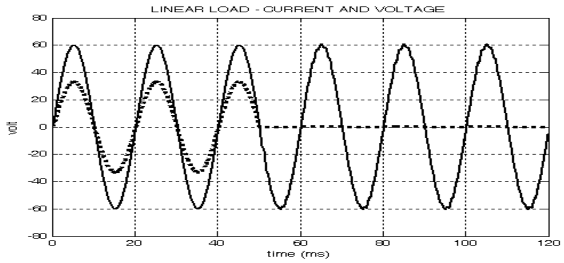

Fig. (9): Simulation results under step load suddenly turned off – load voltage (line) and current load (dash)

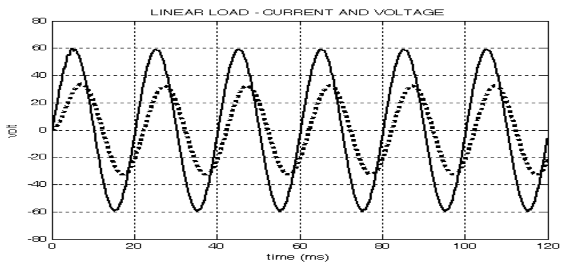

Fig. (10): Simulation results under inductive load - load voltage (line) and current load (dash)

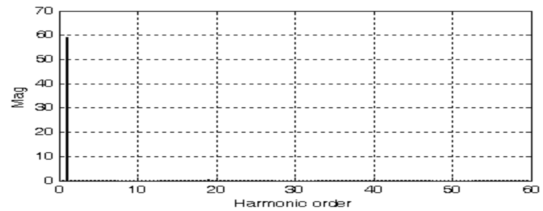

Fig. (11): Frequency spectrum of the load voltage under inductive load

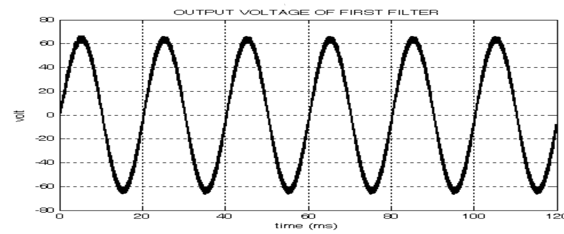

Fig. (12): First filter output voltage with inductive load

VI. Conclusion

In this paper a new filter arrangement with reduced element rate value for output harmonic reduction and to improve voltage regulation is presented. Analysis and simulation of the proposed filter confirm the harmonic reduction in output voltage inverter for different load, that THD is less than 5%.

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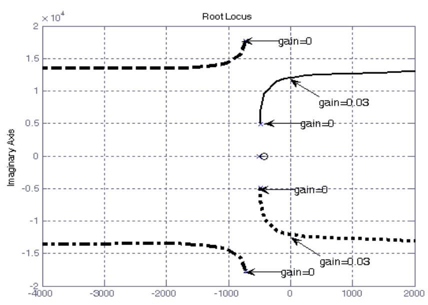
The parameters of the system chosen for analysis and simulations are listed in table III. Fig. 5 shows the root locus of the incremental dependence of the output voltage and capacitor current due to incremental change in duty cycle. Fig. 6 and 7 shows the bode plot of the output voltage and inner current for different loads. The figures show that the inner current exhibits a band pass and output voltage a low pass filter like characteristics.

Table (3): Simulation Parameters

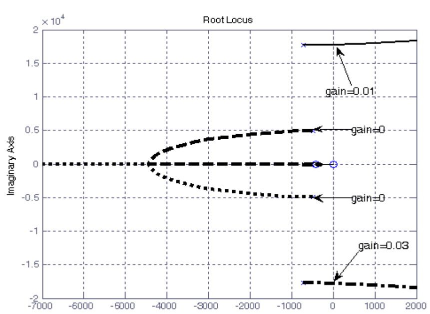
Item	Nominal value
Output voltage	60 V
Output frequency	50 Hz
Rectifier load capacitance	500 µF
Rectifier load resistance	10 Ω
Power factor	0.8 Lag
First filter inductance	0.3 mH
First filter capacitance	80 µF
Second filter inductance	0.1 mH
Second filter capacitance	60 µF
DC input voltage	100 V
Linear load resistance	1.8 Ω
ESR of the first inductor filter	0.30 Ω
ESR of the second inductor filter	0.15 Ω
Switching frequency	6 kHz

