RESEARCH NOTE

A NEW STRATEGY FOR SIMULTANEOUS COMPENSATION OF INSTANTANEOUS REACTIVE POWER AND HARMONICS OF NON-LINEAR LOADS

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Abstract This paper presents a new control method for simultaneous compensation of instantaneous reactive power and current harmonics by parallel active filters (PAFs). Reference compensating currents of PAF are calculated using the subtraction of instantaneous power from its average value. In this way, it is possible omitting high/low pass filter(s) from the control circuit of PAF, which usually results in phase shift and magnitude change of alternating components of instantaneous power. It is possible regulating the DC side voltage of PAF using a closed loop control circuit, easily. The presented method is compared with the classical p-q theory method through simulation results. A simple model for controlling the switches of power electronic converters is offered that is usable in PSCAD/EMTDC simulation package. Experimental results verify the validity of presented control strategy in generating of reference compensation currents.

Key Words Current Harmonics, Current Imbalance, Instantaneous Reactive Compensation

چکیده در این مقاله یک روش جدید برای جبران همزمان قدرت راکتیو لحظه‌ای، هارمونیکهای جریان و نامتعادلی جریان بار ارائه شده است. این روش جریان های مرجع جبران‌ساز فیلتر اکتیو موازی را با استفاده از تفاضل توان لحظه‌ای و مقدار متوسط توان لحظه‌ای محاسبه می‌نماید. با استفاده از این روش نیازی به بکارگیری فیلترهای پائین و یا بالا گذر که عموما منجر به ایجاد شیفت فاز و تغییر دامنۀ هارمونیکهای عبوری از این فیلترها می‌شوند نیست. با استفاده از روش ارائه شده، امکان تنظیم ولتاژ طرف DC فیلتر اکتیو موازی با استفاده از یک مدار کنترل حلقه بسته بسادگی میسر می‌گردد. کارکرد روش ارائه شده با استفاده از نتایج شبیه‌سازی با تئوری توان راکتیو لحظه‌ای مقایسه شده است. همچنین با استفاده از نتایج آزمایشگاهی کارآیی قابل توجه این روش در جبران‌سازی همزمان قدرت راکتیو، هارمونیکهای جریان و نامتعادلی جریان بار ثابت شده است.

INTRODUCTION

Active filters, since their presentation and practical utilization in 1971 and 1976, respectively have been the most suitable systems in power quality related subjects [1,2]. The compensation strategy of these systems has the most important effect on their operation. There are different compensation strategies, which are usable in active filters, but it seems that the instantaneous reactive power theory (p-q theory) is the most popular one among them [3, 4]. This theory may be used in generation of reference compensating currents of parallel active filters (PAFs) for compensation of instantaneous reactive power, successfully. This theory does not guarantee the generation of sinusoidal reference currents in the utility when a non-linear load is connected to the utility.

Simultaneous compensation of reactive power and current harmonics of non-linear loads has attracted a great deal of attention for the last few years [5,6]. This paper introduces a new strategy that is based on using subtraction of instantaneous active power and its average instead of high/low pass filter to extract the undesired terms of instantaneous active power. This strategy compensates for instantaneous reactive power and harmonics of non-linear loads and generates sinusoidal reference currents in the utility side those are in-phase with utility voltages too. Using this strategy makes it possible to regulate the voltage of DC side capacitor in a very simple manner by a closed loop control system too. The paper defines the term p*(t), explains the control strategy, presents some of selected simulation results, compares the results with classic p-q theory and verify the validity of presented control method using experimental results. A moving average calculation method is replaced with the integration of instantaneous power to compute of its average in experiment.

DEFINITION OF p*(t) AND ITS APPLICATION

According to the p-q theory, the three phase voltages and currents transforms from abc coordinates to αβ coordinates using the Equation 1 and Equation 2.

$$\begin{bmatrix} e_\alpha(t) \\ e_\beta(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} e_a(t) \\ e_b(t) \\ e_c(t) \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_\alpha(t) \\ i_\beta(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} \quad (2)$$

