Dynamic Analysis and Control Design of a Single-Phase UPS Inverter with Novel Topology and Experimental Verification

Ghazanfar Shahgholian, Jawad Faiz, Mohsen Arezoomand

Abstract – An uninterruptible power supply (UPS) system with two kinds of filters in the inverter output is analyzed and simulated. The purpose of a voltage controller for UPS inverters is to produce stable output voltage with low distortion under all loading conditions, particularly under nonlinear loads and load transients. The system modeled consists of the output filter, the control system and the single phase inverter. A state-space mathematical model for system is used. The results show that system voltage total harmonic distortion to less than 5% even when supplying nonlinear loads which draw current with a crest factor of 3. The simulation results are confirmed by the experimental results. Copyright © 2009 Praise Worthy Prize S.r.l. - All rights reserved.

Keywords: Uninterruptible Power Supply (UPS), Filter, Harmonic, Two-Port Network, Stability

I. Introduction

With the growth of internet and information technology industry, the need for reliable continuous power to protect data integrity and ensuring uninterrupted service is an important requirement. The major function of a UPS is to provide a high quality output waveform, a fast dynamic response and the capability of carrying any load factors. There are many publications describing the various topologies, analysis and control design of UPS inverter [1]-[2]. In [3], a feed forward based on a particular type of on line trained neural network controller in parallel with a proportional-derivative controller for improving the dynamic response proposed for the control of UPS inverters. The design consideration and performance analysis of an on-line, low-cost, high performance, and single-phase UPS system based on a boost integrated fly back rectifier/energy storage dc/dc converter to achieve power factor correction, fast dynamic response, low battery voltage, and desired output voltage is present in [4]. A simple digital feedback voltage controller for high-performance single-phase UPS inverters proposed in [5]. The proposed control strategy focuses on reducing the output impedance of inverters by a feedback of the load current. An innovative tuning technique based on optimization tools with considers practical design constraints for the design of multi loop lag–lead compensators that are normally used in industrial UPS systems based on the H-infinity robust control theory presented in [6]. In [7] inner-outer loop controllers are adopted to regulate output voltage and to improve system response, and a current weighting distribution control strategy for multi-inverter systems to achieve current sharing is presented. In [8] an improved single-phase passive-standby UPS includes an input rectifier/charger and a switching inverter with or without a dc/dc boost stage according to ones low battery voltage for low cost application is described. Two control strategies for three-phase series-parallel uninterruptible power supplies are described and compared in [9]. In [10] a unified control scheme as well as a novel connection arrangement is developed to simplify the inverter circuit for design of line interactive UPS without load current sensors. An optimal control strategy based on the LQR approach for single phase UPS in continuous time proposed in [11].

The objective of the paper is to develop an uninterruptible power supply (UPS) control system with multiple-filter. The influences of these filters upon the reduction of the output voltage distortion are shown. The remainder of this paper can be outlined as follows. The single phase inverter is describing in section II. The small signal model of the system consists of the output filter, the control system, different loads shown in section III. The two port model of inverter output filter is shown in section IV. In section V, the system open loop transfer functions are described based on averaged model of the inverters.

A comparative analysis of the voltage droop and power loss in mono- and multiple-filter is presented in section VI. The output impedance, which is an index for determining the effect of loading on the inverter, is shown in section VII.

In section VIII, simulation results of the output voltage for different changes in the input voltage and load have been reported. The analysis is performed by using Matlab program and Simulink toolbox to analyze on waveform quality and overall voltage waveform and spectra.

Finally, the experimental results are given for linear and nonlinear load in section IX and discussed in section X.

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II. Voltage Source UPS Inverter

Fig. 1 shows the main circuit of a single-phase UPS inverter. The system modeled consists of the controller part and power circuit parts. The controller part includes the micro controller running the control algorithms and driver circuits. The power circuit part includes the full bridge inverter, filter, dc voltage and the critical load.

