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Comparison of Generalized Instantaneous Power Theory and Modified Generalized Instantaneous Power Theory for Shunt Active Power Line Conditioner

Sanjay C. Patel[1], Tushar A. Patel[2]

Lecturer, Electrical Department, Government Polytechnic, Valsad, India[1]

Lecturer, Electrical Department, Government Polytechnic, Dahod, India[2]

Abstract: In this paper generalized definition of instantaneous power quantity in the multiphase system under unbalanced and non-sinusoidal supply condition is discussed. In the area of Active Power Line Conditioners (APLC), shunt APLC is widely used in practice. Many reference current generation methods are proposed by different researchers, but most of them work optimally with balanced and sinusoidal source voltage. This paper proposes a novel concept of decomposing the multiphase current vector into different components, which represents different component of the power quantity. The formation of calculating compensation current according Generalised Instantaneous Power Theory (GIPT) and Modified GIPT has been studied. Next, the behavior of a shunt APLC with these two theories has been studied. Performance of shunt APLC tested and compared under unbalanced non-sinusoidal supply condition. Under distorted and/or unbalanced system voltages, GIPT does not compensate properly the load currents and injects harmonic currents into the supply, which are not originated from the non linear load. Necessary modifications in GIPT more general compensation objective is possible.The validity of the proposed control scheme is verified by the simulation study.

Keywords: Active filters, instantaneous power, geometric algebra, nonsinusoidal waveforms, power multivector.

I. INTRODUCTION

Load compensation in power engineering is the procedure used to obtain the supply currents that are sinusoidal and balanced. Active power line conditioners (APLCs) make it possible to obtain power-electronic solutions to power quality (PQ) problems. In particular, balanced or unbalanced load compensation in non-sinusoidal supply conditions is possible[1].

Active Power Line Conditioner has become the main research direction of load compensation as its filtering characteristic is not affected by system parameters. Various configurations and control strategies have been researched during the last decades. Shunt APLCs are more widely used for active shunt compensation, which works as a controlled current source and injects required compensation current [2-3]. To obtain efficient SHAPF performance, it is important to choose proper reference generation algorithm and an appropriate current or voltage control strategy. The publication of the instantaneous reactive power theory caused great impact in reference generation. Many approaches have been published since then [4–6]. But all of these definitions are computational intensive and do not provide simple expression of instantaneous power quantity. Most of the methods optimally works with balanced and sinusoidal voltage, but not so good with unbalanced and non-sinusoidal voltage. In year 2004, X. Dai [7] introduced generalized instantaneous power theory which gives a direct and simple expression for instantaneous power quantities.

This paper proposes a control algorithm for generating

reference current for shunt APLC working under unbalanced and non-sinusoidal source conditions. It is proposed to decompose multiphase current vector into quantities that represents different components of power. GIPT is used for separating components of current vectors corresponding to zero-sequence power, reactive power and unwanted component of active power. These components of current vector corresponding to different part of instantaneous powers are used for generating reference for shunt APLC.

This paper is organized as follows. First, a generalized definition of instantaneous active, reactive and apparent power quantity is presented in section II-A. Then, the decomposition of current vector with GIPT is presented in section II-B. Then, the proposed decomposition of current vector with modified GIPT is presented in section II-C. Finally the applications of proposed control scheme to shunt APLC along with simulation results are presented in section III, IV and V. Simulation study for three-phase ac voltage controller with different load in each phase is presented while working with unbalanced non-sinusoidal supply voltage.

II. PROPOSED METHOD FOR SHUNT APLC REFERENCE GENERATION

In the proposed method, the calculation of reference signal

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for shunt APLC is performed in two steps, (i) decomposition of current vector into different components, which represents different components of the power quantity, and (ii) generating reference current corresponding to unwanted components of power quantity.

A. Basic Definations of Generalised Instantaneous Power Theory

This section represents the formulation of basic terms in Generalised Instantaneous Power Theory (GIPT) [7].For a three-phase four-wire system, the instantaneous quantities of load voltage and currents are expressed as $\vec{u} = [u_a\ u_b\ u_c]^T$ and $\vec{i} = [i_a\ i_b\ i_c]^T$.

