Effect of Non-Linear Load Harmonics on Single phase Transformer Losses and Design Active Filter

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Abstract

As a result of the negative effects unshaped on some of the components in power systems such as the transformers, a great concern was shown to treatment this phenomenon so we rise in this search by designing a suitable active filter with two strategies for harmonic repression. To analysis and treatment this case, using a single-phase transformer with full-bridge rectifier, and a resistant load to generate some of total harmonic current and voltage distortions (THDi and THDv). Finally, simulation results with psim software show that the designed active filter with two strategies is very effective in harmonic elimination and power factor correction of the single phase transformer.

Keywords: Harmonic, current load, Transformer, Total harmonic current, non-sinusoidal voltages, active filter.

تأثير توافقيات الحمل اللاخطي على مفاقيد المحولة أحادية الطور و تصميم مرشح فعال

الخلاصة

نتيجة التأثيرات السلبية للتوافقيات المشوهة على بعض العناصر في منظومة القدرة ومنها المحولات اتجهت البحوث الحالية إلى الاهتمام المتزايد في معالجة هذه الظاهرة وبذلك قمنا في هذا البحث بتصميم مرشح فعال مناسب باستخدام نوعين من إستراتيجية التصميم لكبح التوافقيات . ولتحليل ومعالجة هذه الظاهرة ، تم استخدام محولة أحادية الطور مع حمل غير خطي مكون من مقاومة و (full-bridge rectifier) لتوليد عدد من حالات التوافقيات للتيار والجهد المشوه (THDi and THDv). وأثبتت النتائج النظرية باستخدام برنامج psim software بان تصميم هذا النوع من المرشح الفعال مؤثر جدا في إلغاء التوافقيات وتحسين عامل القدرة للمحولة ذات الطور الأحادي .

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1. Introduction

Harmonic is defined as a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency[1]. If, for example, the fundamental frequency 50 Hz, then the 5th harmonic is fife times that frequency, or 250Hz. Harmonic can be discussed in terms of current or voltage. Nonlinear loads draw non-sinusoidal currents. These non-sinusoidal currents pass through different impedances in the power systems and produce voltage harmonics. These voltage harmonics propagate in power systems and affect all of the power system components. These harmonic sources are classified in to Fluorescent Lamps, Switching Power Supplies, Electric Furnace, High-Voltage DC Systems, Adjustable Speed Drives, AC/DC Converters/Inverters and other Harmonic-Producing Loads**.** The principal effect of non-sinusoidal voltages on the transformer's performance is the generation of extra losses in the core [2]. Non-sinusoidal currents generate extra losses and heating of the conductors, enclosures, clamps, boldestc, thus reducing the efficiency of the transformer and accelerating the loss of life of the insulation due to the additional heating of the windings. This will lead to a reduction in expected life length of a distribution transformer and the method of calculating the reduction in life length is clearly explained in IEC 354, *loading guide for oil-immersed power transformers*[3]. An additional effect of harmonics in the network is possible oscillations between the transformer and line capacitances or any installed capacitors. The bridge rectifier is a good example of the non-linear load which is used in this paper to study the effect of the harmonic and mitigate it by using a shunt active filter. Current waveforms from non-linear loads appear distorted because the non-linear waveform is the result of adding harmonic components to the fundamental current. Non-linear loads generate high levels of harmonic currents and when supplying power to these loads, a special transformer design is necessary. With the improved performance of power and control circuits, active filters have gradually been recognized as a viable alternative to passive filters. In this paper we use active filter because it performance independent of system impedance, high cancellation effectiveness: 95% [4], no over-loading and fast response characteristics. The simulation results using the psim software verify the analysis and show the control performance.

2. Estimation of Harmonic load methods:

There are three methods of estimating harmonic load content:

2.1. Total Harmonic distortion (THD)

The square root of the sum of the square of all harmonic currents present in the load including the 50 Hz fundamental. It is usually expressed as a percent of the fundamental [5]. The following is the formula for calculating the total harmonic distortion for current (THDi):

$$I_{r.m.s} = \sqrt{I_1^2 + \sum_{h=2}^{n} I_h^2} \quad \ldots\ldots\ldots\ldots (1)$$

The percentage of the total harmonic distortion (%THD) can be written

$$\mathrm{THD} = \frac{\sqrt{\sum_{h=2}^{n} I_{hr.m.s}^{2}}}{I_{r.m.s}} \times 100\% \quad \dots\dots (2)$$

Where $I_{hr.m.s}$ is the amplitude of the harmonic component of the order h and $I_{r.m.s}$ is the r.m.s values of all the harmonics that can be represented as:

$$I_{r.m.s} = \sqrt{\sum_{h=1}^{n} I_{hr.m.s}^{2}} \quad \dots\dots\dots\dots\dots (3)$$

2.2. K Factor Rated Transformers.

K factor is a means of rating a transformer with respect to the harmonic magnitude and frequency of the load.

$$K_f = \sum_{h=1}^{\infty} (I_{h\,pu})^2 h^2 \dots\dots\dots\dots\dots (4)$$

K factor transformers are designed to supply non-sinusoidal loads and there are used smaller, insulated, secondary conductors in parallel to reduce skin effect but that is more expensive than conventional transformers [6].

