

VOLTAGE AND CURRENT HARMONIC SUPPRESSION BY SHUNT ACTIVE FILTER FEEDING DC LOAD ON DC LINK

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ABSTRACT

Shunt active filter is used for suppression of current harmonics of nonlinear load to adjust total harmonics distortion (THD) of terminal voltage to the IEEE standards to improve the power quality. A specific control strategy which uses voltage detection of harmonic to reduce harmonics distortion in the waveforms of source current and terminal voltage resulting from distorted source and nonlinear load (together or separately) is applied. Moreover, the proposed control strategy is used to adjust the terminal voltage without effect on the other loads connected to the same common coupling point. This is used to reduce the voltage drop caused by current source by reducing harmonics on distribution power system to improve the power quality. The effectiveness and reliability of the specific control strategy used to control the shunt active filter has been verified by simulation results. In addition, theoretical analysis is presented to confirm the validity of the simulation results.

Index Terms-Active filter, power quality, harmonic suppression in distribution power system.

1. Introduction

Over the past few years, the growth in the use of nonlinear loads has caused many power quality problems like high current harmonics, low power factor and excessive neutral current. Nonlinear loads appear to be current sources injecting harmonic currents into the supply network through the utility's point of common coupling (PCC). This results in distorted voltage drop across the source impedance, which causes voltage distortion at the PCC. Other customers at the same PCC will receive distorted supply voltage, which may cause overheating of power factor correction capacitors, motors, transformers and cables, and mal-operation of some protection devices. Therefore, it is important to install compensating devices to eliminate the harmonic currents produced by the nonlinear loads.

So far, shunt passive filters have hitherto been used to suppress harmonics in power systems. However, shunt passive filters have many problems to discourage their applications[1]. Some publications have described the necessary limits for THD like [2], which mention the IEEE Std 519-1992 harmonic limits.

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In recent years there has been considerable interest in the development and applications of active filters because of the increasing concern over power quality [1]. In the past, there has been a number of surveys on various aspects of this topic. Several publications [3-5] have described review of active filters for power quality improvement and technological review. Quantitative analysis of shunt active filter compensation characteristics under different rectifier load situations is described in [6]. Comparisons in circuit configuration and filtering performance between hybrid and pure shunt active filters is described in [7]. In [8], design and implementation of a DSP-based shunt active power filter in three phase four wire system is presented. In [9], design of single-phase shunt active filter for three-phase four-wire distribution systems is discussed. Other several publications [10-20] have described different techniques in steps of control strategy used to control the operation of active filters because the control strategy is the heart of the active filter as mention in [3]. For the distorted node voltage, the current waveform is artificially distorted for the harmonic suppression of both the node voltage and the source current and this discussed in [21-22]. Reference [23] presents the current waveform of the pulse width modulated (PWM) converter system for suppressing the harmonics of the terminal voltage and the source current. The authors propose the current waveform whose harmonic components are in phase with the terminal voltage harmonics, by which damping of the harmonic propagation over the distribution system is possible.

This proposed paper uses control strategy of reference [23] to control the operation of shunt active filter for suppression of large amount of THD of current source and terminal voltage to the limit of IEEE standard mentioned above. Also operation of this control strategy with DC load on Dc link is studied . The effectiveness and riability of the specific control strategy used with shunt active filter has been verified by simulation results. In addition, theoretical analysis is presented to confirm the validity of the simulation results.

2. Shunt active filter based on voltage detection control strategy

2.1. System configuration

Figure. 1 shows a simple model of a power distribution system. The voltage source V_s is a distorted three-phase voltage. R_s , L_s , and C are line resistance, inductance, and power factor correction PFC capacitor, respectively.

1.1. Shunt active filter

Figure. 2 shows a power circuit of the active filter used: It consists of a three-phase voltage-fed PWM inverter using six IGBTs, three interfacing inductors L_a and a dc capacitor C_{dc} . The active filter connected in parallel to the end bus of the line is controlled in such a way as to draw the compensating current i_c from the line.

