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A Three Phase Four Wire Shunt Active Power Filter Control Algorithm under Unbalanced and Distorted Supply Voltage

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Abstract

In this paper a control algorithm is validated with simulation studies in MAT environment and experimental studies are performed in to validate the proposed control algorithm. The projected algorithm to compensate the nonlinear and loads in three phase four wire distribution system using shunt active power filter. In this algorithm a positive sequence extraction of the supply voltage and the theory of instantaneous symmetrical component. To exemplify the concept, a three phase four wire with unbalance and non linear load is considered for compensation and detailed simulation and experimental studies are presented.

Keywords

Active power filter, unbalance, linear, non linear, compensator, power quality, voltage source inverter, distribution static converter (DSTATCOM), theory of instantaneous symmetrical theory

1. Introduction

In the last few decades, the revolution of using power electronics devises increased enormously. The wide use of power electronics based loads causes power pollution severely effecting in distribution systems. As such clean power supply has challenge for power engineers. Various shunt active power filter operation explain in [1-2] to solve various types power quality problems in distribution systems. One of the main constituent of active power filter (APF) is the voltage source inverter (VSI). The shunt connected custom power device called the distribution static compensator (DSTATCOM), injects currents at the point of common coupling (PCC) so that harmonic filtering, power factor correction, and load balancing can be achieved.

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The DSTATCOM consists of a current controlled voltage source inverter which injects currents at the PCC through the interface inductor. The process of VSI is supported by a dc storage capacitor with suitable dc voltage across the VSI. Control methods of the active power filter are based on instantaneous deviation of compensating commands in the form of either voltage of current signal from distorted and harmonic polluted voltage or current signals [3]. There are large numbers of control methods for active power filters are available for compensation of unbalance and non linear loads. The synchronous detection method explained to generate reference filter currents for filter to compensate load under unbalanced and voltages assumes three phase voltage synchronization for each scheme of compensation in [4]. Equal resistance method is not possible for three phase three wire system with compensation target for the supply currents to in proportion and phase with their respective supply voltages. The three phase synchronization makes the control circuit complicated when the supply voltages are unbalanced [5]. Control algorithm based on the pq theory is most popular presented in [6-9], also known as instantaneous reactive power theory. Since the algorithm aims to compensate the total instantaneous reactive power of the load as the supply current is unbalanced and distorted even after compensation. The instantaneous active and reactive power can be compute in terms of distorted voltage and current signals from the supply main. From the instantaneous active and reactive powers, harmonic active and reactive powers are extracted using low pass and high pass filters. From harmonic active and reactive powers using reverse alpha and beta transformation, compensating commands in terms of either current or voltages are derived. However to satisfy the constraints of supplying constant active from the source at unbalanced voltages the compensated currents are distorted. This is not desirable characteristic of the algorithm. The algorithm works very well if we can find positive sequence voltages for unbalance supply voltages and substitute these voltages in control algorithm based on the instantaneous symmetrical components theory.

2. Extraction of Reference Compensator Currents Under unbalanced Voltages

An ideal three phase, four wire compensated system is shown in Fig.1 explained in [10] to understand basic idea of how to design shunt active power filters. The three phase load considered is unbalanced and non linear, the three phase supply voltages also considered unbalanced [11-12]. The compensator and non linear load are connected at the point called point of common coupling (PCC). The compensator is considered is idle and it is comprised of idle three phase voltage source inverter [13].

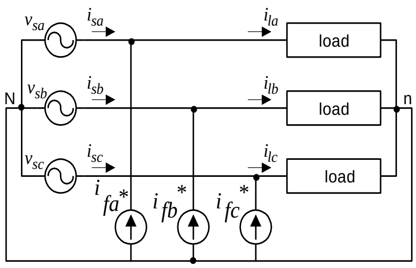

Figure 1: Line diagram of 3-phase, 4-wire compensated system.

The basic schemes of shunt active power filter have been represented with current source shown in Fig. 1. The aim of the scheme is to generate the three reference current waveforms for i_{fa}, i_{fb} and, i_{fc} denoted by, i^*_{fa}, i^*_{fb} ,and i^*_{fc} ,respectively, from the measurements of source voltages and load currents such that the supply sees a balanced load. The compensator will produce required results as long as its bandwidth of the compensator is sufficient to follow the fluctuations in the load. The compensator reference currents are generated using the theory of the instantaneous symmetrical components while considering source voltages are unbalanced and disturbed.