2.3. Crest factor method.

It is means of determining the maximum load that may be safely placed on a transformer that supplies harmonic loads.

$$C_f = \frac{\sqrt{2}\ \text{true rms of the phase current}}{\text{peak of the phase current}} \dots (5)$$

By definition, a perfect sine wave current or voltage will have a crest factor of 1.414 and any deviation of this value represents a distorted waveform [7].

3. Harmonic current effects on transformer losses.

The harmonic currents generated by loads introduce extra losses in the transformers feeding the loads. The total load loss of a transformer can be expressed as [8]

$$P_{LL} = I^2R + P_{EC} + P_{OSL} \dots\dots (6)$$

where I^2R is the eddy current losses, P_{EC} is the loss due to stray electromagnetic flux in the windings and P_{OSL} is the stray loss in components other than the windings. Harmonic currents cause excessive eddy current losses in the transformer windings since these losses are proportional to the square of the currents and the square of the frequencies. Harmonic load currents are frequently accompanied by a dc component in the load current which will increase the transformer core loss slightly. Relatively small dc components (up to the rms magnitude of the transformer excitation current at rated voltage) are expected to have no effect on the load carrying capability of a transformer determined by this recommended practice. Higher dc current components may adversely affect transformer capability and should be avoided.

4. Time-Domain Analysis.

The equivalent circuit of a bridge rectifier which represents the input section of a typical power supply is shown in fig.(1)[9]. L and C smooth out the output dc voltage and R1 is the load resistance.

The current and voltage waveforms are illustrated in fig.(2). During the diode is forward biased, the capacitor will charge through the supply. During the diode is reverse biased, the capacitor will discharge through the load.

To find the supply current i(t) and the output voltage v(t), the circuit of fig.(1) is examined under both transient and steady state conditions. During the diode is forward biased, using Kirchhoff's laws yields;

$$i(t) = c\frac{dv_c(t)}{dt} + \frac{v_c(t)}{R} \dots\dots\dots\dots (7)$$

$$\frac{d^2v_c(t)}{dt^2}+\frac{1}{RC}\frac{dv_c(t)}{dt}+\frac{1}{LC}v_c(t)=\frac{1}{LC}v_s(t)\ \ldots\ldots(8)$$

In equation (8) the second-order differential equation is solved for $v_c(t)$ and from equation (7) the response i(t) is obtained. The complete response is the sum of the natural response and the forced response.

$$v_c(t)=v_n(t)+v_f(t)\ \ldots\ldots\ldots\ldots\ldots(9)$$

where

$$v_n(t)=e^{(at)}(B_1\cos(bt)+B_2\sin(bt))\,..(10)$$

and

$$a=\frac{1}{2RC}\ \ldots.(11)$$

$$b=\frac{\sqrt{\frac{4}{LC}+\frac{1}{R^2C^2}}}{2}$$

The constants B1 and B2 are determined by applying initial conditions to the complete response. By analyzing the circuit of fig.(1) in steady-state the forced response of $v_c(t)$ is obtained as:

$$v_f(t)=v_{mag}\sin(wt\emptyset)\ \ldots\ldots\ldots\ldots(12)$$

Where

$$v_{mag}=v_s\frac{R}{\sqrt{(R-w^2RLC)^2+(wL)^2}}\,..(13)$$

$$\emptyset=\tan^{-1}\frac{wL}{R-w^2RLC}\ \ldots\ldots\ldots.(14)$$

During the diode is reverse biased, the capacitor discharges with a time constant R and C, and

$$v_{(t)}=B_3e^{\left(-\frac{t}{RC}\right)}\ \ldots\ldots\ldots\ldots\ldots..(15)$$

The following initial conditions are applied in order to find the constants B1, B2 and B3:

During the diode is forward biased

$v_c(0)=v_c$ at end of reverse diode.

$i(0)=0$

During the diode is reverse biased

$v_c(0)=v_c$ at end of forworde diode.

4.1. Changing the Value of Circuit Parameter C.

The capacitance of the output filter should be increased to reduce the output ripple voltage of a full-wave rectifier. Fig. (3) shows the output voltage when the capacitance is doubled to 2mF. A comparison of fig.(2) and (3) reveals the reduction in the amplitude of the voltage. In addition, increasing the capacitance makes the input current flatter thus increasing the power factor as shown in fig.(2) and (3) for two different values of C.

