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Study the Robustness Active Filter for a Three-Phase Power Rectifier Considering Line Frequency and Load Variations

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Abstract

Power electronic converters (e.g. AC-DC and DC-AC) produce harmonics which distorting the waveforms of voltage and current. Many research works have examined various techniques to mitigate harmonics at operating conditions (i.e. at a fixed line frequency and a specific load) such as: (i) passive filters, (ii) Current-injection converters, (iii) active filters and (iv) hybrid filters. Active filters are widely used with three-phase bridge rectifiers due to their excellent features for reducing harmonics using power switches instead of passive components that minimize the efficiency of the system. This paper investigates the robustness and the dynamic performance of active filters under the variation of line frequency and DC load. In case of using active filters, it is observed that total harmonic distortion (THD) of voltage and current waveforms is kept at IEEE Standard limits (i.e. less than 5%) under the variation of line frequency . Whilst the performance of passive filters is highly affected by the variations of line frequency and THD of voltage and current waveforms is always greater than 5% except at designed frequency, i.e. 50 Hz. Moreover the load is changed from full-load to half-load, it is observed that the dynamic response of active filters is faster than passive filters for canceling harmonics. It is worth noting that the hysteresis-current-control method is utilized for adjusting the control pulses of active filters due to its rapid dynamic responsem. Simulation results present the highest values of THD of line currents in cases: without any filters , passive filters and active filters are 24.36%, 80.79% and 3.03%, respectively.

Key words:- Active filters, Harmonics mitigation techniques, Three-phase rectifiers, Hysteresis-band-current controller.

الخلاصه

ان مغيرات الكترونيات القدرة والتي يكون مبدأ عملها هو التغيير والتقويم تنتج التوافقيات التي تقوم بتشويه موجة الفولتية والتيار لمصدر تجهيز القدرة. عدة بحوث منشورة سعت الى استخدام تقنيات مختلفة لتقليل التوافقيات ومنها:(1- المرشحات الخاملة، 2- مغيرات حقن التيار، 3- المرشحات الفعالة، 4- المرشحات الهجينة). تستخدم المرشحات الفعالة بصورة واسعة مع المقومات ثلاثية الطور لتقليل التوافقيات باستخدام عناصر خاملة مع مفاتيح دوائر الكترونيات القدرة. يتناول هذا البحث خصائص المرشح الفعال عند تغيير تردد المصدر والحمل. حيث لوحظ ان قيمة التشوه التوافقي الكلي THD هي دائما عند الحد المسموح به (اقل من 5%) للمرشح الفعال، اما للمرشح الخامل فأن قيمة THD هي اعلى من 5% وخصوصاً لموجة التيارات عند تغيير تردد المصدر وان المرشح فقط يعمل عند التردد المصمم عنده (50Hz)، وايضاً، في حالة تغيير الحمل من الحمل التام الى نصف الحمل فأن استجابة المرشح الفعال يكون اسرع من المرشح الخامل. تم استخدام تقنية المسيطر التخلفي الهستيري لتوليد نبضات المرشح الفعال. نتائج المحاكاة تبين اعلى قيم THD للتيارات في الحالات: بدون استخدام اي مرشحات، استخدام المرشحات الخاملة واستخدام المرشحات الفعالة هي كالتالي: 24.36% ، 80.79% و 3.03%.

الكلمات المفتاحية:- المرشحات الفعالة، طرق تقليل التوافقيات، المقومات ثلاثية الاطوار ، المسيطر التخلفي الهستيري.

Introduction:

Three-phase rectifiers are used in several industrial applications such as DC drives, variable speed drives and high-voltage DC transmission lines. Due to non-linearity of these converters, the waveform of line currents is distorted.(Bhonsle *et.al.*, 2011) thus, the performance of the system is affected by harmonics in line currents because of using three-phase rectifiers.(Buso *et.al.*,1998) various techniques have been utilized to decrease harmonics in power converting systems (e.g., non-sinusoidal voltage, distorted currents, unbalance loads) to obtain pure sinusoidal voltage and current waveforms. One of those techniques is; injection opposite reactive currents by using active filter (AF). (KALE, 2015) the hysteresis-band-current controller is the most preferred solution because of advantages including easy implementation and a very fast dynamic response.

Literature Survey and Contributions:

Several research papers demonstrated harmonic elimination techniques such as: passive filters, harmonic current-injection, active filters and hybrid filters. The interested studies have been listed in Table(1). In most publications summarized in Table(1), the performance analysis of 3-phase rectifiers has been demonstrated at a designed frequency, i.e. 50 Hz but in this research, a wide variations range of line frequency (48-52) Hz is applied for testing the robustness of the proposed hysteresis-band-current controller for an active filter. In addition, very low current overshoot is achieved under a step change in DC load.

A background about harmonics that caused by non-linear loads (e.g. three-phase rectifier) and the harmonic mitigation techniques are presented. The proposed active filters based hysteresis-band-current-controller is discussed in details. Finally, the proposed system is implemented in Simulink/SimPowerSys library and the highlighted findings are reported.

Table (1): Literature survey related to techniques of harmonics mitigation

Filter Type	Control Topology	Research Contribution
Passive	Without Controller	(Nassif *et.al.*, 2007) a comparative study has been illustrated for passive filters including design steps based practical consideration.
		(Nassif *et.al.*, 2009) a cost-effective procedures have been demonstrated for selecting filter types that achieving best performance.
Harmonic Current-Injection	Using PI-controller	(Dutta *et.al.*, 2009) a switch mode converter has been designed for power factor correction by injection inverse harmonic currents. The cost of this converter is low due to using a single-power-switch compared with conventional PWM-inverter.
	Without Controller	(Bozovic *et.al.*, 2009) this paper presented a third-harmonic injection method for minimizing THD of line currents. a current injection network connected in the DC side of a bridge rectifier, has been used for producing distorted currents that eliminate the input harmonics. The drawbacks of this method was: (i) consumed power from the source(e.g.8.57%); (ii) THD_i is always greater than 5% and (iii) continuously adjusting passive components in order to obtain sinusoidal voltage waveforms.
Active	Using PI-controller	(Sarasvathi *et.al.*, 2013) the dynamic performance of shunt active filter has been improved by using a PI controller based on Fuzzy logic technique at a specific load.

	Using Indirect Current-Controller	(Miret *et.al.*, 2009) this paper demonstrated indirect current controller based on resonant-selective harmonic circuit. The reference currents were indirectly produced from a voltage regulator based PI-controller. The drawback of this method was operating at only a narrow operating conditions.

