IJERST

International Journal of Engineering Research and Science & Technology

ISSN : 2319-5991
Vol. 1, No. 2
April 2015

2nd National Conference on "Recent Advances in Science Engineering & Technologies" RASET 2015

Organized by
Department of EEE, Jay Shriram College of Technology, Tirupur, Tamil Nadu, India.

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Int. J. Engg. Res. & Sci. & Tech. 2015

International Journal of Engineering Research and Science & Technology

ISSN 2319-5991 www.ijerst.com
Special Issue, Vol. 1, No. 2, April 2015
2nd National Conference on "Recent Advances in Science,
Engineering&Technologies" RASET-2015

Research Paper

POWER QUALITY IMPROVEMENT USING SHUNT ACTIVE FILTER

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Power quality (PQ) problems have obtained increasing attentions as they can affect lots of sensitive end-users including industrial and commercial electrical consumers. This paper describes the development of a low cost shunt active power filter with digital control, which allows dynamic power factor correction and both harmonics and zero-sequence current compensation. The active filter controller is based on the instantaneous power theory (p-q theory) and was implemented using a standard 16 bits microcontroller. The p-q theory is introduced followed by the presentation of some active power filters topologies.

Keywords: Harmonics, Reactive power, Shunt active filters, Power quality

INTRODUCTION

Due to the intensive use of power converters and other non-linear loads in industry and by consumers in general, itcan be observed an increasing deterioration of the power systems voltage and current waveforms. The explanation is simple. Accordingly to Fig. 1, which presents a single-phase system, the voltage across the load terminals is: *vL*= *vS*" 2"Ä*v* where Ä*v* is the voltage drop in the power lines impedances. Even if the supply voltage *v*s is a pure sinusoid, the non-linear load input current is not, and as a result, the supply current *iS*= *iL*1 + *iL*2 includes harmonics which makes both the voltage drop Ä*v*and the load voltage (*vL*) non-sinusoidal The presence of harmonics in the power lines results in greater power losses in distribution, interference problems in communication systems and, sometimes, in operation failures of electronic equipments, which are more and more sensitive since they include microelectronic control systems, which work with very low energy levels. Because of these problems, the issue of the power quality delivered to the end consumers is, more than ever, an object of great concern.

International standards concerning electrical energy consumption impose that electrical equipments should not produce harmonic contents greater than specified values. Meanwhile it is mandatory to solve the harmonic problems caused by those equipments already installed. Passive filters have been used as a solution to solve harmonic current problems, but they present several disadvantages, namely: they only

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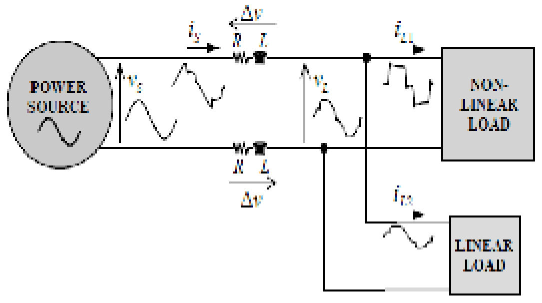
Figure 1: Load Comparision



filter the frequencies they were previously tuned for; their operation cannot be limited to a certain load; resonances can occur because of the interaction between the passive filter and other loads, with unpredictable results. To cope with these disadvantages, recent efforts have been concentrated in the development of active power filters. This paper presents a shunt active filter developed in the Industrial Electronics Department of the University of Minho, which uses a digital controller based on the p-q theory. Its main characteristics are the following:

- Dynamic power factor correction;
- Dynamic compensation of any harmonics currents with frequencies up to about 5 kHz;
- Dynamic zero-sequence current compensation;
- Flexible microcontroller-based implementation;
- Only one power converter: an inverter with just a capacitor on the DC side

2. THE P-Q THEORY

In 1983, Akagi *et al.* [1, 2] have proposed the "The Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits", also known as p-q theory. It is based in instantaneous values in three-phase power systems with or without neutral wire, and is valid for steady-state or transitory operations, as well as for generic voltage and current waveforms. The p-q theory consists of an algebraic transformation (Clarke transformation) of the three-phase voltage sand currents in the *a-b-c* coordinates to the α-β-*0* coordinates, followed by the calculation of the p-q theory instantaneous power components:

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

$$p_0 = v_0 \cdot i_0 \quad \text{- instantaneous zero-sequence power} \quad (2)$$

$$p = v_\alpha \cdot i_\alpha + v_\beta \cdot i_\beta \quad \text{- instantaneous real power}$$

$$q \equiv v_\alpha \cdot i_\beta - v_\beta \cdot i_\alpha \quad \text{- instantaneous imaginary power (by definition)}$$

The power components *p* and *q* are related to the same α-β voltages and currents, and can be written together:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad \text{...(3)}$$

These quantities, illustrated in Fig. 2 for an electrical system represented in α-β-*0* coordinates, have the following physical meaning:

*p*0 = mean value of the instantaneous zero-sequence power – corresponds to the energy per time unity which is transferred from the power supply to the load through the zero-sequence components of voltage and current.

