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ANALYSIS AND SIMULATION OF A THREE-PHASE UPS INVERTER WITH OUTPUT MULTIPLE-FILTER

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Abstract: A mathematical model of an output multiple-filter for three-phase voltage source uninterruptible power supply (UPS) inverter with state-space technique is described in this paper. Performance of the proposed filter is then predicted and result is compared with that of the LC output filter. Simulation results show the harmonic reduction in the output voltage waveform of the UPS due to the application of output multiple-filter.

1. Introduction

Three-phase voltage source inverters cover medium to high power applications. They have been widely used in adjustable speed drives, active filters, ac power supply including uninterruptible power supply (UPS) system, dynamic voltage restorer, unified power flow controllers in power systems and automatic voltage regulator. In recent years, demands for such sensitive and critical loads have been increased. These loads require high availability and continuous power supply systems. Low total harmonic distortion (THD), fast dynamic response, high reliability and high efficiency are commonly required in sensitive load such as communication systems, robots for automation, data acquisition systems, instrumentation plants and medical equipment [1, 2].

The output voltage waveform of the inverter is generally non-sinusoidal and contains undesirable harmonics. Harmonic reduction can be achieved by either filtering, harmonic reduction chopping or pulse width modulation (PWM). Control of the UPS inverter switching is important to minimize the harmonic content of the output voltage. The operation of a three-phase PWM inverter depends on the PWM scheme used. Generally, PWM techniques in inverter are divided into two continuous and discontinuous types [3]. To minimize the harmonic distortion of the output voltage of a PWM inverter, different methods based on modulation strategies such as sinusoidal PWM [4], space vector modulation [5], trapezoidal modulation [6] and delta or hysteresis modulation [7] have been proposed. PWM techniques have many advantages such as high efficiency, easy implementation, reliable operation, low cost, simple control scheme, low voltage harmonic distortion and good utilization of dc power supply. The quality of an UPS depends on the choice of control methods and can be evaluated by THD value of the output voltage and characteristics of transient response. Several control schemes such as iterative learning control [8], deadbeat control

[9], optimal control [10], repetitive control [11] and multi-loop control [12] have been so far proposed to improve the performance of the UPS system. A digital control scheme of three-phase UPS inverter based on multi-loop control strategy consisting of the filter capacitor current and output voltage has been given in [13]. The technique also includes a load predictive feedforward loop in a voltage controller and an output voltage feedforward loop in a current controller.

The objective of this paper is to study the dynamic performance of the proposed output multiple-filter for three-phase voltage source UPS inverter and to compare with the output of an LC filter. The paper is organized as follows. Section II presents a theoretical analysis of the output voltage of three-phase PWM inverter using the switching function of the harmonics. Section III gives state space equation and the dq small signal model of the UPS inverter with output mono-filter. Section IV describes the dq small signal model of output multiple-filter. Finally, the simulation results obtained by Matlab/Simulink are reported in section V. Section VI concludes the paper.

2. Harmonic analysis in three-phase pwm inverter

Fig. 1 shows the main circuit of a three-phase voltage source UPS system. It consists of a dc voltage source, three-phase bridge inverter with active power switches such as IGBT in parallel with diodes, three-phase LC-filter and three-phase star connected inductive load. The load current depends on the configuration and balancing of the load. The proper switching function is essential for the design of the output filter and control of the output voltage of the inverter.

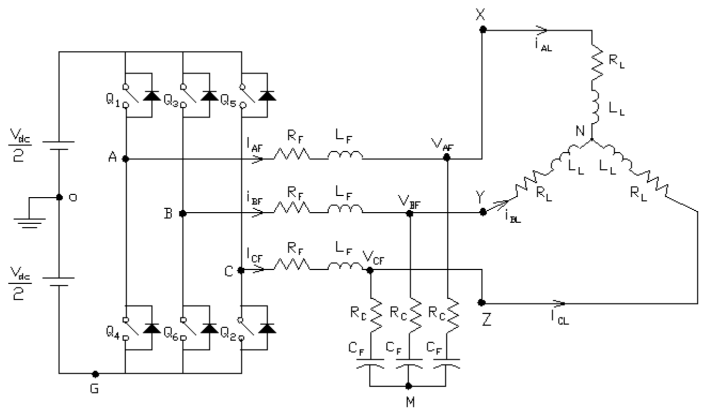

Fig.1. Three-phase voltage source UPS inverter with definition of variables.