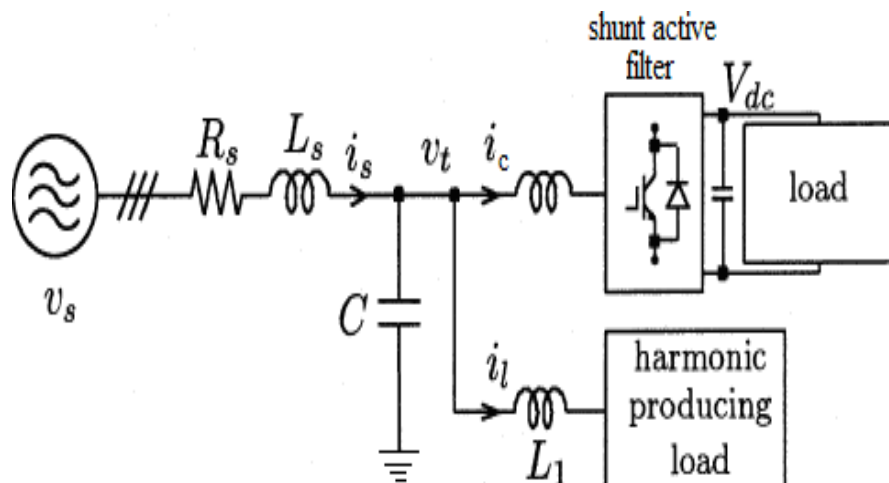


Fig. 1. Model of power distribution system

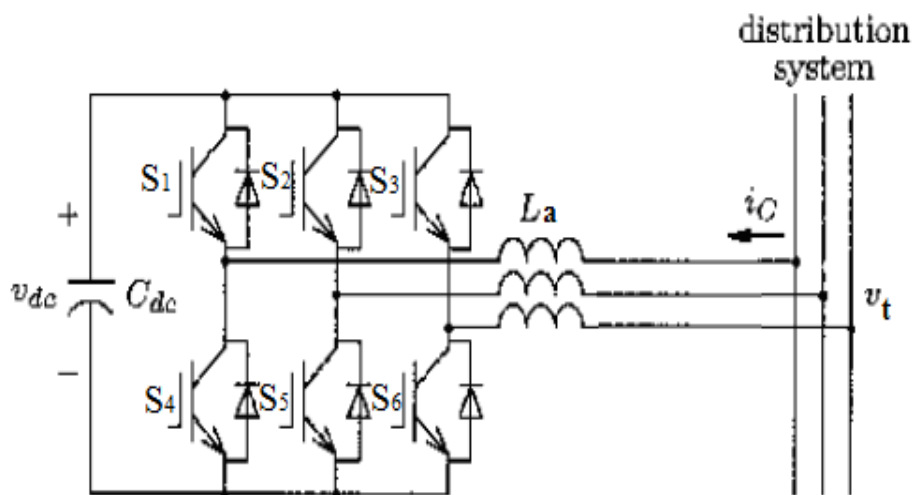


Fig. 2. Power circuit of the shunt active filter

1.2. Control strategy of the shunt active filter

Generally, the terminal voltage V_t of the common coupling point is distorted, due to the existence of the voltage harmonics of the voltage source V_s and the current harmonics of the load harmonic, and is given in (1).

$$v_t(t) = v_{tf}(t) + v_{th}(t) \quad (1)$$

Where $V_{tf}(t)$ and $V_{th}(t)$ are the fundamental and harmonic components of the terminal voltage V_t , respectively.

Under the assumption that the actual compensating current i_c is equal to its reference i_c^* , the active filter behaves like an impedance of $1/|G|k$ [Ω] for harmonic frequencies, taking into account the polarity of i_c in FIGURE 2. Hence the active filter acts as a damping resistor or a harmonic terminator to mitigate harmonic resonance in the distribution line.

In voltage detection each phase voltage V is detected at the point of installation, and then is separated to fundamental component and harmonic components by controlling as described later on. finally, the controller produces a compensating current references i_c^* based on the behaves of active filter like a resistor and voltage detection method. therefore, i_c^* is given in (2).

$$\begin{aligned} i_c^*(t) &= i_{cf}(t) + i_{ch}(t) = Gv_{tf}(t) + |G|Kv_{th}(t) \\ i_{cf}(t) &= Gv_{tf}(t), \quad i_{ch}(t) = |G|Kv_{th}(t), \end{aligned} \quad (2)$$

Where G is a variable by which the current amplitude should be determined and K is a constant which determines the amplitude of the current harmonics. According to reference [23] G must be lower than zero for the PWM to work as inverter and active filter work only as inverter.

FIGURE 3 shows a block diagram of the control strategy to detect the voltage to control the dc voltage and to generate the gate pulses. Three-phase voltages at the point of installation, V_{ta} , V_{tb} and V_{tc} , which are detected by potential transformers (PT), are transformed to V_p and V_q on the d-q coordinates which is synchronously rotating with the source or line phase angle ωt , according to equation (3).

$$\begin{aligned} \begin{bmatrix} v_d \\ v_q \end{bmatrix} &= \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \omega t & \sin \omega t \\ -\sin \omega t & \cos \omega t \end{bmatrix} \\ &\cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \end{aligned} \quad (3)$$

Now to divide the components of V_t in d - q axis V_{tp} and V_{tq} into the fundamental components V_{tpf} and V_{tqf} and the harmonic ones V_{tph} and V_{tqh} the low-pass filters (LPFs) and the high-pass filters (HPFs) with a cut off frequency of 6Hz are used as shown in FIGURE 3. Then the compensation current of the proposed filter current references i_{cp}^* and i_{cq}^* on the d - q coordinates are obtained by the following equation depending on equation (2).

$$\begin{aligned} i_{cp}^* &= Gv_{tpf} + |G|Kv_{tph} \\ i_{cq}^* &= Gv_{tqf} + |G|Kv_{tqh} \end{aligned} \quad (4)$$

The variable G is determined by the proportional–integral (PI) regulator for the dc voltage difference between the reference V_{dc}^* of 350V and the detected voltage V_{dc} .

Finally, i_{cp}^* and i_{cq}^* are transformed into three-phase compensating current references i_{ca}^* , i_{cb}^* and i_{cc}^* for the active filter using equation (5) as follows:

Once the active power filter APF reference compensation currents are determined, the current are used as input to the hysteresis current controller to produce switching signals for the PWM inverter. Using the hysteresis-band PWM technique allows the output signal to oscillate within a predefined error band with advantages of quick response and no need of information of the inverter load characteristics . The dc voltage can be controlled via a small amount of active power fed by the source to cover the inverter switching loss. All control strategy is found in DSP of the experimental system of digital controlled shunt active filter.