II.1. PWM Inverter

There are two PWM switching technique in order to shape the output ac voltage to be as close to a sine wave as possible: unipolar and bipolar PWM switching. In this paper the unipolar pulse width modulation (UPWM) technique (Fig. 2) for the control is used, because the undesired harmonics are shifted to the frequencies around double the carrier frequency (Fig. 3), which is much higher than the reference sinusoidal frequency, and thus can be easily filtered out. In Fig. 2, \( M_f \) is frequency modulation index and \( M_A \) is amplitude modulation ratio.

II.2. Inverter Output Filter

Filters are used to reduce the harmonic content of the voltage injected to the load. With single filter some harmonics manage to pass to the load. The harmonics can be further reduced by going for multiple filters. The distortion in the output voltage waveform, are much more effectively attenuated by going for two filters. Figs. 4-5 show the multiple-filter in the inverter output and the block diagram of a single-phase inverter with two filters in the output, respectively, where \( i_u \), \( u_u \) are current and voltage load, \( u_{F1}, u_{F2} \) are filter capacitor voltage, \( i_{F1}, i_{F2} \) are filter inductor current, \( i_{C1}, i_{C2} \) are filter capacitor current, \( L_{F1}, L_{F2} \) are filter inductance, \( C_{F1}, C_{F2} \) are filter capacitance, \( R_{F1}, R_{F2} \) are equivalent series resistance (ESR) of the filter. In this paper, the parameters of the system are \( L_{F1}=0.09\, \text{mH}, \, C_{F1}=100\, \mu \text{F} \) and \( U_{dc}=50 \text{ volt} \).

In the conventional methods of filter design, the latter is used as interference and the former is considered only to determine the filter values. Ignoring the filters resistances, the open loop state space equation of output filter can be written as:

\[
\begin{align*}
\frac{d}{dt}i_{F1} &= -\frac{R_{F1}}{L_{F1}}i_{F1} - \frac{1}{L_{F1}}u_{F1} + \frac{1}{L_{F1}}u_j \\
\frac{d}{dt}i_{F2} &= -\frac{R_{F2}}{L_{F2}}i_{F2} + \frac{1}{L_{F2}}u_{F1} - \frac{1}{L_{F2}}u_{F2} \\
\frac{d}{dt}u_{F1} &= \frac{1}{C_{F1}}i_{F1} - \frac{1}{C_{F1}}i_{F2} \\
\frac{d}{dt}u_{F2} &= \frac{1}{C_{F2}}i_{F2} - i_j
\end{align*}
\]

(1)

II.3. Load Model

The load on a power system consists of a variety of electrical devices. A linear element in a power system is a component in which the current is proportional to the voltage. Typical examples of linear loads include heaters, motors and incandescent lamps. The differential equation with linear load \( (R_L-L_L) \) is given by:

\[
\frac{d}{dt}i_o = -\frac{R_L}{L_L}i_o + \frac{1}{L_L}u_{F2}
\]

(2)
With the increasing use of nonlinear loads in power systems, the harmonic pollution becomes more and more serious. The non-linear load causes a periodic disturbance. Nonlinear loads draw non-sinusoidal current, even though connected to a sinusoidal voltage. Also, the voltage and current waveforms are not of the same shape and contain fundamental frequency as well as non-fundamental frequencies. With nonlinear loads, the voltage and current waveform will be distorted and the THD will be inevitably increased. Typical examples of nonlinear loads include adjustable speed motor drives, rectifier, ferromagnetic devices and arc welding equipment [12]. The non-linear load as shown in Fig. 6, include single phase full bridge rectifier, second order filter (L-C) and resistor $R_L$.

