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MODELING AND SIMULATION OF A THREE-PHASE INVERTER WITH RECTIFIER-TYPE NONLINEAR LOADS

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Abstract Nonlinear loads generate harmonic currents and voltages in power systems. This paper investigates the effect of inverter output multiple-filter with nonlinear loads on the inverter input current and load voltage. To verify the proposed filter, various simulation results using Matlab/Simulink are presented under nonlinear loads.

1. Introduction

In recent years, there has been a considerable increase in the use of uninterruptible power supply (UPS) to provide a low output voltage distortion, fast dynamic response, high reliability and continuous power supply systems especially for sensitive and critical loads, which cannot afford have unexpected power failure. Critical loads such as computer systems, hospitals and air line reservation systems need UPS [1]. Low total harmonic distortion (THD) and high efficiency are commonly required in high power applications, such as three-phase inverter systems. Nonlinear loads and non-sinusoidal currents can cause more voltage drops on the supply network impedance resulting in unbalanced conditions. They also cause electromagnetic Interference (EMI) and resonances. The harmonics have negative influence on the control and automatic equipment protection systems and other electrical loads, resulting in reduced reliability and availability [2].

Any UPS system has two operating modes: bypass mode and backup mode. Ideally, a UPS should be able to deliver a regulated sinusoidal output voltage with low total harmonic distortion (THD) during the two modes, even when feeding nonlinear loads [3, 4]. Several controllers including repetitive control [5, 6], hysteresis regulation [7, 8], predictive control [9, 10] and multi-loop feedback control [11, 12], have been proposed to obtain an output voltage with low distortion for three-phase UPS inverter.

Many papers have been so far published in the field of control and topologies. Deadbeat control on both output voltage and inductor or capacitor current for three-phase PWM inverter has been proposed, either in multi-loop configurations [13] or in a conventional linear state feedback [14]. Performance of two-stage cascade output filter for single-phase voltage source UPS inverter has been investigated in [15] and compared with an LC output filter. In [15] 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. A digital control scheme of three-phase UPS inverter based on multi-loop control strategy consisting of a filter capacitor current and output voltage is proposed in [16]. The technique also includes a load predictive feed-forward loop in a voltage controller and an output voltage feed forward loop in a current controller. In [17], linear and nonlinear adaptive control strategies for three-phase UPS inverters have been presented. An on-line adaptive learning algorithm has been also described which promotes steady state controller stability.

To prove the effectiveness of the proposed technique, various simulation results using Matlab/Simulink are shown under both no-load and nonlinear loads. The remainder of this paper can be outlined as follows. In section II, a mathematical model of the proposed system including three-phase PWM inverter, nonlinear load, control system and multiple-filter is described. In section III, a small signal equivalent circuit and transfer function dq model of the system are derived. Simulation results are reported and discussed in section IV. Finally, a brief summary is given in section V.

2. Mathematical model of the system

Analytical model is an important tool for prediction of dynamic performance and stability limits using different control laws and system parameters. Mathematical model of the inverter must be established before the design stage. A schematic diagram of the proposed three-phase UPS inverter system is shown in Fig.1, it mainly consists of a controller, switching bridge and an output filter. The block diagram of the system can be divided into four parts:

2.1. A Three-phase PWM Inverter

Fig. 2 shows a typical configuration of a three-phase full-bridge UPS inverter. If switching frequency is high enough, the PWM inverter is considered as a voltage source inverter (VSI) and dynamic response of the UPS inverter is mainly determined by the elements of the filter. SPWM techniques are applied to inverters in order to obtain a sinusoidal output voltage with minimal undesired harmonics.

Semiconductor switching devices (Q1–Q6) of the inverter are controlled by PWM signals to obtain three-phase near sinusoidal ac voltages of the desired magnitude and frequency at the inverter output. The operation of three-phase inverter can be defined in eight modes as shown in Table I which shows status of each switch in each operation mode.

