P-q Theory Based Shunt Active Power Conditioner for Mitigation of Power Quality Problems

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Abstract

In this paper, instantaneous reactive power theory (P-q theory) based control method is proposed for three-phase four-wire shunt active power conditioner (shunt APC) to mitigate some power quality problems namely, harmonic, reactive power, balancing the load currents, and elimination of neutral current. The shunt APC consists of 4-leg voltage source inverter (VSI) with a common DC-link capacitor and hysteresis band PWM current controller. All simulations are performed by using PSCAD/EMTDC software.

Keywords: Power quality; Harmonic; Shunt active power conditioner; P-q theory; Total harmonic distortion.

Introduction

The major causes of power quality problems are due to the wide spread application of nonlinear loads such as static power electronic converters, saturable devices, fluorescent lamps and arch furnaces. These nonlinear loads draw harmonic and reactive power components of current from the ac mains. In three phase system, they could also cause unbalance and draw excessive neutral currents. The injected harmonic, reactive power burden, unbalance, and excessive neutral currents cause low system efficiency and poor power factor, they also cause disturbance to other consumers and interface in nearby communication networks. So far (Hirfumi 1994), shunt passive filters, which consist of tuned LC filters and/or high pass filters, have been used to improve power factor and to suppress harmonics in power systems. However, shunt passive filters have such problems as to discourage their applications which have attracted the attention to develop dynamic and adjustable solution to power quality problems such equipment, generally known as "Active Power Conditioners (APC's)". Control strategy (Bhim 1999 and Joao 2001) is the heart of APC's which are classified into shunt, series, and combination of both. And the development of compensating signals in terms of voltages or currents is the important part of APC's control strategy and affects their ratings and transient as well as steady state performance. The control strategies to generate compensating commands are based on frequency-domain or time-domain. The frequency domain approach implies the use of the Fourier transform and its analysis, which leads to a huge amount of calculations, making the control method very heavy. In the time domain approach, traditional concepts of circuit analysis and algebraic transformations associated with changes of reference frames are used, simplifying the control task. One of the time domain control strategies is the instantaneous reactive power theory based (p-q theory) control strategy which proposed by Akagi et al. (Hirfumi 1983 and Hirfumi1984). And since (Joao 2003) the p-q theory is based on the time domain, it is valid both for steady-state and transient operation, as well as for generic voltage and current waveforms, allowing the control of APC in the real-time; another advantage of this theory is the simplicity of its calculations, since only algebraic operations are required.

Shunt APC

Power circuit (Hirfumi 1994) of shunt APC may be voltage source PWM inverter or current source PWM inverter with a dc reactor or a dc capacitor on the dc side which plays an essential role as energy storage element but it does not need any dc power supply because the shunt APC can be controlled so as to supply the losses PWM inverter from the ac source.

Figure (1) presents the electrical scheme of a shunt APC for three-phase power system with neutral wire, which, can both compensate for current harmonics and load reactive power. Furthermore, it allows load balancing, eliminating the current in the neutral wire. The voltage source PWM inverter controlled in a way that it acts like a current-source. From the measured values of the phase voltages (v_a, v_b, v_c) and load currents (i_a, i_b, i_c), the controller calculates the reference currents (i_{ca}^*, i_{cb}^*, i_{cc}^*, i_{cn}^*) used by the inverter to produce the compensation currents (i_{ca}, i_{cb}, i_{cc}, i_{cn}).

P-q Theory

This theory, also known as "instantaneous reactive power theory" was proposed in 1983 by *Akagi et al.* (Hirfumi 1983 and Hirfumi1984) to control active filters. It based on a set of instantaneous powers defined in time domain. No restrictions are imposed on the voltage or current waveforms, and it can be applied to three-phase systems with or without a neutral wire for three-phase generic voltage and current waveforms. Thus, it is valid not only in steady state, but also in transient states.