Three-Phase Rectifiers Supplying High Inductive Loads:

(Bose, 2002) three- phase bridge rectifiers are illustrated in Fig.(1). The circuit includes a delta-star power transformer for voltage conversion or isolating and a highly inductive load approximately a constant current source. The inductance of the cable Lc is neglected to simplify the analysis. For high inductive load, each diode conducts for a period 2π/3, and the load current will be approximately constant due to the high load inductance. The average DC voltage, V_d , is calculated as follows:

$$V_d = \frac{3}{\pi}\int_{-\pi/6}^{+\pi/6}\sqrt{2}V_{LL}\cos(\omega t)\,\mathrm{dwt} = 1.35\ V_{LL} \tag{1}$$

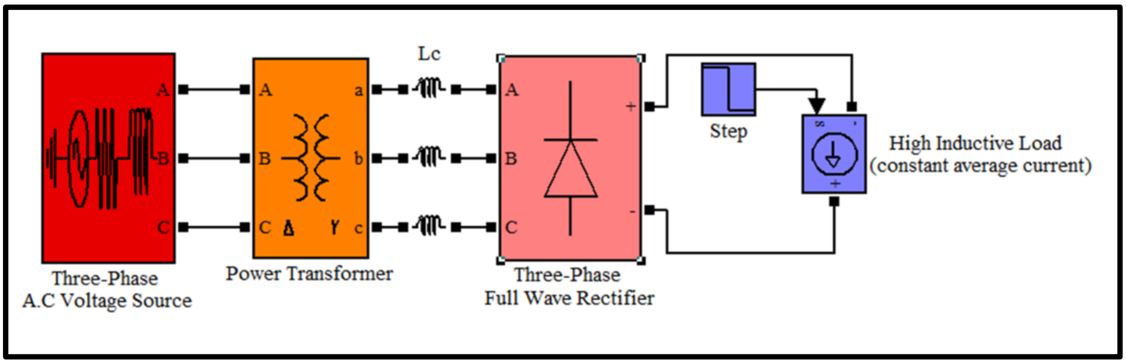
Where V_{LL} is the line-line rms voltage of the source.

The line current can be represented by the Fourier Series as follows:

$$i_s = \frac{2\sqrt{3}}{\pi}I_d\left[\sin(\omega t) - \frac{1}{5}\sin(5\omega t) - \frac{1}{7}\sin(7\omega t) + \frac{1}{11}\sin(11\omega t) + \cdots\right] \tag{2}$$

Where I_d is a constant DC load current.

According to the Fourier series representation, the fundamental rms of current is $(\sqrt{6}/\pi)I_d$, and only $(6n \mp 1)$ harmonics are present.



Passive and Active Filters:

(Chang *et.al.*, 1995) basically, designed passive filters at specific operating conditions. Also, passive filters often require to be significantly overrated to mitigate harmonics from power source. Selecting the passive elements of a filter is based on the amount of reactive power (Q) of a specified load in order to avoid operating in leading power factor under load variations. The above problems can be tackled by using active filters, where compensation of harmonics will not be affected with line frequency and the amount of load reactive power.

Active filters include power devices (MOSFET, IGBT) and the amount of reactive power can be controlled by adjusting PWM pulses. (Deb, 2013) the main difference between passive and active filters is the letter type including, as mentioned above, power switching devices with inductors and capacitors. Thus the inductive or capacitive reactive power is varied with the load. (Akagi, 2006) active filters have various advantages such as (i) best filtering performance, (ii) smaller in hardware size, and (iii) wide flexible in application, In addition, the active filters are slightly low cost and minimum operating losses.

The configuration of active filters can be categorized into pure active filters(PAF) and hybrid active filters (HAF). In terms of PAF are extremely used in power circuits such as: (i) Voltage-source pulse width-modulated (PWM) converters connected with a bulks capacitor in D.C side or (ii) A current-source PWM converters connected with an inductor in D.C side. The voltage-source converters are more suitable than the current source converters in terms of cost, hardware size and efficiency. Whilst, HAF includes single or multiple voltage-source PWM converters connecting with passive components. According to power circuit configuration, PAF can be classified into shunt active filters and series active filters. Shunt active filters are used for harmonic filtering compared with series active filter that its passive components must be designed for rated load current. (Miret, 2009) shunt Active Filters are used in low- and medium-power applications due to simplicity, robustness, and harmonic-rejection capabilities. Shunt filters are usually applied to three-phase systems where a large capacity is required.

Design of DC Link Capacitor:

(Buso *et.al.*, 1998) during transient operation, power is stored in a capacitor in the DC side, which relates to the variation of voltages and the charging period. These variations are caused by transient states due to the changes in instantaneous power absorbed by the load. In the worst case (totally inductive to totally capacitive compensation change), the instantaneous power is considered equally on both sides of the filter.

The amount of DC capacitor for an ideal voltage source inverter is given by:

$$C = \frac{S_n}{V_{dc}\Delta V_{dc}} \frac{1}{2\omega_1} \tag{3}$$

where S_n is the filter rated power, V_{dc} is the average DC voltage across the capacitor, ΔV_{dc} is the estimated ripple voltage and ω_1 is the angular velocity of the source.

Hysteresis-Band-Current-Controller:

(Chelli *et.al.*, 2015) there are several control techniques have been used for improving the performance of shunt active filters. Power control method is widely used for shunt active filters for generating the instantaneous reference currents under load variations. The current errors are adjusted by a hysteresis-band relay for extracting switching pulses for the inverter. When the supply current is greater than the upper limit, the comparators generate control pulses in such a way to minimize the supply current and keep it between its bounded values. (KALE, 2015) it is worth noting that the hysteresis band current controller is widely used due to its high efficiency.

Effect of Frequency Variation:

(Pelly, 1971) according to the typical Fourier harmonic analysis, the line current can be demonstrated as unity amplitude as follows:

$$i_L = F_1(\theta_i) - F_1(\theta_i + \pi) \tag{4}$$

$$i_L = \frac{2\sqrt{3}}{\pi}\left[\sin(\theta_i) - \frac{1}{5}\sin 5(\theta_i) - \frac{1}{7}\sin 7(\theta_i) + \frac{1}{11}\sin 11(\theta_i) \ldots\ldots..\right] \tag{5}$$

As shown in Eq.(5) the amplitude of the fundamental component is $(\frac{2\sqrt{3}}{\pi})$ multiply by the peak value. Each of the even harmonic components of the 3-pulse waveform totally cancels one another in the 6-pulse waveform, whereas the other harmonic components do not cancel. The harmonic components have frequencies of 5th,7th,11th,….etc. In general, it can be expressed as $(6n \mp 1)$ of the fundamental frequency, and the magnitude of any given harmonic, relative to the fundamental, is equal to the reciprocal of the harmonic order.