Three-phase switching state functions S_a, S_b and S_c of the inverter are used to calculate the line output voltages of PWM inverter which is described by the help of Fig. 2 [18]:

$$\begin{bmatrix} U_{AB} & U_{BC} & U_{CA} \end{bmatrix}^T = \underbrace{\begin{bmatrix} T_{AV} & T_{BV} & T_{CV} \end{bmatrix}^T}_{T_V} U_{dc} \tag{1}$$

where

$$\begin{bmatrix} T_{AV} \\ T_{BV} \\ T_{CV} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix}. \tag{2}$$

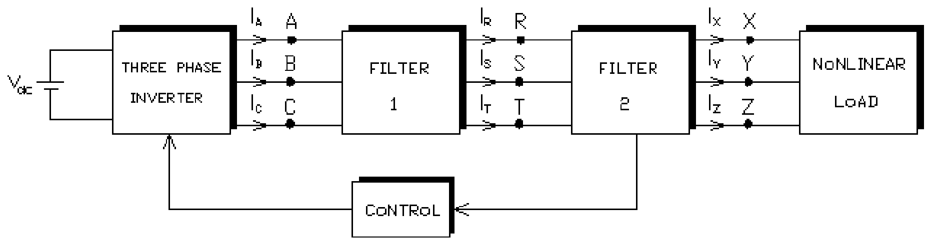


Fig.1. Structure of a three phase inverter system.

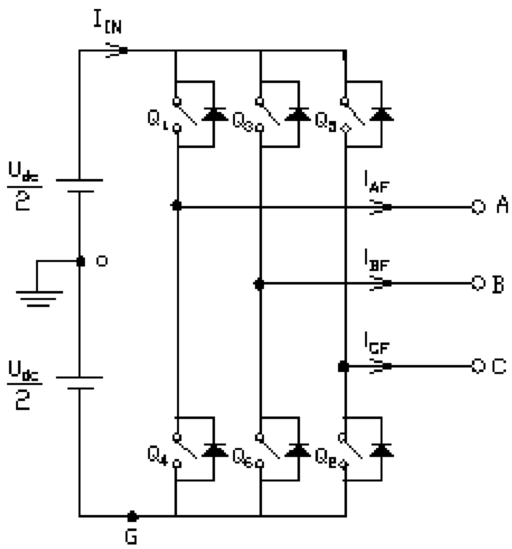


Fig.2. Basic three-phase voltage source inverter.

Table 1. Reference frame dq voltage.

Mode	Vqs	V_{ds}	V_{os}
A	0	0	$\frac{V_{dc}}{2}$
B	$\frac{V_{dc}}{3}$	$-\frac{V_{dc}}{\sqrt{3}}$	$\frac{V_{dc}}{6}$
C	$\frac{V_{dc}}{3}$	$\frac{V_{dc}}{\sqrt{3}}$	$\frac{V_{dc}}{6}$
D	$\frac{2V_{dc}}{3}$	0	$-\frac{V_{dc}}{6}$
E	$-\frac{2V_{dc}}{3}$	0	$-\frac{V_{dc}}{6}$
F	$-\frac{V_{dc}}{3}$	$-\frac{V_{dc}}{\sqrt{3}}$	$-\frac{V_{dc}}{6}$
G	$-\frac{V_{dc}}{3}$	$\frac{V_{dc}}{\sqrt{3}}$	$-\frac{V_{dc}}{6}$
H	0	0	$-\frac{V_{dc}}{2}$

The inverter input current (I_{IN}) can be calculated as:

$$I_{IN} = S_A \, I_{AF} + S_B \, I_{BF} + S_C \, I_{CF} \, . \tag{3}$$

Fig. 3 shows the block diagram detailed description for inverter phase and line voltages based on the transfer functions. The switching functions can be mathematically represented as follows [19]:

$$\begin{cases} S_a(\omega t) = \sum\limits_{k=1,3,...}^{\infty} A_k \sin k\omega t, \\ S_b(\omega t) = \sum\limits_{k=1,3,...}^{\infty} A_k \sin k(\omega t - \frac{2\pi}{3}) \, , \\ S_c(\omega t) = \sum\limits_{k=1,3,...}^{\infty} A_k \sin k(\omega t - \frac{4\pi}{3}). \end{cases} \tag{4}$$