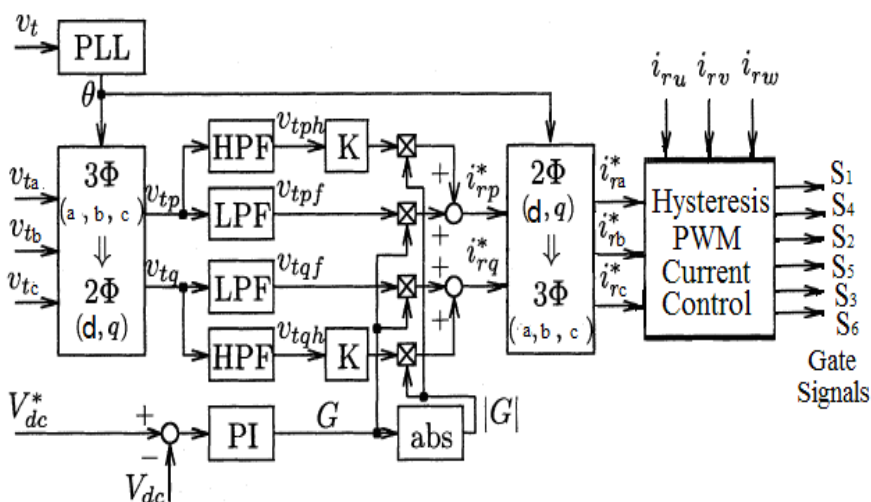


Fig. 3. Control strategy of shunt active filter

2. Harmonic suppression effect of the system with shunt active filter

Figure. 4 shows the single-phase equivalent circuit for harmonics of the distribution model in FIGURE 1. In the figure, the voltage source v_{sh} and the current source i_{lh} represent the harmonic voltage of the distorted voltage source V_s and the harmonic current of the harmonic producing load, respectively. The source harmonic current i_{sh} , the terminal harmonic voltage v_{th} , the capacitor harmonic current i_{Fh} , and the harmonic current i_{ch} of the shunt active filter in FIGURE 4 are given by:

$$i_{sh} = i_{Fh} + i_{ch} - i_{lh} \quad (5)$$

$$v_{th} = v_{sh} - \frac{i_{sh}}{Y_s} \quad (6)$$

$$i_{Fh} = Y_c v_{th} \quad (7)$$

$$i_{ch} = |G|K v_{th} \quad (8)$$

Where the line admittance Y_s and the capacitor admittance Y_c are given by:

$$Y_s = 1/(R_s + j\omega L_s) \quad (9)$$

$$Y_c = j\omega C \quad (10)$$

using the above relations from (5) to (10), v_{th} and i_{sh} are given as follows:

$$v_{th} = \frac{1}{Y_s + Y_c + |G|K} i_{lh} + \frac{Y_s}{Y_s + Y_c + |G|K} v_{sh} \quad (11)$$

$$i_{sh} = -\frac{Y_s}{Y_s + Y_c + |G|K} i_{lh} + \frac{Y_s(Y_c + |G|K)}{Y_s + Y_c + |G|K} v_{sh} \quad (12)$$

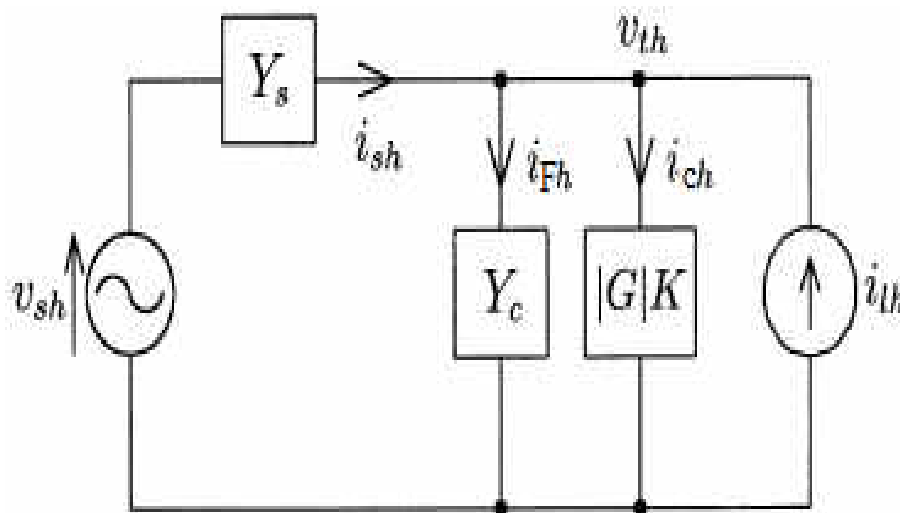


Fig. 4. Equivalent circuit for harmonics of distribution system

There are three cases for the harmonic sources , which can be summarized as follows:

2.1. Harmonic current source

Under constant harmonic current source i_{lh} and $v_{sh}=0$, the terminal harmonic voltage v_{th} and the source harmonic current i_{sh} are given as follows:

$$v_{th} = \frac{1}{Y_s + Y_c + |G|K} i_{lh} \quad (13)$$

$$i_{sh} = -\frac{Y_s}{Y_s + Y_c + |G|K} i_{lh} \quad (14)$$

It's clear from the above two equations (13) and (14), that the harmonic suppression effect on the terminal voltage v_{th} and the source current i_{sh} is decided by the control in the admittance $|G|k$, because it is the only admittance available for change or control. For higher harmonic suppression effect is obtained by changing the constant k in direction that increase the denominator to decrease the amount of harmonic from harmonic current source i_{lh} that effects on terminal voltage and source current.

