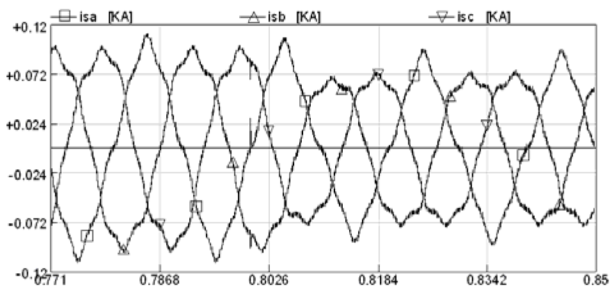

Fig.3)c. Source currents after compensation for p-q theory.

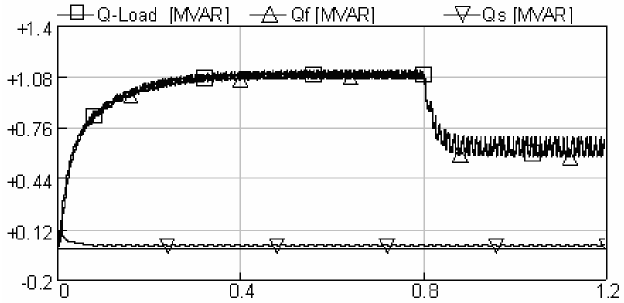

Fig.3)d. APF compensation reactive power , load reactive power, and source supplied reactive power.

Fig.3. Simulation results for p-q theory.

As shown in Fig3.)c, this theory can not compensate the source currents when the source voltages are distorted and imbalanced. A single phase breaker applies at t=0.8 sec. As shown in Fig2)d,, this theory compensates the reactive power, instantly.

B)simulation results for proposed approach

Fig.4 shows the simulation results for p-q theory.

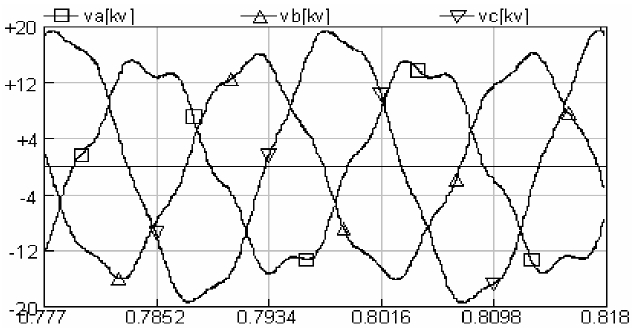

Fig.4)a. Imbalanced and distorted source voltages.

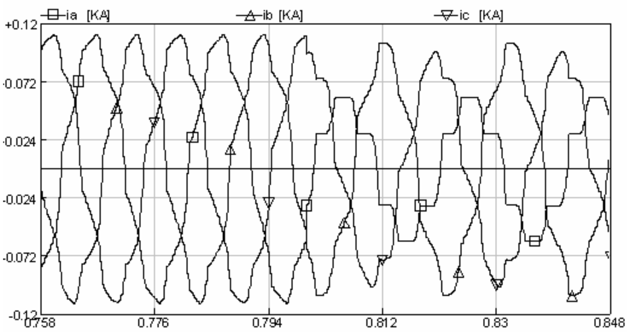

Fig.4)b. Distorted load current

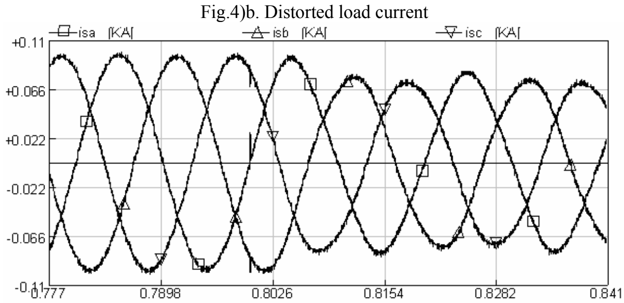

Fig4)c. Source currents after compensation for proposed approach.

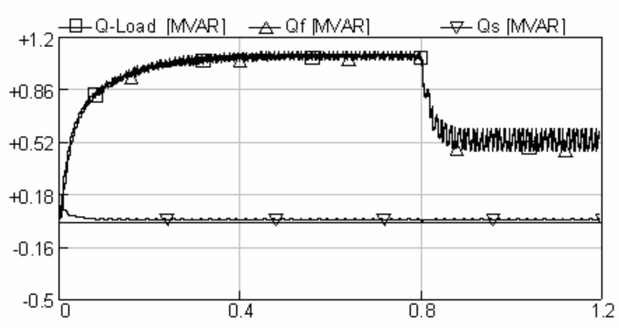

Fig.4)d. APF compensation reactive power, load reactive power, and source supplied reactive power.

Fig4. Simulation results for proposed approach.

As shown in Fig.4)c, this theory compensates the source currents when the source voltages are distorted imbalanced. A single phase breaker applies on phase 'a' at t=.8 sec. As shown in Fig.4)c, this strategy responds rapidly. Fig.4)d, shows that this theory compensates the reactive power instantly.

V. CONCLUSIONS

This paper proposed a simple, useful, and efficient approach to determine the reference compensation currents to control the shunt active power filter when the source voltages are imbalanced and/or distorted. In this approach, there is no reference frame transformation requirement. Therefore the proposed approach yields a simpler design of the shunt APF controller. The *PSCAD/EMTDC* simulation results for both p-q theory and proposed approach show that this strategy can compensate harmonic components and reactive power required by the non-linear load, when the source voltages are severely distorted.

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