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Simulation of The DC Capacitor Voltage Controlled Single Phase Shunt Active Power Filters for Power Quality Improvement

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ABSTRACT

In this paper, a new algorithm has been introduced to regulate the DC capacitor voltage in single phase shunt active power filters to supply converter losses over the grid. In the system, the DC busbar voltage cannot be kept stable due to converter losses. The variation in DC busbar voltage decreases the power supplied by an active power filter. Conventionally, the voltage of a DC capacitor is regulated with a PI controller to overcome this problem. In this study, a new algorithm has been introduced to compensate for converter losses in the grid. According to this algorithm, converter losses are calculated by comparing the real average active power and the reference average active power of the converter at the fundamental frequency. The power losses calculated have been added to average active power of the load and then the power losses consumed by converter have been supplied from the grid. The executed simulation results demonstrate the simplicity, effectiveness and low cost of the new algorithm.

Key Words: *Shunt active filter, Harmonics, DC voltage control.*

1. INTRODUCTION

Local and industrial loads such as power electronic equipment and non-linear electronic devices cause a type of voltage and current waveform distortion in power systems called as “harmonics” [1]. Harmonics cause several problems in consumer products and in power systems, such as higher losses, capacitor bank failure, extra neutral current, low power factor, shortened usage time of electronics equipment, errors on zero crossing sensitive control systems and resonance [2-4].

Conventionally LC passive filters are used to reduce to effects harmonics is due to their simple structure and low cost. However, effectiveness of passive filters is limited to a few harmonics and they can cause resonance in the power system. Addition, passive filters have the drawback of bulky size [5]. The alternative technique to prevent harmonics and compensate for reactive power is a shunt active power filter in power systems.

There are various studies on three and single phase shunt active power filters [6-14]. The studies focused on the calculation of reference compensation currents, current control and regulation of DC capacitor voltage. Calculation of reference current of the single phase shunt active power filter was presented by H.L. Jou *et al.* [6]. In this study a PI controller was used for the regulation of DC capacitor voltage. C.Y. Hsu *et. al.* performed a technique to provide regulation of DC

[♠] Corresponding author, e-mail: icolak@gazi.edu.tr capacitor voltage in a single phase shunt active power filter [7]. This technique decreased fluctuations of DC capacitor voltage, but requires complex calculations. In "Least Compensation Current Control Method" introduced by L. Zhou and Z. Li, the reference compensation current for a single phase active power filter was calculated [8]. The initial value of the fundamental frequency of the load current's active component causes a time delay in the calculation. S. Buso *et. al.* demonstrated that hysteresis current control provided better results than linear current control or deadbeat control for active power filters [9]. W. Shireen has proposed a technique to prevent converter losses over the DC capacitor and to regulate DC capacitor voltage [10]. In the studies done previously a PI was used controller for DC capacitor voltage. Furthermore, DC capacitor voltage was regulated with fuzzy logic in [15]. However the design of PI controller parameters and control rules for fuzzy logic circuits can be determined only through complex and quite difficult processes.

This study is focused on regulation of DC capacitor voltage and the prevention of converter losses over a DC capacitor. So, a new algorithm has been proposed. The algorithm proposed determines the converter losses by comparing reference average active power of compensation and real average active power of compensation at the fundamental frequency. The determined power losses are added to the average active power of the load and then the power losses consumed by the converter are supplied over the grid. The simulation data used to design the active power filter were achieved using MATLAB Simulink Toolbar.

2. DEFINITION OF SYSTEM AND CALCULATION OF REFERENCE COMPENSATION CURRENT

Fig.1 shows the power system connected to a non-linear load and a single phase shunt active power filter. The Single phase shunt active power filter consists of a DC capacitor located in the DC busbar as an energy storage element, a H-bridge converter and a filter inductor (L_c) to smooth the switching ripples and to limit the converter current.