The ripple voltage can be expressed by the following approximate formula [8]:

$$v_r=\frac{I}{Rf}\ \ldots\ldots\ldots\ldots(16)$$

Where

V_r = peak-to-peak ripple voltage

I = dc load current

f = ripple frequency

C = capacitance

v_r can be expressed in terms of the output voltage V_{dc} by substituting for $I={}^{V_C}\!/_{C}$

$$v_r=\frac{V_C}{RCf}\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots.(17)$$

For most applications the ripple voltage is considered small enough when it is less than 10% of the output voltage.

Therefore,

$$\frac{v_r}{v_c}=\frac{1}{RCf}=0.1$$

and

$$C=\frac{1}{0.1Rf}=\frac{1}{0.1*120*100}=833\mu f$$

The value of C cannot be increased for ever because a large capacitor acts as a constant dc source. In the analysis above the upper limit for C was 2 mF.

4.2. Changing the Value of Circuit Parameter L.

The inductance of the output filter has a similar impact on the output voltage and the input current of the bridge rectifier. In addition to decreasing the ripple voltage, increasing L increases the pulse-width of the input current and hence decreases its harmonic content (see fig. (4) and (5)). The value of L is constrained by its physical size and its cost.

The above analyses is important to understand how the parameters (RLC) effect on the input current and then on the element on the power system. It is useful to design a suitable filter to protect the electrical element from the effect of harmonics.

5. Active filter operation and strategies

In this paper, we are assumed that a nonlinear load consisting of a single phase rectifier consisting two diode and two thyristors with resistive loads is connected to a single phase transformer in secondary side which is connected to a sinusoidal voltage source. To avoid flowing of the switching frequency of the voltage source to the active filter, a passive LCR filter is used. Two types for the power converters [10] of the active filter have been shown in Fig. 6.

The principle work of the active filter is generating a harmonic that is reverse in phase to the distorted harmonic current it measures. Harmonics are thus cancelled and the result is a non-distorted sinusoidal current. The two branch strategies of active filter, transformer, voltage source and rectifier load is shown in Fig.7. The single phase equivalent circuit of the system and the strategy of Fig. 6a, when the S1, S4 are on and the S2, S3 are off and then the capacitor C3 is discharged as shown in Fig.8. From Fig.8, we have the following equations:

$$i_{c3} = i_{c1} + i_{L2} \dots\dots (18)$$

$$i_L = i_{L2} + i_2 \dots\dots (19)$$

$$i_L = i_{Lh} + i_{Lf} \dots\dots (20)$$

If $i_{L2} = i_{Lh}$, then from subtract equations (19) from (20), we have:

$$i_2 = i_{Lf} \dots\dots\dots\dots (21)$$

The single-phase equivalent circuit of the system and strategy of Fig.6a, when the S1, S4 are off and the S2, S3 are on and then the capacitor C3 is charged as shown in Fig. 9. From Fig. 9, we have the following equations:

$$i_2 = i_L + i_{L2} \dots\dots\dots (22)$$

If $i_{L2} = -i_{Lh}$, then, we have:

$$i_2 = i_{Lf} \dots\dots\dots\dots\dots\dots (23)$$

It is a same case discussion for the strategy shown in Fig. 6b. The single phase equivalent circuit of the system and the strategy of Fig. 6b, when the S1 is on and the S2 is off, are shown in Fig.10. In this case, the capacitor C3 is discharged. The single phase equivalent circuit of the system and the strategy of Fig. 6b, when the S1 is off and the S2 is on and then the capacitor C3 is charged as shown in Fig. 11.

6. Simulation Results

In this paper, we are using a shunt active filter to reduce and overcome the effect of the harmonic in single phase systems consisting of a single phase transformer and bridge rectifier with resistive loads. The simulation results using the psim software which is suitable and easy to verify the analysis and demonstrate the control performance. The active filter with a control circuit, using the psim software are designed and simulated as shown in fig(12). A band-pass filter has been used for generating harmonic components of the load current. The band-pass filter has been tuned at 50 Hz with the passing band of 20 Hz, because the source fundamental frequency is 50 Hz. The band-pass filter generates reference harmonic currents which should be followed by active filter. Generally, an active filter generates a harmonic that is converse in phase to the distorted harmonic current it measures in order to make sinusoidal source current and also correct the supply side power factor.

According to the analysis in figs (6 to 11), two strategies, using the psim software are designed and simulated. The supply voltage is 220v with the frequency of 50 Hz. The values of the LRC passive filter are chosen 10 Ohm, 1µF, 2mH and 0.5mH. The Switching control of MOSFETs is connected. The frequency of the triangular signal is selected 100 kHz. The values of capacitors used instead of MOSFETs in Fig. 6b are selected 1mF. The capacitor value which connects parallel with switch control of MOSFETs is 12µf. The block diagram of the designed system with the strategy of Fig. 6a, using the psim software, is shown in Fig.12. The advantages of the proposed control method are the simplicity and lower cost.