$$V_{DC} = \frac{6}{2\pi}\int_{\frac{\pi}{3}}^{\frac{2}{3}\pi} \sqrt{3}V_S \sin(wt)\, dt = \frac{3\sqrt{3}}{\pi}V_S = 1.654\ V_S \tag{6}$$

$$V_L = \sqrt{\frac{9}{\pi}\int_{\frac{\pi}{3}}^{\frac{2}{3}\pi} V_S^2.\sin^2(wt)dt} = V_S\sqrt{\frac{3}{2}+\frac{9.\sqrt{3}}{4\pi}} = 1.655\ V_S \tag{7}$$

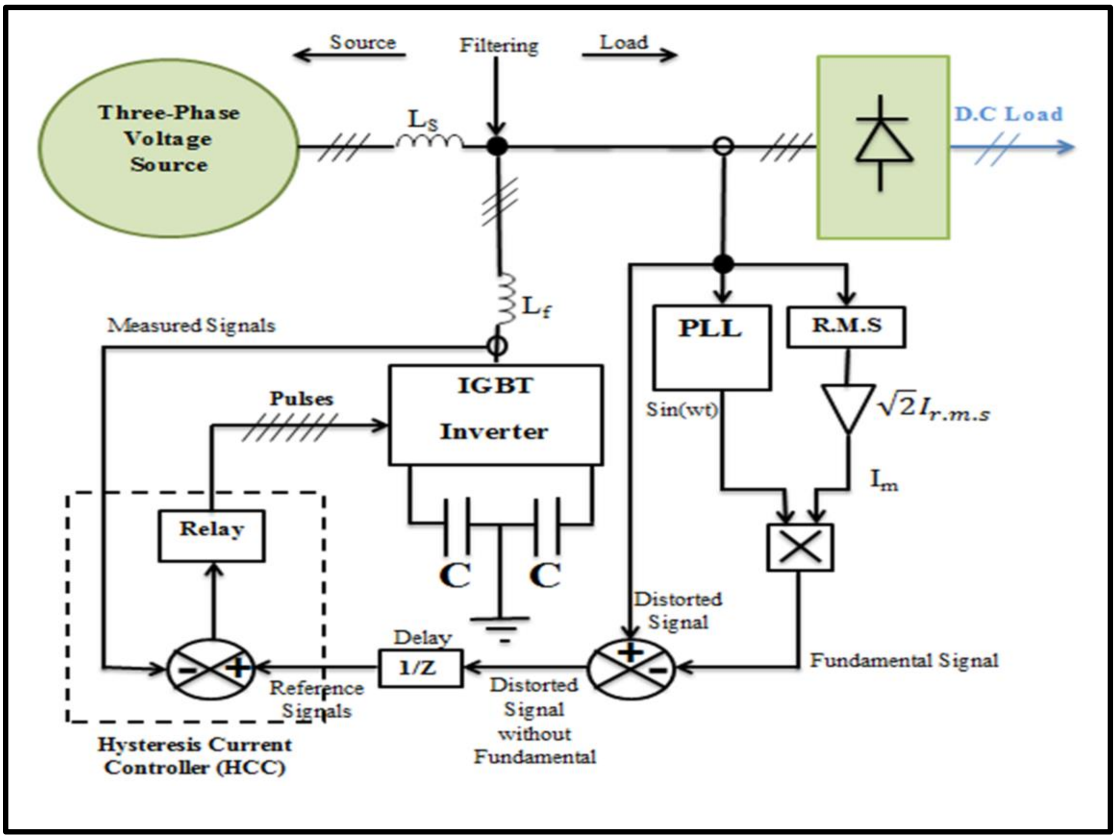
The rms current is represented in terms of resistive load as follows:

$$I_S = \frac{\sqrt{3}V_S}{R_L}\sqrt{\frac{2}{\pi}\left(\frac{\pi}{6}+\frac{\sqrt{3}}{4}\right)} \tag{8}$$

$$I_d = \frac{\sqrt{3}V_S}{R_L}\sqrt{\frac{1}{\pi}\left(\frac{\pi}{6}+\frac{\sqrt{3}}{4}\right)} \tag{9}$$

Block Diagram of the Proposed Active Filter for a Three-Phase Rectifiers:

(Dey *et.al.*, 2015) active filters are utilized to mitigate the harmonic distortion caused by non-linear loads, such as three-phase rectifier circuits. Figure(2) shows the power circuit diagram of an active filter with its controller.



Figure(2): Block diagram of the proposed active filter for a three-phase Rectifier.

(SmitaSinghai *et.al.*, 2017) it is clear from Fig.(2) that the reference signals are generated based on phase to locked loop (PLL) and hysteresis switching control, which has several advantages such as; strict stability, fast response and perfect accuracy. PLL is used for generating the fundamental component frequency of the load current multiplies with the rms value of load current for extracting the reference signals for hysteresis-current-controller (HCC). Consequently, the reference signals are compared with measured currents of the active filter for generating pulses for three-phase voltage source inverter. The time domain description of three-phase load current can be represented as follows:

Distorted 3-phase current: $i(n\omega t) = I_m \sin(n\omega t - \varphi)$ (10)

where n=1,5,7,11,…..

Fundamental 3-phase current: $i(\omega t) = I_m \sin(\omega t - \varphi)$ (11)

Distorted 3-phase current without fundamental: $i(n\omega t) = I_m \sin(n\omega t - \varphi)$ (12)

