Analysis and design of multiple feedback control loops for both Inverter and Rectifier of single-phase UPS under Non-linear Load

Seyed Reza Hadian Amrei, Seyed Morteza Alizadeh, A. Yaghoubi, A. Bemani

Abstract

In this article, a controlling method is proposed for single-phase Uninterruptible Power Supplies. The proposed method is capable of reducing the distortion in the output voltage and also changing the output voltage into a desirable sine wave when UPS supplying non-linear and variable loads. In this method, two controlling loops are used, based on output voltage feedback (outer loop) and self current feedback (inner loop). Using the results of simulation in MATLAB/SIMULIN software, the result of the proposed method is compared to the result of the controlling method based on output voltage feedback only. The proposed controlling method (multiple feedbacks) leads to a better regulation and better responding of UPS to different types of loads, as compared to the controlling methods using simple feedback. In addition, the proposed method improves the input power factor, using the appropriate controlling strategy in the rectifier part of the UPS in which a rectifier with a BOOST convertor is used as the circuit correcting the power factor.

Keyword(s): controlling method, single-phase, MATLAB/SIMULIN, UPS

1.Introduction

The rapid development of technology and the production of accurate, sensitive electronic devices have increased the need for a secure power networks as the supplying resources for such devices. On the other hand power lines have not adequate reliability to be used as the power supply for such systems, due to the problems such as power outage, over voltage or voltage drop, line noise, frequency changes, etc. Using Uninterruptible Power Supplies is one of the major choices for this problem. Uninterruptible Power Supplies provide a backup circuit for supplying sensitive and essential loads, so that in case the power system faces any problem, supplying the sensitive load maintains continuous. Since the emergency power sources of UPS systems are usually rechargeable batteries, the existence of an inverter in the structure of such systems is inevitable. UPS systems are divided into three categories: 1) Static, 2) Rotary, 3) Hybrid (static/rotary). The most commonly-used UPS are static UPS which are used in a wide variety of low-power systems, such as personal computers, and medium-power systems, such as medical and telecommunication systems, and also high-power systems. High efficiency, high reliability, and low THD are the advantages of this type of UPS. As the disadvantages of this type of system can be note undesirable performance against instable and nonlinear loads, and the need for an appropriate controlling method to gain the desired output voltage when supplying such loads. Static UPS systems are divided into three classes:

-1 Off-line UPS

-2 On-line UPS

-3 Line interactive UPS

This paper focuses on the topology of On-line UPS, the diagram block of which is represented in Figure 1. In On-line UPS system, when in normal state, the rectifier both charges the battery and provides the power needed for the load through the inverter. A wide range of voltage variations and also the exact regulation of output voltage are the advantages of this method. The main disadvantages of this topology can be note low input power factor, and high distortion of output voltage. Therefore, the main objective of control in such UPSs will be decreasing the distortion in the output voltage and providing a desirable sine voltage at the output system, and also decreasing the harmonics of input currents and increasing the input power factor. This article proposes the method of instant feedback controlling for UPS systems. Designing an inner loop by feed backing self current, beside the outer loop of voltage, leads to a better performance of the system when supplying nonlinear and variable loads. In addition, in the input part of the UPS system studied in this article, a rectifier and a BOOST convertor are used to decrease the harmonics of the input current .

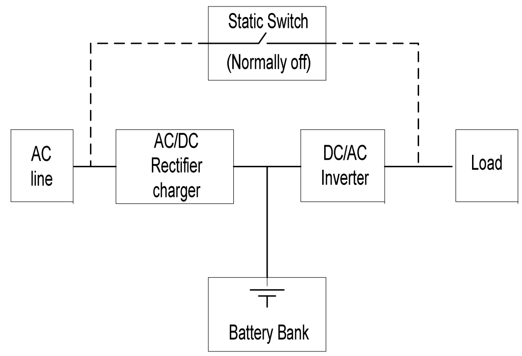


Fig.1: The block diagram of On-Line UPS

Using MATLAB simulator, the performance of the studied UPS is first evaluated with separating the rectifier and the inverter and using the proposed controlling methods, and ultimately, the performance of the total UPS system is simulated and evaluated with connecting the rectifier and the inverter.