2.2. Nonlinear Load

Nonlinear loads draw non-sinusoidal current, even when 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. Three-phase loads that use three-phase rectifier in distribution systems include adjustable motors, UPS systems and battery charger. When a non-linear load such as a capacitor input diode bridge is connected to UPS, the peaky current flows once in a half cycle and the output voltage become distorted. Three-phase rectifier is used for higher power applications, up to several MW. The circuit of the full-bridge rectifier for three-phase system is shown in Fig.4. The rectifying topology is similar to single-phase rectifiers but with a front end for connection of three-phase. The non-sinusoidal load current is drawn from the mains. If the diode bridge is turned on, the nonlinear load can be expressed as

$$\frac{d}{dt} i_L = -\frac{1}{L_{DC}} u_O + \frac{1}{L_{DC}} u_{LINE} , \tag{5}$$

$$\frac{d}{dt} u_O = \frac{1}{C_{DC}} i_L - \frac{1}{C_{DC}} i_O , \tag{6}$$

where u_O is the dc-side voltage of diode bridge rectifier, i_L is the nonlinear load current, L_{DC} is the inductor and C_{DC} is the capacitor dc-side of LC filter. When the diode bridge is turned off, the nonlinear load can be expressed as

$$\frac{d}{dt} u_O = -\frac{1}{C_{DC}} i_O , \tag{7}$$

$$i_L = 0. \tag{8}$$

Eqs. (5)–(8) define the dynamic model for non-linear load.

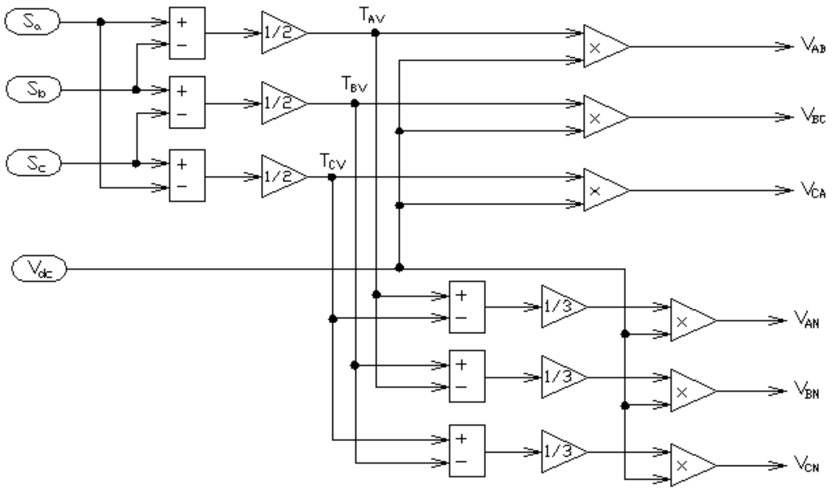


Fig.3. Block diagram based on switching state functions for Inverter line and phase voltages

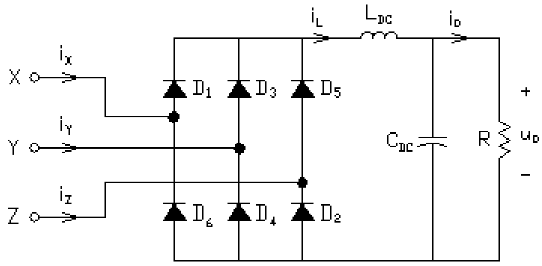


Fig4. Nonlinear load.