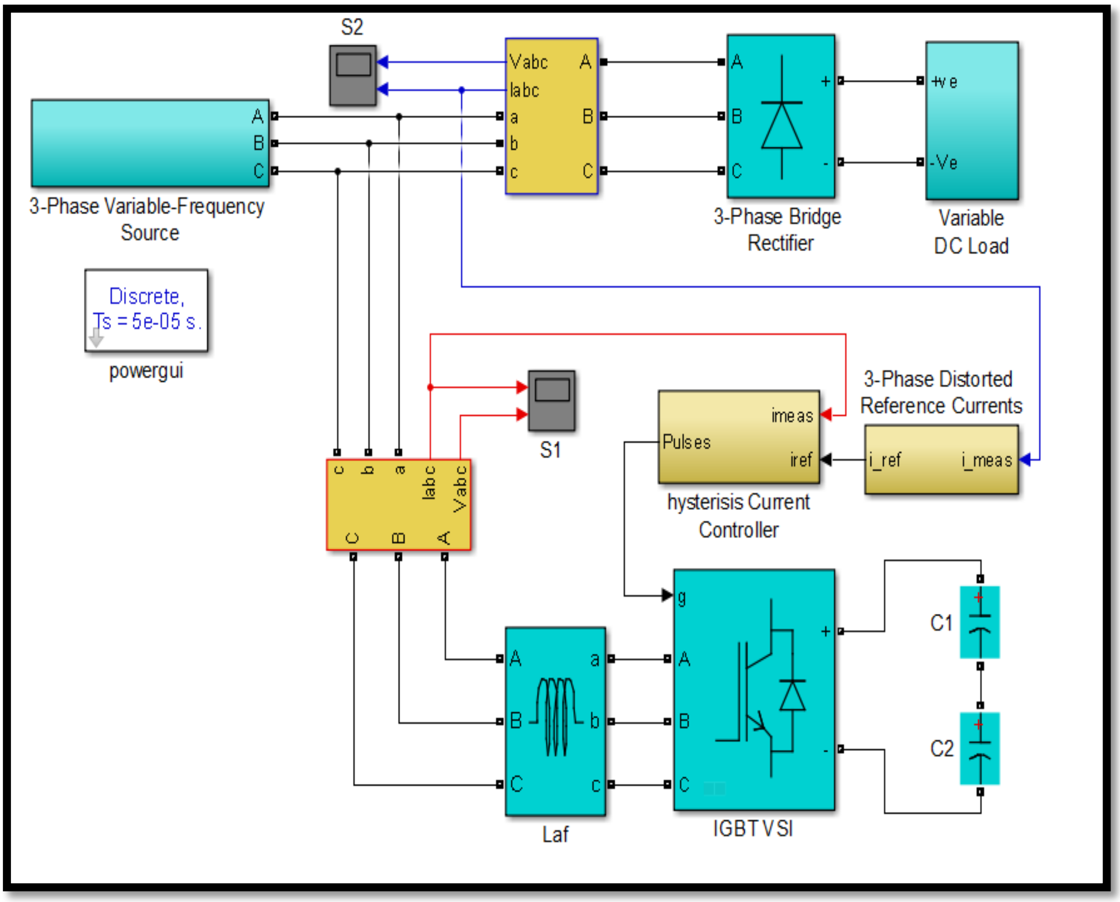
where n=5,7,11,…..

Simulink Model of a Three-phase Rectifier with Active Filter:

Figure(3) illustrates a Matlab/Simulink implemented of a 3-phase bridge rectifier with the proposed active filter. The line three-phase currents of the active filter are adjusted to follow the three-phase distorted reference currents via the hysteresis-band-current controller. The basic parameters of the simulated circuit are listed in Table (2).

Table (2) Parameters of the implemented circuit

Parameter	Value
RMS voltage, *V*	128.69 V
Line frequency, *f*	50 Hz
Source resistance, R_s	50 mΩ
Source inductance, L_s	5 mH
Full-load current, I_l	5 A
DC capacitor, *C*	100 µF

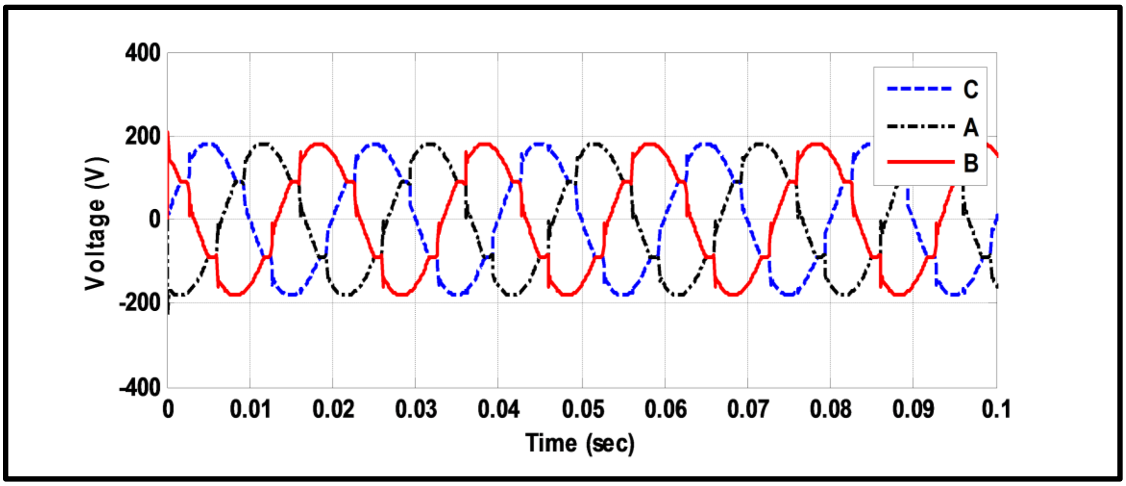


Figure(3): Simulink model of the proposed system.

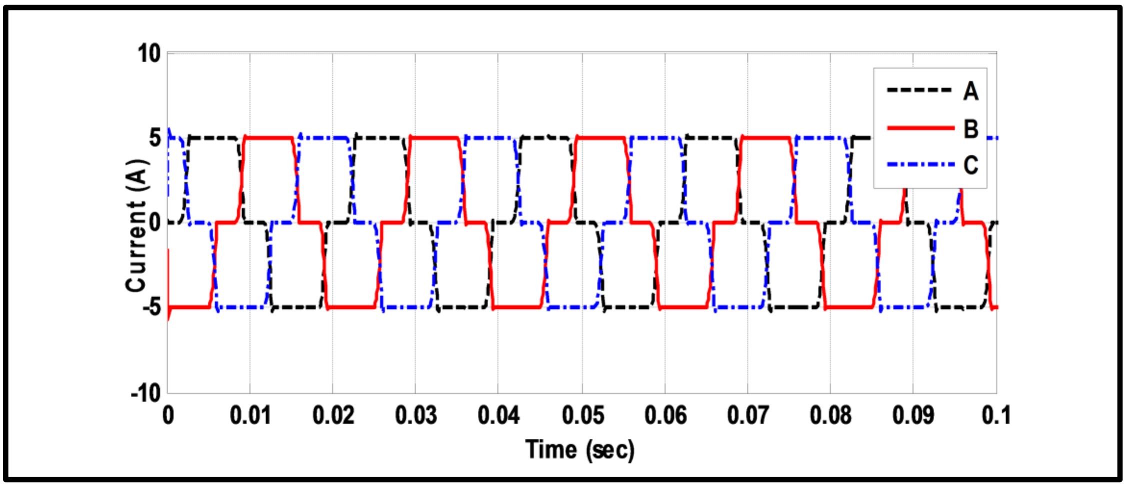
Results and Discussion:

A.1. Analysis of THD without using Passive and Active Filters:

The waveforms of voltage and currents for a three-phase rectifier at full-load (without using any filters) are illustrated in figures (4) and (5), respectively. It is clear that the waveforms of voltage and currents are non-sinusoidal including only odd harmonics (except of multiple of 3). In this paper, the line frequency and the load are varied to demonstrate the values of THD of line-line voltage (THD_v)and THD of line-line current (THD_i) as shown in Figures (6) and (7), respectively.