2.2. Harmonic voltage source

Under constant harmonic voltage source v_{sh} and $i_{lh}=0$, the terminal harmonic voltage v_{th} and the source harmonic current i_{sh} are given as follows:

$$v_{th} = \frac{Y_s}{Y_s + Y_c + |G|K} v_{sh} \quad (15)$$

$$i_{sh} = \frac{Y_s(Y_c + |G|K)}{Y_s + Y_c + |G|K} v_{sh} \quad (16)$$

It's clear from the above two equations (15) and (16), that the harmonic suppression effect on the terminal voltage v_{th} and the source current i_{sh} is decided by the control in the admittance $|G|k$ because it is the only admittance available for change of control. Higher harmonic suppression effect is obtained by changing the constant k in direction that increase the denominator to decrease the amount of harmonic from harmonic voltage source V_{sh} that effects on terminal voltage and source current. [Like the previous case.]

2.3. Harmonic current and voltage source simultaneously

Under constant harmonic current source i_{lh} and harmonic voltage source v_{sh} , the terminal harmonic voltage v_{th} and the source harmonic current i_{sh} are given as follows:

$$v_{th} = \frac{1}{Y_s + Y_c + |G|K} i_{lh} + \frac{Y_s}{Y_s + Y_c + |G|K} v_{sh} \quad (17)$$

$$i_{sh} = -\frac{Y_s}{Y_s + Y_c + |G|K} i_{lh} + \frac{Y_s(Y_c + |G|K)}{Y_s + Y_c + |G|K} v_{sh} \quad (18)$$

It's clear from the above two equations (17) and (18), that the harmonic suppression effect on the terminal voltage v_{th} and the source current i_{sh} is decided by the control in the admittance $|G|k$ because it is the only admittance available for changing of control. Higher harmonic suppression effect is obtained by changing the constant k in direction that increase the denominator in two terms of i_{lh} and v_{sh} to decrease the amount of harmonic from harmonic current source i_{lh} and harmonic voltage source V_{sh} that effects the terminal voltage and source current. [Like two previous cases.]

3. Simulation results

3.1. System configuration in simulation model

The system configuration as a simulation model is the same model system shown in FIGURE 1. The voltage source v_s is three phase, 200V, and 60Hz. Table 1 shows the system parameters of the simulated model.

Table 1
System parameters of simulation model

R_s	1.0 Ω
L_s	1.68 mH
C	92.1 μF
L_l	4.0 mH

Figure. 2 shows the shunt active filter configuration for simulation model . We increase resistive load connected L_a in parallel with dc link of active filter to 2 KW . The interconnection reactor L_a is 8mH and the dc link capacitor C_d is 500 μF , and the control strategy is explained before.

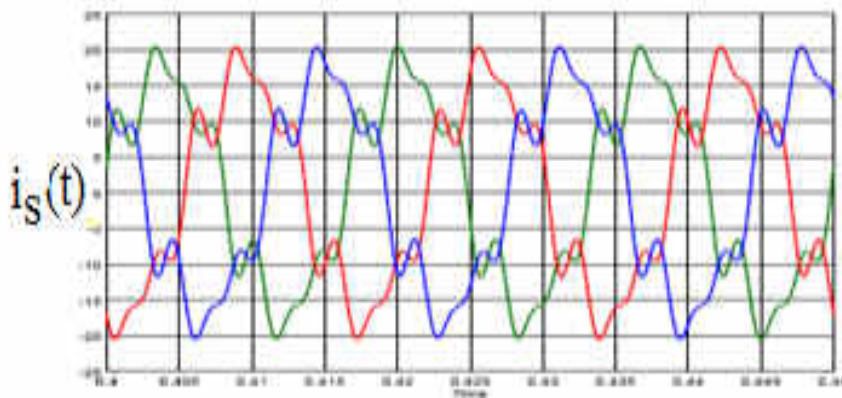
Three types of tests are carried out to prove the theoretical analysis mentioned above .Other tests to validate the control strategy under different conditions of distribution system are arranged. In the first test, a symmetrical three phase voltage source and a 2kW harmonic-producing load consisting of a diode bridge circuit having a smoothing capacitor and a load resistor are used. In the second test, the harmonic producing load is omitted and a harmonic voltage source having 1.9% seventh harmonics is used. In the third test, a