From the simulation results, active filter eliminate the harmonic distortion resulting from nonlinear load (as shown in fig. (14b)).

And we can see that the third harmonic is canceled as shown in spectrum figure (fig. (14e)).

With the strategy of Fig. 6b, the block diagram of the designed system using the psim software, is shown in Fig.13.

The simulation results for two strategies of the shunt active filter are shown in Fig.14 and 15. From Fig.14 and Fig.15 we see the strategy of Fig.6b has the same presentation of the strategy of Fig.6a, but it has lower cost by using two capacitors instead of two MOSFET switches. The THDi values of secondary currents active filter in secondary side of the transformer shown in Fig. 14 and Fig. 15 are 0.1019 and 0.17067 respectively. So, the advantages of the strategy shown in Fig. 6b, from the presentation are acceptable and economic is lower cost. Tables (1 and 2) showing the THDi%, K factor and the efficiency power for different values of secondary currents before and after filtered. A variation of THDi% before and after filter due to the variation of secondary currents in secondary side of the transformer is shown in Fig.(16) we can see the different between them. Fig.(17) showing variations of K factor before and after filter due to the variation of secondary currents. Fig. (18) showing variations of efficiency power before and after filter due to the variation of secondary currents. The efficiency of the power in active filter is higher than without filter.

Table (1) Simulation results for different values of secondary currents before filtered

Secondary current(A)	THDi %	K factor	Efficiency power η%
11	26.96	1.84	76.3
7	21.99	2.05	67.8
5.5	27.81	2.8	61.2
4	28.27	2.9	55.7
3.6	28.26	2.4	51
3	28.27	1.7	47.2
2.71	28.19	1.7	43.8

Table (2) Simulation results for different values of secondary currents after filtered.

Secondary current(A)	THDi %	K factor	Efficiency power η%
11	6.533	0.36	80.7
7	1.31	1.77	71.6
5.5	5.41	0.88	64.4
4	8.53	1.37	58.2
3.6	9.75	1.23	53
3	10.6	1.4	49
2.7	12.8	1.1	45.5

7. Conclusions.

The slight differences in the current waveforms are due to the differences in the values of the output filter parameters (L and C) of the power supplies.

The increased losses are eddy current losses that are proportional to the squares of the frequencies of the harmonic currents [11]. These losses increase the operating temperature of the transformer and require dating the transformer to a fraction of its capacity.

Analysis, simulations, and design conducted in this paper are given to study, analysis and economical solution for harmonic current.

In this paper, harmonic distortion is canceled successfully by using two strategies of the shunt active filter. The designed active filter can be implemented with lower cost in practice and it has higher efficiency. By using the strategy of Fig.6b has the same presentation of the strategy of Fig.6a, but it is lower cost because it is using two capacitors instead of two MOSFET switches. The simulation results using the psim software verify the analysis and show the control performance.

8. Reference.

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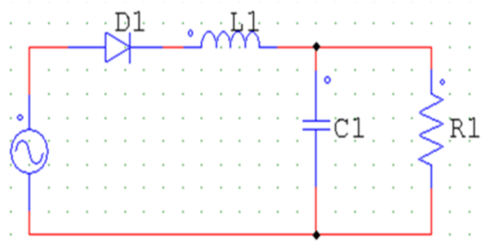
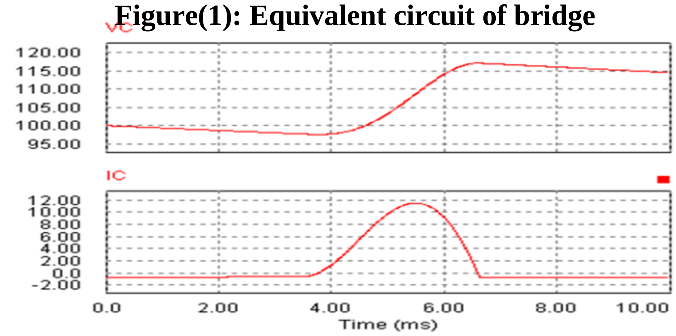