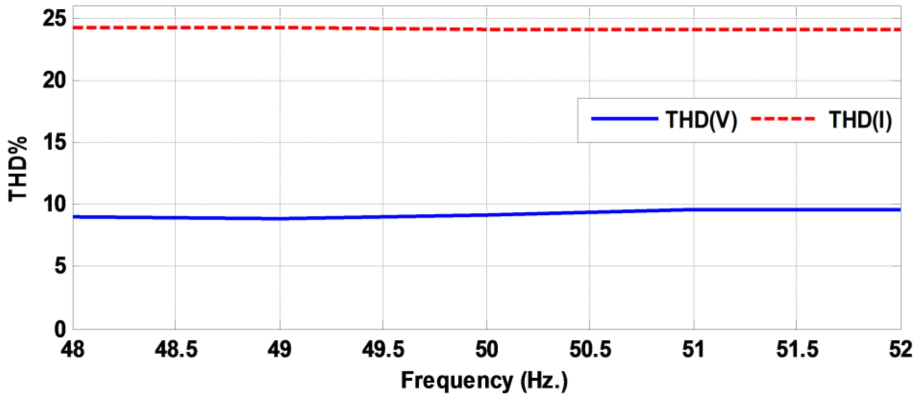


Figure(4): The waveform of three-phase voltage without filters at 50 Hz.

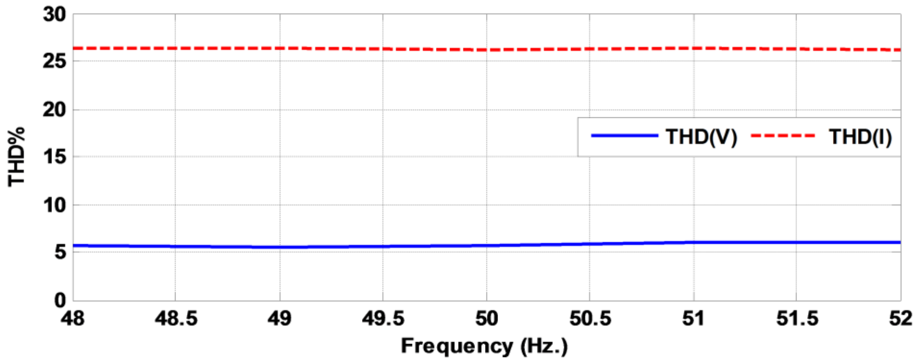


Figure(5): The waveform of three-phase current without filters at 50 Hz.

Figures (6) and (7) show the relationship of THD versus line frequencies for a three-phase rectifier without using any filter at respectively full-load and half-load. It can be seen that THD_v and THD_i do not meet with IEEE STD 519 (i.e. the values of THD are greater than 5%) especially for current waveform.



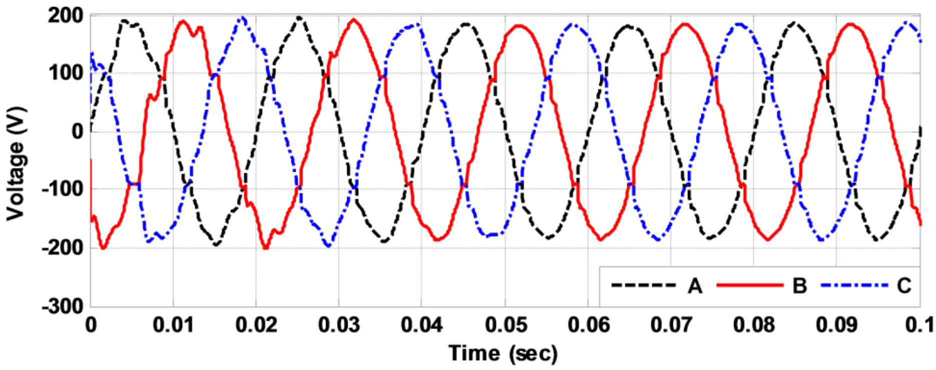
Figure(6): The relationship between THD and the line frequency without any filter at full-load.



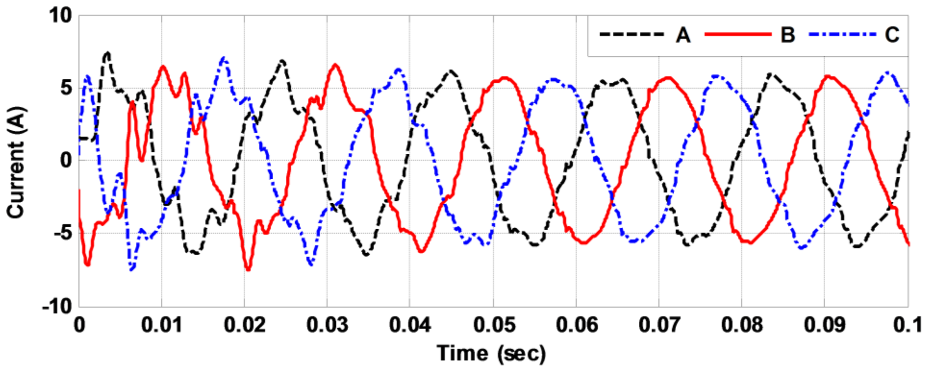
Figure(7): The relationship between THD and the line frequency without any filter at half-load.

A.2. Analysis of THD using Passive Filters:

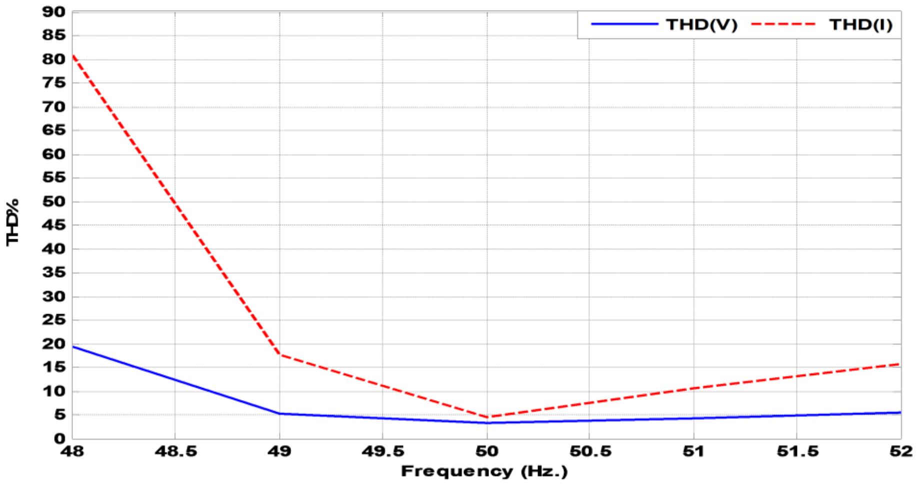
The waveforms of voltage and currents for a three-phase rectifiers at full-load using passive filters are shown in figures (8) and (9), respectively. It is clear that the waveforms of voltage and currents are sinusoidal and including distortion during transient period. In this study, the line frequency and the load are changed to obtain the values of THD_v and THD_i as shown in Figures (10) and (11), consequently.