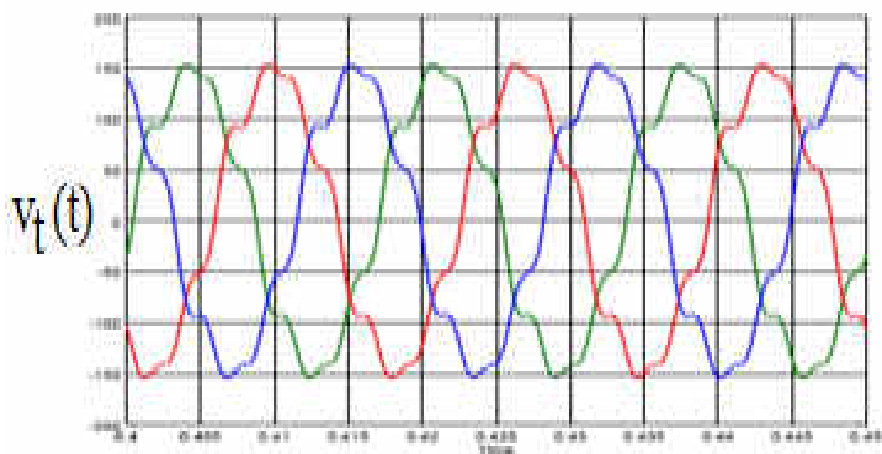
harmonic voltage source having 1.9% seventh harmonics is used and the 2kW harmonic-producing load are used simultaneously.

In all theoretical cases mentioned above the magnitude of k must increase in the negative direction for the denominators of the equations from (14) to (19) to increase because the line admittance Y_s is equal to $(.714-j.452 \text{ } \Omega)$ and the admittance of the capacitance Y_c is equal to $(j0.0347 \text{ } \Omega)$ From the two quantities Y_s and Y_c the direction for increase the denominators via increase the constant k is in negative direction because the admittance $|G|k$ is considered as imaginary part because the neutral of the active filter do not draw any active power from the distribution system. we don't need to know the real magnitude of Y_s and Y_c but only known the difference between them approximately to know in what direction to increase the magnitude of k positive or negative mentioned before .In most cases the negative direction is the correct direction because the inductance effect is always larger than the capacitance effect in distribution system.

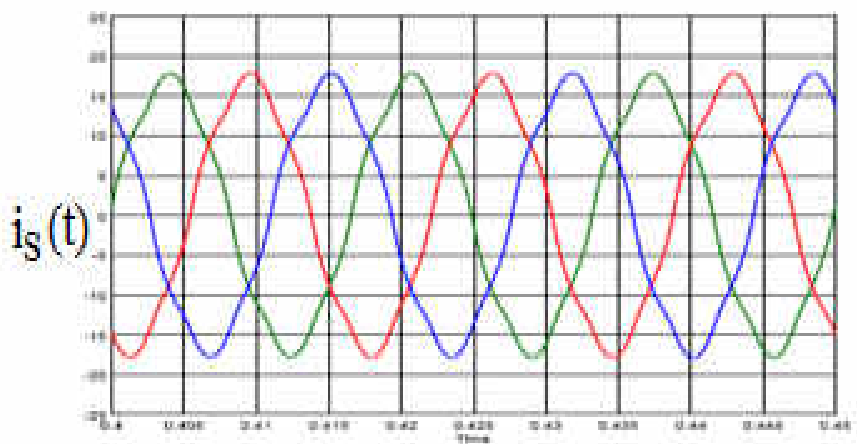
3.2. Test for harmonic current source

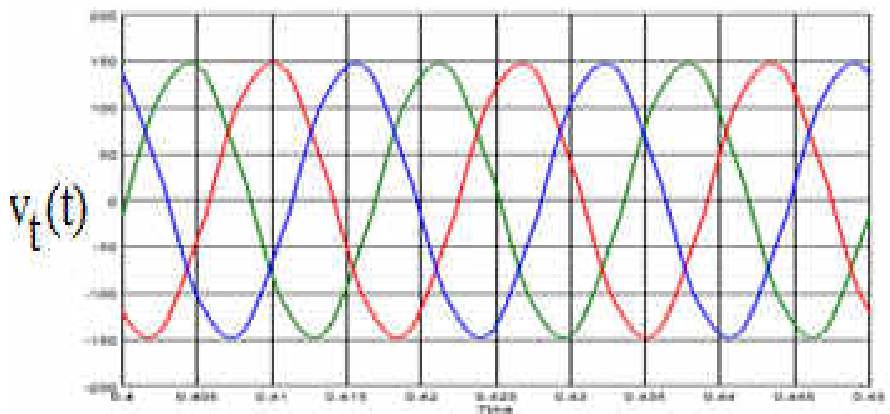
Figure. 5 shows the resulting waveforms i_s and v_t of the simulation test for the harmonic current source of a 2-kW diode bridge circuit when suppressing harmonic content of source current and terminal voltage. Table 2 shows the THDs of the terminal voltage, the source current and other quantities.