The *p-q* Theory first transforms voltages and currents from the *a-b-c* to *α-β-o* coordinates, and then defines instantaneous power on these coordinates. Hence, this theory always considers the three-phase system as a unit, not a superposition or sum of three single-phase circuits. The *p-q* Theory uses the *α-β-o* transformation, also known as the *Clarke* transformation, which consists of a real matrix that transforms three-phase voltages and currents into the *α-β-o* stationary reference frames. The *α-β-o* transformation or the *Clarke* transformation maps the three-phase instantaneous voltages and currents in the *a-b-c* phases into the instantaneous voltages and currents on the *α-β-o* axes.

The *Clarke* Transformation (Hirfumi 1999) of three-phase generic voltages and load currents are given by:

$$\begin{bmatrix} v_o \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_{Lo} \\ i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{2}$$

One advantage of applying the *α-β-o* transformation is to separate zero-sequence component from the *a-b-c* phase components. The *α* and *β* axes make no contribution to zero-sequence components. According to The *p-q* theory, the instantaneous power components on the load side are defined as:

$$\begin{bmatrix} P_o \\ P_L \\ q_L \end{bmatrix} = \begin{bmatrix} v_o & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_{Lo} \\ i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \tag{3}$$

Where:

$P_o = i_{Lo} v_o$ Is the instantaneous zero-sequence power,

$P_L = v_\alpha i_{L\alpha} + v_\beta i_{L\beta}$ Is the instantaneous real power,

$q_L = v_\alpha i_{L\beta} - v_\beta i_{L\alpha}$ Is the instantaneous imaginary power.

The instantaneous real and imaginary power of load (Hirfumi 1994 and Fang 1998) may be, respectively, spilt into two parts as:

$$P_L = \overline{P}_L + \tilde{P}_L \tag{4}$$

$$q_L = \overline{q}_L + \tilde{q}_L \tag{5}$$

Where $\overline{P}_L$ and $\overline{q}_L$ are the average parts of active (real) and reactive (imaginary) power originating from the symmetrical fundamental (positive-sequence) component of the load current, $\overline{P}_L$ is the average active power delivered to the load (it is, indeed the only desired power component to be supplied by the power source), $\overline{q}_L$ is the average reactive power circulating between the phases, and $\tilde{P}_L$ and $\tilde{q}_L$ are the oscillating parts of real and reactive power originating from harmonic and asymmetrical fundamental (negative-sequence) component of the load current.

$\tilde{P}_L$ corresponds to active power oscillating between source and load. Since the average of $\tilde{P}_L$ is zero, it could be filtered out by a compensator with an energy-storage element absorbing this oscillating power.

While $\tilde{q}_L$ corresponds to reactive power oscillating between the phases. $\tilde{q}_L$ could not filtered out by a compensator without energy-storage element. Furthermore, $\tilde{P}_L$ and $\tilde{q}_L$ can be respectively spilt into two parts (2ω components and harmonic components) as:

$$\tilde{P}_L = P_{L2\omega} + P_{Lh} \tag{6}$$

$$\tilde{q}_L = q_{L2\omega} + q_{Lh} \tag{7}$$

Where $P_{L2\omega}$ and $q_{L2\omega}$ are the negative active and reactive power (2ω components) originated from asymmetrical fundamental (negative sequence) component of the load current, and P_{Lh} and q_{Lh} are the harmonic active and reactive power (harmonic components) of the load current. $\overline{P}_L$, $\overline{q}_L$ and $\tilde{P}_L$, $\tilde{q}_L$ or $P_{L2\omega}$, $q_{L2\omega}$ and P_{Lh}, q_{Lh} can be extracted by means of low-pass or band-pass Butterworth analog filters. The commands of three-phase compensating currents injected by shunt APC in the *α-β* coordinates, i_{co}^*, $i_{c\alpha}^*$, $i_{c\beta}^*$ can be calculated by the following equation:

$$\begin{bmatrix} i^*_\alpha \\ i^*_\beta \end{bmatrix} = \frac{1}{v_\alpha^{\ 2} + v_\beta^{\ 2}} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} -p^* \\ -q^* \end{bmatrix} \tag{8}$$

Where P^* and q^* are the power components of active and reactive powers to be compensated by the shunt APC. And the reason for including minus signals in the compensating powers is to emphasize that the shunt APC should draw a compensating current that produces exactly the inverse of the undesirable powers drawn by the nonlinear load. Table I summarizes the compensation objectives of shunt APC and the corresponding selected values for P^* and q^*.