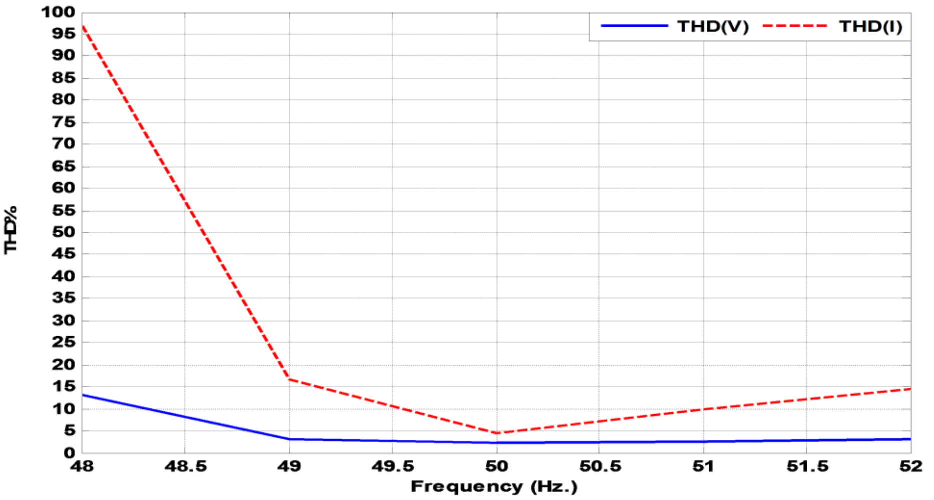
Figure(8): The waveform of three-phase voltage with passive filter at 50 Hz.



Figure(9): The waveform of three-phase current with passive filters at 50 Hz.



Figure(10): The relationship between THD and the line frequency with passive filter at full-load.

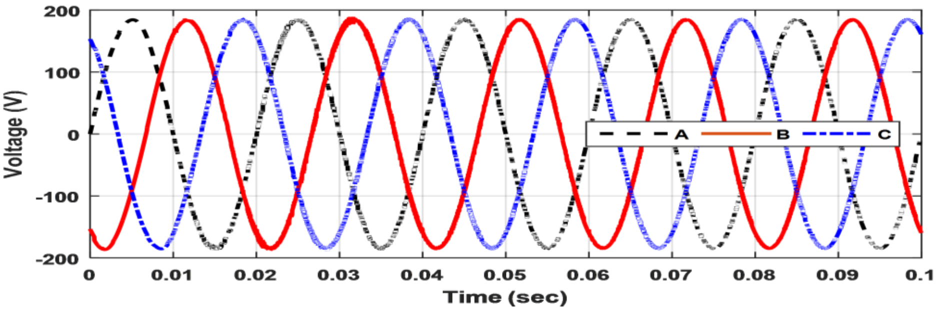


Figure(11): The relationship between THD and the line frequency with passive filter at half-load.

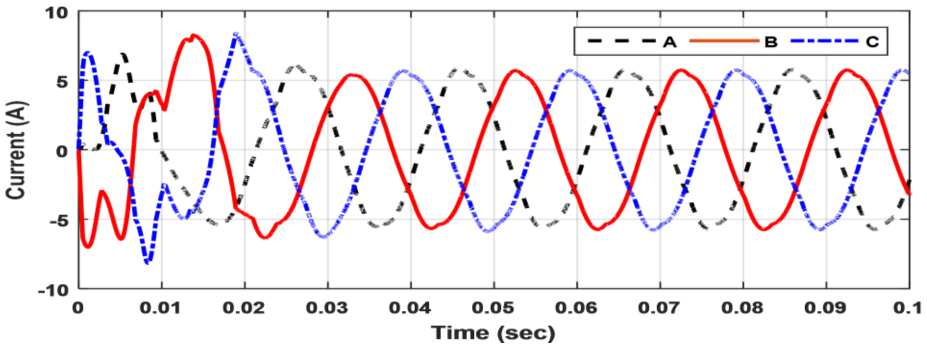
Figures (10) and (11) show the relationship of THD versus line frequencies for a three-phase rectifier using a passive filter at full-load and half-load, respectively. It can be seen that THD_v and THD_i meet with IEEE STD 519 around 50 Hz, especially for current waveform.

A.3. Analysis of THD using Active Filters:

The waveforms of voltage and currents for a 3-phase full-wave rectifier at full-load using active filters are illustrated in figures (12) and (13), respectively. It is clear that the waveforms of voltage and currents are sinusoidal, current waveform including very little distortion in transient. The line frequency and the load are also varied to demonstrate the values of THD_v and THD_i as shown in Figures (14) and (15), respectively.

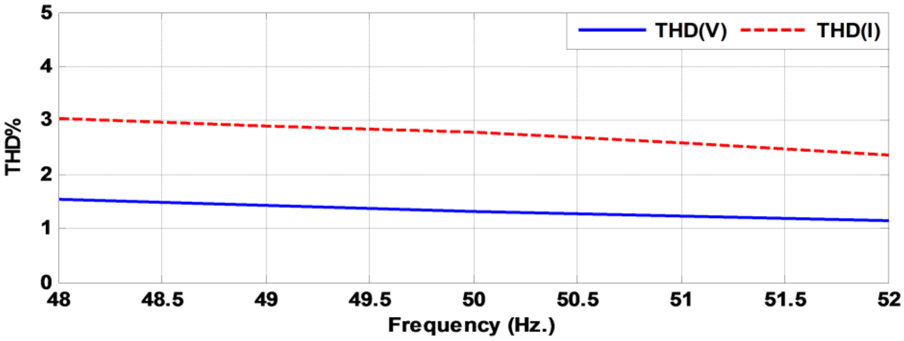


Figure(12): The waveform of three-phase voltage with active filter at 50 Hz.