V. Simulation Results

This section presents simulation results under different loading conditions obtained with Matlab/Simulink, which show the good steady state performance for multiple-filter. The simulation results for case where the full load suddenly turnson and turnsoff are shown in figs. 8 and 9, respectively. The THD of the output voltage for resistive load is 0.40% and the voltage regulation is less than 1%.



(a) Output voltage



(b) Capacitor current

Fig (5): Root locus for resistive load

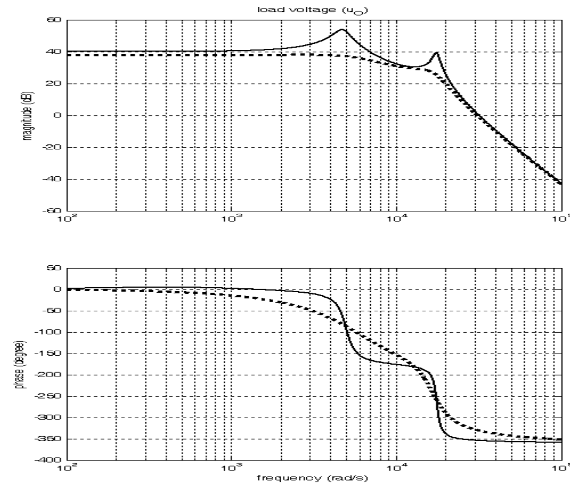


Fig. (6): Bode diagram of the open loop transfer function of the output voltage for resistive load (dash) and no-load (line)

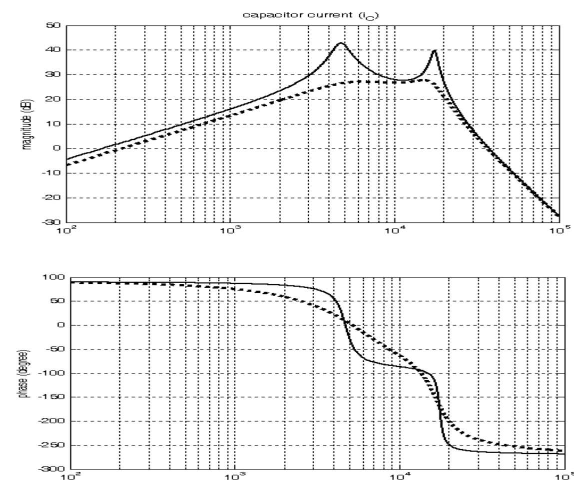


Fig. (7): Bode diagram of the open loop transfer function of the inner current for resistive load and no-load

The Figures show that the load voltage is nearly sinusoidal waveform too necessity to gives stable response at any load type. Figs. (10-12) show the results simulation under inductive load. Just as seen, response is stable with fourth order output filter (multiple-filter). The THD of the output voltage for inductive load is 1.7% and the voltage regulation is 1.13%.