Basic Definition of Instantaneous Symmetrical Components

Any three phase instantaneous currents are assumed by i_{fa}, i_{fb}, and i_{fc}. The power invariant instantaneous symmetrical components are then defined by [8]

$$\begin{bmatrix} i_{a0} \\ i_{a1} \\ i_{a2} \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

where $a = e^{j120°}$. It is to be noted that the instantaneous vectors i_{a1} and i_{a2} are complex conjugate of each other i_{a0} is a real quantity which is zero if the line currents are which is zero if the line currents are balanced.

In the scheme presented below, initially assumed that the supply voltages are balanced, in addition, it can be shown that the angle between vectors i_{sa1} and v_{sa1} is the power factor angle between the balanced supply voltages and currents. In the proposed algorithm this power factor angle can be unequivocally set to any desired value. In addition, we instruct that the compensator is not required to supply average power.

The proposed compensation scheme can be applied to a three-phase, three-wire system and a three-phase, four-wire system. However, the intention in both the cases is to provide balanced supply currents such that its zero sequence components is zero. We therefore have

$$i_{sa} + i_{sb} + i_{sc} = 0 \tag{2}$$

From the power factor consideration, we assume that the phase of the vector i_{sa1} lags that of v_{sa1} by an angle ϕ,

i.e $\angle\left\{v_{sa} + av_{sb} + a^2 v_{sc}\right\} = \angle\left\{i_{sa} + ai_{sb} + a^2 i_{sc}\right\} + \phi$ (3)

where $a = e^{j120°}$. Substituting the value of a and as the supply voltage is balanced, the above equation can be written as

$$\left(v_{sa} - \tfrac{1}{2}v_{sb} - \tfrac{1}{2}v_{sc}\right) - j\frac{\sqrt{3}}{2}(v_{sb} - v_{sc}) =$$
$$\left(i_{sa} - \tfrac{1}{2}i_{sb} - \tfrac{1}{2}i_{sc}\right) - j\frac{\sqrt{3}}{2}(i_{sb} - i_{sc}) + \phi$$

$$\tan^{-1}\left(K_1/K_2\right) = \tan^{-1}\left(K_3/K_4\right) + \phi \tag{4}$$

Where

$$K_1 = \frac{\sqrt{3}}{2}\left(v_{ab} - v_{ac}\right); K_2 = v_{sa} - \frac{1}{2}v_{sb} - \frac{1}{2}v_{sc};$$
$$K_3 = \frac{\sqrt{3}}{2}\left(i_{sb} - i_{sc}\right); K_4 = i_{sa} - \frac{i_{sb}}{2} - \frac{i_{sc}}{2} = \frac{3}{2}i_{sa}$$

Defining $\beta = \tan\frac{\phi}{\sqrt{3}}$, and solving (4) we get

$$(v_{sb}-v_{sc}-3\beta v_{sa})i_{sa}+(v_{sc}-v_{sa}-3\beta v_{sb})i_{sb}+(v_{sa}-v_{sb}-3\beta v_{sc})i_{sc}=0 \quad (5)$$

It is interesting to note the implication of equation (5). When the power factor angle is assumed to be zero, (5) implies that the instantaneous reactive power supplied by the source is zero. On the other hand, when this angle is nonzero, the source supplies a reactive power that is equal to β times instantaneous power.

The instantaneous power in a balanced three-phase circuit is constant while for an unbalanced circuit it has a double frequency component in addition to the dc value. The objective of the compensator is to supply the double frequency component such that the source supplies the dc value of the load power.
Therefore we obtain

$$v_{sa}i_{sa}+v_{sb}i_{sb}+v_{sc}i_{sc}=P_{lav} \quad (6)$$

The average load power (P_{lav}) may be computed by using a moving average (MAF) filter that has an averaging time of half a cycle. Any harmonic component in the load does not require any real power from the source. The formulation of equation (6) is thus applicable even when the load current contains harmonics or is no interrupted.
Assuming that reference currents generated by using the proposed theory, accurately Tracked by the compensator, i.e., $i_{fa}=i^*_{fa}$, etc., we get the Following equation from ideal compensator shown in Fig. 1.

$$i_{sa}=i_{la}-i^*_{fa},\ i_{sb}=i_{lb}-i^*_{fb},\ i_{sc}=i_{lc}-i^*_{fc} \quad (7)$$