Figure(1): Equivalent circuit of bridge



Figure(2): Imaginary voltage and current waveforms for C=1 mF, L=1mH and R1=150Ω

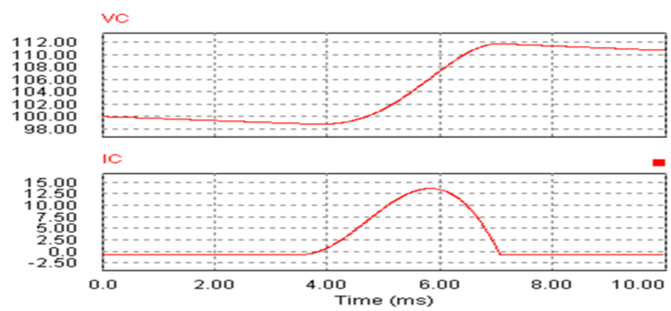


Figure (3): Imaginary voltage and current waveforms for C=2mF, L=1mH and R1=150Ω

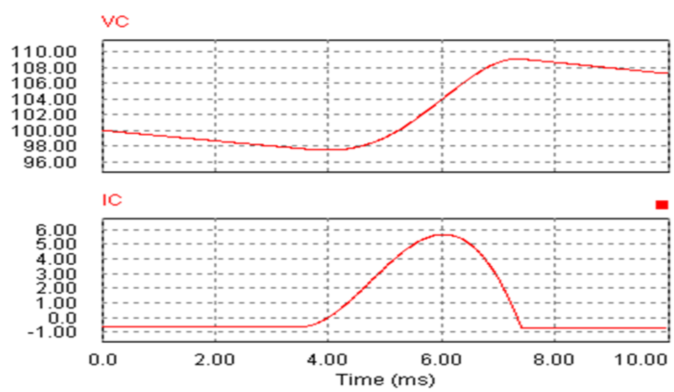


Figure (4): Imaginary voltage and current waveforms for C=1mF, L=3mH and R1=150Ω

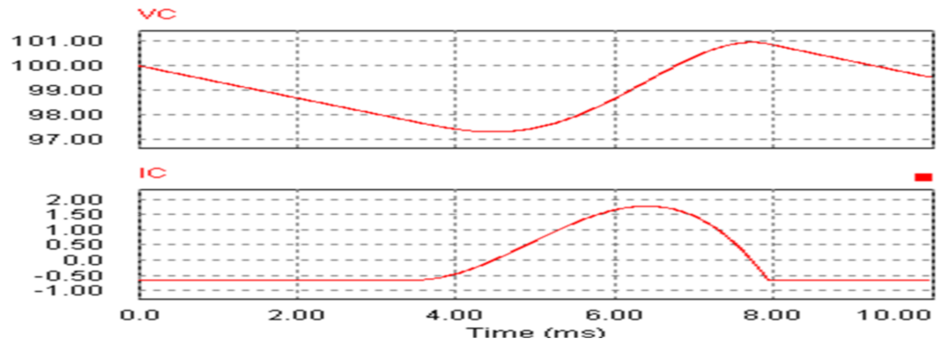
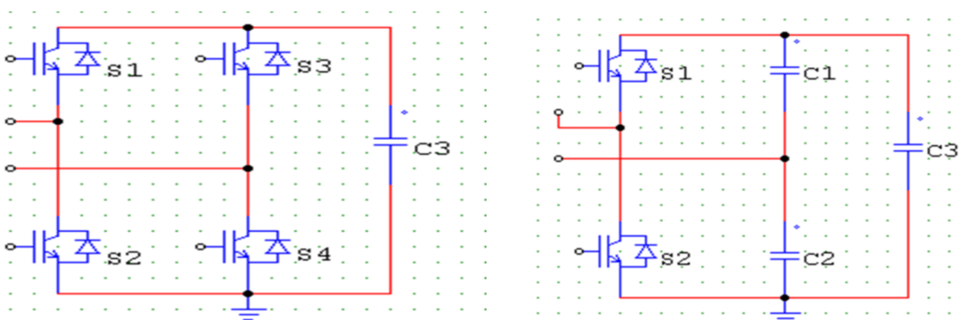
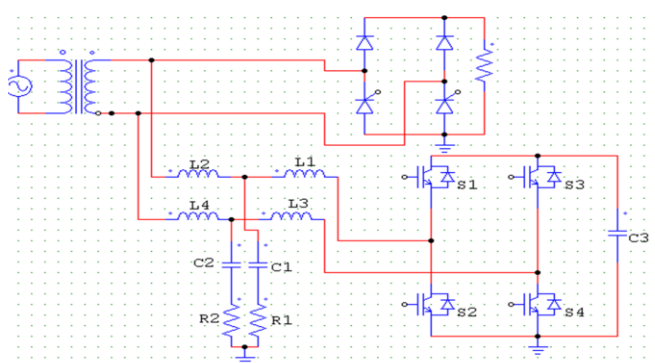


Figure (5): Imaginary voltage and current waveforms for C=1 mF, L=5mH and R1=150Ω