The LC filter is for smoothing the current and attenuating the ripple voltage in the dc side. The differential equation describing the behavior of the system variables with non linear load are given by:

a) When one diode pair is on:

\[
\frac{d}{dt}i_L = -\frac{1}{L}u_C - \frac{1}{L}u_o
\]

\[
\frac{d}{dt}u_C = \frac{1}{C}i_L - \frac{1}{R_L C}u_C
\]

b) When diodes are off:

\[
i_L = 0
\]

\[
\frac{d}{dt}u_C = -\frac{1}{R_L C}u_C
\]

where $i_L$ and $u_C$ are current and voltage of DC-side LC filter. Therefore $Z_L(s)$ for nonlinear load is [13] (eq. (7)):

\[
Z_L(s) = \begin{cases} \infty & \text{where rectifier bridge turn off} \\ \frac{L}{s^2 + \frac{1}{R_L C} s + \frac{1}{LC}} & \text{where rectifier bridge turn on} \end{cases}
\]

II.4. Two-Port Model

The plant of output filter satisfies linear property, so it is possible to represent MIMO (Multi Input - Multi Output) system as shown in Fig. 7. The output voltage and output current of inverter in terms of load voltage and current in Laplace domain are as follows:

\[
U_I(s) = A(s)U_O(s) + B(s)I_O(s)
\]

\[
I_I(s) = C(s)U_O(s) + D(s)I_O(s)
\]

where $A$, $B$, $C$ and $D$ are transfer parameters of filter. Assuming that the resistance associated with the filter inductor is negligibly small; the equivalent parameters for different inverter output filters are shown in Table I. The output voltage is:

\[
U_O(s) = H_I(s)U_I(s) - H_O(s)I_O(s)
\]

where the transferring characteristic and inverter output impedance are:

\[
H_I(s) = \frac{1}{A(s)}
\]

\[
H_O(s) = \frac{B(s)}{A(s)}
\]

In linear loads the function $H_I(s)$ has little effect but in nonlinear loads and load variations its effect cannot be ignored. If the filter resistances are disregarded, then the function $H_I(jo)$ will be real and $H_I(jo)$ will be imaginary. Inverters may be confronted with no-load or small load conditions due to interferences. No-load or light load cases has no effect on the stability of the UPS system, therefore sensitivity of the load change has little effect on the inverter output impedance. The output voltage harmonics depend on both the harmonics generated by the inverter output voltage and load current. The transfer function of output voltage and inverter output current is represented as follows:

\[
T_O(s) = \frac{U_O(s)}{I_I(s)} = \frac{Z_I(s)}{A(s) Z_I(s) + B(s)}
\]

\[
T_I(s) = \frac{I_I(s)}{U_I(s)} = \frac{A(s) C(s) Z_I(s) + B(s)}{A(s) Z_I(s) + B(s)}
\]
TABLE I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mono filter</th>
<th>LCL filter</th>
<th>Multiple filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$1 + L_{p1}C_{p1}s^2$</td>
<td>$1 + L_{p1}C_{p1}s^2$</td>
<td>$1 + (L_{p1}C_{p1} + L_{p2}C_{p2} + L_{p3}C_{p3})s^2 + L_{p1}L_{p2}C_{p1}C_{p2}s^4$</td>
</tr>
<tr>
<td>B</td>
<td>$L_{p1}s$</td>
<td>$(L_{p1} + L_{p2})s + L_{p1}L_{p2}C_{p1}s^3$</td>
<td>$(L_{p1} + L_{p2})s + L_{p1}L_{p2}C_{p1}s^3$</td>
</tr>
<tr>
<td>C</td>
<td>$C_{p1}s$</td>
<td>$C_{p1}s$</td>
<td>$(C_{p1} + C_{p2})s + L_{p1}C_{p1}C_{p2}s^3$</td>
</tr>
<tr>
<td>D</td>
<td>$1$</td>
<td>$1 + L_{p2}C_{p1}s^2$</td>
<td>$1 + L_{p2}C_{p1}s^2$</td>
</tr>
</tbody>
</table>

The transfer function of capacitor current of second filter is given by:

$$T_C(s) = \frac{I_{C2}(s)}{U_I(s)} = \frac{Z_L(s)C_{p2}s}{A(s)Z_L(s) + B(s)} \quad (15)$$

The plant open loop roots are dependent on the load impedance. The open loop root locus with load resistance changing from zero to infinite for multiple-filter and mono-filter are shown in Figs. 8 and 9 respectively.

As shown in the diagram, the points marked by (A) are the pole positions under no load condition. The points marked by (B) are the plant pole root positions under zero load condition. It can be observed that the location of the system poles vary with different kinds of loads, input dc voltage, the parameters of inverter output filter and the incremental change in the modulation index.