The instantaneous power multi-vector is defined as the geometric product of voltage and current vectors:

$$\vec{s}(t) = u(t)i(t) = u(t) \bullet i(t) + u(t) \times i(t) \tag{1}$$

where the scalar product is denoted by $p(t)$ and the cross product is denoted by $\vec{q}(t)$. Load instantaneous apparent power‘s’ is defined as $s = \|\vec{u}\| \|\vec{i}\|$ where $\|\vec{u}\| = \sqrt{u_a^2 + u_b^2 + u_c^2}$ and $\|\vec{i}\| = \sqrt{i_a^2 + i_b^2 + i_c^2}$

Load instantaneous active power ‘p’ is defined as an inner product of voltage and current vectors.

$$p(t) = \vec{u}(t) \bullet \vec{i}(t) = u^T i = u_a i_a + u_b i_b + u_c i_c \tag{2}$$

Load instantaneous reactive power $\vec{q}(t)$ is defined as the outer product of voltage and current vectors $\vec{q}(t) = \vec{u}(t) \times \vec{i}(t)$. The outer product is defined by means of the tensor product $\vec{u}(t) \times \vec{i}(t) = \vec{i}(t) \otimes \vec{u}(t) - \vec{u}(t) \otimes \vec{i}(t)$.

$$\vec{q}(t) = \vec{u}(t) \times \vec{i}(t) = \begin{bmatrix} 0 & -q_{ab} & q_{ca} \\ q_{ab} & 0 & -q_{bc} \\ -q_{ca} & q_{bc} & 0 \end{bmatrix} \tag{3}$$

with each components definedas:

$$q_{ab} = u_a i_b - u_b i_a;\ q_{bc} = u_b i_c - u_c i_b;\ q_{ca} = u_c i_a - u_a i_c$$

$\vec{q}(t)$ is denoted as instantaneous reactive tensor and its norm is defined as instantaneous reactive power $\|\vec{q}\| = \sqrt{q_{ab}^2 + q_{bc}^2 + q_{ca}^2}$.

B. Reference current calculation from Generalised Instantaneous Power Theory

Using Eq. (2), the component of load instantaneous current vector ‘$\vec{i}_p$’, can be expressed as

$$\vec{i}_p = [i_{pa}\ i_{pb}\ i_{pc}]^T = \frac{p(t)}{\|\vec{u}\|^2}[u_a\ u_b\ u_c]^T \tag{4}$$

where, ‘$\vec{i}_p$’is denoted as instantaneous active current tensor and its norm is defined as instantaneous active current $\|\vec{i}_p\| = \sqrt{i_{pa}^2 + i_{pb}^2 + i_{pc}^2}$.

Using Eq. (3), the component of load instantaneous current vector ‘$\vec{i}_q$’, represents reactive or inactive power can be expressed as $\vec{q}(t) = \vec{u}(t) \times \vec{i}_q(t)$. Multiplying both sides by voltage vector $\vec{u}(t)$ and using Appendix A.2 for performing cross product on right hand side following expression is obtained

$$\vec{q}(t) \times \vec{u}(t) = \vec{u}(t) \times \vec{i}_q(t) \times \vec{u}(t) \tag{5a}$$

$$\vec{q}(t) \times \vec{u}(t) = (\vec{u}(t) \bullet \vec{u}(t))\ \vec{i}_q(t) - (\vec{u}(t) \bullet \vec{i}_q(t))\ \vec{u}(t) \tag{5b}$$

$$\vec{q}(t) \times \vec{u}(t) = \|\vec{u}\|^2 \vec{i}_q(t) - 0 \tag{5c}$$

$$\vec{i}_q(t) = [i_{qa}\ i_{qb}\ i_{qc}] = \frac{\vec{q}(t) \times \vec{u}(t)}{\|\vec{u}(t)\|^2} \tag{5d}$$