Since the zero sequence current must be compensated, the reference compensating current in the (0) axis is i_o itself so that:

$$i^*_{co} = -i_{Lo} \tag{9}$$

By using inverse *Clark* transformation, the instantaneous values of the three-phase compensating current references i^*_{ca}, i^*_{cb}, and i^*_{cc} can be calculated. The compensating currents in the *a-b-c* coordinates are given in equation (10):

$$\begin{bmatrix} i^*_{ca} \\ i^*_{cb} \\ i^*_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{3} \end{bmatrix} \begin{bmatrix} i^*_{co} \\ i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} \qquad (10)$$

And the neutral reference compensating current is calculated as follows:

$$i^*_{cn} = i^*_{ca} + i^*_{cb} + i^*_{cc} \qquad (11)$$

Figure (2) shows the complete block diagram for the control algorithm of Shunt APC based on P-q theory for load balancing, harmonic cancellation and reactive power compensation purposes. P_{loss} represents a small amount of average real power which must be added to the compensated real power P^* to compensate switching and ohmic losses in the voltage source inverter.

Table 1. Compensation Objectives of Shunt APC and Corresponding Selected Values for P^* and q^*.

Compensation Objective	**References of Shunt APC**
Instantaneous Reactive Power	$P^* = 0, q^* = \tilde{q}_L$
Negative-Sequence and Harmonic Currents	$P^* = \tilde{P}_L, q^* = \tilde{q}_L$
Fundamental Positive-Sequence Reactive Power	$P^* = 0, q^* = \bar{q}_L$
Reactive Power and Harmonics	$P^* = \tilde{P}_L, q^* = q_L$
Negative-Sequence	$P^* = P_{L2\omega}, q^* = q_{L2\omega}$
Harmonic Current	$P^* = P_{Lh}, q^* = q_{Lh}$

Simulation Results

Figure (3) shows the system that was implemented in PSCAD/EMTDC simulator. A three-phase four-wire balanced power source is considered and three phase 6-pulse thyristor converter with (30^o) firing angle is used as a nonlinear load. To achieve unbalance a single-phase diode rectifier with inductive load is connected in parallel with the three-phase thyristor load. The Shunt APC consists of 4-leg VSI, 3-leg are needed to compensate the three phase load currents (generates i_{ca}, i_{cb}, and i_{cc} in figure 1) and 1-leg compensate the neutral current (generate i_{cn} in figure 1). Hysteresis band PWM current controller has been used to obtain the VSI control pulses for each inverter branch. For harmonic cancellation, reactive power compensation, load balancing, and neutral current elimination, the values of P^* and q^* are selected such that: $P^* = \tilde{P}$ and $q^* = q$ .System currents are shown in figure (4), where the source currents i_{sa}, i_{sb}, and i_{sc} becomes sinusoidal due to three-phase currents i_{ca}, i_{cb}, and i_{cc} injected by shunt ACP and have less r.m.s values than the three-phase load currents i_{La}, i_{Lb}, and i_{Lc} due to reactive power compensation. Also the source neutral current i_{sn} becomes nearly zero due to the elimination of load neutral current i_{Ln} by injecting the same value with opposite direction i_{cn} by the shunt APC. Total harmonic distortion (THD) of source and load three-phase currents given in table (II) which clears that, the three-phase source currents have less value than the three-phases load current and these values are within standards. In addition three-phase harmonic spectrum for load and source currents are shown in figure (5) and figure (6) respectively. Figure (7) shows system real and imaginary powers where the source real power P_s becomes constant due to compensation of oscillating part $\tilde{P}$ in the load real power P_L and the source imaginary power q_s is zero because the load imaginary power has been totally compensated by shunt APC.