This theory has defined the conventional instantaneous active power, i.e. p(t) in the αβ coordinates as follows:

$$p(t) = e_\alpha(t)\, i_\alpha(t) + e_\beta(t)\, i_\beta(t) \quad (3)$$

On the other hand, from physical point of view the active power that the load dissipates from its connection instant to the utility (i.e. t_0) to an arbitrary time t, may be defined as follows:

$$p_a(t) = \frac{1}{t - t_0} \int_{t_0}^{t} p(t)dt \quad (4)$$

Using Equation 3 and setting t_0 equal with zero in Equation 4 results in the following equation:

$$p_a(t) = \frac{1}{t} \int_{0}^{t} [e_\alpha(t) i_a(t) + e_\beta(t) i_\beta(t)] dt \quad (5)$$

This equation makes it possible to compute the average of instantaneous active power from zero to a desired time, instantaneously. The $p_a(t)$ is the desired term of instantaneous active power. This equation is a general case of classical definition of active power in alternating voltage and current case. Equation 6 is the definition of classical active power in this case.

$$P = \frac{1}{T} \int_{0}^{T} p(t)dt \quad (6)$$

Where, P is the conventional active power and T is the period of instantaneous active power. Comparing Equation 6 with Equation 4 shows that this equation is an especial case of Equation 4 with $t_0 = 0$ and t = T. In other words, in alternating voltage and current case, active power means averaging of $p_a(t)$ over its period, T.

Subtraction of $p_a(t)$ from p(t) results in the instantaneous compensation power that parallel active filter (PAF) should deliver to the utility. The following equation shows this subject:

$$p^*(t) = p(t) - p_a(t) \quad (7)$$

Providing p*(t) by PAF, results in supplying only the $p_a(t)$ by utility. Using Equations (3), (5) and (7) show that it is possible to compute p*(t) by some multipliers and operational amplifiers, easily. In this method, it is not necessary using high/low pass filter to extract the undesired terms of p(t) [7]. In this way, neither phase shift nor amplitude change occurs on alternating terms of p(t). Indeed, using these filters, which is a usual case, is replaced with an integrator (see Equation 6).

The reference compensating currents of PAF results from modifying the well-known formula of p-q theory. It is enough to replacing the zero that is used in the classical p-q theory with -p*(t) [3]. This results in the following equation:

$$\begin{bmatrix} i_{C\alpha}(t) \\ i_{C\beta}(t) \end{bmatrix} = \begin{bmatrix} e_\alpha(t) & e_\beta(t) \\ -e_\beta(t) & e_\alpha(t) \end{bmatrix}^{-1} \begin{bmatrix} -p^*(t) \\ -q(t) \end{bmatrix} \quad (8)$$

Where, $i_{C\alpha}(t)$ and $i_{C\beta}(t)$ are the reference compensating currents in α and β coordinates, respectively. The authors refers to this control strategy as "p* method". The term of q(t) shows the instantaneous reactive power. Instantaneous reactive power is defined by the following equation:

$$q(t) = e_\alpha(t)\, i_\beta(t) + e_\beta(t)\, i_\alpha(t) \quad (9)$$

Transforming the reference compensating currents from $\alpha\beta$ coordinates to abc coordinates results in the following equation:

$$\begin{bmatrix} i_{Ca}(t) \\ i_{Cb}(t) \\ i_{Cc}(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -0.5 & \sqrt{3}/2 \\ -0.5 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{C\alpha}(t) \\ i_{C\beta}(t) \end{bmatrix} \quad (10)$$

In this equation, $i_{Ca}(t)$, $i_{Cb}(t)$ and $i_{Cc}(t)$ are the reference compensating currents which must be injected to the phases a, b and c, respectively. Injection of these currents by PAF compensates for instantaneous reactive power and current harmonics of non-linear load simultaneously and instantaneously.

CONTROL STRATEGY

Figure 1 shows the block diagram of control strategy. This circuit bases on the equations of previous section. In this figure, i_a, i_b and i_c are load side currents and e_a, e_b and e_c are the utility side voltages in the phases a, b and c, respectively. A minor closed loop control circuit regulates the voltage of DC side capacitor of PAF. In this figure, V_C, V^*_C and ΔV_C show the capacitor voltage, reference capacitor voltage and the error voltage of DC side capacitor, respectively.

The possibility of including the DC voltage regulating term in the reference compensating currents in such a simple way is another feature of presented control method.

It is possible using the block of $\frac{1}{t}\int_0^t p(t)dt$ to simulate the operation of control method, but it must be replaces with a moving average block in practical utilization. It is because of permanently increasing of time (i.e. "t") that results in an un-bounded size of memory after starting the operation of active filter.