2) The Strategy of Controlling the Inverter of UPS

Generally, the two parts of power and control make the inverter up. The convection of power and transforming it from dc to ac is the responsibility of the power section, and producing reference signals regarding the intended controlling objective, and tracking these signals is the responsibility of the control part in UPS systems. The controlling methods which are designed for UPS inverter focus on the way reference signals are generated with a regard to the intended controlling objectives. The controlling objective based on which the controlling method has been proposed in this paper is regulation and the ability of UPS to respond to different types of loads appropriately. In order to accomplish that, the inverter control method needs to be of enough resistance against different types of loads and their variations, in order to generate the wanted reference signals. If the required reference signals are generated in the form of reference voltages, voltage-type modulators can be employed to track these signals. These modulators have fixed switching frequencies and hence, result in the better performance of the inverter. The performance of the voltage-type modulators and the modulation methods employed in them can be assessed by investigating the output voltage on the inverter in the open-loop control.

2) Open-Loop Inverter Controlling

The simplest method for open-loop controlling the output voltage of the inverter is using Sine Pulse Width Modulation (SPWM) in the inverter voltage modulator. In addition to the key components, the SPWM inverter output voltage has good harmonics around the multiples of switching frequency, yet, the harmonics of the low levels of the inverter output voltage decrease significantly. In Sine Pulse Width Modulation, fire signals are generated by comparing a sine reference signal with a triangular conveyer wave of the frequency of f_c. The frequency of the reference signal, f_r, defines the frequency of the inverter output, f_o. Its amplitude (A_{ref}) defines the modulation index (A_m), and consecutively, controls the efficient amount of the output voltage.

$$A_m = \frac{A_{ref}}{A_c} \ , \ V_{o_1} = A_m V_{dc}$$

(1)

Fig.2: A uniphase, full bridge inverter

The Sine Pulse Wide Modulator for a uniphase, full bridge inverter represented in

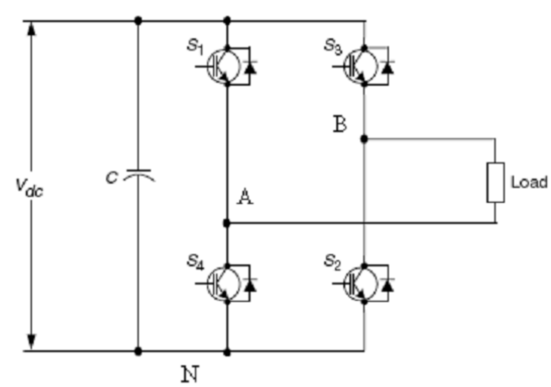


figure 2 can be done in two ways of Unipolar Modulation and Bipolar Modulation.

In bipolar modulation, the controlling of the switches is done so that, in each half cycle, the output voltage gets the values of $+V_{dc}$ and zero, or $-V_{dc}$ and zero. The switching pattern of the inverter in this method is as presented below:

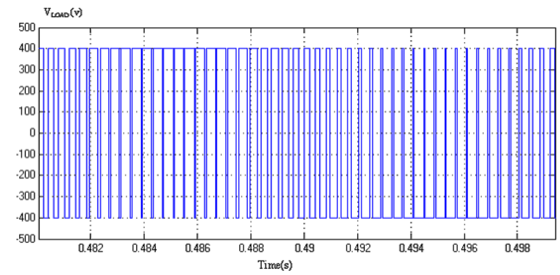
(2)

$$\begin{cases} V_{ref} > V_c \rightarrow s_1 : on \ \& s_2, s_3, s_4 : off \\ V_{ref} < V_c \rightarrow s_4 : on \ \& s_1, s_2, s_3 : off \\ -V_{ref} > V_c \rightarrow s_3 : on \ \& s_1, s_2, s_4 : off \\ -V_{ref} < V_c \rightarrow s_2 : on \ \& s_1, s_3, s_4 : off \end{cases}$$