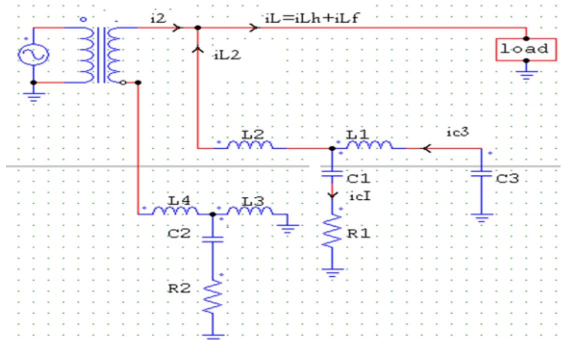


(a) (b)

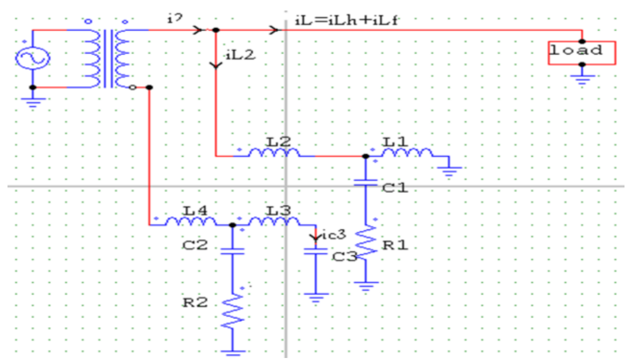
Figure(6): (a) Two branches active filter. (b) One branch active filter with two capacitors.



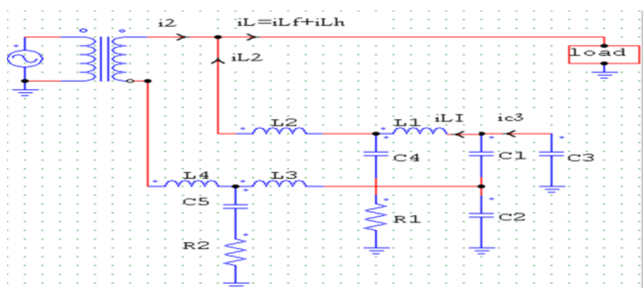
Figure(7): Two branches active filter, transformer, voltage source and rectifier load.



Figure(8): Equivalent circuit of the system and Fig. 6a in the case of S1, S4=on and S2, S3=off.



Figure(9): Equivalent circuit of the system and Fig. 6a in the case of S1, S4=off and S2, S3=on.



Figure(10): Equivalent circuit of the system and Fig. 6b in the case of S1=on and S2=off.

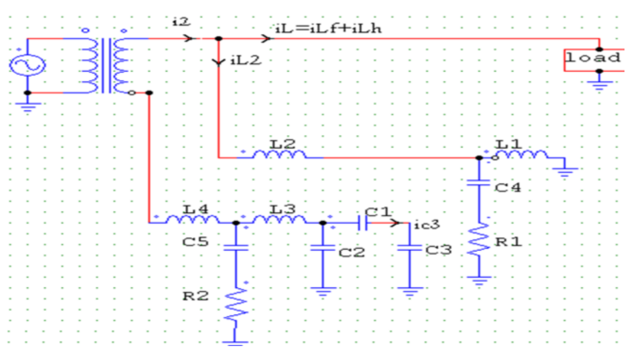


Figure (11): Equivalent circuit of the system and Fig. 6b in the case of S1=off and S2=on.