A hysteresis controller is used to control the switches of PAF. The operation of three independent hysteresis current controllers in each of the phases, forces the current of PAF to follow the reference compensation currents of control circuit.

SIMULATION RESULTS

Figure 2 shows one line diagram of simulated power circuit. This figure shows a three-phase three-wire utility, a parallel active filter and a three-phase diode rectifier with a R-L load. The following equation defines the voltage of utility in the phase "a":

$$e_a(t) = 120\sqrt{2}Sin(\omega t) \quad (11)$$

The frequency of utility is 60 Hz and the voltages of phases b and c have $-\frac{2\pi}{3}$ and $\frac{2\pi}{3}$ phase shift compared with the voltage of phase "a", respectively.

The simulation package of PSCAD/EMTDC is used to simulate the operation of this circuit [7]. This software uses GTO as force commutable switches of inverter. It is possible turning ON and OFF of these switches by connecting the integer numbers of "1" and "2" to its gate port, respectively. This makes it possible using a simple

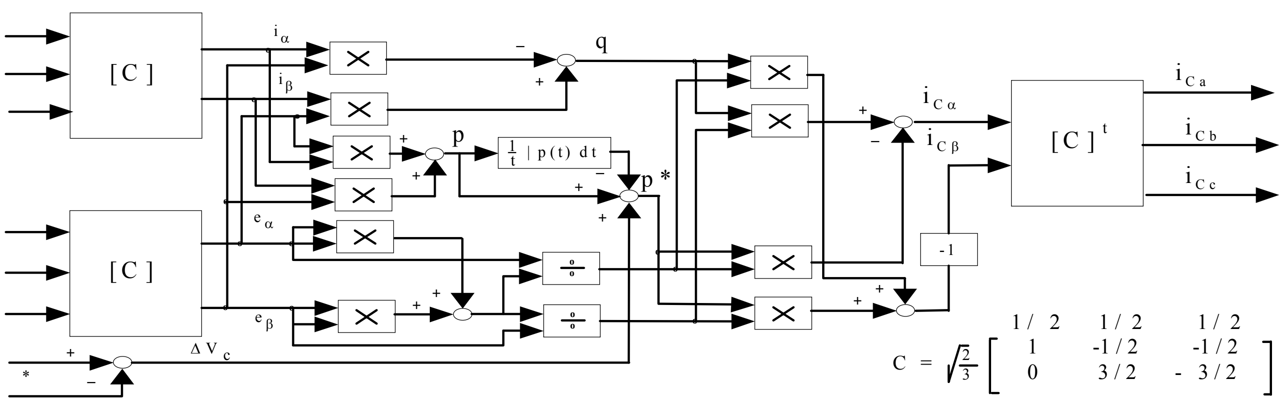

Figure 1. Block diagram of control strategy.

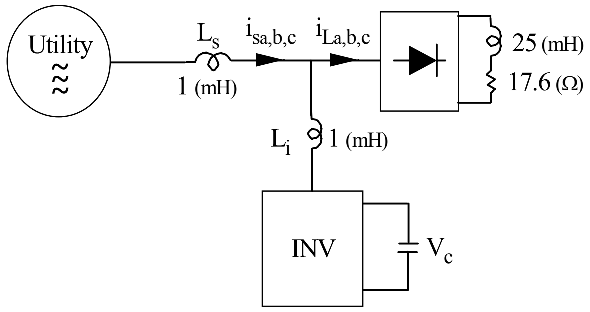

Figure 2. One line diagram of simulated power circuit.

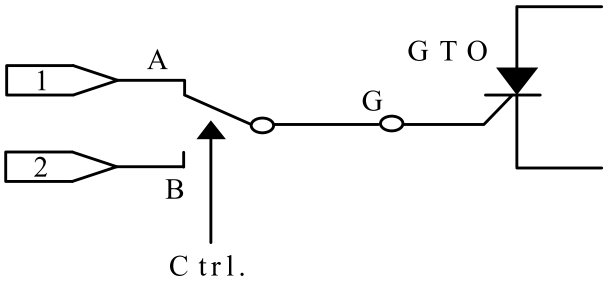

Figure 3. A simple ON/OFF controller usable in PSCAD/EMTDC simulated circuits.

changeover switch for controlling the ON/OFF state of GTO. Figure 3 shows such a circuit. The ports of A and B connects to the numbers "1" and "2" and the common port connects to the gate of GTO, respectively A hysteresis current controller generates the gating signal of GTO. Using this simple model makes it possible to simulate the operation of overall system, easily. In this way it is not necessary to write a complicate Fortran program that is a usual case.