III. Voltage Droop and Loss Reduction

By ignoring the filter capacitor series resistance, the equivalent circuits of the averaged system for mono- and multiple-filter are shown in Figs. 10 and 11 respectively. In the mono-filter, $L_F$ is filter inductance, $C_F$ is filter capacitance and $R_F$ is equivalent series resistance (ESR) of the filter. In this section analysis is based on a criterion such as the same load impedance, dc voltage, total inductance and capacitance, therefore $L_F = L_{F1} + L_{F2}$, $C_F = C_{F1} + C_{F2}$ and $R_F = R_{F1} + R_{F2}$. If $L_{F2} = K_L L_{F1}$ and $C_{F2} = K_C C_{F1}$, the inductors and capacitors reactance in the multiple-filter in terms of the inductor and capacitor reactance in the mono-filter are:

$$X_{C1} = (K_C + 1)X_C \quad (16)$$

$$X_{C2} = \frac{K_C + 1}{K_C}X_C \quad (17)$$

$$X_{F1} = \frac{1}{K_F + 1}X_F \quad (18)$$

$$X_{F2} = \frac{K_F}{K_F + 1}X_F \quad (19)$$

The system variables in the steady state in terms of the load parameters and filter components at the modulating signal frequency ($\omega$), are obtained using the phasor analysis. The filter inductor current in the steady state for mono-filter for a pure resistive load with resistance $R_L$ is:

$$\bar{I}_F = \left(\frac{1}{R_L} + j \frac{1}{X_C}\right)\bar{U}_0 \quad (20)$$
The filter inductors currents in the steady state for multiple-filter for a pure resistive load with resistance $R_L$ are:

$$\tilde{I}_{F2} = \left( \frac{1}{R_L} + j \frac{k_c X_F}{(1+k_c) X_C} \right) \tilde{U}_O$$

(21)

and eq. (22):

$$\tilde{T}_{F1} = \tilde{T}_{F2} + \tilde{T}_{C1} =$$

$$= \left[ \frac{1}{R_L} \left( \frac{k_c X_F}{(1+k_c) X_C} \right) + \frac{R_{F2} K_c}{(1+k_c) X_C} \right] \tilde{U}_O$$

$$+ j \left[ \frac{1}{X_C} \left( \frac{k_c K_c X_F}{(1+k_c) X_C} + \frac{R_{F2}}{1+k_c R_L} \right) \right] \tilde{U}_O$$

The ESR of the inductor filter is very small and it means that $\left| 1 - L_p C_p \omega^2 \right| >> 0$, therefore $L_p C_p \omega^2 << 1$ and will be $X_p = X_C$. With ignoring of filter inductor ESR, the inductor current of first filter is:

$$\tilde{T}_{F1} = \left[ \frac{1}{R_L} \left( \frac{k_c X_F}{(1+k_c) X_C} \right) + \frac{R_{F2} K_c}{(1+k_c) X_C} \right] \tilde{U}_O$$

(23)

Of comparison (22) and (23) with (20) will be $|\tilde{T}_{F1}| < |\tilde{T}_F|$ and $|\tilde{T}_{F2}| < |\tilde{T}_F|$. The power loss in two cases is:

$$P_L_{\text{MONO}} = R_F |\tilde{T}_F|^2$$

(24)

$$P_L_{\text{MULTIPLE}} = R_{F1} |\tilde{T}_{F1}|^2 + R_{F2} |\tilde{T}_{F2}|^2$$

(25)

Consequently, power loss in multiple-filter is less than mono-filter. The voltages droop in two cases mono- and multiple-filter are:

$$\frac{\Delta \tilde{U}_{\text{MONO}}}{\tilde{U}_O} = j \frac{X_F}{R_L} \frac{X_F}{X_C}$$