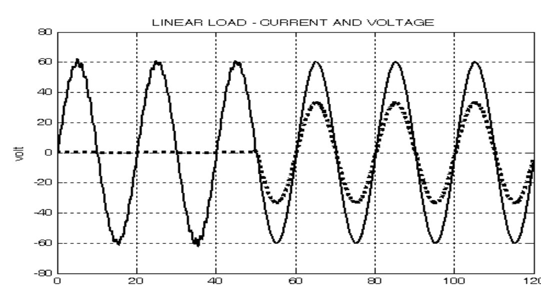


Fig. (8): Simulation results under step load suddenly turned on – load voltage (line) and current load (dash)

Table (1): THD and odd harmonics of output voltage of the single BPWM inverter system

THD of output voltage	131%
19th harmonic	28.74%
21th harmonic	90.16%
23rd harmonic	29.18%
41rd harmonic	33.76%
43rd harmonic	33.26%
45rd harmonic	18.67%

Table (2): THD and odd harmonics of output voltage of the single UPWM inverter system

THD of output voltage	67%
19th harmonic	0.02%
21rd harmonic	0.17%
23rd harmonic	0.33%
41rd harmonic	33.80%
43rd harmonic	33.70%
45rd harmonic	18.64%

III. Mathematical Model

Mathematical modeling of the system is required for designing control systems. State equations are commonly used in the simulation procedure. The system state variables (as shown in Fig.1) are: the inverter output current (i_F), the second filter capacitor current (i_C), the first filter capacitor voltage (u_F), the output voltage (u_O) and the output current (i_O). In state space form, the system equations will be as follows:

$$\frac{d}{dt}i_F = -\frac{R_{F1}}{L_{F1}}i_F - \frac{1}{L_{F1}}u_F + \frac{1}{L_{F1}}u_I \quad (2)$$

$$\frac{d}{dt}u_F = \frac{1}{C_{F1}}i_F - \frac{1}{C_{F1}}i_C - \frac{1}{C_{F1}}i_O \quad (3)$$

$$\frac{d}{dt}i_C = \left(\frac{R_L}{L_L} - \frac{R_{F2}}{L_{F2}}\right)i_O - \frac{R_{F2}}{L_{F2}}i_C + \frac{1}{L_{F2}}u_F - \left(\frac{1}{L_L} + \frac{1}{L_L}\right)u_O \quad (4)$$

$$\frac{d}{dt}u_O = \frac{1}{C_{F2}}i_C \quad (5)$$

$$\frac{d}{dt}i_O = -\frac{R_L}{L_L}i_O + \frac{1}{L_L}u_O \quad (6)$$

The block diagram of the proposed inverter output filter is shown in Fig. (4), that $G_{F1}(s)$ and $G_{F2}(s)$ are filter inductors admittance, $G_{C1}(s)$ and $G_{C2}(s)$ are filter capacitors impedance. If $D_C(s)$ is duty cycle, K_{PWM} and T_{PWM} are gain and dead time of PWM inverter, the PWM inverter transfer function is:

$$G_{PWM}(s) = \frac{U_I(s)}{D_C(s)} = \frac{K_{PWM}}{1+T_{PWM}s} \quad (7)$$

IV. Output Impedance

Fig. (4) provides a more detailed insight into how all the variables relate to each other. The output voltage of the open loop system can be written as follow as:

$$U_O(s) = T_O(s)U_I(s) + Z_{OUT}(s)I_O(s) \quad (8)$$

where $T_O(s)$ is tracking characteristic and $Z_{OUT}(s)$ is the output impedance. The $Z_{OUT}(s)$ is a parameter for determining the effect of loading on the inverter, which can be calculated by assuming the inverter output voltage to be zero:

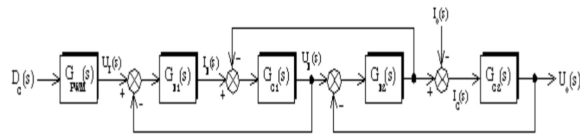


Fig. (4): Averaged equivalent circuit of the system

$$Z_{OUT}(s) = \left.\frac{U_O}{-I_O}\right|_{U_I=0} = \frac{N_O(s)}{D_O(s)} \quad (9)$$