Figure 4 shows the three-phase sinusoidal and balance utility side voltages of power circuit of Figure 2. Figure 5 shows the load side currents of this circuit in the phases a, b and c. Figure 6 shows the source side currents which are resulted from *control circuit* of p* method (only for monitoring purpose). This figure shows that this control strategy only compensates for instantaneous reactive power but also produces sinusoidal current waveforms in the utility side. To compare the operation of p* method with the classical p-q theory, the control circuit of power system of Figure 2 is replaced with classical p-q control strategy [3]. Figure 7 shows the utility side currents, which are resulted from control circuit of classical p-q theory. This figure shows that p-q theory compensates for reactive power even with non-linear loads but it cannot produces sinusoidal currents in this case. Figures 8 and 9 show the source side currents after the operation of PAF which are resulted from p* method and classical p-q theory control circuits, respectively. These figures show the effect of switching harmonics of PAF on the utility side current waveforms. It is possible to reduce these high frequency harmonics using parallel passive filters but they are not considered in these simulations.

Figure 10 shows the variations of instantaneous active power p(t) and p*(t). This figure shows that p*(t) is the fluctuating term of p(t). Figure 11 shows the injected currents by the operation of PAF. These currents compensates for instantaneous reactive power and current harmonics of non-linear load.

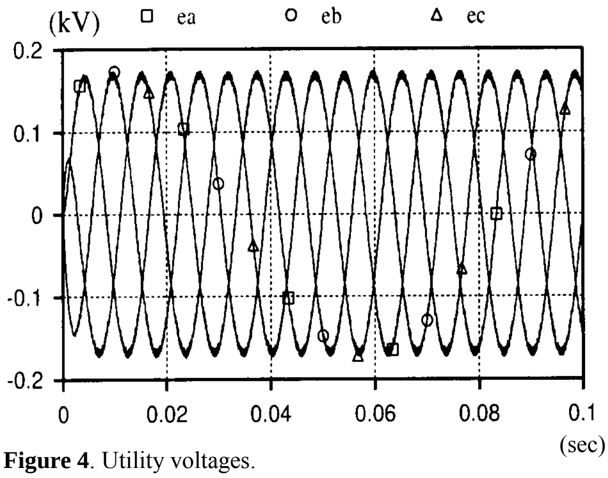

Figure 4. Utility voltages.

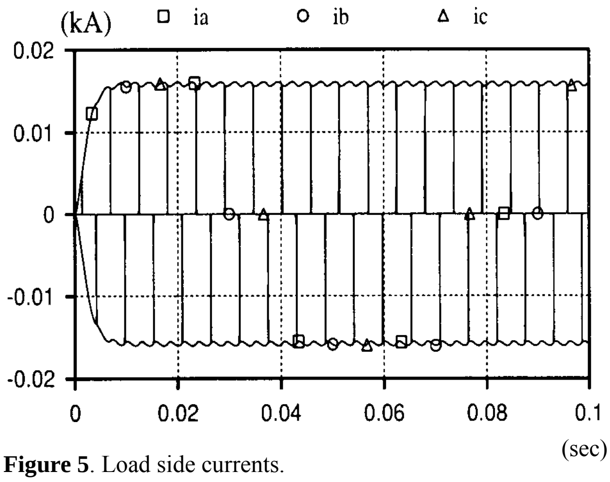

Figure 5. Load side currents.

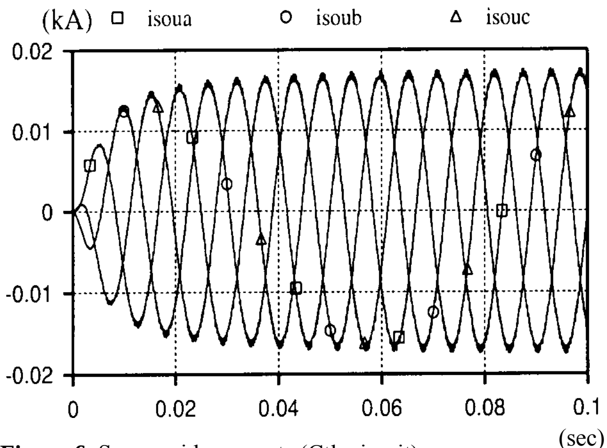

Figure 6. Source side currents (Ctl. circuit).