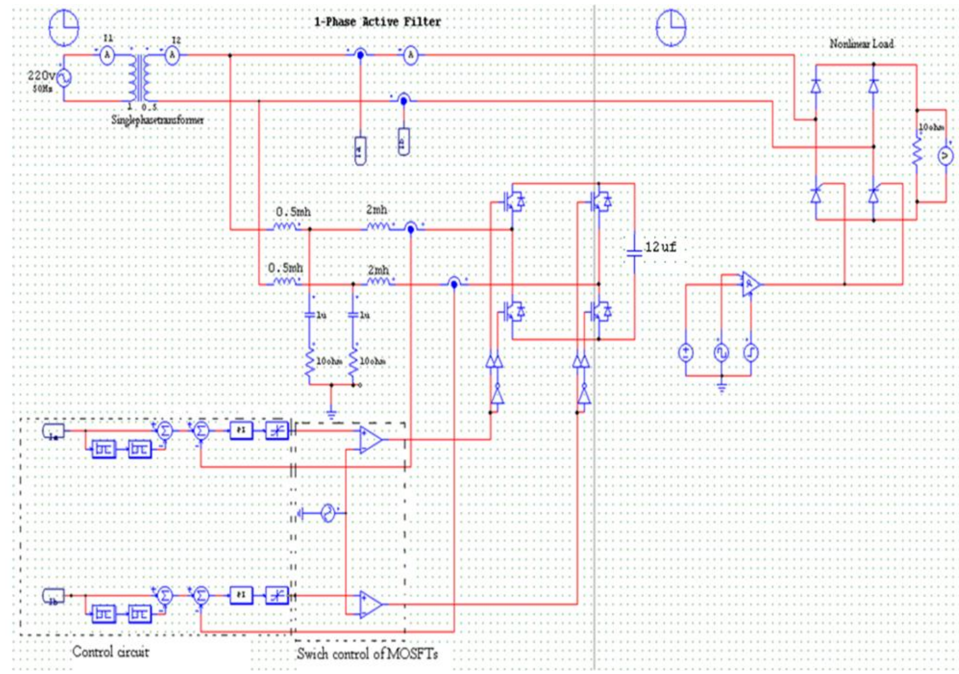
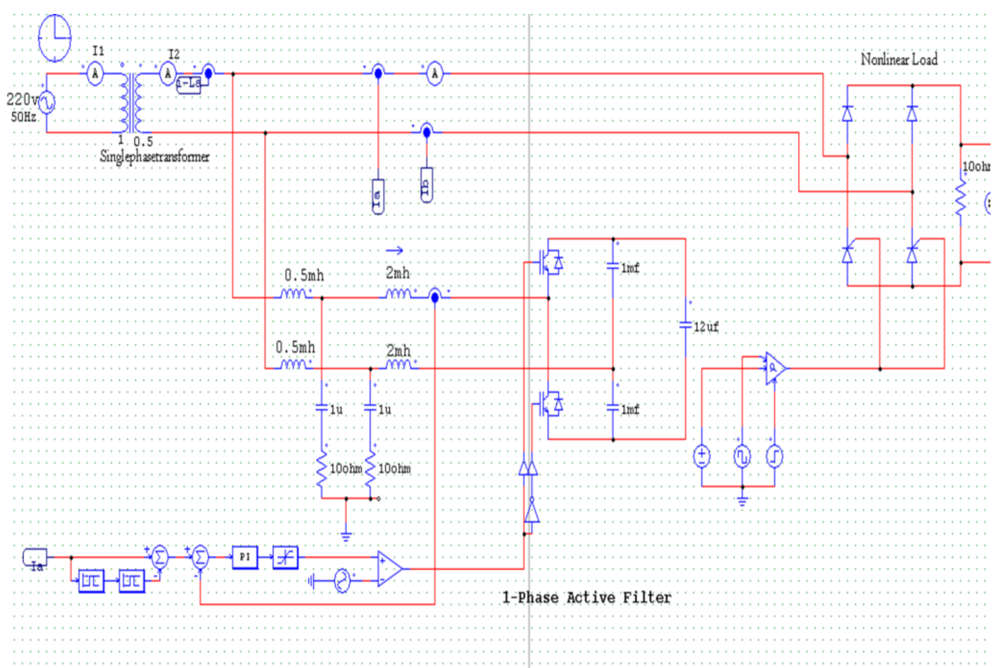
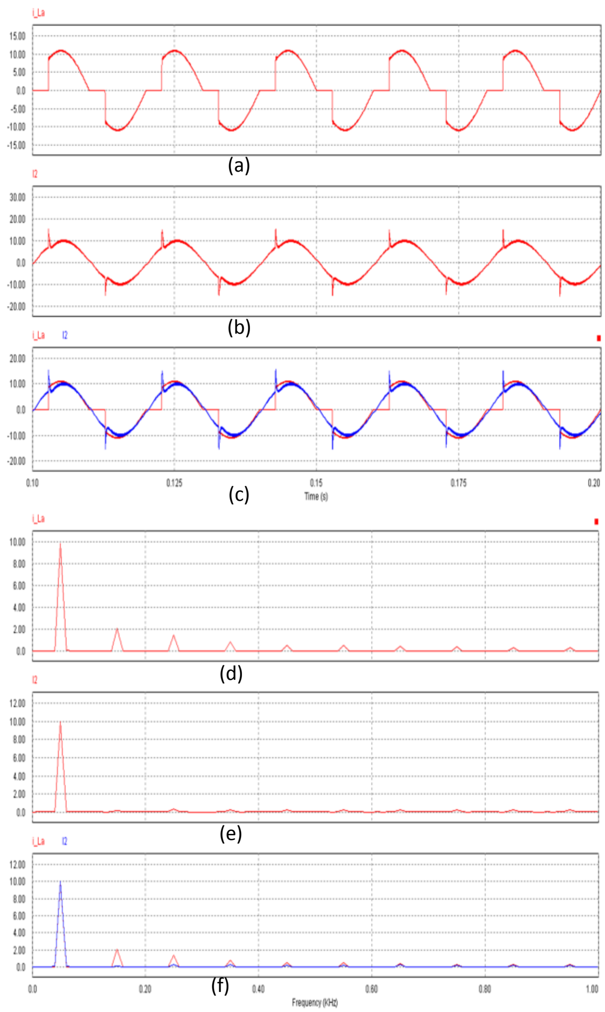