Sensitivity of the load has little effect on the inverter output impedance, because light load or no load cases has no effect on the stability of the UPS system. The large voltage distortion is caused by high output impedance at the frequecies of harmonic load currents. To minimize distortion in the output voltage caused by nonlinear load, the output impedance is desirable to be small, which may be achieved by increasing switching frequency and increasing the closed loop control bandwidth [1]. For fourth order filter $N_O(s)$ and $D_O(s)$ in (8) are:

$$N_O(s) = G_{C2}(s)[1 + G_{C1}(s)G_{F1}(s) + G_{C1}(s)G_{F2}(s)] \quad (10)$$

$$D_O(s) = G_{C1}(s)G_{F2}(s) + [1 + G_{C2}(s)G_{F2}(s)][1 + G_{C1}(s)G_{F1}(s)] \quad (11)$$

where:

$$G_{F1}(s) = \frac{1}{L_{F1}s + R_{F!}} \quad (12)$$

$$G_{F2}(s) = \frac{1}{L_{F2}s + R_{F2}} \quad (13)$$

$$G_{C1}(s) = \frac{1}{C_{F1}s} \quad (14)$$

$$G_{C2}(s) = \frac{1}{C_{F2}s} \quad (15)$$

The characteristic equation of the system with ignored of the equivalent series resistance of the filter is:

$$\Delta(s) = s^5 + \frac{R_L}{L_L}s^4 + \left[\frac{1}{C_{F1}}\left(\frac{1}{L_{F1}} + \frac{1}{L_{F2}}\right) + \frac{1}{C_{F2}}\left(\frac{1}{L_{F2}} + \frac{1}{L_L}\right)\right]s^3 + \frac{R_L}{L_L}\left(\frac{1}{L_{F1}L_L} + \frac{1}{L_{F2}C_{F1}} + \frac{1}{L_{F2}C_{F2}}\right)s^2 + \frac{L_{F1}+L_{F2}+L_L}{L_{F1}L_{F2}C_{F1}C_{F2}L_L}s + \frac{R_L}{L_{F1}L_{F2}C_{F1}C_{F2}L_L} \quad (16)$$

The transient response performance and relative stability are directly related to the location of the closed loop roots of the characteristic equation in the s-plane. There are several open loop system properties we need to know before we design the controller. From the state equations, the plant control to output transfer function is:

$$H_U(s) = \frac{U_O(s)}{U_I(s)} = \frac{Z_L(s)T_O(s)}{Z_L(s) + Z_{OUT}(s)} \quad (17)$$

$$H_I(s) = \frac{I_C(s)}{U_I(s)} = \frac{Z_L(s)T_O(s)}{G_{C2}(s)[Z_L(s) + Z_{OUT}(s)]} \quad (18)$$

where $Z_L(s)$ is load impedance in s-domain and tracking characteristic is:

current controller systems depends on the feedback control strategy used, which can be broadly categorized into linear and nonlinear systems.

This paper investigates the performance of output multiple- filter for single phase voltage source UPS inverter compared to output mono-filter. The analysis is performed by using Matlab program and Simulink toolbox to analyze on waveform quality and overall voltage and current waveform and spectra. In section II the plant model of the system is described. In section III state space averaging technique used to model the system as different transfer functions. The output impedance is given in section IV. Section V presents some simulation results under different loading conditions that shows the transient performance of the proposed multiple-filter and compares it with the mono-filter. Finally, section VI draws the conclusion.

II. System Description and Harmonic Analysis

The scheme of a single phase full bridge voltage source PWM inverter with fourth order output filter used in an UPS system is shown in Fig. 1. It consists dc supply U_{dc}, filter inductors L_{F1} and L_{F2}, filter capacitors C_{F1} and C_{F2}, the equivalent series resistance of the filters R_{F1} and R_{F2}, power switches Q_1-Q_4 and inductive load with resistance R_L and inductance L_L. The voltage waveform of actual inverter is non-sinusoidal with a number of harmonic components.

Harmonic analysis has been widely used for system planning, operation criteria development, equipment design, troubleshooting, verification of standard compliance, and so on. Ideally, output voltage harmonics are grouped around the carrier frequency and its multiples.