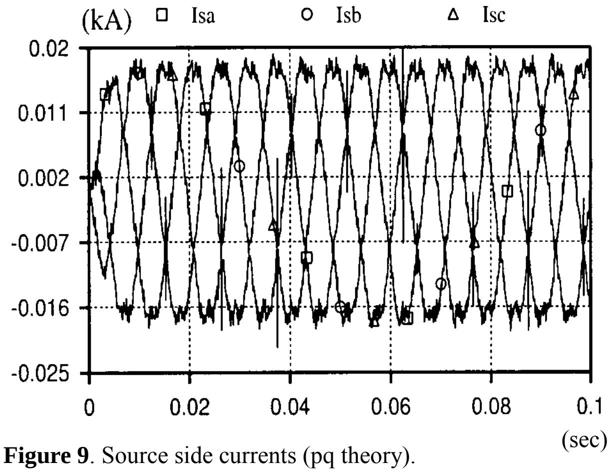

Figure 9. Source side currents (pq theory).

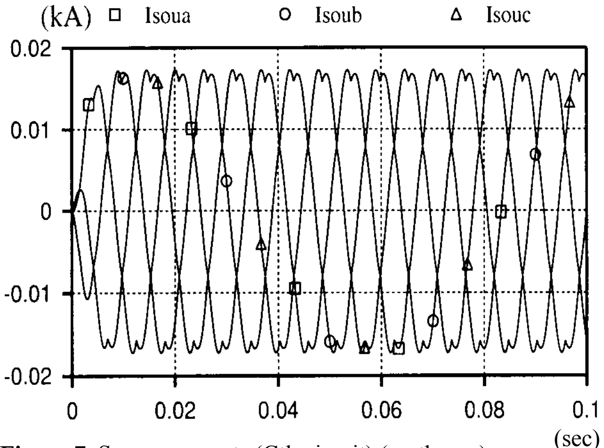

Figure 7. Source currents (Ctl. circuit) (pq theory)

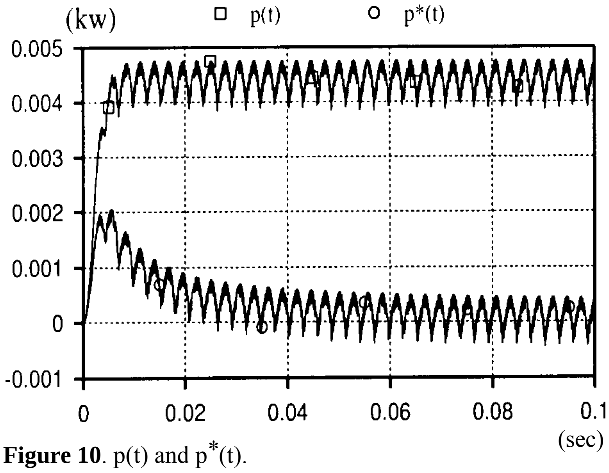

Figure 10. p(t) and $p^*(t)$.

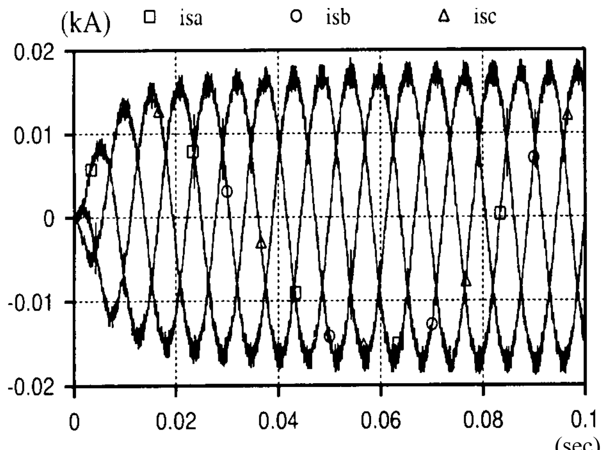

Figure 8. Source side currents.