Here harmonic analysis for a VSI is proposed using the switching function concept. The output voltage of a VSI depends on the input dc voltage and duty cycle of the inverter. The fundamental frequency and amplitude of the inverter output voltage are directly proportional to the sinusoidal reference voltage waveform [14]. The relationship between these quantities (input and output variables) is obtained by defining a switching function. Based on the switching function, phase and line voltages of the output inverter can be obtained as follows:

$$\begin{bmatrix} V_{AB} \\ V_{BC} \\ V_{CA} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_A \\ S_B \\ S_C \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_A \\ S_B \\ S_C \end{bmatrix} \tag{2}$$

where S_A, S_B, S_C denote status of the inverter switching devices and defined as

$$S_A = \begin{cases} 1 & Q_1 \to ON, Q_4 \to OFF, \\ 0 & Q_1 \to OFF, Q_4 \to ON, \end{cases}$$

$$S_B = \begin{cases} 1 & Q_3 \to ON, Q_6 \to OFF, \\ 0 & Q_3 \to OFF, Q_6 \to ON, \end{cases}$$

$$S_C = \begin{cases} 1 & Q_5 \to ON, Q_2 \to OFF, \\ 0 & Q_5 \to OFF, Q_2 \to ON, \end{cases}$$

The eight possible switching states for the three-phase VSI and the inverter output line voltage with amplitude V_{dc}, 0 and $-V_{dc}$ are shown in Table 1.

Table 1. Switching states in a three-phase voltage source inverter and output voltage

Mode	Switches			Line to line voltage		
	Q_1	Q_3	Q_5	V_{AB}	V_{BC}	V_{CA}
A	ON	ON	ON	0	0	0
B	ON	ON	OFF	0	V_{dc}	$-V_{dc}$
C	ON	OFF	ON	V_{dc}	$-V_{dc}$	0
D	ON	OFF	OFF	V_{dc}	0	$-V_{dc}$
E	OFF	ON	ON	$-V_{dc}$	0	$-V_{dc}$
F	OFF	ON	OFF	$-V_{dc}$	V_{dc}	0
G	OFF	OFF	ON	0	$-V_{dc}$	V_{dc}
H	OFF	OFF	OFF	0	0	0

3. System equations

In the design of control system for a three-phase UPS inverter, an analytical model is an important tool for predication of dynamic performance and stability limits different control methods and system parameters. For this analysis, differential equations are expressed in matrix form as follows:

$$\dot{X} = AX + BU, \tag{3}$$

$$Y = CX + DU, \tag{4}$$

Matrices A, B, C and D can be found by applying current and voltage equations in the circuits. The system state space equation in the rotating reference frame is as follows:

$$\frac{d}{dt}\begin{bmatrix} v_{Fq} \\ v_{Fd} \\ i_{Fq} \\ i_{Fd} \end{bmatrix} = \begin{bmatrix} 0 & -\omega & \frac{1}{C_F} & 0 \\ \omega & 0 & 0 & \frac{1}{C_F} \\ -\frac{1}{L_F} & 0 & -\frac{R_F}{L_F} & -\omega \\ 0 & -\frac{1}{L_F} & \omega & -\frac{R_F}{L_F} \end{bmatrix} \begin{bmatrix} v_{Fq} \\ v_{Fd} \\ i_{Fq} \\ i_{Fd} \end{bmatrix} + \begin{bmatrix} -\frac{1}{C_F} & 0 \\ 0 & -\frac{1}{C_F} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} i_{Lq} \\ i_{Ld} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{L_F} & 0 \\ 0 & \frac{1}{L_F} \end{bmatrix} \begin{bmatrix} v_{qs} \\ v_{ds} \end{bmatrix}, \qquad (5)$$

where ω is the fundamental angular frequency of three-phase variables, v_{Fd} and v_{Fq} are the dq transformation of the three-phase voltage of the capacitor filter, i_{Fd} and i_{Fq} are the dq transformation of the three-phase current of inductors filter, v_{qs} and v_{ds} are the dq transformation of the three-phase output voltage of inverter, and i_{Ld}, i_{Lq} are the dq transformation of the load currents.