Table 2. THD for Load and Source Currents.

Phase	Source current	Load current
a	25.450%	0.630%
b	25.485%	0.653%
c	18.635%	0.760%

Conclusions

In this paper shunt APC has been proposed to improve some power quality problems caused by usage of nonlinear loads in power systems namely, harmonics, reactive power, load balancing, and neutral current elimination. The control method is based on P-q theory which is simple and effective, since all the calculations are algebraic operations and have the advantage of easily selection of compensation objective. Hysteresis band PWM has been used to generate the 4-leg VSI switching pulses.

The simulation results prove the following objectives have been successfully achieved:

1. The three-phase power source currents become sinusoidal, balanced, and in phase with the source voltages in other words the power source sees the load as a purely resistive symmetrical load.
2. The neutral wire current is made equal to zero.
3. Instantaneous real power supplied to load is made constant.

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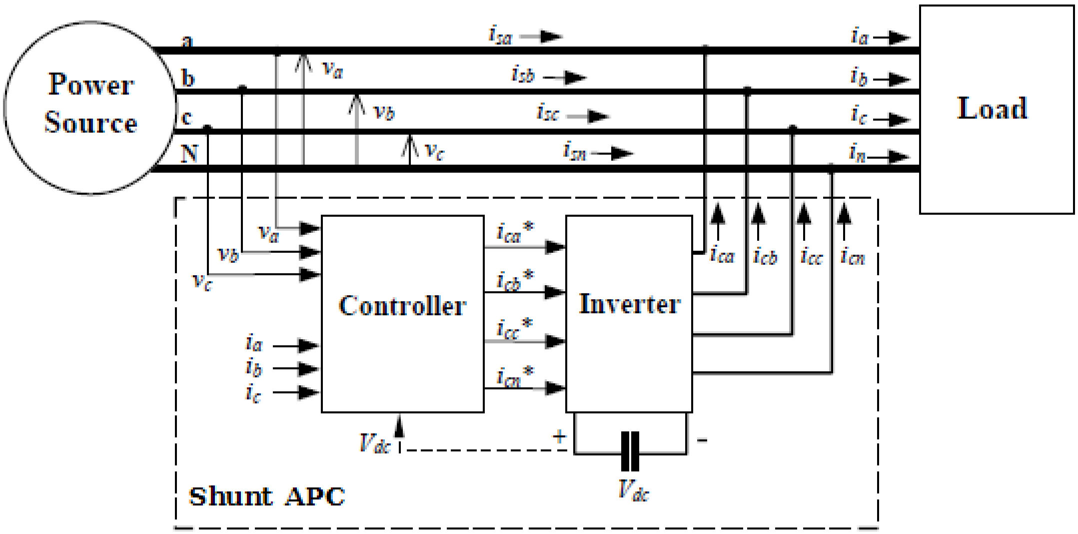

Fig. 1. Electrical Scheme of a Shunt APC.