Equation (5d) expresses the load instantaneous current vector ‘$\vec{i}_q$’ which represents reactive power quantity. Using Appendix A.3, the cross product is calculated as

$$\vec{i}_q(t) = [i_{qa}\ i_{qb}\ i_{qc}] = \frac{[\vec{q}]_x\ \vec{u}(t)}{\|\vec{u}(t)\|^2} \tag{6a}$$

$$\vec{i}_q(t) = \frac{1}{\|\vec{u}(t)\|^2} \begin{bmatrix} 0 & -q_{ab} & q_{ca} \\ q_{ab} & 0 & -q_{bc} \\ -q_{ca} & q_{bc} & 0 \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \tag{6b}$$

The vector ‘$\vec{i}_q$’ is denoted as instantaneous reactive current tensor and its norm is defined as instantaneous reactive current $\|\vec{i}_q\| = \sqrt{i_{qa}^2 + i_{qb}^2 + i_{qc}^2}$.

From Eq. (2) instantaneous real power can be written as sum of mean value of instantaneous real power ($\bar{p}(t)$) and alternating value of instantaneous real power ($\tilde{p}(t)$).

$$p(t) = \bar{p}(t) + \tilde{p}(t) \tag{7}$$

The compensating current corresponding to unwanted component of active power can be expressed as

$$\vec{i}_{pc} = [i_{pa}\ i_{pb}\ i_{pc}]^T = \frac{\tilde{p}(t)}{\|\vec{u}\|^2}[u_a\ u_b\ u_c]^T \tag{8}$$

From Eq. (5d) and Eq. (8) overall reference current for shunt APLC is expressed as

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$$\vec{i}_c = \vec{i}_{pc} + \vec{i}_q \qquad (9)$$

C. Reference current calculationfrom Modified Generalised Instantaneous Power Theory

In this section, modification in GIPT is proposed. The reference current is obtained under unbalanced sinusoidal and unbalanced non-sinusoidal supply voltage situation.

For an unbalanced source conditions, a zero-sequence voltage vector can be defined as follows

$$\vec{v}_o = [v_o \ v_o \ v_o]^T \qquad (10)$$

where, $v_o = \frac{1}{3}[u_a + u_b + u_c]$

Thus, the voltage vector without zero-sequence components is

$$\vec{v} = \vec{u} - \vec{v_o} \qquad (11)$$

Using Eq. (2), the component of load instantaneous current vector ‘ $\vec{i}_{pv}$ ’, which represents active power without zero-sequence power can be expressed as $\vec{p}_v(t) = \vec{v}(t) \bullet \vec{i}_{pv}(t)$.

$$\vec{i}_{pv} = [i_{pav} \ i_{pbv} \ i_{pcv}]^T = \frac{p_v(t)}{\| \vec{v} \|^2} [v_a \ v_b \ v_c]^T \qquad (12)$$

The total balanced active power and current component corresponding to this power is expressed using positive sequence voltage and current of the system.

$$\vec{p}^+(t) = \vec{v}^+(t) \bullet \vec{i}_f^{\,+}(t) \qquad (13)$$

$$\vec{i}_{p+} = [i_{pa+} \ i_{pb+} \ i_{pc+}]^T = \frac{p^+(t)}{\| \vec{v}^+ \|^2} [v_a^{\,+} \ v_b^{\,+} \ v_c^{\,+}]^T \qquad (14)$$

Where $\vec{v}^+$ is the positive sequence voltage vector without zero-sequence component and $\vec{i}_f^{\,+}$ is the fundamental positive sequence current vector.