(26)

and eq. (27):

$$\frac{\Delta \tilde{U}_{\text{MULTIPLE}}}{\tilde{U}_O} =$$

$$= j \frac{X_F}{R_L} \left( \frac{K_F}{(1+K_F)^2} \frac{X_F}{X_C} \right) \frac{X_F}{X_C}$$

$$\times \left( \frac{1}{1+K_F} \left( \frac{K_F}{(1+K_F)(1+K_c)} X_F^2 + \frac{K_F}{(1+K_c)} \left( 1 + \frac{1}{K_F} \left( 1 + \frac{1}{K_c} \right) \right) \right) \right)$$

Figs. 12 and 13 shows the frequency characteristic of the open loop system of the output voltage in terms of change of $K_F = L_{F2} / L_{F1}$, and $K_c = L_{C2} / L_{C1}$.

At high frequency ranges (more than 1000 Hz), harmonics attenuation is 80 dB per decade in two filter case. Thus a multiple-filter with the same size as a second order filter causes more attenuation in harmonics. Using multiple filter the resonance frequency given by equation (16), depends only to values of the filter components.

$$\omega^4 \left( \frac{1}{L_{F2} C_{F1}} + \frac{1}{L_{F2} C_{F2}} + \frac{1}{L_{F2} C_{F1}} \right) \omega^2 +$$

$$+ \frac{1}{L_{F1} L_{F2} C_{F1} C_{F2}} = 0$$

(28)

Consequently, voltage droop in multiple-filter is less than mono-filter. Figs. 12 and 13 shows the frequency characteristic of the open loop system of the output voltage in terms of change of $K_F = L_{F2} / L_{F1}$, and $K_c = L_{C2} / L_{C1}$.

The resonant frequencies would be equal $\omega_1$ and $\omega_2$, that $\omega_1$ less than $\omega_2$. Figs. 14 and 15 shows the change of small and big resonant frequency changes in terms of
change of $K_c$ and $K_p$, which is the resonant frequency of one filter:

\[ \omega_c = \frac{1}{\sqrt{L_1 C_{F1}}} \]  \hfill (29)

The filter performance with respect to the load voltage is determined by its resonance frequency. In order to achieve an almost sinusoidal output voltage, the resonance frequency of the filter has to be well below the lowest harmonic frequency of the inverter voltage resulting from PWM [14].

IV. Output Impedance

Output impedance is an operational parameter for determining the effect of loading on the UPS inverter. Large output impedance is undesirable, because the voltage distortion at the frequencies of harmonic load currents is large. Also the phase shift would introduce a lag in the load control loop [15]. Therefore require that the inverters have low output impedance and insensitivity to load and input voltage variations from the control point of view [16]. To reduce the voltage distortion under 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. The instantaneous feedback control techniques have been applied to improved disturbance rejection via lower output impedance [17]. The frequency domain behavior of the output impedance can be analyzed through the bode diagram shown in Fig. 16.

V. Control System

One of the fundamental for reasons for adding control to a system is that steady state errors reduced by the action of the control system. According to the feedback control system theory, the standard close control loop should the feedback signal from the output voltage directly. One of the most common controllers available com-
mercially is the proportional-integral-derivative (PID) controller. The three-mode or PID controllers are widely utilized in industries, because of its available, simplicity and low cost. It us weil know that the main control objective in a ups inverter is the tracking of the delivered voltage towards a desired sinusoidal reference in spite of the presence of distorted loads [18].

The system block diagram of controller is shown in Fig. 17, where $K_{PWM}$ is gain of PWM inverter, $K_{B}$ is feedback gain. The error signal ($u_{e}$) is obtained from successive comparison of the output voltage ($u_{O}$) with reference voltage ($u_{R}$). The inverter switching pattern is then obtained from a comparison of error signal and a fixed high frequency triangular waveform.