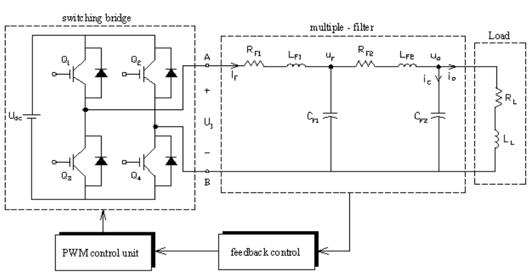


Fig. (1): Single phase UPS inverter with multiple filters

If this frequency is made high enough, output voltage harmonics are easily filtered by the load in many applications. However, switching frequency is generally limited and the switching loss increase with the elevation of the switching frequency. To obtain less distortion in the output voltage waveform, many modulating methods and various means for the control of PWM voltage inverters have been developed to reduce harmonic content. Similar to a linear system, ac voltage output of inverter can be expressed as components of input voltage and defined the transferred harmonics via the inverter [2]. If $S(\omega t)$ is the transfer function of the single phase inverter, the output voltage of the inverter is as flows:

$$U_I(\omega t) = U_{dc}\underbrace{[M_a \sin S(\omega_o t) + \sum_{k=3,5,...}^{\infty} A_K \sin(k\omega_o t)]}_{S(\omega t)} \qquad (1)$$

where ω_o is angular frequency of main component, M_a is modulation index and A_K is the coefficient of Fourier series. If the frequency modulation ratio (M_f) or carrier frequency is high enough, the PWM inverter is considered as a voltage source and dynamic response of the UPS inverter is mainly determined by the elements of filter [3]. For full bridge inverter, there are bipolar and unipolar switching techniques. These have different characteristic output voltage, current and voltage waveforms and harmonic contents. Figs. (2) and (3) show results of the simulation of PWM inverter for U_{dc}=100V, M_a=0.85 and M_f=21.

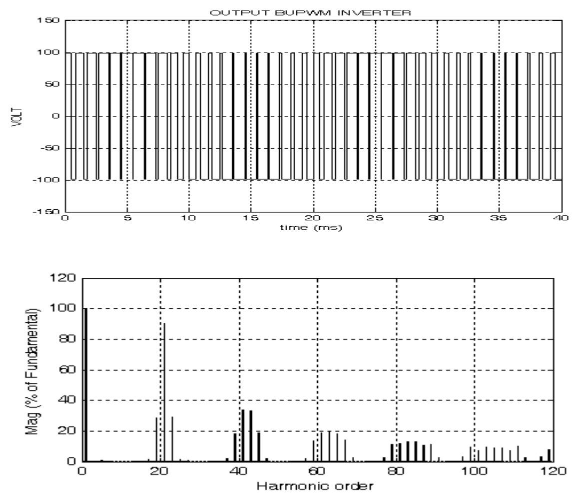


Fig. (2): Simulation results of bipolar PWM inverter

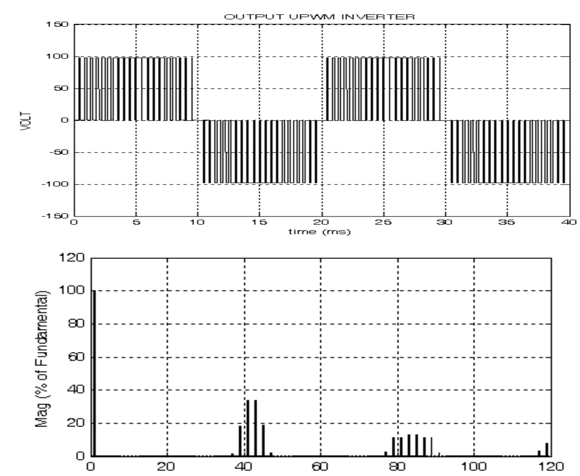


Fig. (3): Simulation results of unipolar PWM inverter

The THD and odd harmonics of the output voltage of the system operated under no-load with UPWM and BPWM are listed in Table I and II. The effective switching frequency of the output voltage waveform in UPWM switching scheme is doubled and the ripple is reduced.