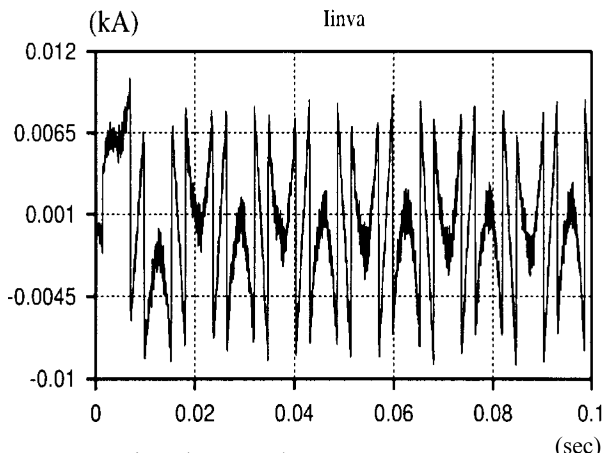

Figure 11. Injected currents by PAF.

EXPERIMENTAL RESULTS

Figure 12 shows the experimental power circuit. The utility voltages are sinusoidal and balanced with RMS value of 100 V(L-G) and fundamental frequency of 60 Hz. A 220/220 V (L-L) Δ/Y step down transformer reduces the voltage and produces the electrical isolation between utility and the rest of circuit. The inductance of utility, L_s is assumed to be 2 (mH).

The reference value of DC side voltage of active filter is set on 430 (V). Active filter, that is

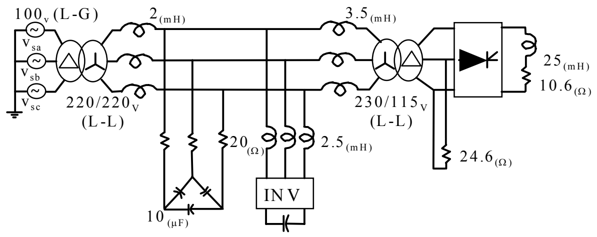

Figure 12. Experimental power circuit.

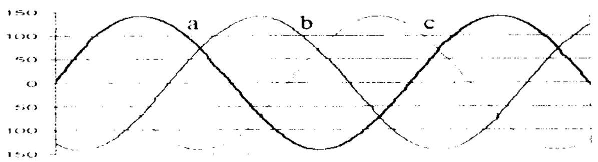

Figure 13. Utility side voltages.

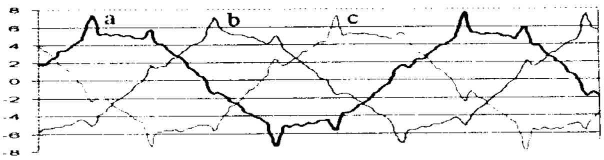

Figure 14. Source side currents.

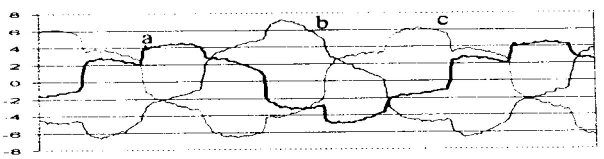

Figure 15. Load side currents.

basically a voltage source inverter (VSI), has used IGBTs with anti-parallel diodes as its switches.

The DSP of TMS 320C32 is used for controlling of the switching pattern of these switches. The value of inductances between inverter and utility are 2.5 (mH).

A Y/Δ transformer with the voltage ratio of 230/115 (V)(L-L) is used for reduction of voltage in the load side. This transformer feeds a three-phase Thyristor Bridge and a resistor. The load of Thyristor Bridge is series connection of a resistor and an inductor. This Thyristor Bridge generates current harmonics and exchanges reactive power with the utility. Figure 13 to 15 shows the utility voltages, source side currents and load side currents, respectively. Except than current harmonics due to commutation effect of Thyristor Bridge and high switching harmonics of active filter, these figures show acceptable operation of active filter and control strategy in compensation for reactive power and current harmonics. Reactive power injection effect of passive filter has resulted in small phase lead of source side currents compared with the utility side voltages.

CONCLUSION

A new control strategy for generation of reference currents of parallel active filters has been introduced. This method can be used for simultaneous compensation for reactive power and current harmonics of non-linear loads. Using this method, it is possible omitting high/low pass filter(s) from the control circuit of PAF. In this way there will be neither phase shift nor magnitude change of alternating components of instantaneous power.

The superiority of presented method is compared with the classical p-q theory through simulation results. A simple model for controlling the switches of power electronic converters is offered that is usable in PSCAD/EMTDC simulation package, easily. Experimental results have been used to verify the validity of presented control strategy. It is possible to regulate the DC side voltages of active filter using a simple minor loop control circuit, too.

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