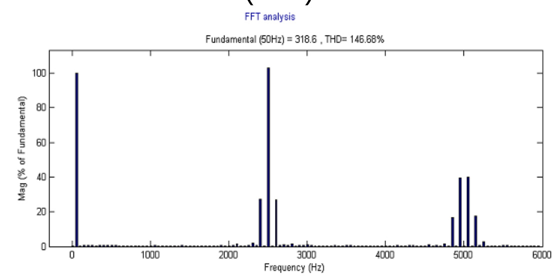
The output voltage of a full bridge inverter with bipolar modulation, the switching frequency of 2500 HZ and the reference signal of 50 HZ, and its harmonic spectrum is shown in figure (3). The frequencies at which voltage harmonics are generated are identified through the equation (3):

$$f_n = (jm_f \pm k) f_{ref}$$
$$m_f = \frac{f_c}{f_{ref}} \quad j = 1,2,3,\ldots \ , \ k = 1,3,5,\ldots$$

(3)



(1-3)



(2-3)

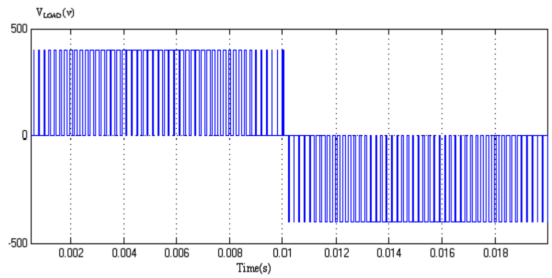
Fig.3: The output voltage of a full bridge inverter with bipolar modulation (1-3) and its harmonic spectrum (2-3).

The controlling of the switches in Unipolar modulation is in a way that the switches put on a single arm are never turned on at the same time. The switching pattern of the inverter in this method is:

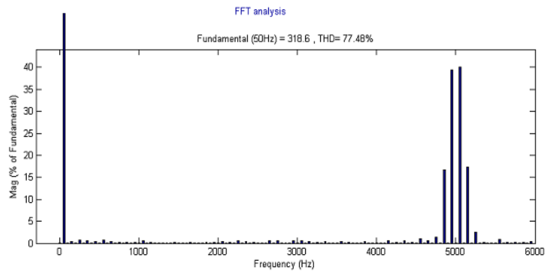
(4)

$$\begin{cases} V_{ref} > V_c \rightarrow s_1, s_2 : on \ \& s_3, s_4 : off \\ V_{ref} < V_c \rightarrow s_3, s_4 : on \ \& s_1, s_2 : off \end{cases}$$

Figure (4) shows the output voltage of a full bridge inverter with unipolar modulation, the switching frequency of 2500 HZ and the reference signal of 50 HZ, and its harmonic spectrum. The frequencies at which voltage harmonics are generated are identified through the equation (5).



(1-4)



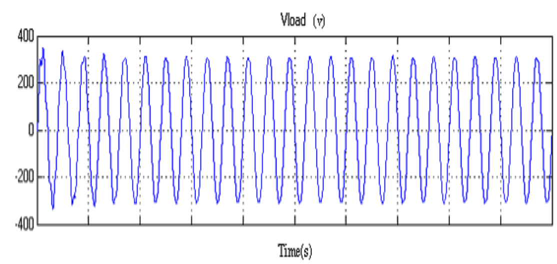
(2-4)

Fig.4: The output voltage of a full bridge inverter with unipolar modulation (1-4) and its harmonic spectrum (2-4)

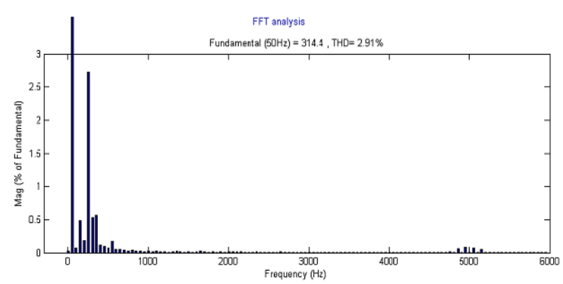
$$f_n = \left(j\,(2m_f) \pm k\right) f_{ref}$$