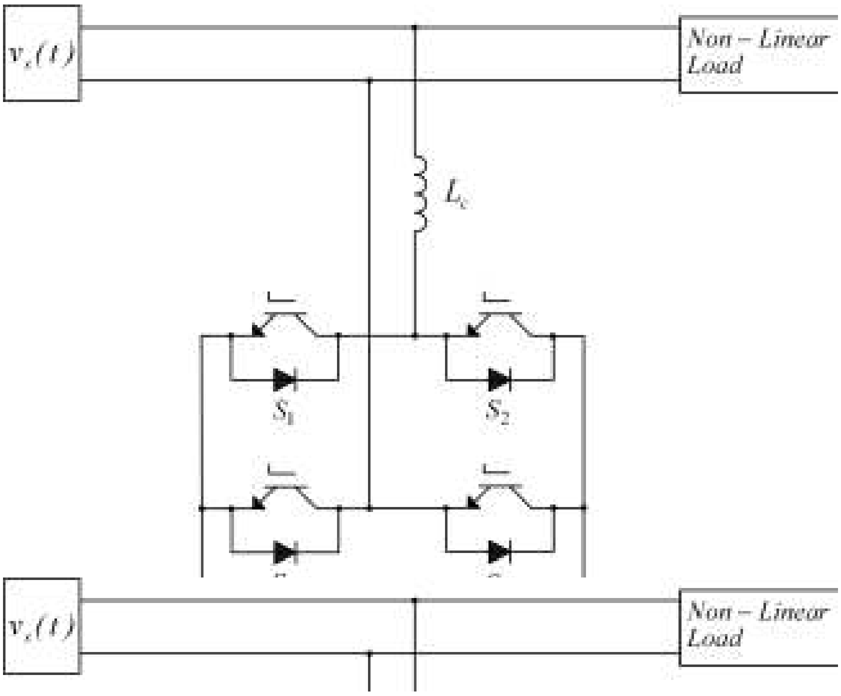


Figure 1. Non-linear load and a single phase shunt active power filter.

If the voltage of the grid is a pure sinusoidal wave form, the instantaneous value of the voltage can be represented as Eq.1.

$$v_S(t) = v_S \sin(\omega t) \qquad (1)$$

Non-linear load demands current contain harmonics from the grid. This current can be described as in Eq.2.

$$i_L(t) = \sum_{n=1}^{\infty} i_n \sin(n\omega t - \theta_n) \qquad (2)$$

Eq.2 can be expressed as Eq.3

$$i_L(t) = \underbrace{i_1 \sin(\omega t - \theta_1)}_{1} + \underbrace{\sum_{n=2}^{\infty} i_n \sin(n\omega t - \theta_n)}_{2} \qquad (3)$$

The first part is the fundamental component of the load current and the second part is the harmonic component. The active power filter provides both harmonic elimination and reactive power compensation of the load current. In another words, only the real component of the load current has been supplied from the grid while the harmonics and reactive component demanded by the load is being provided by the active power filter. This sharing of the load current is depicted in Figure 2.

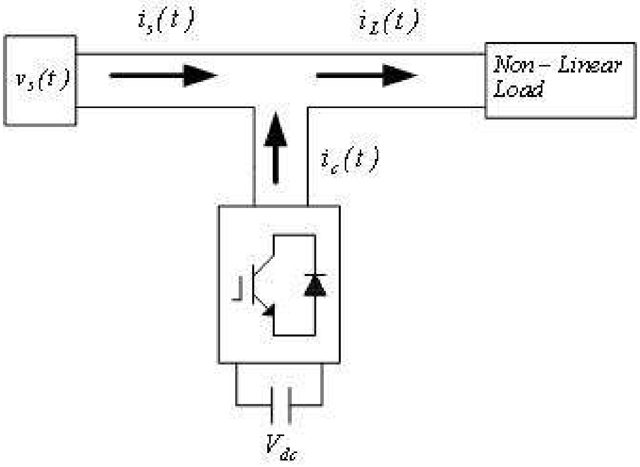


Figure 2. Sharing of the load current.