The compensating current corresponding to unwanted component of powers can be expressed as

$$\vec{i}_{pc} = \vec{i}_{pv} - \vec{i}_{p^+} \qquad (15)$$

The current corresponding to reactive power is derived using Eq. (5d) by considering voltage vector without zero sequence voltage and overall reference current for SAPF is expressed as

$$\vec{i}_c = \vec{i}_{pc} + \vec{i}_q \qquad (16)$$

For calculating reference under unbalanced and non-sinusoidal supply condition further consideration of fundamental component of supply voltage is required. The total balance active power and current component corresponding to this power is expressed using positive sequence fundamental voltage and current of the system as

$$\vec{p}_f^{\,+}(t) = \vec{v}_f^{\,+}(t) \bullet \vec{i}_f^{\,+}(t) \qquad (17)$$

$$\vec{i}_{pf+} = [i_{paf^+} \ i_{pbf^+} \ i_{pcf^+}]^T = \frac{p_f^+(t)}{\| \vec{v}_f^{\,+} \|^2} [v_{af}^+ \ v_{bf}^+ \ v_{cf}^+]^T \qquad (18)$$

Where $\vec{v}_f^{\,+}$ is the positive sequence voltage vector without zero-sequence component and $\vec{i}_{pf}^{\,+}$ is the fundamental positive sequence current vector.

The compensating current corresponding to unwanted component of powers can be expressed as

$$\vec{i}_{pc} = \vec{i}_{pv} - \vec{i}_{pf^+} \qquad (19)$$

The current corresponding to reactive power is considered as unbalanced non-sinusoidal supply case and overall reference current for Shunt APLC is expressed as

$$\vec{i}_c = \vec{i}_{pc} + \vec{i}_q \qquad (20)$$

The compensation current presented in Eq. (20) guarantees the achievement of balanced and sinusoidal source current with any supply voltage condition.

III. SHUNT APLC SIMULATION MODEL

For evaluating performances of shunt APLC, using the proposed methods, simulation study is performed in PSIM software. Fig.1 shows shunt active power filter connected to a three-phase four-wire source that supplies a non-linear load. The control strategies generates the reference current i_c(a,b,c) for shunt APLC. Instantaneous values of current components $\vec{i}_{pc}$ and $\vec{i}_q$ are calculated from three phase supply voltages and load currents for calculating reference of shunt APLC. The calculated reference current is injected via shunt APLC to compensate for unbalance and harmonic currents. Table I shows the system parameter values with which the simulation study is done.

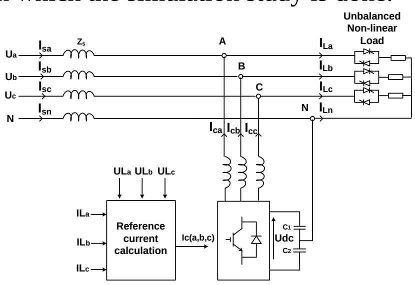

Fig:1 Three-phase four-wire source with nonlinear load and Shunt APLC

TABLE1:COMMON SYSTEM PARAMETERS

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Sr. No.	Quantity	Value
1	Source Impedance	Rs = 0.1 Ohm, Ls = 0.1mH
2	DC Capacitor	4000uF
3	Shunt APLC Inductor	L = 0.5mH
4	EMI Filter	L_f = 3mH, C_f = 2uF, R_f = 0.1Ω
5	DC Link Voltage	1200V
6	Load	Three phase AC voltage controller with Phase A: R=7 Ohm, L =5mH, Firing Angle =30° Phase B: R=3 Ohm, L =5mH, Firing Angle =30° Phase C: R=5 Ohm, L =5mH, Firing Angle =30°
7	Switching Frequency	20 kHz

Table I shows the system parameter values with which the simulation study is done. Simulation study is to verify theperformance of control algorithm while working under unbalanced non-sinusoidal source voltage.

IV. RESULTS OF SHUNT APLCS SIMULATION

The simulation of shunt APLC configuration with proposed control methods are done in the PSIM simulation software. The three-phase ac voltage controller with different load in each phase. The performance of shunt APLC with GIPT and modified GIPTtested and results are presented in following sub section. The supply voltage valuesare:

$$V_{an} = 325\sin(\omega t) + 3.25\sin 5(\omega t)$$

$$V_{bn} = 292\sin(\omega t - 2\pi/3) + 2.92\sin 5(\omega t - 2\pi/3) \quad \text{and}$$