$$m_f = \frac{f_c}{f_{ref}} \quad j = 1,2,3,\ldots \ , \ k = 1,3,5,\ldots$$

Regarding equations (3) and (5) and the harmonic spectrum of the output voltage of the inverter, we can see that unipolar modulation is doubled for the frequencies around which voltage harmonics are generated. The easiest method to reduce low harmonics and the distortions of the output voltage is raising the switching frequency of the inverter and using a filter in its output to remove high frequency harmonics. In unipolar modulation, as the frequency of the harmonics is twice as that of bipolar modulation, the filter cutoff frequency can be higher. This results in a decrease in the size of the filter. The output voltage of the inverter with a filter and unipolar modulation is represented in figure (1-5) and figure (2-5) shows the voltage's harmonic spectrum.



(1-5)



(2-5)

Fig.5: the output voltage of a full bridge inverter with a filter and unipolar modulation (1-5) and its harmonic spectrum (2-5)

As you may observe, the filter deteriorates high frequency harmonics.

Using a filter at the inverter's output influences the transformation function of the entire inverter. The existence of a filter for linear loads in stable states does not result in any problem for the inverter, yet, it causes the distortion of the output voltage for nonlinear loads in stable states. A nonlinear load is shown in figure (6) and figure (7) shows the output voltage of the inverter and its harmonic spectrum when feeding this nonlinear load. As you may notice the distortion factor of the output voltage of the inverter raises when feeding nonlinear loads. Due to the fact that the inverter experiences vast load fluctuations and there is a direct relationship between the filter function and the output load, when the output load alters, the open loop transformation function of the whole inverter changes greatly, which like feeding nonlinear loads, it leads to many problems in open loop controlling of the inverter. In order to solve these problems we can use controlling with feedback to control the close loop of the inverter.

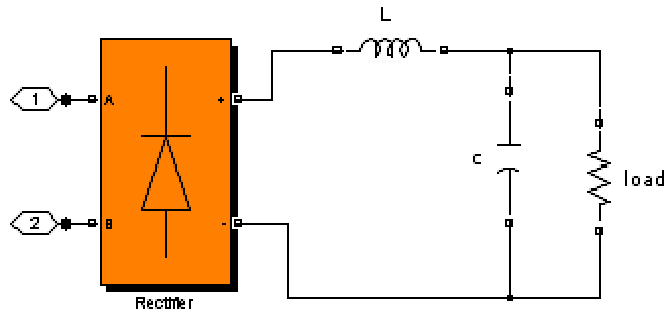
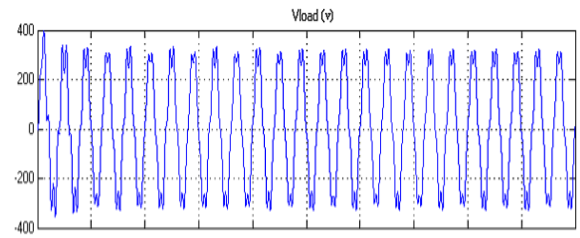
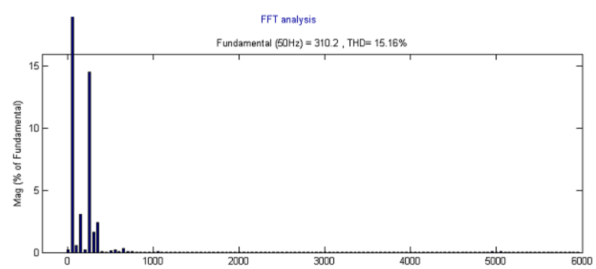


Fig.6: nonlinear loads



(1-7)



(2-7)

Fig.7: the output voltage of the inverter (1-7) and its harmonic spectrum (2-7) when feeding nonlinear loads

2-2) Close Loop Controlling of the Inverter (Controlling Methods with Instant Feed Backing)

Making use of feedback in controlling systems improves the dynamic response and reduces the sensitivity of the system to the changes in parameters and undesirable turbulences. By instant feedback controlling we will gain a little-distorted output voltage in the output section of UPS inverters.