In Figure 2, $i_s(t)$ is the active component of the load current which is in phase with the voltage of the grid at the fundamental frequency. $i_c(t)$ is the compensation current and $i_L(t)$ is the total current demanded by the load.

$$i_L(t) = i_s(t) + i_c(t) \tag{4}$$

Eq.5 is explained as Eq.6

If the active component of the fundamental load current is calculated, the compensation current needed for switching signals can be found by subtracting the total current from the active component. The magnitude of the active component of the fundamental load current can be obtained from the average active power of the load. Instantaneous power demanded from the load is formulated as in Eq.5.

$$p_L(t) = v_s(t).i_L(t) \tag{5}$$

$$p_L(t) = \underbrace{v_s.i_1 \sin^2(\omega t).\cos\theta_1}_{1} + \underbrace{v_s.i_1 \sin(\omega t).\cos(\omega t).\sin\theta_1}_{2} + \underbrace{\sum_{n=2}^{\infty} v_s \sin(\omega t).i_n \sin(n\omega t - \theta_n)}_{3} \tag{6}$$

The first term is the active power of load current at the fundamental frequency and it must be provided by the supply.

$$p_s^*(t) = v_s.i_1 \sin^2(\omega t).\cos\theta_1 \tag{7}$$

The second term is the reactive power of the load current at the fundamental frequency and the third term is the power constituted by harmonics. These two powers are provided by the active power filter.

$$p_c^*(t) = v_s.i_1 \sin(\omega t).\cos(\omega t).\sin\theta_1 + \sum_{n=2}^{\infty} v_s \sin(\omega t).i_n \sin(n\omega t - \theta_n) \tag{8}$$

The average active power of the load can be calculated at the fundamental frequency as Eq.9 and Eq.10.

$$P_s^* = \frac{1}{T}\int_0^T p_L(t)dt \tag{9}$$

$$P_s^* = \frac{v_s.i_1.\cos\theta_1}{2} = V_s.I_1\cos\theta_1 \tag{10}$$

The total average active power which must be supplied by the grid is equal to sum of average losses of the converter and average active power of the load. So, calculation of converter losses is very important.

$$P_s = P_s^* + P_{loss} \tag{11}$$

The magnitude of total active current which must be supplied by grid can be calculated as Eq.12.

$$I_1\cos\theta_1 = \frac{P_s}{V_s} \tag{12}$$

The instantaneous value of this current is obtained by multiplying the magnitude of total active current with sinus signal which is in phase with the grid voltage at the fundamental frequency as in Eq.13.

$$i_s(t) = \sqrt{2}.i_1\cos\theta_1.\sin(\omega t) \tag{13}$$

The reference compensation current of the converter is calculated by subtracting the instantaneous value of the total active current from the total current demanded the by load as in Eq.14.

$$i_c^*(t) = i_L(t) - i_s(t) \tag{14}$$

3. THE CURRENT CONTROL

Various control techniques have been used to generate a current reference in an active power filter. The most predominant control techniques are hysteresis control, PWM control, deadbeat control and linear control [9]. Because of its simple and extremely robust structure, hysteresis control has been the most widely used technique a seen in literature. The switching signals are derived from the comparison of the current error with a fixed hysteresis band in the basic implementation of the hysteresis current controller. The basic block diagram of the hysteresis current control technique is shown in Figure 3.

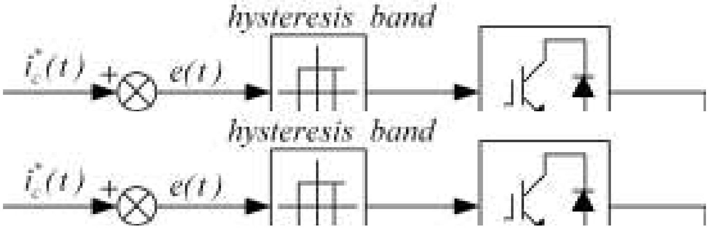


Figure 3. Block diagram of hysteresis current control.