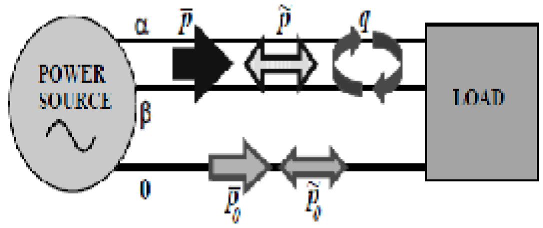
*p*0 ~ = alternated value of the instantaneous zero-sequence power – it means the energy per time unity that is exchanged between the power supply and the load through the zero-sequence components. The zero-sequence power only exists in three-phase systems with neutral wire. Furthermore, the systems must have unbalanced voltages and currents, or multiple of 3 harmonics in both voltage and current of at least one phase.

p = mean value of the instantaneous real power – corresponds to the energy per time unity which is transferred from the power supply to the load.

p~ = alternated value of the instantaneous real power – It is the energy per time unity that is exchanged between the power supply and the load.

q = instantaneous imaginary power – corresponds to the power that is exchanged between the phases of the load. This component does not imply any transference or exchange of energy between the power supply and the load, but is responsible for the existence of undesirable currents, which circulate between the system phases. In the case of a balanced sinusoidal voltage system and a balanced load, with or without harmonics, *q* (the mean value of the instantaneous imaginary power) is equal to the conventional reactive power (*q*= 3"*V* “*I*1 “*sin*ϕ1).

Figure 2: Power Components of the P-Q Theory



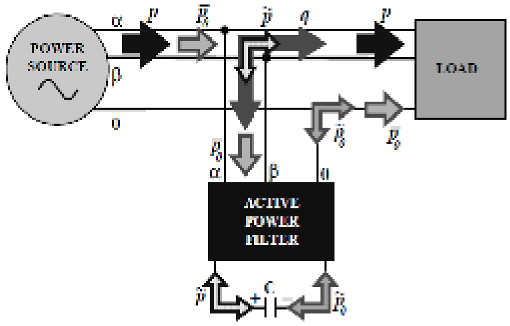
The P-q Theory Applied To Active Filters

From all the power components obtained through the p-q theory, only *p* and *p*0 are desirable, as they correspond to the energy transferred from the supply to the load. The other quantities can be compensated using a shunt active power filter (Fig. 3). Even *p*0 , which is related to a load unbalance (an undesirable operation condition), should be compensated whenever possible. *Watanabe et al* presented a way to compensate *p*0 , without the need of using any power supply in the active filter.

They showed that the value of *p*0 can be delivered from the power source to the active filter through the á-â coordinates, and then the active filter can supply this power to the load through the *0*coordinate (see Fig. 3). This means that the energy previously transferred from the source to the load through the zero-sequence components of voltage and current, is now delivered from the source phases through the active filter, in a balanced way. It is also possible to see in Fig. 3 that the active filter capacitor is only necessary to compensate *p*~ and 0 *p* ~ ,since these quantities must be stored in this component at one moment to be later delivered to the load.

The instantaneous imaginary power (*q*), which includes the conventional reactive power, can be compensated without any capacitor. If the undesired power components (*q*~ , *q* , *p*~ , *p* ~ *p*0 , 0) are compensated, and for a three-phase system with balanced sinusoidal voltages, the supply currents are also sinusoidal balanced, and in phase with the voltages. In other words, the power supply “sees” the load as a purely resistive symmetrical load. Since all the instantaneous

Figure 3: Compensation of Power Components $\tilde{p}$, q, $\tilde{p}_0$ and $\bar{p}_0$ in α-β-0 coordinates.



zero-sequence power will be compensated, the reference compensation current in the*0* coordinate is *i0* itself: *i*c0* = *i*0