In order to reduce the steady state error between the output voltage and its reference waveform, a PI controller may be used in the feed forward path of the outer load voltage feedback loop. When a PI controller is used for the system, the load voltage is given by:

$$U_{O}(s)=\frac{K_{PWM}G_{O}(s)}{A(s)+K_{B}K_{PWM}G_{O}(s)}U_{R}(s)+\frac{B(s)}{A(s)+K_{B}K_{PWM}G_{O}(s)}i_{O}(s)$$

(30)

where:

$$G_{O}(s)=K_{P}+\frac{K_{I}}{s}$$

(31)

The closed loop transfer function of the control system is:

$$T(s)=\frac{U_{O}(s)}{U_{R}(s)}=rac{K_{PWM}G_{O}(s)Z_{I}(s)}{B(s)+Z_{I}(s)[A(s)+K_{PWM}K_{B}G_{O}(s)]}$$

(32)

The steady state error between the output voltage and its reference waveform decreases with increasing values of $K_{I}$. Conversely, increasing the $K_{P}$ decreases the both the main components of output voltage and THD.

The state space equations of the closed loop system with inductive load as shown Fig. 18 are given by:

$$\frac{d}{dt}i_{F1}=\frac{R_{F1}}{L_{F1}}i_{F1}+\frac{1}{L_{F1}}u_{F1}-\frac{K_{PWM}K_{B}}{L_{F1}}u_{F2}+$$

$$+\frac{K_{PWM}}{L_{F1}}e_{I}+\frac{K_{PWM}K_{P}}{L_{F1}}u_{R}$$

(33)

$$\frac{d}{dt}i_{F2}=\frac{R_{F2}}{L_{F2}}i_{F2}+\frac{1}{L_{F2}}u_{F1}-\frac{1}{L_{F2}}u_{F2}$$

(34)

$$\frac{d}{dt}u_{F1}=\frac{1}{C_{F1}}i_{F1}-\frac{1}{C_{F2}}i_{F2}$$

(35)

$$\frac{d}{dt}u_{F2}=\frac{1}{C_{F2}}i_{F2}-\frac{1}{C_{F2}}i_{O}$$

(36)

$$\frac{d}{dt}i_{O}=\frac{1}{L_{L}}u_{F2}-\frac{R_{L}}{L_{L}}i_{O}$$

(37)

$$\frac{d}{dt}e_{I}=-K_{I}K_{P}u_{F2}+K_{I}u_{R}$$

(38)

where $e_{I}$ is output of integral control, $K_{P}$ is proportional gain, $K_{I}$ is integral gain and state variables vector is:

$$X=[i_{F1}\ i_{F2}\ u_{F1}\ u_{F2}\ i_{O}\ e_{I}]^{T}$$

(39)

The closed loop system root loci for changing of controller parameters are presented in Figs. 19 and 20. The step response with $K_{P}=0.01$ and $K_{I}=40$ is show in Fig. 21.

VI. Simulation Results

Simulink is widely used in many fields because it can do most type of simulation for industrial application. In this section, a Simulink model of the control scheme as shown in Fig. 22 are developed to study the performance and dynamic system simulation of the basic UPS system.
Fig. 20. Closed loop root locus for change of $K_c$ ($K_c=40$)

Fig. 21. Step response of closed loop system with $K_c=0.01$ and $K_c=40$

Runge-Kutta is used for the calculation method of the main circuit and the calculating step size is set at $1\mu s$.

Figs. 23 show the Bode diagram of the open loop transfer function of the filter capacitor current and Figs. 24 are the Bode diagram of the open loop transfer function of the output voltage for two types of filters in the inverter output under inductive load ($Z_L=3.4, PF=0.8$). At high frequency ranges (higher than $1000\ Hz$), harmonics attenuation is $40\ dB$ per decade in LC filter and $80\ dB$ per decade in two filter case. At low frequencies the harmonic attenuation is almost the same in filters, in other words the behavior of two filters is similar to the single one. Thus a multiple LC filter with the same size as a LC filter causes more attenuation in harmonics. The values of $L_{F1}$ and $L_{F2}$ are lower in two filter case than the value of $L_F$ in the single case and there is less voltage loss in the two-filter case. The main problem of the two filter case is a high current ripple in the inductor $L_{F1}$. Bode diagram of the close-loop transfer function of the outer voltage loop of the UPS system for mono- and multiple-filter shown in Figs. 25.
Figs. 24. Frequency characteristic of the open loop system of the output voltage for different filters.