In this study, the hysteresis current control technique is used to generate reference compensation current in an active power filter. The switching signals of the converter indicated in Figure 1 are derived by following rules;

a-) If $i_c < (i_c^* - hb)$, then S_1 and S_4 switches are off and S_2 and S_3 switches are on

b-) If $i_c > (i_c^* + hb)$, then S_1 and S_4 switches are on and S_2 and S_3 switches are off

4. THE PROPOSED CONTROL OF DC VOLTAGE

The DC busbar voltage of the converter, $v_c(t)$, cannot be kept constant because of the power loss of the converter [6]. DC link capacitor losses are combined, which decreases the compensation power provided by the active power filter. Moreover, DC voltage of the capacitor fluctuates [10]. In general, this problem can be solved by controlling the voltage of the DC capacitor with a PI controller. The PI controller output supplies a correction signal to compensate for converter losses. This signal is added to the total active current. However, to determination of PI controller parameters is quite difficult in non-linear systems [16]. In addition, the system requires an extra voltage sensor to determine DC capacitor voltage, thus increasing the cost of the control system. Classic DC voltage control is given in Figure 4.

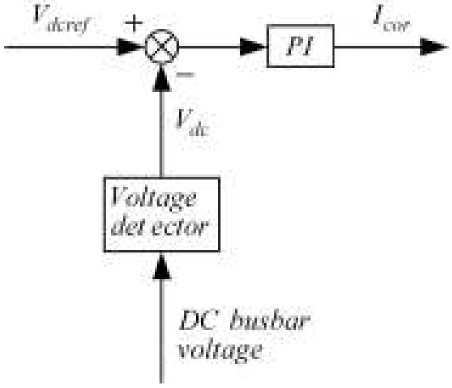


Figure 4. Classical block diagram of DC busbar voltage control.

In this paper, the new algorithm has been proposed to regulate the voltage of the DC capacitor. According to the new algorithm, the reference compensation current, $i_c^*(t)$, does not contain the active current at fundamental frequency. Hence, reference average active power of the converter, P_c^*, must be equal to zero at the fundamental frequency. This situation is shown in Eq. 15.

$$P_c^* = \frac{1}{T}\int_0^T v_s(t).i_c^*(t)dt = 0 \qquad \ldots(15)$$

Similarly, real compensation current, $i_c(t)$, generated by the switches, should not contain active current at the fundamental frequency. However, real average active power of the converter is not equal to zero because of converter losses.

$$P_c = \frac{1}{T}\int_0^T v_s(t).i_c(t)dt \neq 0 \qquad \ldots(16)$$

The difference between real and reference power of the converter shows converter losses of the filter at the fundamental frequency. The power losses of the converter must necessarily be supplied by the grid. The total average power required, which must be supplied by grid, will be calculated by adding the obtained dissipation power value to the active power demanded by the load. The block diagram of proposed algorithm is depicted in Figure 5.

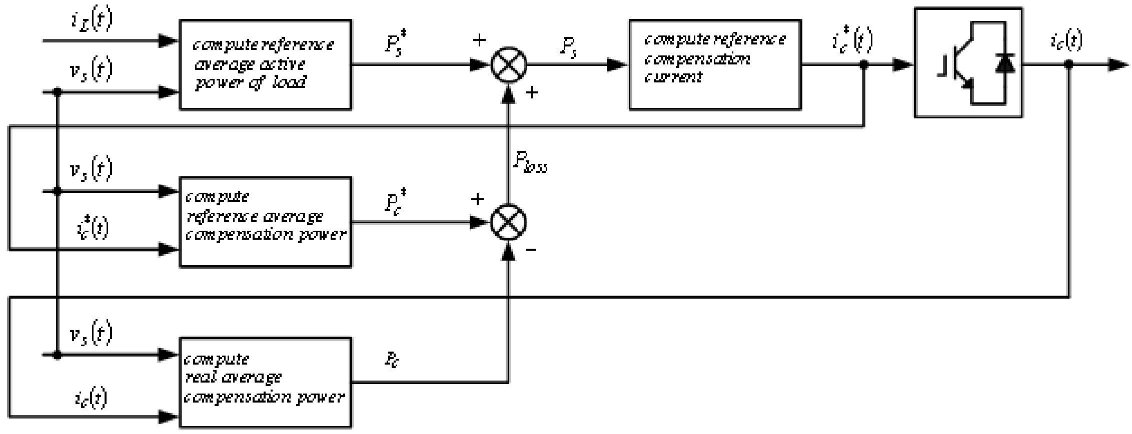


Figure 5. Block diagram of the proposed algorithm.