1-2-2) Simple Instant Feedback Controlling (Controlling Loop with a Feedback)

The diagram block of a controlling system with a simple feedback loop is shown in figure (8). In this method, the output voltage of the inverter is compared with a sine reference. In order to generate the reference signal of the modulator, SPWM is applied on a PI controller. It is not easy to stabilize an inverter with an LC filter in the output and with a sine reference, especially when connecting to a nonlinear load such as diode bridges and capacitors. Connecting the load with a diode bridge or a capacitor to the UPS output leads to bridge diodes to be turned off and the close loop system to be at its output with no load, at some times in the sine circle, and at other times, the bridge diodes are tuned on, and in addition to the consumer current being provided at this part of the circle, the consumer input capacitor, which may be several times larger than the UPS output LC filter capacitor, gets parallel to the filter capacitor, and the close loop system is positioned in an entirely different condition. Consequently, PI controllers, which are frequently employed in switching transformers, will not have enough efficiency in this method. To overcome this problem, PID controllers are employed in controlling loop with a feedback, as represented in figure (9), or a controlling loop with two feedbacks (Current and voltage feedbacks) is employed. The inverter shown in figure (2) with a simple controlling loop is simulated for regulating output voltage of the linear load of RL, by the reference value of 220 RMS. The transformer function controlling PID and its controlling factors are as below:

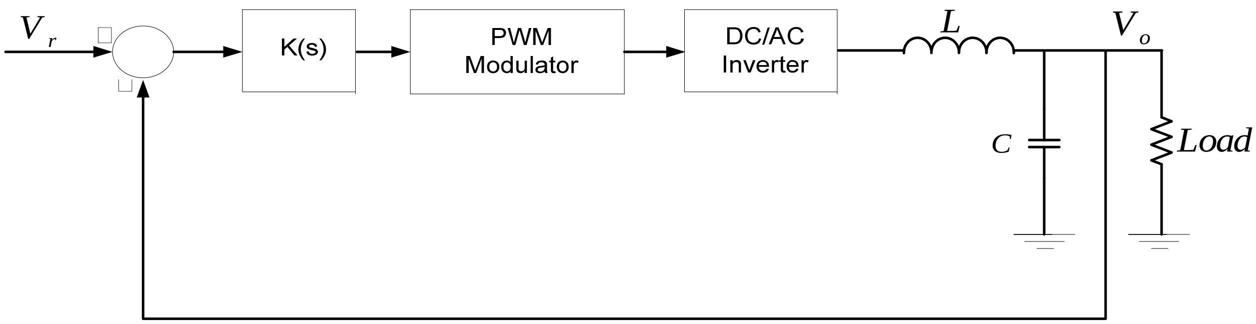


Fig.8: The diagram block of the controlling system with a simple feedback loop

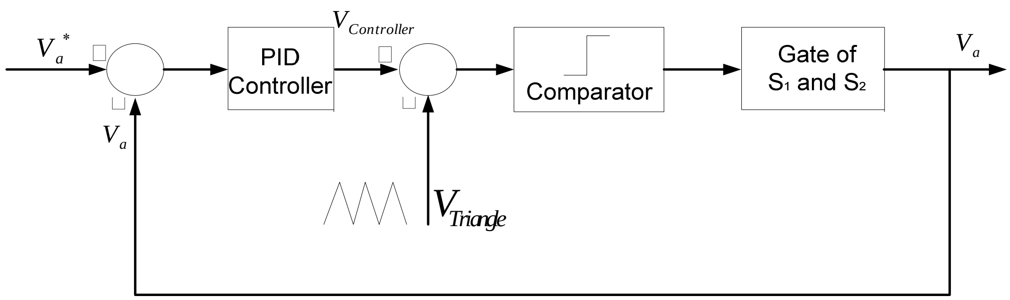


Fig.9: block diagram of the controlling system with a simple feedback loop and PID controller

$$G_c(s) = k_p + k_d s + \frac{k_I}{s}$$
$$k_p = 10,\ k_I = 1,\ k_d = 0.001$$

The output voltage of the inverter and its efficient value (RMS) is represented in Fig.10 . As you may notice, the output voltage of the inverter is adjusted to have the desirable reference value. Based on Fig.11 which represents the harmonic spectrum of the output voltage, total harmonic distortion (TDH) of output voltage has been reduced as compared to that of open loop control scheme.