(b) For $k=0$





(b) For $k=-10$

Fig. 5. Result waveforms for harmonic current source test

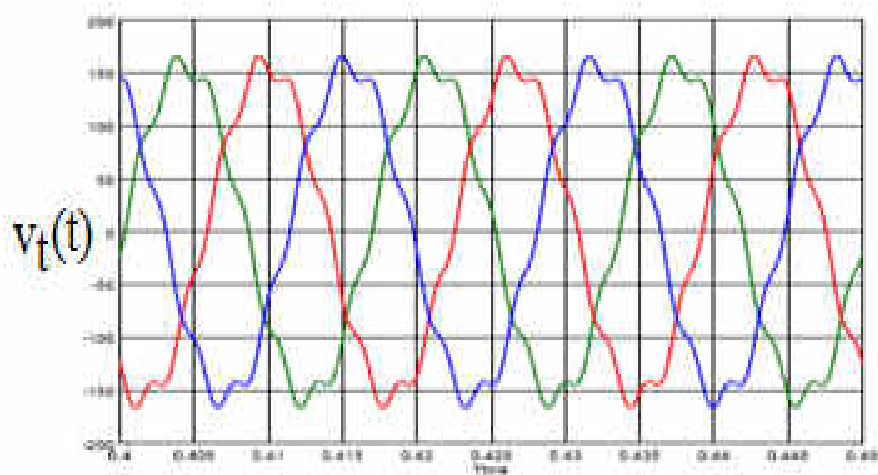
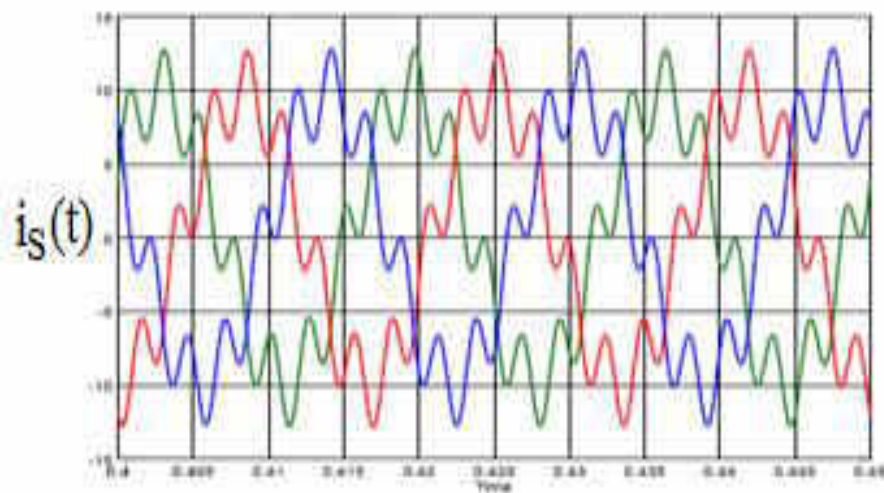
Table 2

Simulation results of harmonic current source

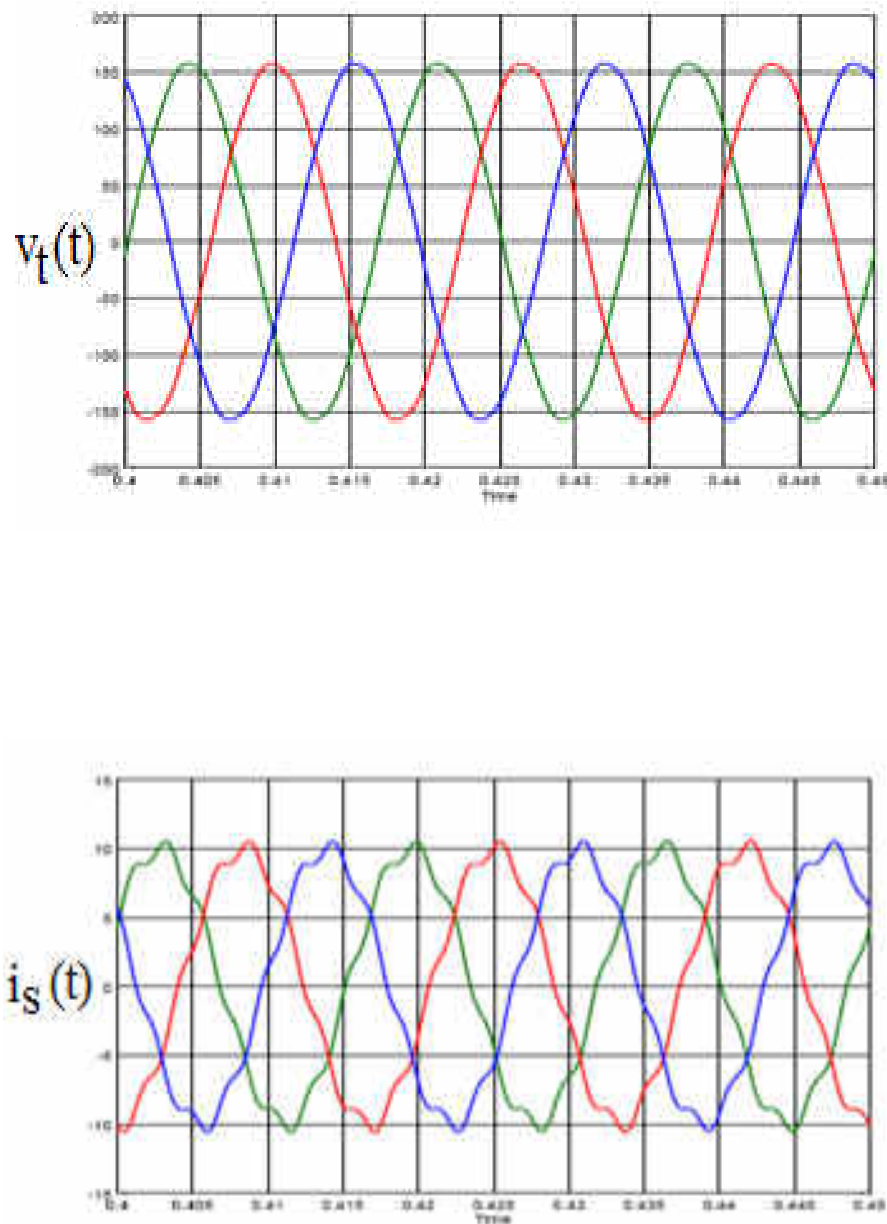
	THD[%]					
	not found	K=0	K=-1	K=-2	K=-3	K=-10
i_c	-----	3.51	8.3	12.13	14.71	21.23
v_t	11.47	11.37	7.4	5.72	4.7	2.11
i_s	50.39	24.95	17.36	13.81	11.5	5.2
i_L	21.26	21.4	22.1	23.04	23.76	25.54