The total average active power which must be supplied by the grid, P_s, can be calculated by using Eqs. 17 and 18.

$$P_{loss} = P_c^* - P_c \qquad \ldots(17)$$

$$P_s = P_s^* + P_{loss} \qquad \ldots(18)$$

5. MODELING STUDIES

Table 1. The circuit parameters.

AC source voltage	V_s	220 V (RMS)
Fundamental frequency	F	50 Hz
Source inductance	L_s	1 mH
Load $R_L // C_L$	$R_L // C_L$	20 Ω/1000 µF
DC bus capacitor	C_{DC}	660 µF
Filter inductor	L_c	1.2 mH

A simulation prototype design was built to compare the performance of the new algorithm for the DC voltage controller with a conventional PI controller in an active power filter. The application that contains nonlinear load current has been developed in a Matlab/Simulink/simpower tool to prove the validation of the proposed technique as shown in Figure 6. The circuit parameters are given in Table 1.

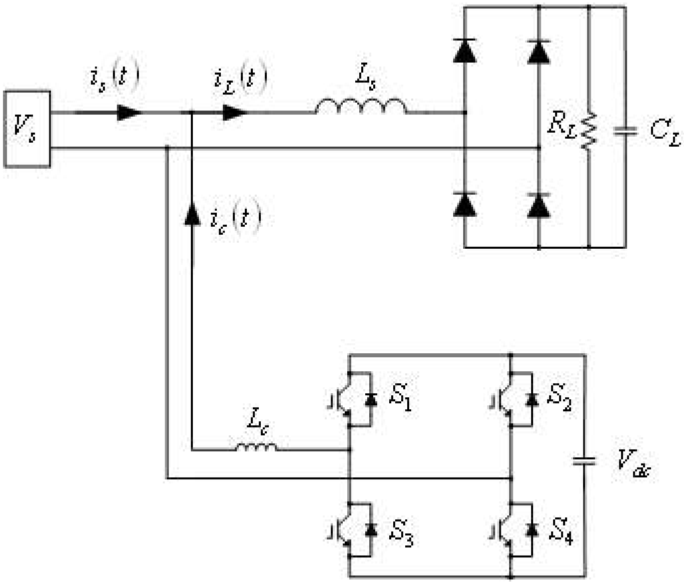
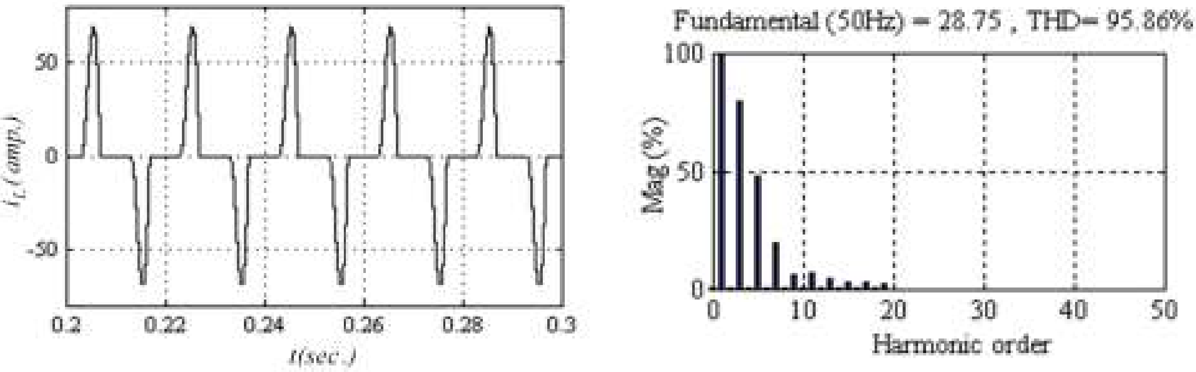


Figure 6. Model circuit.

Figure 7 (a) illustrates the waveform of the load current while the THD analysis of the load current is shown in Figure 7 (b). The load current has equal to the mains current before the connection of the active power filter and the load current THD ratio of a nonlinear load has been measured as 95.86%. The peak value of the load current has been measured as 69.8A with a 20Ω load resistor and a 1000µF load capacitor.