To calculate the reference compensation currents in the α-β coordinates, the expression (3) is inverted and the powers to be compensated (*px* and *qx*) are used:

$$\begin{bmatrix} i_{c\alpha}{}^{*} \\ i_{c\beta}{}^{*} \end{bmatrix} = \frac{1}{{v_\alpha}^2 + {v_\beta}^2} \cdot \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} p_x \\ q_x \end{bmatrix}$$

$$p_x = \tilde{p} - \Delta\bar{p} \qquad \Delta\bar{p} = \bar{p}_0 \qquad (4)$$

$$q_x = q = \bar{q} + \tilde{q}$$

$$\begin{bmatrix} i_{ca}{}^{*} \\ i_{cb}{}^{*} \\ i_{cc}{}^{*} \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{c0}{}^{*} \\ i_{c\alpha}{}^{*} \\ i_{c\beta}{}^{*} \end{bmatrix} \qquad (5)$$

$$i_{cn}{}^{*} = -\left(i_{ca}{}^{*} + i_{cb}{}^{*} + i_{cc}{}^{*}\right)$$

In order to obtain the reference compensation currents in the *a-b-c* coordinates the inverse of the transformation given in expression (1) is applied:

ACTIVE FILTERS

There are basically two types of active filters: the shunt type and the series type. It is possible to find active filters combined with passive filters as well as active filters of both types acting together. Further more, it allows load balancing ,eliminating the current in the neutral wire. The power stage is, basically, a voltage-source inverter controlled in a way that it acts like a current-source. From the measured values of the phase voltages (*va*, *vb*, *vc*) and load currents (*ia*, *ib*, *ic*), the controller calculates the reference currents (*ica**, *icb**, *icc**, *icn**) used by the inverter to produce the compensation currents (*ica*, *icb*, *icc*, *icn*). This solution requires 6 current sensors and 4 voltage sensors, and the inverter has 4 legs(8 power semiconductor switches). For balanced loads (three-phase motors, three-phase adjustable speed drives, three-phase controlled or non-controlled rectifiers, etc) there is no need to compensate for the current in neutral wire. These allow the use of a simpler inverter (with only three legs) and only 4 current sensors. It also eases the controller calculations. It is the dual of the shunt active filter, and is able to compensate for distortion in the power line voltages, making the voltages applied to the load sinusoidal (compensating for voltage harmonics). The filter consists of a voltage-source inverter (behaving as a controlled voltage source) and requires 3 single-phase transformers to interface with the power system.

The series active filter does not compensate for load current harmonics but it acts as high-impedance to the current harmonics coming from the power source side. Therefore, it guarantees that passive filters eventually placed at the load input will not drain harmonic currents from the rest of the power system. Another solution to solve the load current harmonics is to use a shunt active filter together with the series active filter (Fig. 6), so that both load voltage sand the supplied currents are guaranteed to have sinusoidal waveforms.

Pulse Width Modulation Technique

The advent of the transformer less multilevel inverter topology has brought forth various pulse width modulation (PWM) schemes as a means to control the switching of the active devices in each of the multiple voltage levels in the inverter. The most efficient method of controlling the output voltage is to incorporate pulse width modulation control (PWM control) within the inverters. In this method, a fixed d.c. input voltage is supplied to the inverter and a controlled a.c. output voltage is obtained by adjusting the on and–off periods of the inverter devices. Voltage-type PWM inverters have been applied widely to such fields as power supplies and motor drivers. This is because: (1)such inverters are well adapted to high-speed self turn-off switching devices that, as solid-state power converters, are provided with recently developed advanced circuits; and (2) they are operated stably and can be controlled well.

The PWM control has the following advantages:

- The output voltage control can be obtained without any additional components.
- With this type of control, lower order harmonics can be eliminated or minimized along with its output voltage control. The filtering requirements are minimized as higher order harmonics can be filtered easily.

The commonly used PWM control techniques are:

(a) Sinusoidal pulse width modulation (sin PWM)

(b) Space vector PWM

The performance of each of these control methods is usually judged based on the following parameters: a) Total harmonic distortion (THD) of the voltage and current at the output of the inverter, b) Switching losses within the inverter, c) Peak-to-peak ripple in the load current, and d) Maximum inverter output voltage for a given DC rail voltage.

From the above all mentioned PWM control methods, the Sinusoidal pulse width modulation (sin PWM) is applied in the proposed inverter since it has various advantages over other techniques. Sinusoidal PWM inverters provide an easy way to control amplitude, frequency and harmonics contents of the output voltage.