Combining (2), (5) and (7) we write the vector matrix form

$$Ai^*_f=Ai_l-P_l \quad (8)$$

Where $i^*_f=\begin{bmatrix} i^*_{fa} \\ i^*_{fb} \\ i^*_{fc} \end{bmatrix};\ i_l=\begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix};\ P_l=\begin{bmatrix} 0 \\ 0 \\ P_{lav} \end{bmatrix}$

And the matrix A is given by

$$\begin{pmatrix} 1 & 1 & 1 \\ (v_{sb}-v_{sc}-\beta v_{sa}) & (v_{sc}-v_{sa}-\beta v_{sb}) & (v_{sa}-v_{sb}-\beta v_{sc}) \\ v_{sa} & v_{sb} & v_{sc} \end{pmatrix}\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix}=\begin{bmatrix} 0 \\ 0 \\ P_{lav} \end{bmatrix}$$

Substitute Eq. (2) in the above equation we get the following.

$$i^*_{fa}=i_{la}-\frac{v_{sa}+(v_{sb}-v_{sc})\beta}{\Delta}P_{lav}$$

$$i^*_{fb}=i_{lb}-\frac{v_{sb}+(v_{sc}-v_{sa})\beta}{\Delta}P_{lav} \quad (9)$$

$$i^*_{fc}=i_{lc}-\frac{v_{sc}+(v_{sa}-v_{sb})\beta}{\Delta}P_{lav}$$

Where $\Delta=v_{sa}^2+v_{sb}^2+v_{sc}^2$

It can be shown by simplifying (9) that if the load is balanced and ϕ is the same as of the phase of the load current, the compensator currents become zero.
Let the source voltages are considered unbalanced and distorted:

$$\left.\begin{aligned} V_{sa}(t)&=\sum_{n=1}^{k}V_{man}\sin(nwt+\varphi_{vsn}) \\ V_{sb}(t)&=\sum_{n=1}^{k}V_{mbn}\sin(nwt+\varphi_{vsn}) \\ V_{sc}(t)&=\sum_{n=1}^{k}V_{mcn}\sin(nwt+\varphi_{vsn}) \end{aligned}\right\} \quad (10)$$

The set of fundamental zero, positive and negative sequences of supply voltages are expressed in time domain as following

$$\left.\begin{aligned} V^0_{sa1}(t)&=\sqrt{2}\left|V^0_{sa1}\right|\sin(wt+\angle V^0_{sa1}) \\ V^0_{sb1}(t)&=\sqrt{2}\left|V^0_{sa1}\right|\sin(wt+2\pi/3+\angle V^0_{sa1}) \\ V^0_{sc1}(t)&=\sqrt{2}\left|V^0_{sa1}\right|\sin(wt-2\pi/3+\angle V^0_{sa1}) \end{aligned}\right\} \quad (11)$$

$$\left.\begin{aligned} V^+_{sa1}(t)&=\sqrt{2}\left|V^0_{sa1}\right|\sin(wt+\angle V^+_{sa1}) \\ V^+_{sb1}(t)&=\sqrt{2}\left|V^0_{sa1}\right|\sin(wt-2\pi/3+\angle V^+_{sa1}) \\ V^+_{sc1}(t)&=\sqrt{2}\left|V^0_{sa1}\right|\sin(wt+2\pi/3+\angle V^+_{sa1}) \end{aligned}\right\} \quad (12)$$

$$\left.\begin{aligned} V^-_{sa1}(t)&=\sqrt{2}\left|V^0_{sa1}\right|\sin(wt+\angle V^-_{sa1}) \\ V^-_{sb1}(t)&=\sqrt{2}\left|V^0_{sa1}\right|\sin(wt+2\pi/3+\angle V^-_{sa1}) \\ V^-_{sc1}(t)&=\sqrt{2}\left|V^0_{sa1}\right|\sin(wt-2\pi/3+\angle V^-_{sa1}) \end{aligned}\right\} \quad (13)$$

The synchronization of only one phase is needed to realize the positive sequence voltages. This is the advantage over synchronous detection method. The objective is to provide balance and sinusoidal supply currents after compensation, such that the zero sequence components carried by neutral wire is zero.