The output voltage waveform and harmonic spectrum of the inverter with simple control loop and nonlinear load shown in Fig.6, is represented in Fig.12. Comparing figures (12) and (7), we can notice the TDH of inverter output voltage with a simple control loop under nonlinear load is enhanced significantly, as compared with that of the inverter with an open loop control.

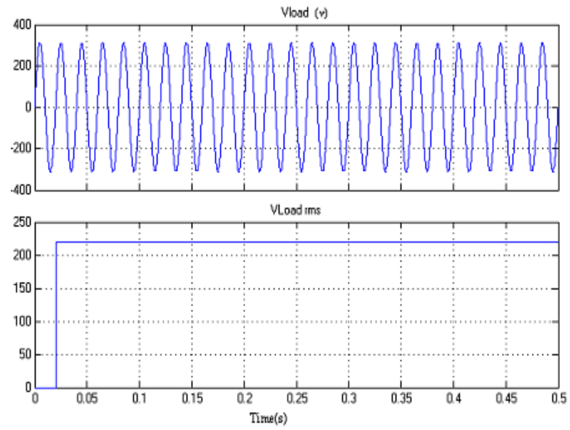


Fig.10: The output voltage of the inverter and its efficient value with a simple feedback loop

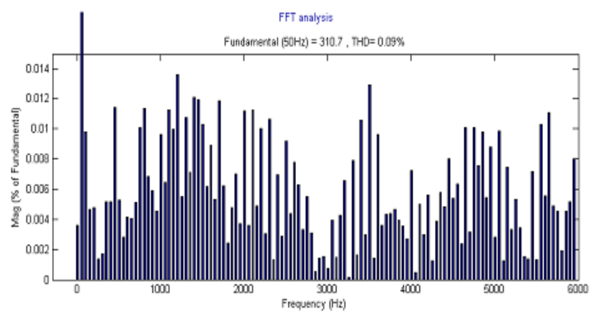


Fig.11: the harmonic spectrum of the output voltage with a simple feedback loop

Fig.13 shows the changes of inverter output voltage with a simple control loop, with the changes of input dc, during the period between 0.2s and 0.3s and returning to the normal state. As you may notice, the output voltage follows the reference sine voltage truly.

Fig.14 shows the changes of inverter output voltage with a simple control loop, and the changes of the inverter in response to the change of the load of the inverter, during the period between 0.2s and 0.3s and returning to the nominal value. The The inverter with simple control loop also shows a good response when the load is changed.

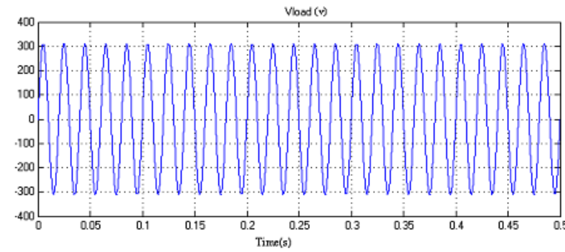


Fig. (12-1)

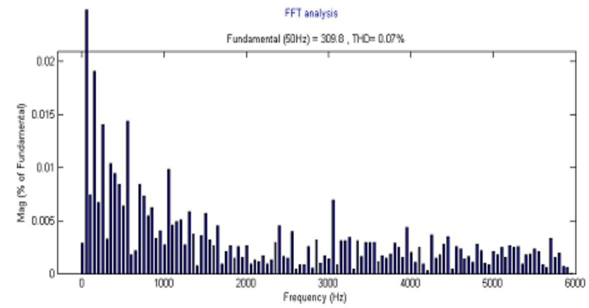


Fig. (12-2)

Fig.12: the output voltage of the inverter with a simple controlling loop hen feeding nonlinear load (12-1) and its harmonic spectrum (12-2)