SINUSOIDAL PULSE WIDTH MODULATION

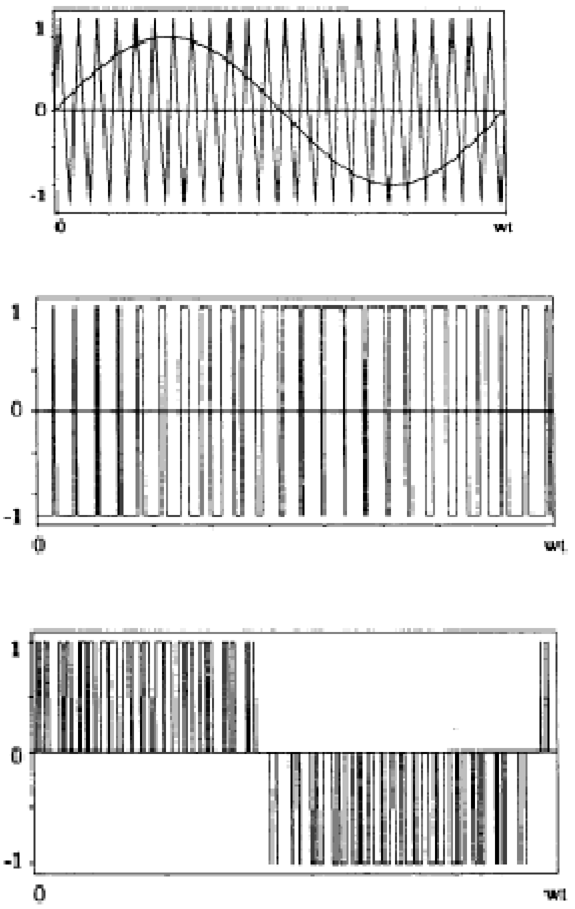
In the Sinusoidal pulse width modulation scheme, as the switch is turned on and off several times during each half-cycle, the width of the pulses is varied to change the output voltage. Lower order harmonics can be eliminated or reduced by selecting the type of modulation for the pulse widths and the number of pulses per half-cycle. Higher order harmonics may increase, but these are of concern because they can be eliminated easily by filters. The SPWM aims at generating a sinusoidal inverter output voltage without low-order harmonics. This is possible if the sampling frequency is high compared to the fundamental output frequency of the inverter.

Sinusoidal pulse width modulation is one of the primitive techniques, which are used to suppress harmonics presented in the quasi-square wave.

SAMPLING TECHNIQUE

In this method of modulation, several pulses per half-cycle are used. Instead of maintaining the width of all pulses, the width of each pulse is varied proportional to the amplitude of a sin-wave evaluated at the centre of the same pulse. By comparing a sinusoidal reference signal with a triangular carrier wave, the gating signals are generated. The frequency of reference signal determine the inverter output frequency and its peak amplitude, controls the modulation index, M, and then in turn the RMS output voltage. Fig.3.2 shows the more commoncarrier technique, the conventional sinusoidal pulse width modulation (SPWM) technique, which is based on the principle of comparing a triangular carrier signal with a sinusoidal reference waveform (natural sampling). The figure below gives the sinusoidal pulse width modulation.

Graph 3.1: (a), (b), (c) Sinusoidal Pulse Width Modulation (SPWM)



(a) Modulating/reference and carrier waveform.

(b) Line-to-neutral switching pattern.

(c) Line-to-line output waveform.

By varying the modulation index M, the RMS output voltage can be varied. It can be observed that the area of each pulse corresponds approximately to the area under the sine-wave between the adjacent midpoints of off periods on the gating signals.

The phase voltage can be described by the following expressions:

$$V(t) = M\frac{E}{2}\cos(\omega_m t + \theta) + \frac{2E}{\pi}\sum_{m=1}^{\infty} J_0\left(\frac{m\pi M}{2}\right)\sin\left(\frac{m\pi}{2}\right)\cos(m\omega_c t)$$

$$+\frac{2E}{\pi}\sum_{m=1}^{\infty}\sum_{n=\pm 1}^{\pm\infty}\frac{J_n\left(\frac{m\pi M}{2}\right)}{m}\sin\left(\frac{(n+m)\pi}{2}\right)\cos(m\omega_m t + n\omega_c t + (m+n)\theta)$$

Where *wm* is the angular frequency of modulating or sinusoidal signal.

WC is the angular frequency of the carrier signal.

M is modulation index.

E is the dc supply voltage.

*f*is the displacement angle between modulating and carrier signals.

And *Jo* and *Jn* are Bessel functions of the first kind.