3.3. Test for harmonic voltage source

FIGURE 6 shows the resulting waveforms i_s and V_t of the simulation test of the harmonic voltage source having 1.9% seventh harmonics when suppressing harmonic content of source current and terminal voltage. Table 3 shows the THDs of the terminal voltage, the source current and other quantities.



(b) For $k=0$



(b) For $k=-10$

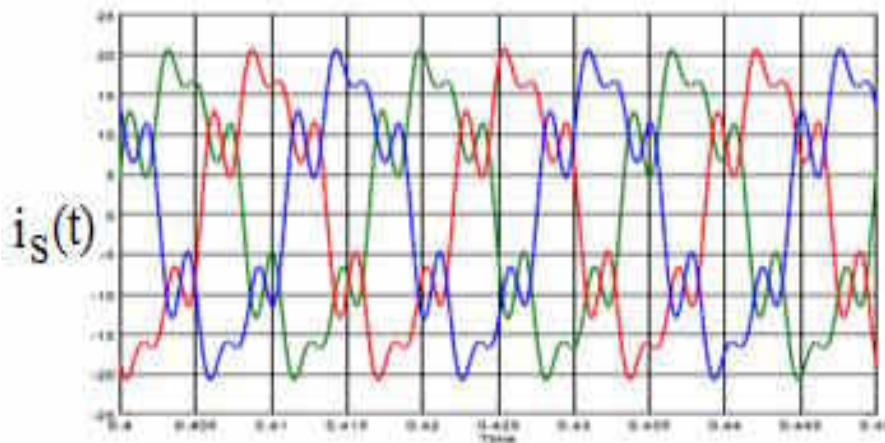
Fig. 6. Result wave forms for harmonic voltage source test

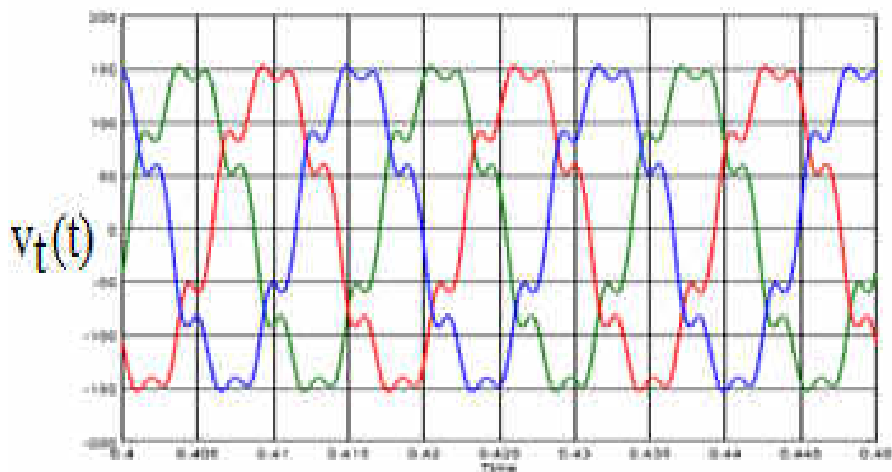
Table 3
Simulation results of harmonic voltage source

	THD[%]					
	not found	K=0	K=-1	K=-2	K=-3	K=-10
i_c	not found	3.78	5.5	6.77	7.19	8.5
v_t	7.29	7.49	4.2	2.82	2.11	0.77
i_s	51.02	28.59	16.33	11.62	9.6	6.84
v_s	1.9	1.9	1.9	1.9	1.9	1.9