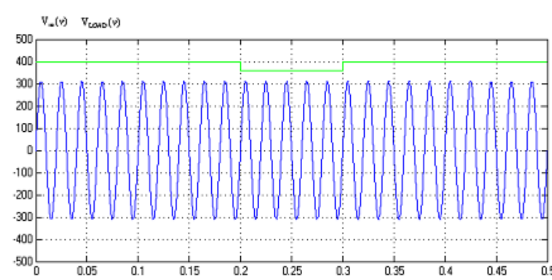


Fig.13: the output voltage of the inverter with a simple controlling loop when the input dc voltage is changed during the period between 0.2s and 0.3s

2-2-2) Multiple Instant Feedback Controlling (Controlling Loop with Two Feedbacks)

Fig.15 shows the block diagram of control system with multiple feedback loops is. In this controlling method, subsequent to comparing the output voltage to the sine reference voltage, the error signal is sent to PI controller for generating the reference current. The output of PI controller (Reference current), after being compared with the current of the filter capacitor /inductor or output current (which has been fed back), is applied to current regulator that is typically PI controller.

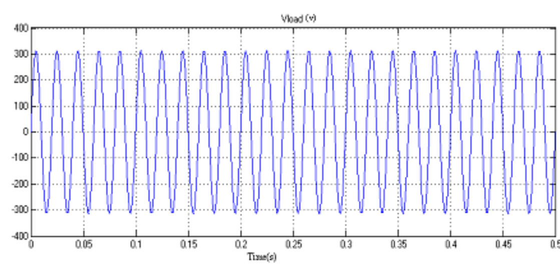


Fig. (14-1)

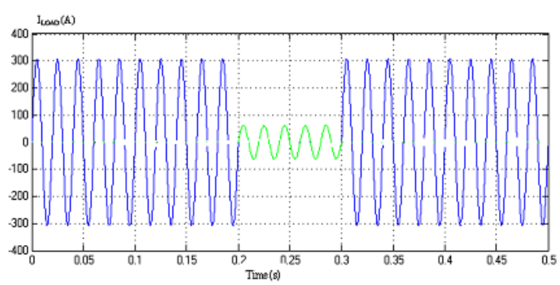


Fig. (14-2)

Fig.14 inverter output voltage with a simple control loop when the output voltage is changed during the period between 0.2s and 0.3 s (14-1) the output voltage of the inverter (14-2)

The output signal of PI controller is employed as a reference for the inverter modulator. In dual-loop feedback, the outer feedback of voltage with a PI controller is employed for decreasing errors and the loop of filter capacitor/inductor current is employed for achieving a fast response. Designing the inner loop results in easier designing of the outer loop and a better responding to load variations. Additionally, due to the increased control bandwidth, the performance of inverter with multiple-feedback loop is improved for non-linear loads, as compared to the simple feedback loop. The performance of multiple-feedback control loop inverter is assessed by simulation in MATLAB -SIMULINK environment with control parameters selected of voltage and current regulator loops represented in Table.1.

Table.1 Control parameters of current and voltage regulator loops in multiple-feedback control

Controller / Parameter	Voltage regulator	Current regulator
		1
	0.5	0.5

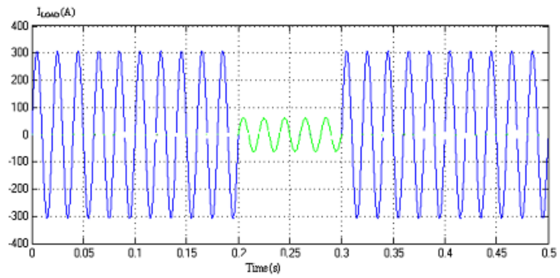


Fig.15 block diagram of a control system with multiple-feedback loops

Fig.16 shows the output voltage waveform and RMS value, along with the harmonic spectrum for two control loop inverter feeding a linear load. Comparing Fig.16 and Fig.11, we can observe that the output voltage TDH of the dual control loop inverter is enhanced, as compared to that of its single control loop counterpart.

Fig.17 represents output voltage and current of dual control loop inverter with a nonlinear load consisted of a diode bridge and capacitor. The harmonic spectrum is shown in Fig.18, respectively. Comparing Fig.18and Fig.18we can conclude that the TDH of dual control loop inverter output voltage is significantly enhanced, as compared to that of single control loop one.