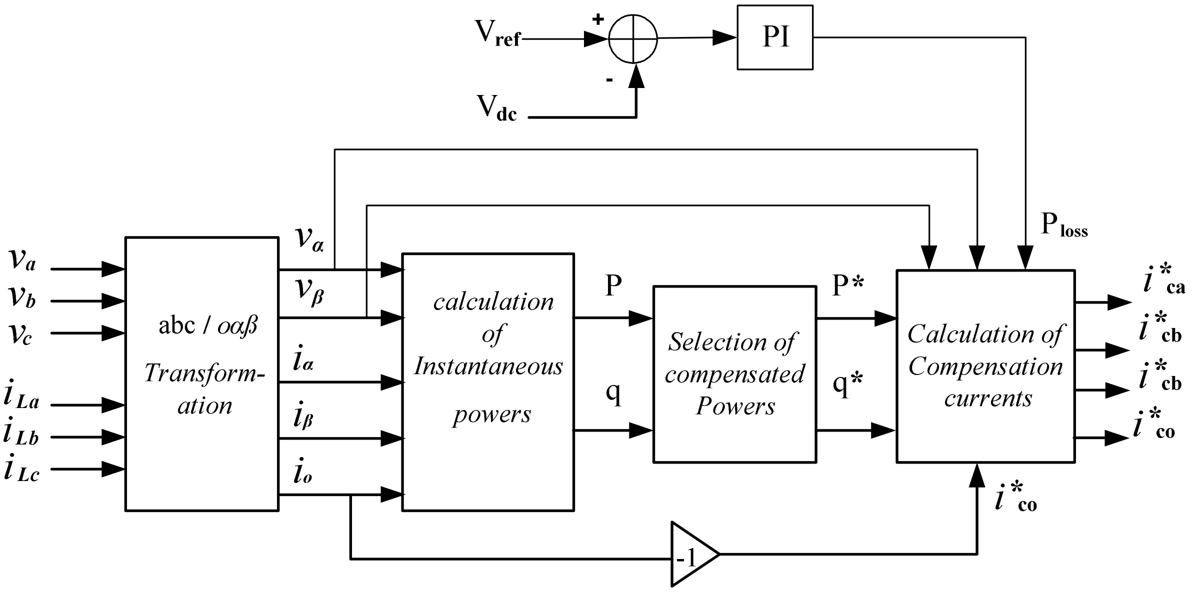

Fig. 2. Complete Block Diagram for the Control Algorithm of Shunt APC Based on P-q Theory.

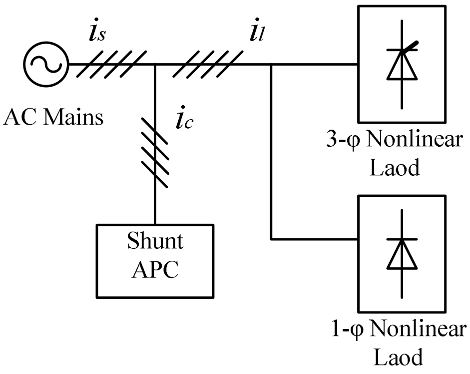

Fig. 3. Studied System Implemented in PSCAD/EMTDC.

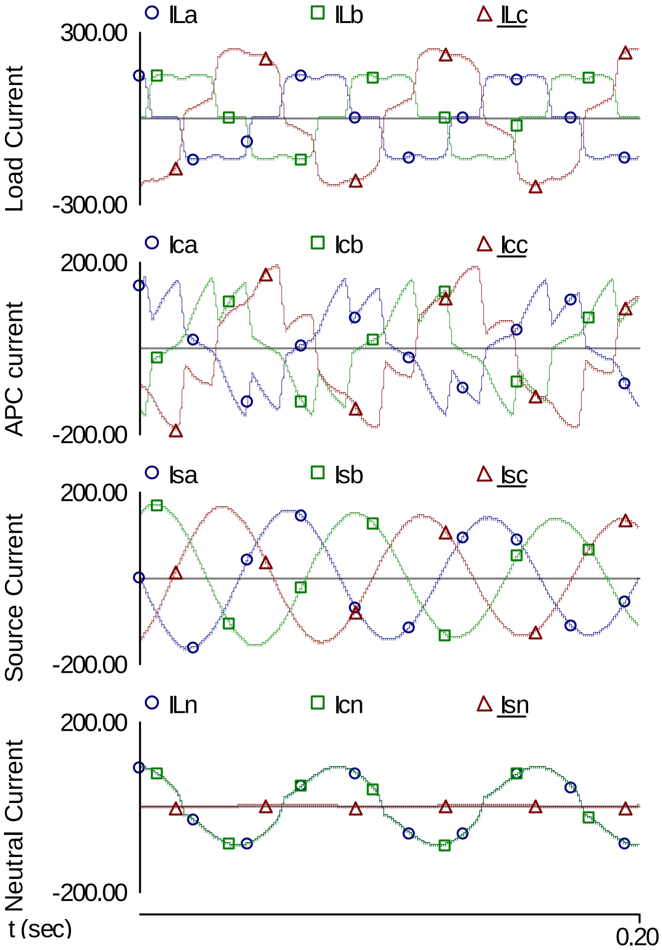

Fig. 4. System Currents.