The dq rotating reference frame model of the three-phase UPS inverter with a mono-filter output is obtained using (5) as shown

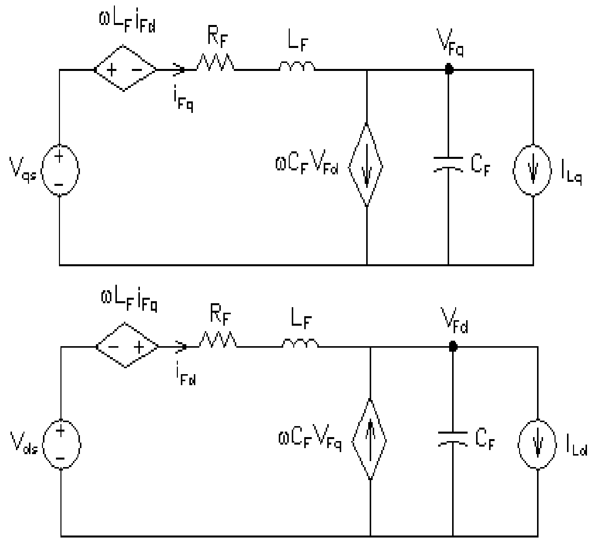

Fig.2. Equivalent dq model of three-phase UPS inverter with mono filter.

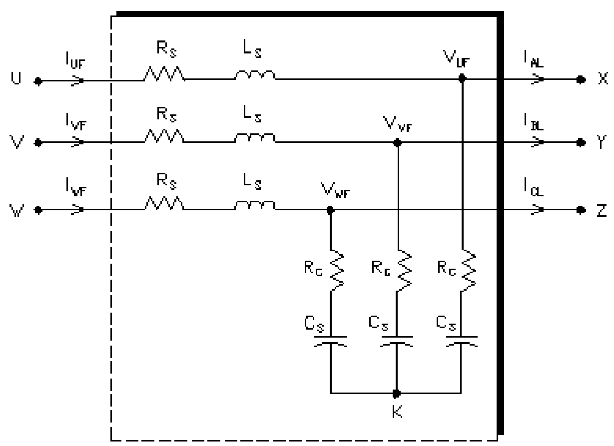

Fig.3. Second output filter for three-phase inverter in Fig. 2. Referring to Fig. 2, the q and d sub-circuits have coupled voltage and current sources.

4. Model of multiple-filter

With a single filter, some harmonics success to pass the load. The harmonics can be more reduced by going for multiple-filter. As shown in Fig. 3, a multiple-filter is obtained by connecting an LC filter, between the first filter and the load. The continuous state equation for system with multiple-filter in synchronous reference frame is as follows:

$$\frac{d}{dt}\begin{bmatrix} v_{Fqd} \\ v_{Sqd} \\ i_{Fqd} \\ i_{Sqd} \end{bmatrix} = \begin{bmatrix} \omega J & O & \frac{1}{C_F}I & -\frac{1}{C_F}I \\ O & \omega J & O & \frac{1}{C_S}I \\ -\frac{1}{L_F}I & \frac{1}{L_F}I & \omega J & O \\ \frac{1}{L_S}I & -\frac{1}{L_S}I & O & \omega J \end{bmatrix} \begin{bmatrix} v_{Fqd} \\ v_{Sqd} \\ i_{Fqd} \\ i_{Sqd} \end{bmatrix} + \begin{bmatrix} O \\ O \\ \frac{1}{L_F}I \\ O \end{bmatrix} U_{qd} + \begin{bmatrix} O \\ -\frac{1}{C_S}I \\ O \\ O \end{bmatrix} I_{qd}, \tag{6}$$

where

$$U_{qd} = [v_{qs} \quad v_{ds}]^T$$

$$V_{Sqd} = [V_{Sq} \quad V_{Sd}]^T$$

$$V_{Fqd} = [v_{Fq} \quad v_{Fd}]^T$$

$$I_{Fqd} = [i_{Fq} \quad i_{Fd}]^T$$

$$I_{Sqd} = [i_{Sq} \quad i_{Sd}]^T$$

$$I_{qd} = [i_{qL} \quad i_{dL}]^T$$

$$J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$O = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix},$$

v_{Sd} and v_{Sq} are the dq transformation of three-phase voltages of capacitor of second filter and i_{Sd} and i_{Sq} are the dq transformation of the three-phase currents of inductance of the second filter (i_{UF}, i_{VF}, i_{WF}). dq components of three-phase voltages of capacitor filters (v_{Fqd} and v_{Sqd}) and dq components of three-phase currents of inductance filters (I_{Fqd} and I_{Sqd}) are the state variables of the system The inverter output line voltage (v_S) is the control input and the load current is defined as a disturbance (I_L). Eq. (6) can be represented by equivalent circuits shown in Fig.4. The equivalent series resistances of the filters capacitors have not been