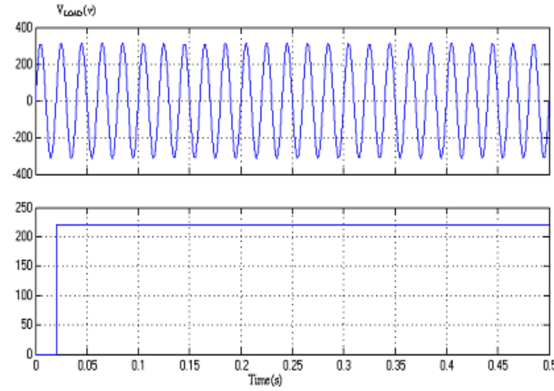


Fig.(16-1)

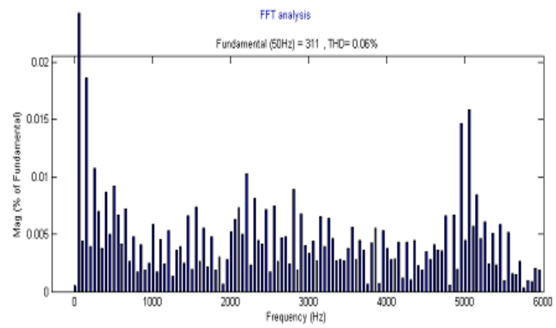


Fig. (16-2)

Fig.16: output voltage waveform and RMS value of multiple-feedback loop inverter (16-1) the multiple-feedback loop inverter output voltage harmonic spectrum (16-2)

Therefore, it can be concluded that multiple feedback inverter represents better voltage specifications, as compared to the single feedback loop control method.

The low output voltage TDH is a central objective in UPS control system designing. In addition, the control system should provide the appropriate condition to decrease the harmonics of UPS's input line and increase the input power factor, respectively. Next part explains the application of proper control strategy in UPS rectifier stage, in order to enlarge the input power factor.

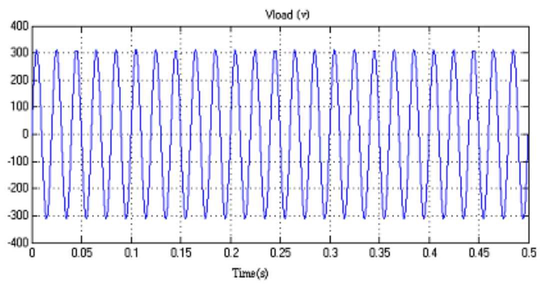


Fig.(17-1)

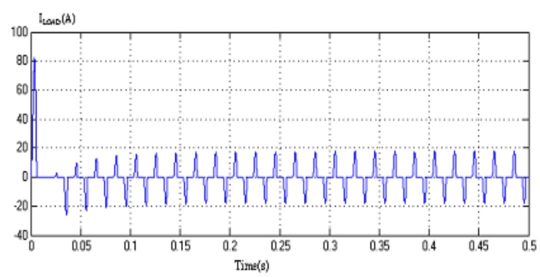


Fig.(17-2)

Fig.17: the output voltage of the inverter with two controlling loops when feeding the nonlinear load of the diode bridge and the capacitor (17-1), the output current of the inverter (17-2)

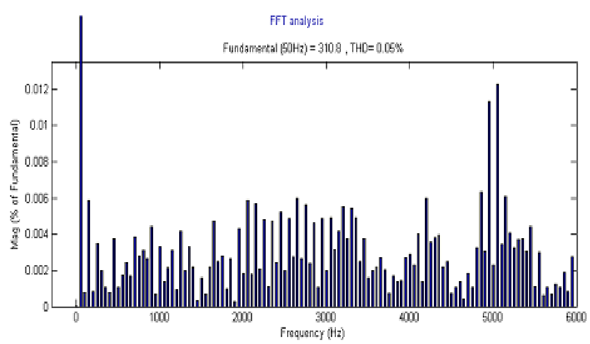


Fig.18: the harmonic spectrum of the output voltage of the inverter with two controlling loops when feeding nonlinear load if the diode bridge and the capacitor

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BIOGRAPHIES

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