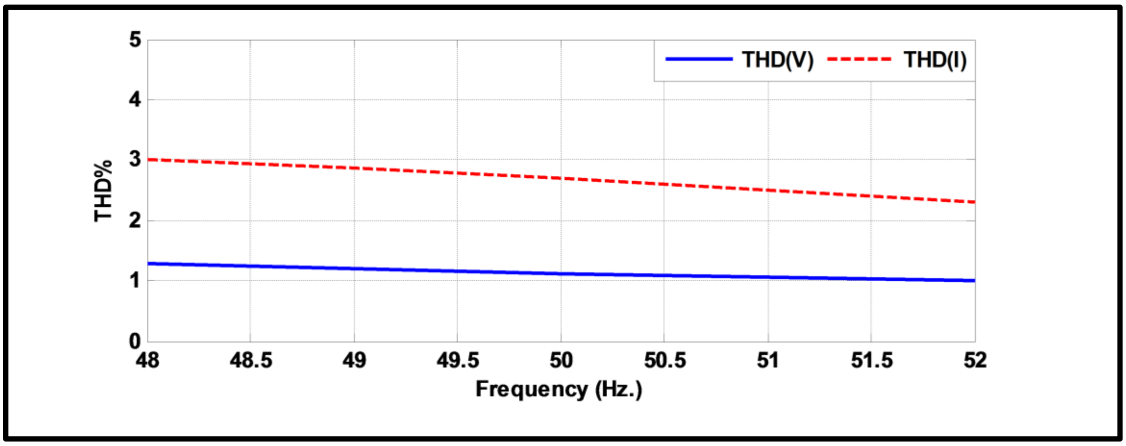


Figure(13): The waveform of three-phase current with active filters at 50 Hz.

Figures (14) and (15) show the relationship of THD versus line frequencies for a three-phase rectifiers using active filter at full-load and half-load, respectively. It can be seen that THD_v and THD_i are always less than 5% .



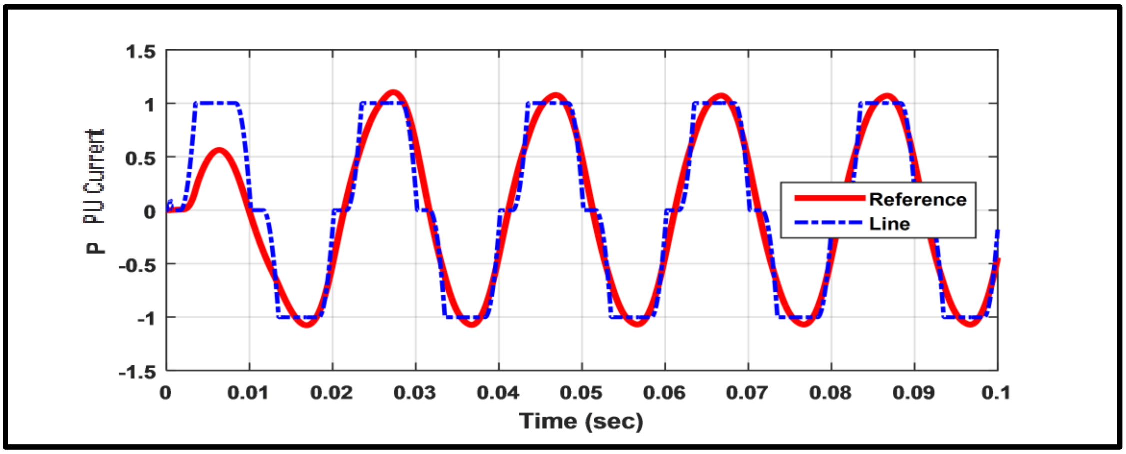
Figure(14): The relationship between THD and the line frequency with active filter at full-load.



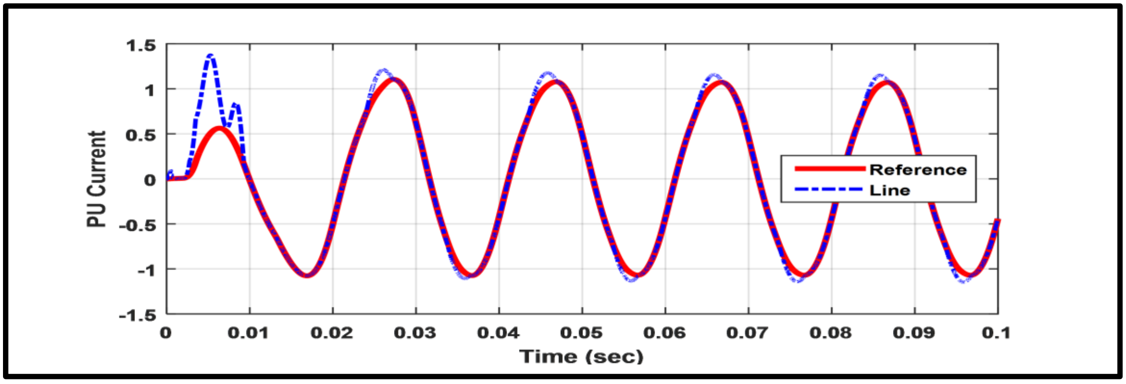
Figure(15): The relationship between THD and the line frequency with active filter at half-load.

It is worth noting that the worst THD_i cases: without any filters, passive filters and active filters are respectively 24.36%, 80.79% and 3.03%.

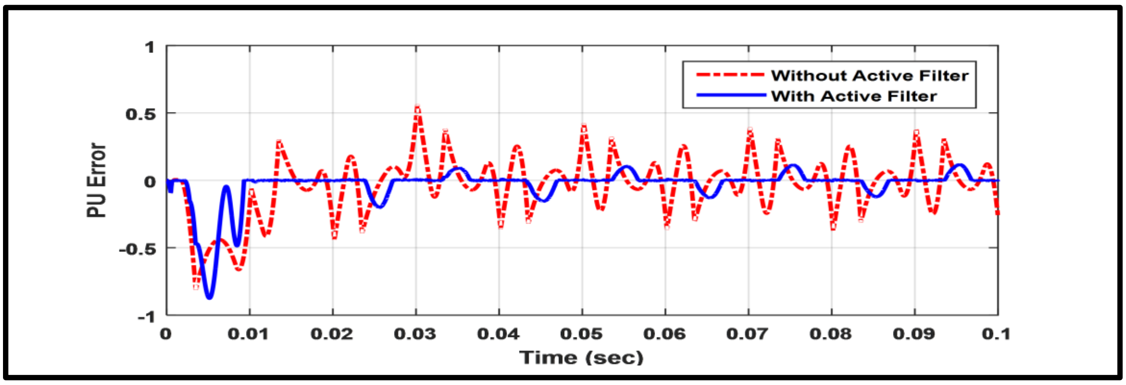
B.1. Validation of Hysteresis-band-current controller at full-load:



Figure(16):Waveform of reference and line currents without Active Filter.