Figs. 25. Bode diagram of the close loop transfer function of the outer voltage for multiple filter (solid) and mono filter (dot).

The characteristics of the control system for $K_p=0.05$ and $K_i=40$ for resistive load ($R_2=3.4\Omega$), inductive load ($R_1=3.4\Omega$, $L_4=0.02H$) and no load are shown in Table II. Fig. 26 shows the Fourier spectrum of inverter output voltage under linear load. Figs. 27-28 show simulation results under nonlinear load with $L=0$, $C=2000\mu F$ and $R_L=3\Omega$.

**TABLE II**

<table>
<thead>
<tr>
<th>Different Loads</th>
<th>Fundamental (V)</th>
<th>THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Load</td>
<td>33.04</td>
<td>0.54%</td>
</tr>
<tr>
<td>50% Load</td>
<td>33.06</td>
<td>0.45%</td>
</tr>
<tr>
<td>200% Load</td>
<td>33.02</td>
<td>0.42%</td>
</tr>
<tr>
<td>No Load</td>
<td>33.07</td>
<td>0.99%</td>
</tr>
</tbody>
</table>

Fig. 26. Fourier spectrum of inverter output voltage under linear load.

**VII. System Tests and Verification**

To show the validity of the proposed output filter and control method, a small experimental system with the scheme as shown in Fig. 29 was built and operated in the laboratory. The system has an inverter consisted of a single phase MOSFET full bridge with a switching frequency of 8000 Hz and multiple output filters. The PWM pulse generation circuit, Inverter controller and PWM pulse generation circuit for switches in the each link are shown in Figs. 30-31-32, respectively. The dead time force circuit show in Fig. 33.
The experimental results corresponding to the simulated cases are presented in Figs. 34-35. When loads connected at the output of the inverter are nonlinear in nature, the load currents consist of harmonics in addition to the fundamental frequency component. The advantages of multiple-filter are reduction of devices size and voltage ratings for the switches, more attenuation in harmonics, less voltage loss and the improvement of control response.

![PWM pulse generation circuit](image1)

**Fig. 30. PWM pulse generation circuit**

![PI controller](image2)

**Fig. 31. PI controller**

![PWM pulse generation circuit for switches in the each link](image3)

**Fig. 32. PWM pulse generation circuit for switches in the each link**

![Dead time force circuit](image4)

**Fig. 33. Dead time force circuit**

The experimental results corresponding to the simulated cases are presented in Figs. 34-35. When loads connected at the output of the inverter are nonlinear in nature, the load currents consist of harmonics in addition to the fundamental frequency component. The advantages of multiple-filter are reduction of devices size and voltage ratings for the switches, more attenuation in harmonics, less voltage loss and the improvement of control response.

![Output voltage of the single inverter system operating with a pure resistance](image5)

**Figs. 34. Output voltage of the single inverter system operating with a pure resistance (a) simulation with Matlab (b) measurement**

![Output waveform of Load current with nonlinear load](image6)

**Figs. 35. The results waveform of Load current with nonlinear load Experimental result (upper) – Simulation result (down) (Current scale 10A/div, Time scale 50ms/div)**

Also, the THD of load voltage reduction, because the harmonics reduced by going for multiple filters.

**VIII. Conclusion**

In this paper an uninterruptible power supply (UPS) system with two LC filter in the inverter output is analysed and their effects on reducing the distortion in the output voltage are shown. The proposed model uses the Laplace transform and two-port network. Also, it has been implemented in Matlab/Simulink. By running the simulation model, the comprehensive performances of multi-filter can be obtained efficiently. Fourier analysis use to predict the load voltage harmonic spectrum. Inverter output voltage have THD to less than 5% even when supplying power to highly nonlinear loads which draw...
current with a crest factor of 3. Finally, simulation and experimental results have been reported and discussed.

The simulation is achieved under the dc source voltage is ripple free and constant. Also, in the simulation, the inverter switching devices are assumed as ideal switches, but SPWM modulation is not an ideal amplification including dead time and conducting resistance of device. Therefore, the THD of experimental result is higher than the simulation.

References


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