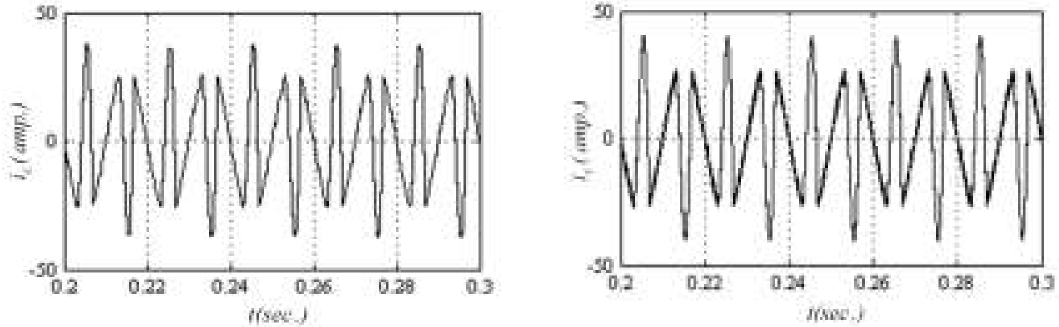


a) waveform of load current

b) THD analysis

Figure 7. Waveform and THD analysis of load current.

Figure 8 depicts the comparison of the proposed controller algorithm and the conventional PI controller outputs of compensation currents, $i_c^*(t)$, after the connection of the active power filter to the system.

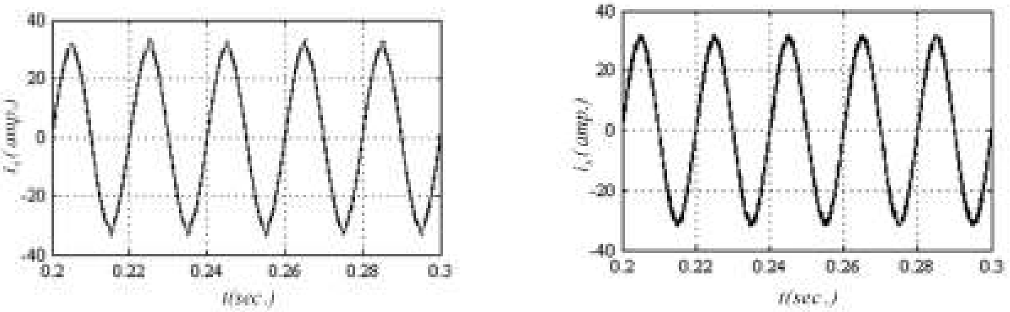


a) proposed control

b) PI control

Figure 8. Waveform of compensation current.

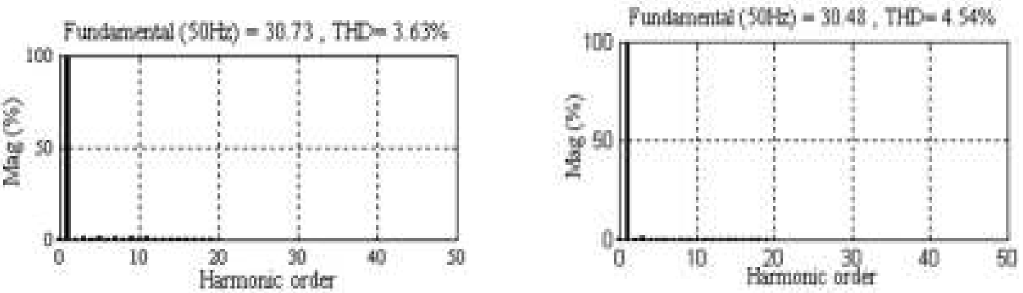
The measured peak value of the mains current, $i_s(t)$, with the proposed controller algorithm was 30.73A while it was 30.48A with a PI controller. The RMS values of the mains current were 21.72 A in the controller algorithm and 21.55A in the PI controller. The THD ratio of the mains current has been decreased from 95.86% to 3.63% by using the proposed controller algorithm. The THD ratio obtained using a PI controller was 4.54%. The waveforms of the mains current obtained using the proposed algorithm and the PI controller is shown in Figure 9 (a) and Figure 9 b) respectively. The THD analysis and comparison are depicted in Figure 10 (a) and Figure 10(b).



a) proposed control

b) PI control

Figure 9. Waveform of mains current.