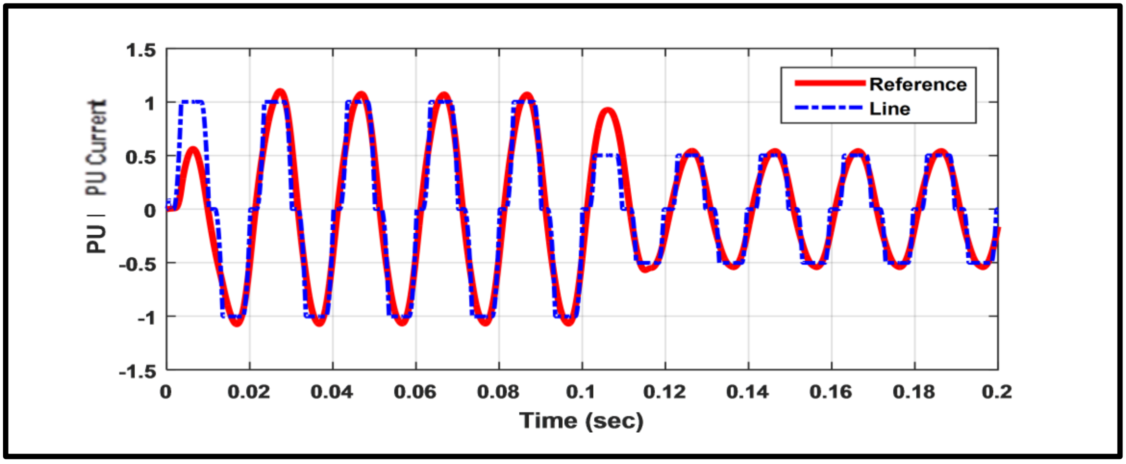
Figure(17):Waveform of reference and line currents with Active Filter.



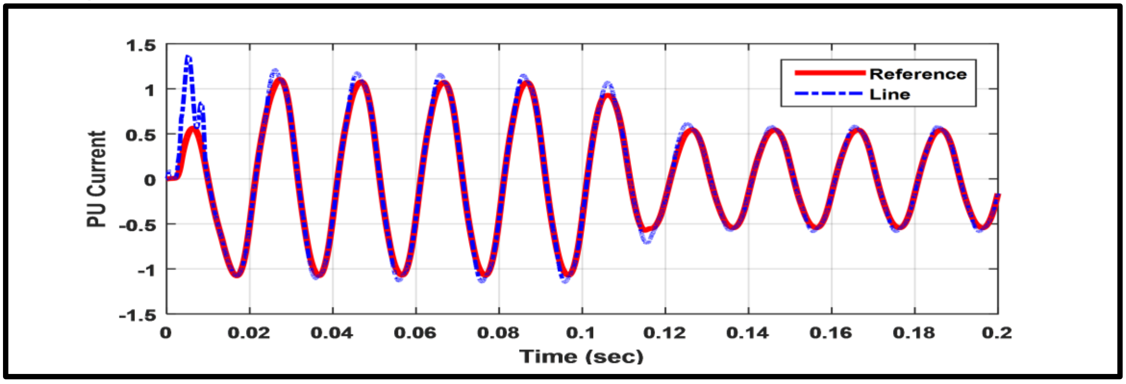
Figure(18):Current error of hysteresis current controller.

As mentioned above, the current controller aims to adjust the line current to follow the fundamental reference current. It can be seen in Fig.(16) that the line current is semi-quad waveform, while in Fig.(17), the proposed active filter is used so that the line current waveform is closed to reference signals. Figure(18) shows the current error signals of the current controller, it is clear that the current error (in case of using active filter) is around zero compared to the case when no active filter is used where the peak value of current error is 0.52.

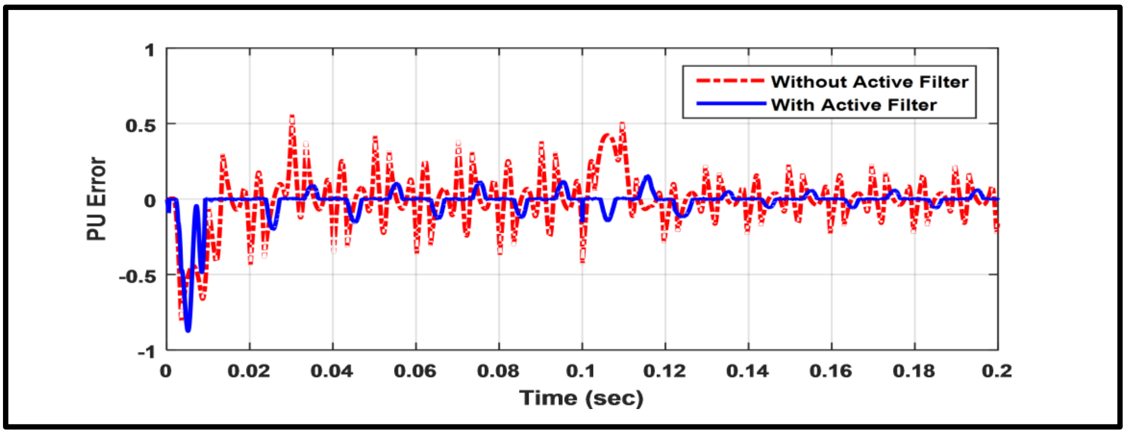
B.2. Validation of Hysteresis-band-Current Controller at step change in load:



Figure(19):Waveform of reference and line currents without Active Filter.



Figure(20):Waveform of reference and line currents with Active Filter.



Figure(21):Current error of hysteresis current controller.

The robustness of current controller is verified by changing the load from its full value to half value to present the dynamic response. Figures (19) and (20) show the line current waveforms without and with the active filter, respectively. It is clear that the controller response is very fast with small overshoots. In case of no active filter is used, the peak value of current errors is 0.52A in comparison with using the active filter the current errors are around zero.

Conclusions:

In this research, an active filter based on hysteresis-band-current controller is used to eliminate harmonics caused by a three-phase rectifiers connected to a variable DC load. According to the obtained results, we deduce the following findings: (i) active filters are effectively cancelled the harmonics caused by nonlinear loads under the variation of line frequency and THD of voltage and current waveforms are always less than 5%; (ii) the dynamic response of active filters is very fast for the sudden load changes; (iii) the proposed hysteresis-band-current controller for active filters can be efficiently used for any non-linear loads; (iv) the proposed hysteresis-band-current controller is the best techniques employed for adjusting the pulses of active filters due to its advantages such as simplicity in control and rapid-response current control and (v) it is concluded that the highest per-unit value of THD_i (for active filters) is 0.61 compared with cases (without using any filters) is 4.87 and (with passive filters) is 16.16.

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