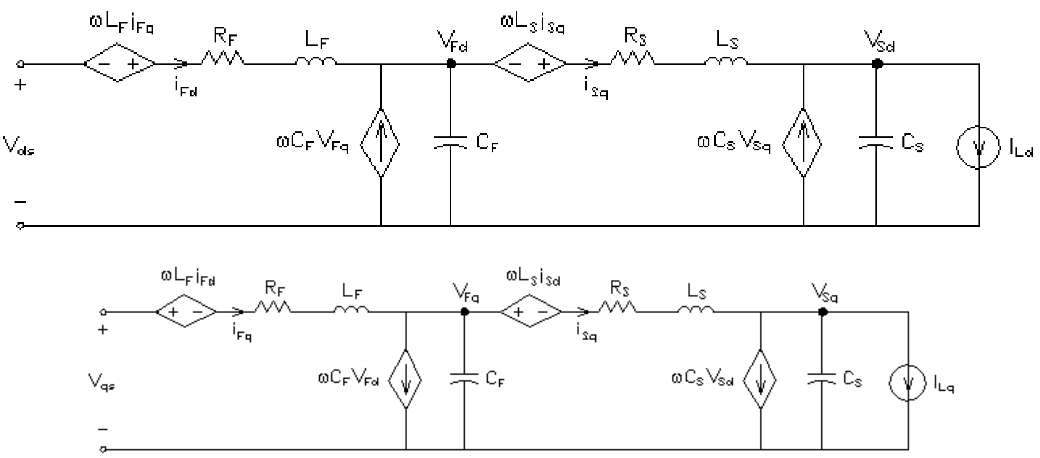

Fig.4. Equivalent dq model of three-phase UPS inverter with multiple filters considered in the model. Fig. 5 shows the block diagram of the system in the synchronous reference frame. It can be converted into a two-phase stationary reference frame model by setting ω=0.

5. Simulation results

In power systems, simulation is mainly performed to analyze and design the circuit configuration and applied control strategy. The proposed multiple-filter for the three-phase UPS inverter is implemented using Matlab/Simulink and simulation voltage and current waveforms are presented. The inverter of UPS consists of a full-bridge three-phase IGBT and multiple- filter. Key parameters of the three-phase full-bridge PWM inverter, multiple-filter and load are listed in Table II. Note that the phase voltage is 40.80 V, line voltage is 70.7 V, peak phase voltage is 57.7 V, and peak line voltage is 100 V.

In the steady-state operation, the mean value of the modulation index is 0.5, therefore the fundamental component of inverter output voltage is

$$V_{ab,rms} = \frac{1}{\sqrt{2}} M_a V_{dc} \sin\frac{\pi}{3} = 76.5 \text{ V}, \tag{7}$$

As shown in Fig.6, the THD of the output voltage is 0.56% and regulation is 1%. The simulation results when the full load is suddenly applied are shown in Figs.9 and 10.

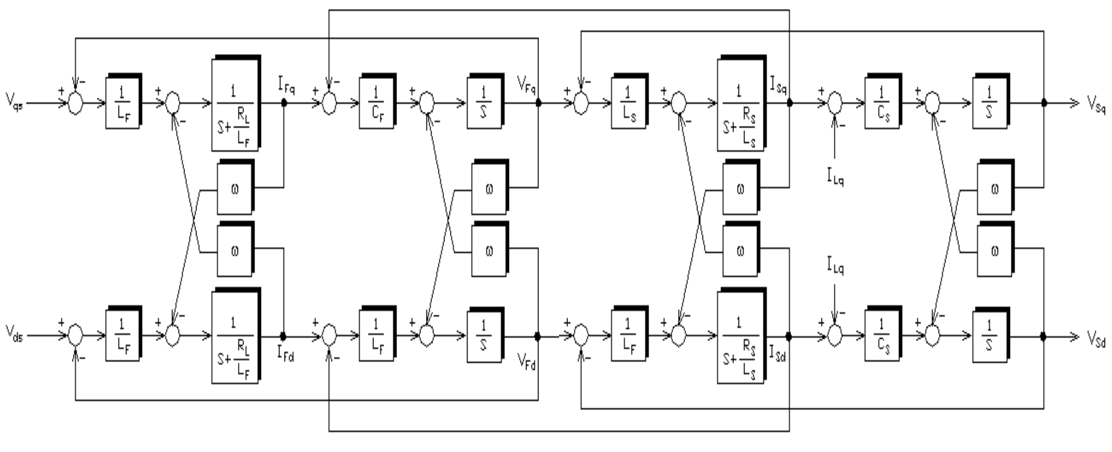

Fig.5. System block diagram in a synchronous reference frame.