The amplitude of the fundamental frequency components of the output is directly proportional to the modulation depth. The second term of the equation gives the amplitude of the component of the carrier frequency and the harmonics of the carrier frequency. The magnitude of this term decreases with increased modulation depth. Because of the presence of sin (*m*p /2), even harmonics of the carrier are eliminated. Term 3 gives the amplitude of the harmonics in the sidebands around each multiple of the carrier frequency. The presence of sin((*m*+*n*) p/ 2) indicated that, for odd harmonics of the carrier, only even-order sidebands exist, and for even harmonics of the carrier only odd order sidebands exist. In addition, increasing carrier or switching frequency does not decrease the amplitude of the harmonics, but the high amplitude harmonic at the carrier frequency is shifted to higher frequency. Consequently, requirements of the output filter can be improved. However, it is not possible to improve the total harmonic distortion without using output filter circuits. In multilevel case, SPWM techniques with three different disposed triangular carriers were proposed as follows:

1. All the carriers are alternatively in opposition (APO disposition)
2. All the carriers above the zero value reference are in phase among them, but in opposition with those below (PO disposition)
3. All the carriers are in phase (PH disposition)
4. Multi carrier modulation technique

SIMULATION OUTPUT AND DISCUSSION

During the development process of the shunt active filter, simulations were performed, which allowed the study of its behavior under different operation conditions, and permitted the tuning of some controller parameters together with the optimization of the active filter components values. There are not many simulation tools that allow working with electrical systems, power electronics and control systems.

Figure 4: simulation Diagram of Shunt Active Filter

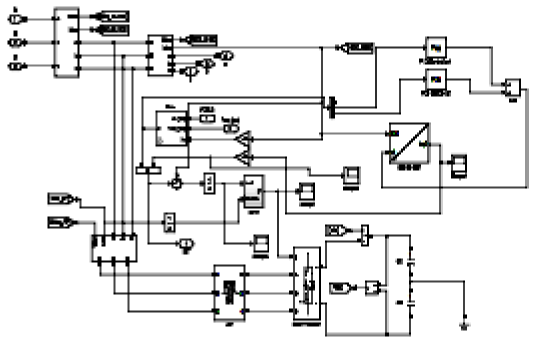


Figure 4.1(a): THD Level Without Filter

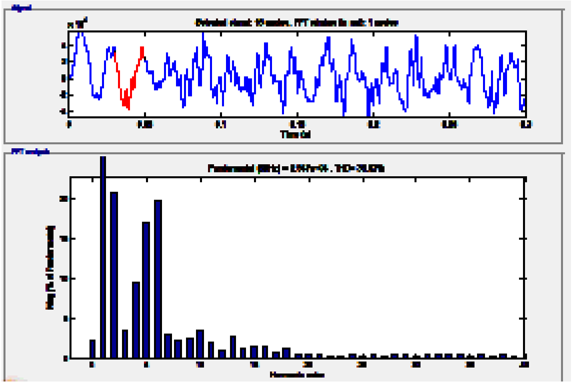
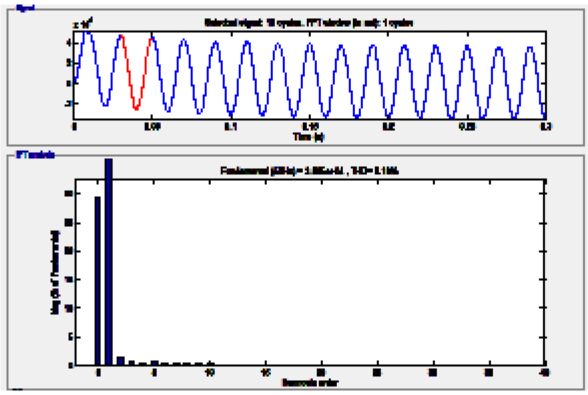


Figure 4.1(b): THD Level After Included Filter



The THD of the system before active filter is 35.63% and the THD of the system after included active filter is reduced to 2.18%

CONCLUSION

This paper presents a shunt active power filter as a reliable and cost-effective solution to power quality problems. The active filter controller is based on the p-q theory, which proved to be a powerful tool, but simple enough to allow the digital implementation of the controller using a standard and inexpensive microcontroller with minimum additional hardware. The filter presents good dynamic and steady-state response and it can be a much better solution for power factor and current harmonics compensation than the conventional approach (capacitors to correct the power factor and passive filters to compensate for current harmonics). Besides, the shunt active filter can also compensate for load current unbalances, eliminating the neutral wire current in the power lines. Therefore, this active filter allows the power source to see an unbalanced reactive non-linear load, as a symmetrical resistive load. The proposed low-cost solution allows the use of a large number low-power active filters in the same facility, close to each problematic load (or group of loads), avoiding the circulation of current harmonics, reactive currents and neutral currents through the facility power lines. This solution reduces the power lines losses and voltage drops, and avoids voltage distortions at the loads terminals.

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International Journal of Engineering Research and Science & Technology
Hyderabad, INDIA. Ph: +91-09441351700, 09059645577
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ISSN 2319-5991
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