$$V_{cn} = 260\sin(\omega t - 4\pi/3) + 2.60\sin 5(\omega t - 4\pi/3).$$

Case-1: Performance of shunt APLC with GIPT

The performance of shunt APLC with three-phase AC voltage controller having unbalanced load is simulated and the results are as shown in Fig. 2. Fig. 2(a) shows the waveform of unbalanced supply voltage, which is followed by unbalanced load current, shunt APLC current and source current in Fig. 2(b), (c) and (d) respectively.It is observed from the source current waveform that source currentdoes not compensate load current harmonics properly and injects harmonics into the source current which are not originated by load when the supply voltage is unbalanced and non-sinusoidal.

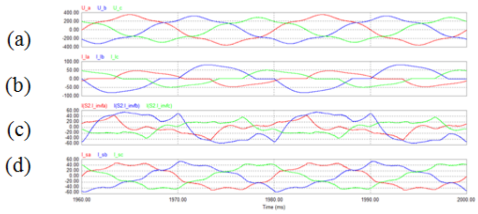


Fig:1 Simulation results of shunt APLC for case-1 (a) source voltages, (b) load currents, (c) injected currents,and (d) supply currents.

The FFT analysis of supply current waveform with and without Shunt APLC is shown in Fig.3. It is observed that the THD in the source current without compensation is 28.7%, 19.04% and 25.29% from which it is 13.21%, 14.01% and 13.27% in phase A, phase B and phase C respectively when Shunt APLC is connected for compensation. It is observed from Fig.3 (b) that harmonics are injected into source current under unbalanced non-sinusoidal supply voltage supplied to unbalanced non-linear load situation.

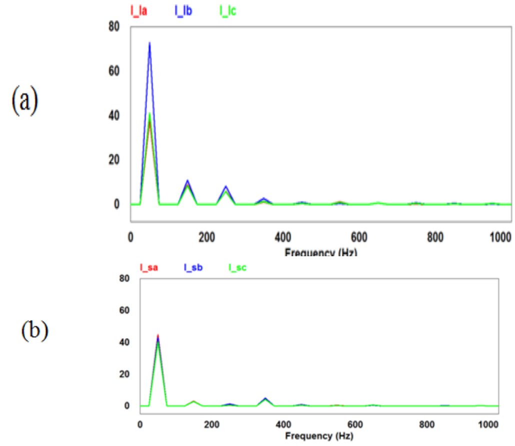


Fig.3 FFT analysis of source current (a) without Shunt APLC (b) with shunt APLC

Case-2: Performance of shunt APLC with Modified GIPT

The performance of shunt APLC with three-phase AC voltage controller having unbalanced load is simulated and the results are as shown in Fig. 4. Fig. 4(a) shows the waveform of unbalanced supply voltage, which is followed by unbalanced load current, shunt APLC current and source current in Fig. 4(b), (c) and (d) respectively. It is observed from the source current waveform that source current is balanced sinusoidal in this extreme conditions of unbalanced non-linear load and unbalanced non-sinusoidal source, which shows the effectiveness of proposed method.

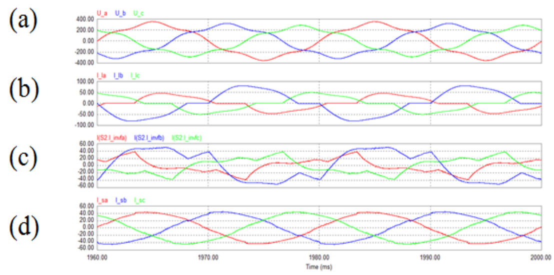
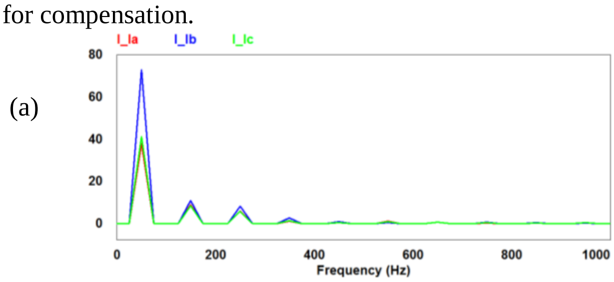


Fig.4 Simulation results of shunt APLC for case-2 (a) source voltages, (b) load currents, (c) injected currents, and (d) supply currents.