Modeling and Simulation of the Single Phase Voltage Source UPS Inverter With Fourth Order Output Filter

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Abstract: A UPS inverter operates in wide load impedance ranges from resistive to capacitive or inductive load. At the same time, fast transient load response, good load regulation and good switching frequency suppression is required. The variation of the load impedance changes the filter transfer characteristic and thus the output voltage value. In this paper, an analysis and simulation of the single phase voltage source uninterruptible power supply (UPS) with fourth order filter (multiple-filter) in output inverter, based on the state space averaging and small signal linearization technique, is proposed. The simulation results show the high quality sinusoidal output voltage at different loads, with THD less than %5.

Index Terms: UPS inverter, output filter, harmonic, modeling, simulation.

I. Introduction

Uninterruptible power supply (UPS) systems are required for supplying sinusoidal output voltage for linear and nonlinear loads. UPS provides high quality power, uninterrupted and reliable for sensitive and critical loads such as life supporting systems, telecommunication systems, on-line system for banks, satellite and computers to supply constant voltage and constant frequency power. Performance of a UPS system even with nonlinear and step changing loads is evaluated in terms of several factors, such as: voltage regulation, output impedance, total harmonic distortion (THD) output voltage, value power factor of the input current, characteristics of transient response and transfer time [4,5]. They depend mostly on the control technique applied to the UPS inverter, such as sliding mode control [6], optimal control [7], repetitive control [8], multi-loop feedback control [9] and many others [10, 11, 12]. In [13] a control scheme based on a deadbeat control both on the output voltage and inductor current is proposed, which a disturbance observer is used for the estimation of the load current and for any other source of errors.

A digital multiple feedback control has been proposed in [14]. In this technique the current dead beat control and an outer voltage feedback loop with fuzzy control are used to ensure load voltage to be sinusoidal and well regulated. In [15], a robust model reference adaptive controller including a repetitive control for single phase UPS appli–cations is presented. It can effectively eliminate periodic waveform distortion resulting by unknown periodic disturbances, and it is globally stable in the presence of un-modeled dynamics. In [16], a feed forward based on a particular type of online trained neural network controller in parallel with a proportional–derivative controller for improving the dynamic response is proposed for the control of UPS inverters. In [17] a multi-filter and waveform feedback of voltage for reduction harmonics in a single phase UPS inverter with rectifier load is described.

Based on aim of control system, different feedback control schemes for UPS inverters are classified [18-19]: 1) Continuous-time and discrete-time control: Feedback control strategies devised for UPS inverters can be broadly classified as continuous-time control (CTC) and discrete-time control (DTC). With advent of fast microcontrollers, DTC strategies have been proposed. The response time of such schemes are limited by microcontroller speed and give rise to considerable distortion with nonlinear loads. CTC strategies are much faster and can lead to much less distortion, 2) analog and digital control: the controllers can also be classified into two groups: analog based such as multiple feedback loops and digital based such as deadbeat controller. Most of the analog based controllers were designed based on linearized model and traditional frequency domain analysis. In designing a digital controlled PWM switching converter, two switching frequency requires careful selection: the PWM switching frequency of the power converter and the sampling frequency of the digital controller. There are many advantages in digital controllers, such as immune to drifts, insensitive to component tolerances, ease of implementation and changeable control law software updating and 3) linear and nonlinear control: the controllers on the basis of design and analytic approach can be divided into two main groups: linear such as predictive control and ramp comparisons current, and nonlinear such as the neural network, hysteresis current control, H_∞ control and fuzzy logic. It appears that the nonlinear controller is more suitable than the linear type since the inverter is truly a nonlinear system. Various methods of current control can be used in UPS inverter to provide over current protection, to improve the performance of output voltage controller and to simplify parallel operational. The performance of