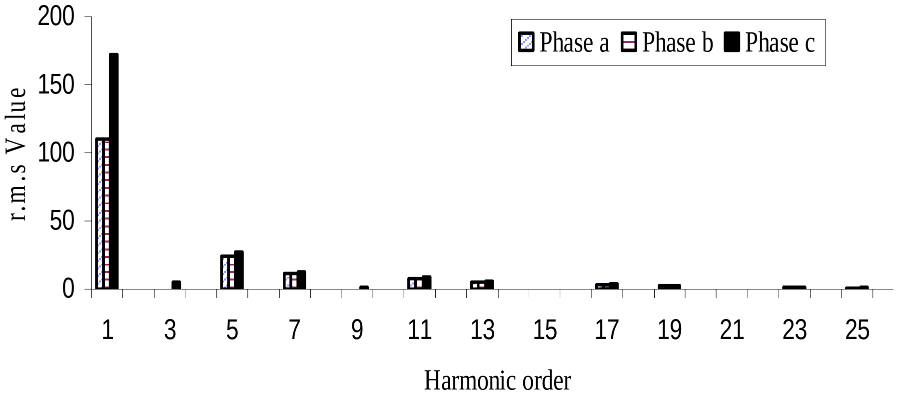

Fig. 5. Three-phase Harmonic Spectrum for Load Current.

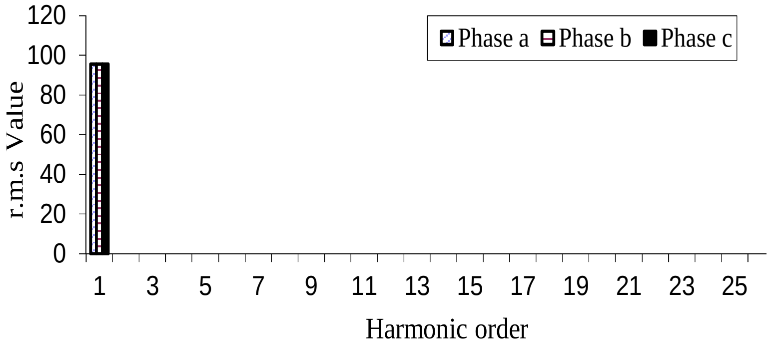

Fig. 6. Three-phase Harmonic Spectrum for Source Current.

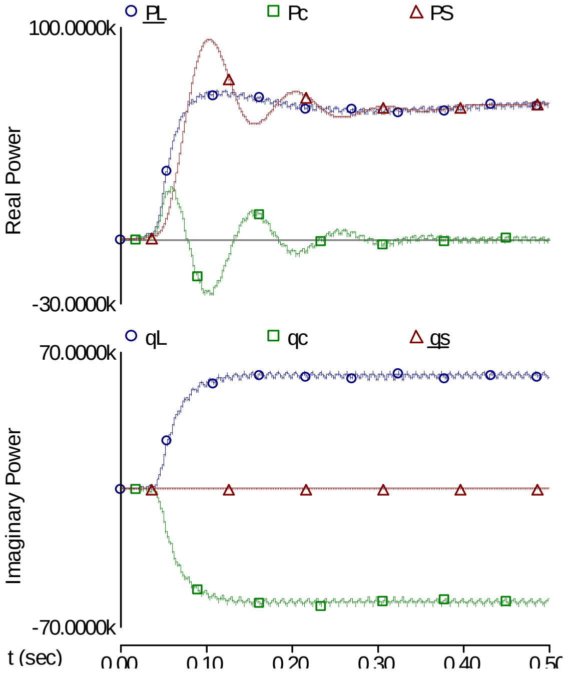

Fig. 7. System Real and Imaginary Powers.

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