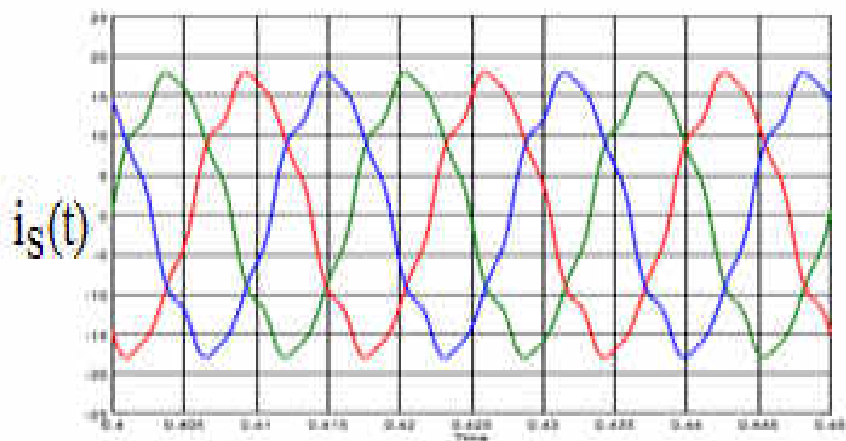
3.4. Test for Harmonic current and voltage source simultaneously

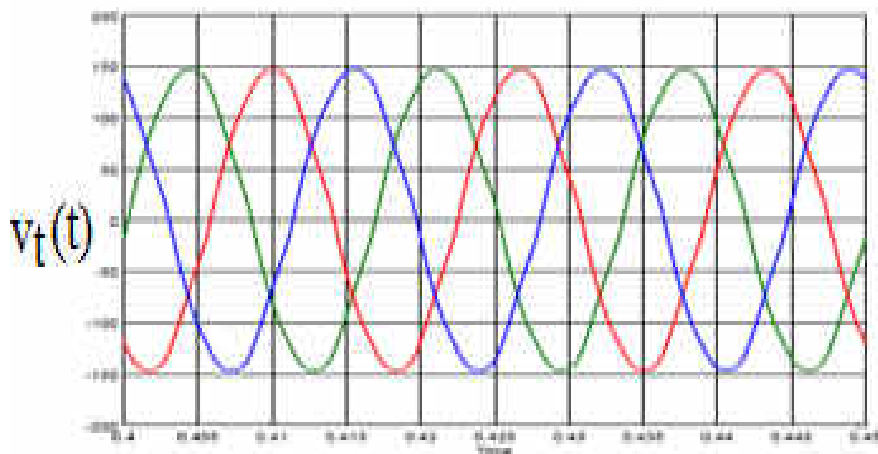
Figure 7 shows the resulting waveforms i_s and v_t of the simulation test of the harmonic voltage source having 1.9% seventh harmonics and harmonic current source of a 2-kW diode bridge circuit simultaneously when suppressing harmonic content of source current and terminal voltage. Table 4 shows the THDs of the terminal voltage, the source current and other quantities.





(b) For $k=0$





(f) For $k=-10$

Fig. 7. Result waveforms for harmonic current and voltage source simultaneously test

Table 4

Simulation results of harmonic current and voltage source simultaneously

	THD[%]					
	not found	$K=0$	$K=1$	$K=2$	$K=3$	$K=10$
i_c	-----	3.53	10.45	14.89	17.51	24.3
v_t	16.15	15.63	9.78	7.23	5.78	2.43
i_s	65.35	32.3	22.1	17.15	14.12	6.99
i_L	23.76	23.48	23.11	23.98	24.56	25.99
v_s	1.9	1.9	1.9	1.9	1.9	1.9

4. Conclusions

This paper applies a specific control strategy for controlling the operation of shunt active filter for suppression of harmonics current source and terminal voltage. The results show that in the case of only harmonic current source representing harmonic-producing load, the THD of the terminal voltage reduces to the acceptable level but the source current needs some improvement to reach to the desired limit. Also, in the case of harmonic

voltage source representing the distorted source voltage, the THD of the terminal voltage is reduced to the acceptable level but the source current needs little improvement to reach the desired limit.

In the cases of harmonic current and voltage sources simultaneously. The THD of the terminal voltage have reduced to the acceptable level but the source current needs little improvement to reach the desired limit. In all above cases, k could not increase above (-10) because the increase of k has an effect on the period needed for system to reach to steady state.

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ملخص :

يقدم البحث استراتيجية تحكم لتنظيم عمل المرشح الفعال التوازي وذلك لاختامد وتقليل التوافقيات فى التيار والجهد فى شبكة التوزيع الكهربائية نتيجة تغذية الشبكة بمصدر جهد مشوش او تحميل الشبكة بحمل غير خطى مثل الموحدات . ويستخدم هذا المرشح الفعال ايضا لتحسين جودة قدرة الشبكة. وفى هذا البحث تم تمثيل شبكة التوزيع مع الحمل الغير خطى ومصدر كهربي مشوش بدائرة مكافئة للتوافقيات ومن خلال هذه الدائرة امكن ايجاد علاقة بين مصدر التوافقيات من جهد او تيار وبين معاملات المرشح الفعال او عناصر التحكم للمرشح . ومن هذه العلاقة امكن ايجاد قيم عناصر التحكم للمرشح لاختامد التوافقيات . وقد تم عمل تمثيل لنظام شبكة التوزيع مع المرشح الفعال المحكوم باستراتيجية التحكم المقترحة . اثبتت النتائج ان الحاكم المقترح اكثر فعالية وذلك عن طريق تحسين جودة قدرة الشبكة من ناحية الجهد والتيار .

الكلمات المفتاحية :

- 1- المرشح الفعال
 - 2- جودة القدرة
 - 3- اختامد التوافقيات فى شبكة التوزيع المعامل الكلى لتشويش التوافقيات
- THD