Table 2. Parameters of system.

Parameter		Symbol	Nominal value
DC input voltage (V)		V_{dc}	250
Switching frequency (kHz)		f_{SW}	8
Reference sine-voltage frequency (Hz)		f_O	50
Output voltage (V)		V_{LINE}	100
Rated output power (kVA)		S_O	0.9
First Filter	Inductor (mH)	L_{F1}	0.3
	Resistance (Ω)	R_{F1}	0.25
Second Filter	Inductor (mH)	L_{F2}	0.15
	Resistance (Ω)	R_{F2}	0.125
1st filter capacitor (μF)		C_{F1}	120
2nd filter capacitor (μF)		C_{F2}	80

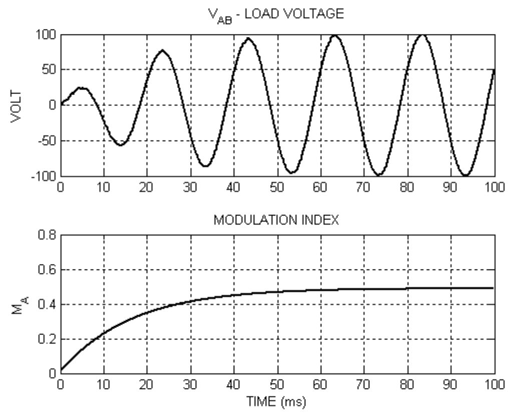

Fig.6. Load voltage and modulation index-resistive load.

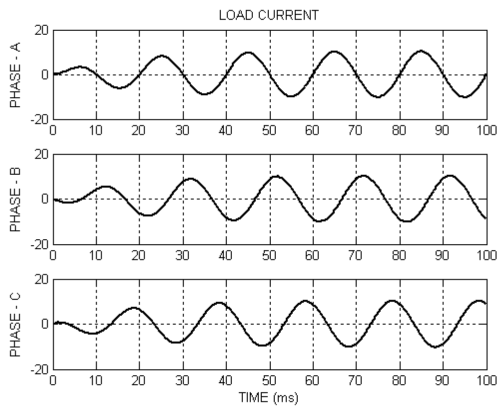

Fig.7. Load Current-resistive load.

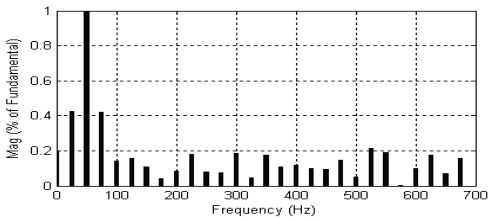

Fig.8. Spectrum of output voltage-resistive load.

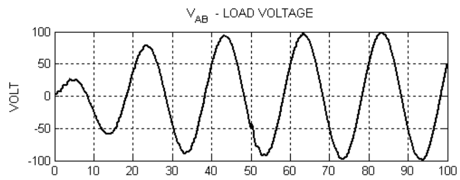

Fig.9. Load voltage under applied step load.

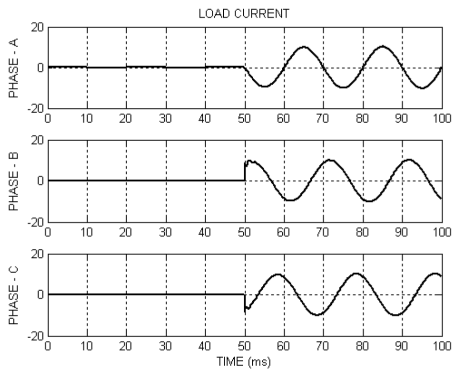

Fig.10. Load current under step load suddenly turned.

6. Conclusion

The output voltage of the UPS system should be sinusoidal with minimum THD irrespective of load conditions. This paper presented the dynamic analysis of a three-phase PWM voltage source inverter with output multiple-filter in UPS system. The mathematical model of the proposed filter has described and the simulation results shown harmonic reduction in the output waveform due to the application of multiple-filter. The simulation results exhibit low THD (less than 4%) and low steady-state error with linear (resistive) load.

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