The FFT analysis of supply current waveform with and without Shunt APLC is shown in Fig.5. It is observed that the THD in the source current without compensation is 28.7%, 19.04% and 25.29% which is reduced to very small value 3.48%, 4.53% and 3.22% in phase A, phase B and phase C respectively when Shunt APLC is connected for compensation.



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(b)

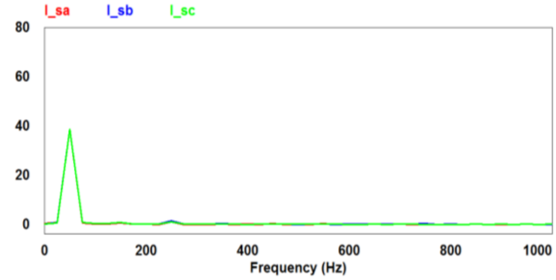

Fig.5 FFT analysis of source current (a) without Shunt APLC (b) with shunt APLC

V. PERFORMANCE OF SHUNT APLC WITH GIPT AND MODIFIED GIPT

The performance of SAPF with unbalanced non-sinusoidal supply supplied tothree-phase ac voltage controller with different load in each phase is simulated and results are tabulated in Table II. It is observed from the Table II that significant reduction in source current THD in all three phases is achieved with Modified GIPT.The reduced THD in source current is below 5% which is well below IEEE limits.

TABLE II: Performance of Shunt APLC

System		% THD_i Phase A	% THD_i Phase B	% THD_i Phase C
Without Shunt APLC		28.70	19.04	25.29
With Shunt APLC	GIPT	13.21	14.01	13.27
	Modified GIPT	3.48	4.53	3.22

VI. CONCLUSION

In this paper a control scheme based on decomposing current vector using Generalised Instantaneous Power Theory and Modified Generalised Instantaneous Power Theory for shunt APLC working under unbalanced non-sinusoidal source is presented. Formulation for decomposing different power quantities in terms of current components is presented. These components are directly associated with three phase instantaneous voltages and currents and are separated without any form of artificial transformations. Application of this decomposition in generating reference signal for shunt APLC is demonstrated. It is observed via simulation study that the shunt APLC derived from Modified Generalised Instantaneous Power Theory very effectively draws balanced and sinusoidal current from source while working under different source and load conditions.

APPENDIX A

A.1 Inverse of a vector

Considering voltage vector $\vec{v}$, its inverse $\vec{v}^{-1}$ into the geometric algebra framework, can be defined as $\vec{v}^{-1} = \frac{\vec{v}^{\dagger}}{\vec{v}^{\dagger}\,\vec{v}} = \frac{\vec{v}^{\dagger}}{\|\vec{v}\|^2} = \frac{\vec{v}}{\|\vec{v}\|^2}$, where $\|\vec{v}\|$ is the instantaneous norm of vector $\vec{v}(t)$ and the fact that $\vec{v}^{\dagger} \equiv \vec{v}$ has been considered [12].

A.2 Cross Product of Three Vectors

In the geometric algebra framework, the cross product of three vectors can be performed using expression,

$$\vec{a}\times\vec{b}\times\vec{c} = (\vec{a}\bullet\vec{c})\,\vec{b} - (\vec{a}\bullet\vec{b})\,\vec{c}$$

A.3 Conversion of Cross Product into Matrix Multiplication

In the geometric algebra framework, the conversion of this outer product multiplication to matrix multiplication is done using following relations. $\vec{a}\times\vec{b} = [\vec{a}]_x\vec{b} = [\vec{b}]_x^T\vec{a}$ and if $\vec{a} = \vec{c}\times\vec{d}$, $[\vec{a}]_x = \left(\vec{c}\,\vec{d}^T\right)^T - \vec{c}\,\vec{d}^T$

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