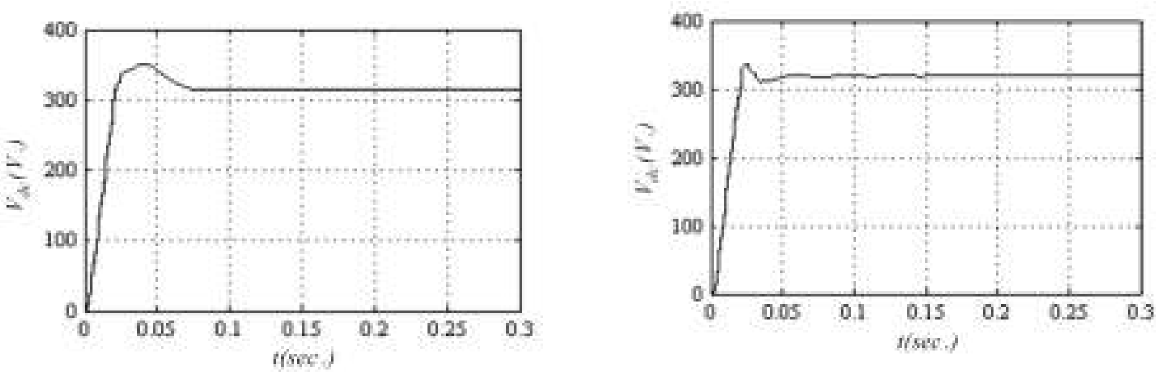


a) proposed control

b) PI control

Figure 10. THD analysis of mains current.

Figure 11 (a) Figure 11 (b) show the DC side capacitor voltage with the proposed algorithm and with PI control respectively. Table 2 compares the results of the proposed control with a PI control. Although the PI control has a better overshoot and settling time compared to the proposed method, the proposed control has a better THD ratio result.



a) proposed control

b) PI control

Figure 11. Voltage of DC capacitor.

Table 2. Results of comparison proposed control with PI control.

Control algorithm	*Overshoot* *%*	*t_r (rising time)* *(ms)*	*t_{set} (settling time)* *(ms)*	*THD* *%*
PI	5	16	26	4.54
Proposed control	11.07	17	74	3.63

6. CONCLUSIONS

The harmonic contents seen are due to the effects of local and industrial loads which cause low power factor and losses in power systems. In this study, a new technique has been proposed to regulate the DC voltage of a capacitor and to compensate for converter losses over the grid in a single phase active power filter of a converter which significantly solves power quality problems. In general, previous studies were based on PI control of DC capacitor processes. However, the main difficulty in PI control is the definition of the parameters. Moreover, the voltage of the DC capacitor should be detected with a voltage sensor. In the proposed method, capacitor voltage was maintained as a constant value without complex processes or an additional voltage sensor. The simulation results obtained clearly show the effectiveness, simplicity and low cost of the proposed algorithms.

Nomenclature

$v_s(t)$ = grid voltage

v_s = peak value of grid voltage

V_s = rms value of grid voltage

T = period of the mains

θ_n = phase of the nth – order harmonic of load current

θ_1 = phase of the fundamental component of load current

i_n = peak value of nth – order harmonic of load current

i_1 = peak value of the fundamental component of load current

I_1 = rms value of the fundamental component of load current

$i_L(t)$ = load current

$i_s(t)$ = mains current

$i_c(t)$ = real compensation current

$i_c^*(t)$ = reference compensation current

I_{cor} = output of the PI controller

$p_L(t)$ = instantaneous power of load

$p_s^*(t)$ = instantaneous active power of load

$p_c^*(t)$ = instantaneous power provided by active power filter

P_s^* = reference average active power of load

P_s = real average active power of load

P_c^* = reference average compensation power

P_c = real average compensation power

P_{loss} = average power loss of the converter

hb = hysteresis band

$e(t)$ = error value

C_{dc} = DC capacitor

$v_{dc}(t)$ = DC capacitor voltage

V_{dc} = average voltage of DC capacitor

V_{dcref} = reference voltage of DC capacitor

L_c = filter inductor

L_s = source inductance

C_{DC} = DC bus capacitor

REFERENCES

[1] Grady, W.M., Santoso, S., “Understanding Power System Harmonics”, ***IEEE Power Eng. Rev.***, 21 (11): 8-11 (2001).