$$i_{sa}+i_{sb}+i_{sc}=0 \quad (14)$$

The reference compensator currents are reduced to the following

$$\left.\begin{aligned} i_{fa}^{*} &= i_{la} - \frac{v_{vsa1}^{+} + \left(v_{sb1}^{+} - v_{sc1}^{+}\right)\beta}{\Delta_1^{+}} P_{lav} \\ i_{fb}^{*} &= i_{lb} - \frac{v_{vsb1}^{+} + \left(v_{sc1}^{+} - v_{sa1}^{+}\right)\beta}{\Delta_1^{+}} P_{lav} \\ i_{fc}^{*} &= i_{lc} - \frac{v_{vsc1}^{+} + \left(v_{sa1}^{+} - v_{sb1}^{+}\right)\beta}{\Delta_1^{+}} P_{lav} \end{aligned}\right\} \quad (15)$$

The above algorithm gives balanced source currents after compensation irrespective of unbalanced and distorted supply voltages.

3. Simulation and Experimental studies with actual compensator

To understand the actual compensator, a neutral clamped 3-phase, 4-wire voltage source inverter is chosen and simulated in MAT Lab environment, shown in Fig.2. The source, compensator and the load are connected at one point which is point of common coupling (PCC). The voltage source inverter is consisting of of six IGBT switches each with anti parallel diodes and identical capacitors. The middle point of the two capacitors is connected to the neutral of the load and source as shown in fig. The midpoint of the inverter legs are connected to the PCC through interface inductor. A small resistance is considered which interface inductors resistance.

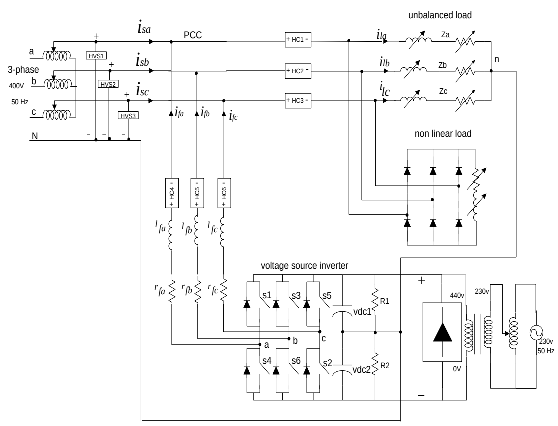

Figure 2: Neutral clamped voltage source inverter

The systems parameters for the simulation and experimental studies are given in Table 1.

Table 1: system parameters for simulation and experimental studies

System parameters	Value
Source voltage	400 V (peak) unbalanced and distorted
System frequency	50 Hz
DC capacitors	2000 micro farads
Inter face inductors	0.04 H (Iron core)
Inter face resistance	10 Ohms
PI controller gain	Kp=10, Ki= 1
Reference voltage	600 V
Unbalanced load parameters	Za=25 ohms (Resistance only) Zb=67 ohms (R &L) Zc= 87 ohms (R &L)
Non linear load	Three phase diode rectifier with R= 600ohms, L= 0.1 H

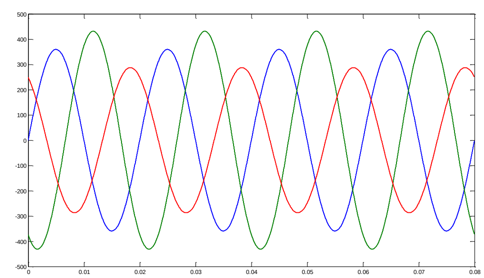

Figure 3: Three phase unbalanced source voltages

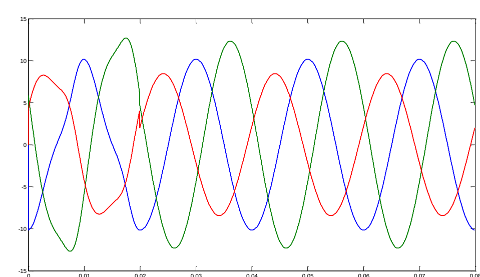

Figure 4: Three phase source currents before compensation

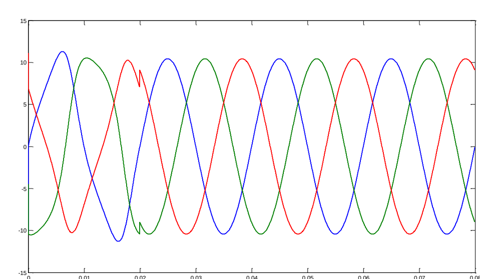

Figure 5: Three phase source currents after compensation

Using the instantaneous symmetrical components theory unbalanced source voltages are developed which are shown in Figure 3. The source and load currents are same before compensation which are unbalanced because of unbalanced loads currents drawn from the source also unbalance which are shown in figure 4. After compensation the load currents are balanced and sinusoidal show in figure 5, this is because of the compensator injecting reactive power into the system to compensate unbalanced non linear loads.