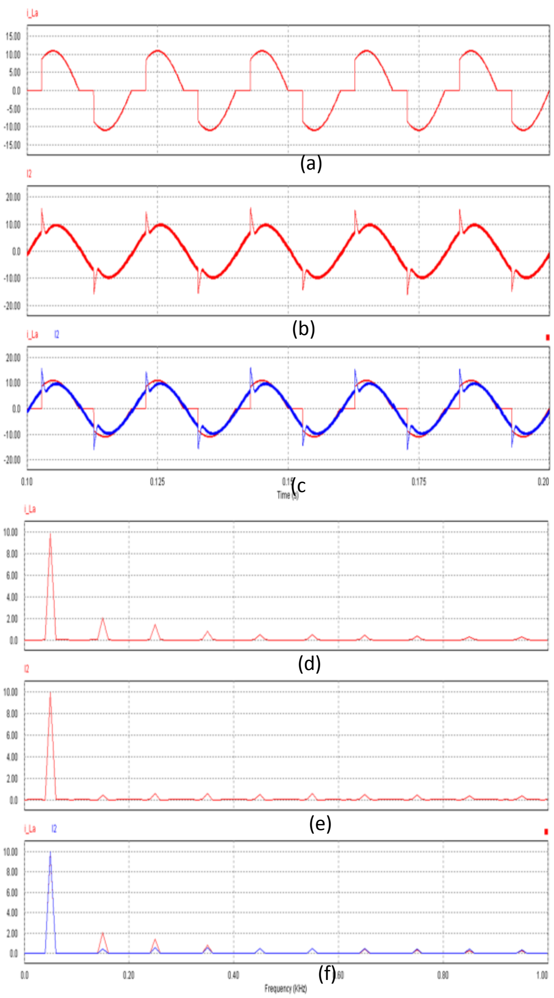
Figure (12): The block diagram of the designed system with the strategy of Fig. 6a, using the psim software.



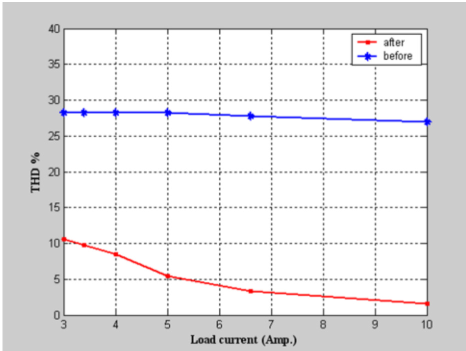
Figure(13): The block diagram of the designed system with the strategy of Fig. 6b, using the psim software.



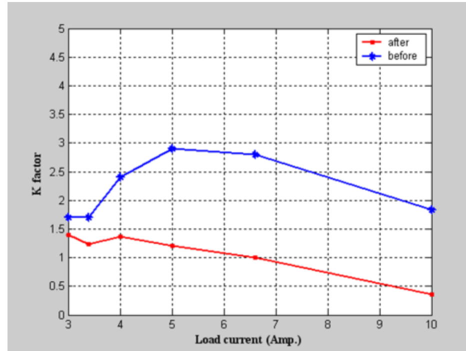
Figure(14): (a)secondary current before filtered. (b)secondary current after filtered. (c)the compaction between secondary currents by using Fig.6a. Two branches active filter. (d, e and f) Showing the spectrums for the secondary currents before, after filtered and compaction between them, respectively.



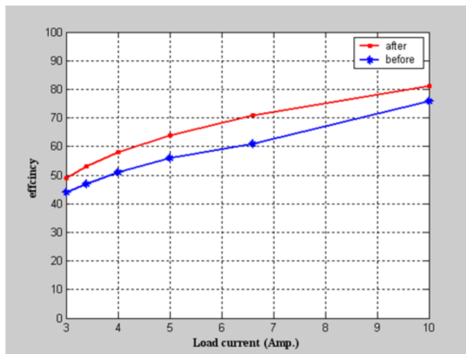
Figure(15): (a)secondary current before filtered. (b)secondary current after filtered. (c)the compaction between secondary currents by using Fig.6b. one branch active filter. (d, e and f) Showing the spectrums for the secondary currents before, after filtered and compaction between them, respectively.



Figure(16):Variations of THDi% before and after filter due to the variation of secondary currents.



Figure(17): Variations of K factor before and after filter due to the variation of secondary currents.



Figure(18): Variations of efficiency power before and after filter due to the variation of secondary currents.