[2] Subjak, J.S., Mcquilin, J.S., “Harmonics-Causes, Effects, Measurements and Analysis”, IEEE T. Ind. Appl., 26 (6): 1034-1042 (1990).

[3] Martzloff, F.D., Gruzs, T.M.,” Power Quality Site Surveys: Facts, Fiction and Fallacies”, ***IEEE T. Ind. Appl.***, 24 (6): 1005-1018 (1988).

[4] Wagner, V.E., Balda, J.C., Griffith, D.C., McEachern, A., Barnes, T.M., Hartman, D.P., Phileggi, D.J., Emannuel, A.E., Hortion, W.F., Reid, W.E., Ferraro, R.J., Jewell, W.T., “Effects of Harmonics on Equipments”, ***IEEE T. Power Deliver***, 8 (2): 672-680 (1993).

[5] Izhar, M., Hadzer, C.M., Syafrudin, M., Taib, S., Idris, S., “Performance for Passive and Active Power Filter in Reducing Harmonics in the Distribution System”, ***National Power & Energy Conference (PECon)***, Kuala Lumpur, 104-108 (2004).

[6] Jou, H.L., Wu, J.C., Chu, H.Y., “New Single-Phase Active Power Filter”, ***IEE P-Elect. Pow. Appl.***, 141 (3): 129-134 (1994).

[7] Hsu, C.Y., Wu, H.Y., “A New Single Phase Active Power Filter with Energy-Storage Capacity”, ***IEE P-Elect. Pow. Appl.***, 143 (1): 25-30 (1996).

[8] Zhou, L., Li, Z., “A Novel Active Power Filter Based on the Least Compensation Current Control Method”, ***IEEE T. Power Electr.***, 15 (4): 655-659 (2000).

[9] Buso, S., Melesani, L., Mattavelli, P., “Comparison of Current Control Techniques for Active Filter Applications”, ***IEEE T. Ind. Electron.***, 45 (5): 722-729 (1998).

[10] Shireen, W., Tao, L., “A DSP-Based Active Power Filter for Low Voltage Distribution Systems”, ***Electr. Pow. Syst. Res.***, 78 (9): 1561–1567 (2008).

[11] Tanaka, T., Hiraki, E., Ueda, K., Sato, K., Fukuma, S., “A Novel Detection Method of Active and Reactive Currents in Single-Phase Circuits Using the Correlation and Cross-Correlation Coefficients and Its Applications”, ***IEEE T. Power Deliver***, 22 (4): 2450-2456 (2007).

[12] Rahmani, S., Al-Haddad, K., Kanaan, H.Y., “A Comparative Study of Shunt Hybrid and Shunt Active Power Filters for Single-Phase Applications: Simulation and Experimental Validation”, ***Math. Comput. Simulat.***, 71 (4): 345-349 (2006).

[13] Akagi, H., Kanazawa, Y., Nabae, A., “Instantaneous Reactive Power Compensator Switching Devices without Energy Storage”, ***IEEE T. Ind. Appl.***, IA-20 (3): 625-629 (1984).

[14] Singh, B., Al-Haddad, K., “A New Control Approach to Three-Phase Active Filter for Harmonics Reactive Power Compensation”, ***IEEE T. Power Syst.***, 13 (1): 133-138 (1998).

[15] Jain, S.K., Agrawal, P., Gupta H.O., “Fuzzy Logic Controlled Shunt Active Power Filter for Power Quality Improvement”, ***IEE P-Elect. Pow. Appl.***, 149 (5): 317-328 (2002).

[16] Atacak, I., Duran, F., Bay, O., “Design of A Fuzzy-PI Controlled Three-Phase Active Power Filter”, ***5th International Advanced Technologies Symposium (IATS)***, Karabuk, 231-236 (2009).