In Fig 6–Fig 9 various experimental results are shown. The three phase source and neutral currents are unbalanced shown in figure 6, this is because of unbalanced non linear load, the neutral current is flowing due unbalance in three phases. After compensation three phase source voltages are sinusoidal which show in figure 7. In figure 8 the neutral current is zero, which is clearly showing that all the three phases are balanced. Under unbalanced and non linear case the filter will supply reactive power require by the load which is shown in figure 9.

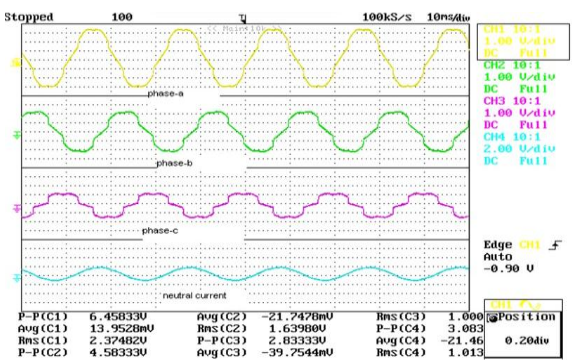

Figure 6: unbalanced three phase source and neutral currents before compensation

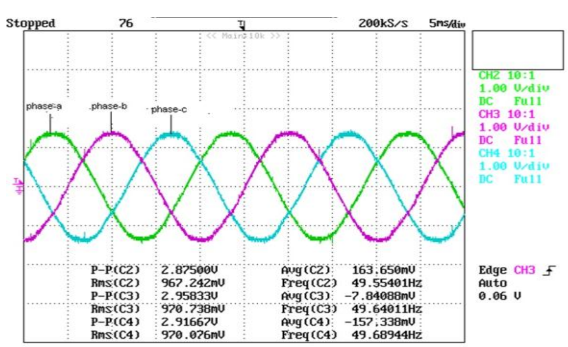

Figure 7: Three phase source voltages after compensation

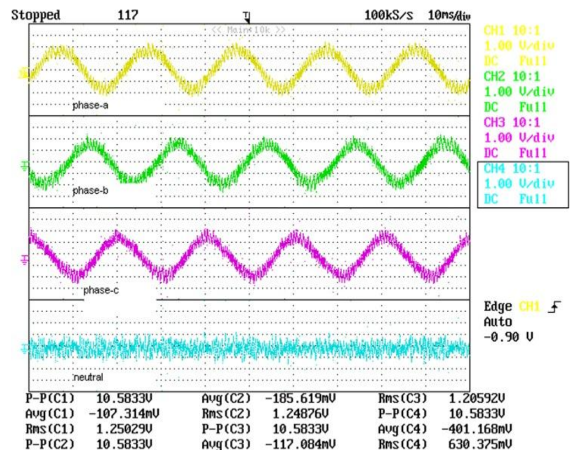

Figure 8: Three phase source and neutral currents after compensation

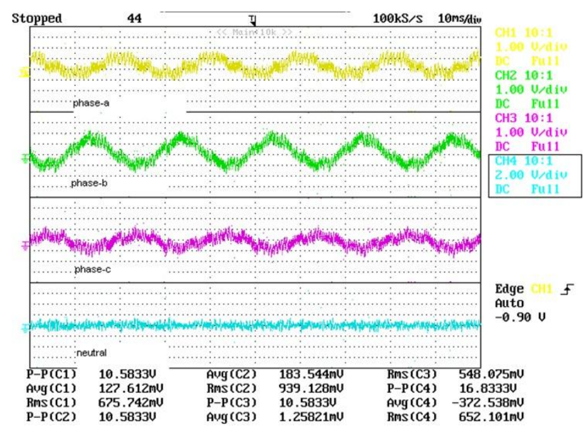

Figure 9: Three phase filter and neutral currents after compensation

4. Conclusions

This paper presents a three phase four wire active power filter operation under stiff source and the algorithm presented in this works effectively even the supply voltages are unbalanced and distorted. The compensator based on this algorithm maintains supply currents are balanced and sinusoidal. The detailed simulation and experimental results are presented to support the concept presented in this paper.

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