2.3. Multiple-filter

Some harmonics success to pass through the load when a mono-filter is used. The harmonics can be more reduced by going for multiple-filter. A multiple-filter is obtained by connecting a LC filter between the first filter and the load. Output multiple-filter connects the utility (A, B and C) inverter to the load (X, Y and Z) through two LC filters, as shown in Fig.5. For a balanced three-phase system, the following set of equations describes the voltage and current conditions on the multiple-filter:

$$\frac{d}{dt}i_{FABC} = -\frac{R_F}{L_F}i_{FABC} - \frac{1}{L_F}u_{FABC} + \frac{1}{L_F}u_{ABC}, \tag{9}$$

$$\frac{d}{dt}u_{FABC} = \frac{1}{C_F}i_{FABC} - \frac{1}{C_F}i_{SABC}, \tag{10}$$

$$\frac{d}{dt}i_{SABC} = -\frac{R_S}{L_S}i_{SABC} - \frac{1}{L_S}u_{SABC} + \frac{1}{L_F}u_{FABC}, \tag{11}$$

$$\frac{d}{dt}u_{SABC} = \frac{1}{C_S}i_{SABC} - \frac{1}{C_S}i_{LABC}, \tag{12}$$

where u_{FABC} is the first filter capacitors voltage, u_{SABC} is the second filter capacitors voltage, i_{FABC} is the inverter output currents, i_{SABC} is the second filter inductors current and i_{LABC} is the three-phase load current:

$$u_{FABC} = \begin{bmatrix} u_{FA} & u_{FB} & u_{FC} \end{bmatrix}^T , \tag{13}$$

$$u_{SABC} = \begin{bmatrix} u_{SA} & u_{SB} & u_{SC} \end{bmatrix}^T , \tag{14}$$

$$i_{FABC} = \begin{bmatrix} i_{FA} & i_{FB} & i_{FC} \end{bmatrix}^T , \tag{15}$$

$$i_{SABC} = \begin{bmatrix} i_{SA} & i_{SB} & i_{SC} \end{bmatrix}^T , \tag{16}$$

$$i_{LABC} = \begin{bmatrix} i_{LA} & i_{LB} & i_{LC} \end{bmatrix}^T , \tag{17}$$

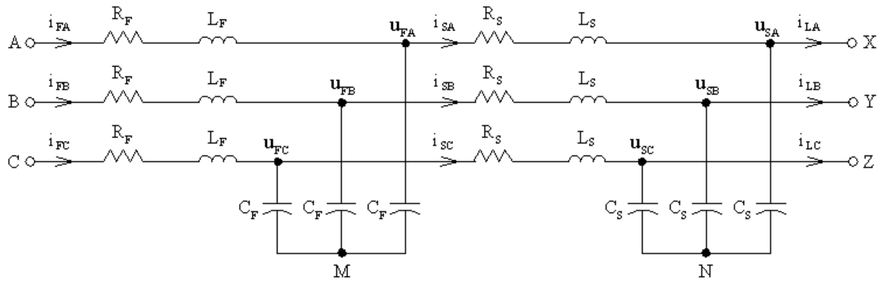


Fig.5. Inverter output filter.

Also, L_F and L_S are the filter inductances, C_F and C_S are filter capacitances and R_F and R_S are the equivalent series resistances of the filter.

2.4. Control system

In most cases, control design for a three-phase PWM converter involves two steps: choice of modulation strategy, which corresponds to an open-loop converter control, and design of dynamic closed loop control.

The instantaneous voltage control scheme is applied to the proposed circuit. Fig. 6 shows the block diagram of the control circuit. The output voltage is compared with a reference sinusoidal wave V_R. Hence, the control scheme is simple compared with others. The classic PID (proportional–integral-derivative) controller has been used in many industrial control systems, mainly due to its simple structure that can be easily understood and implemented in practice, and its excellent flexibility made possible by adjustment of the coefficients K_P, K_I and K_D.

3. DQ model of small signal analysis

Small signal model can obtained using perturbation and linearization around an operation point. The dynamics of some converter variables can be analyzed using small signal model. An open-loop dynamic analysis has been made using the linear small signal model. This analysis is based on transfer functions and Bode plots, and is similar to the analysis of single-input-single-output systems. u_{Fqd} , u_{Sqd} , i_{Fqd} , i_{Sqd} and i_{Lqd} are the qd components of the u_{FABC} , u_{SABC} , i_{FABC} , i_{SABC} and i_{LABC} , respectively,

$$u_{Fqd} = \begin{bmatrix} u_{Fq} & u_{Fd} \end{bmatrix}^T, \tag{18}$$

$$u_{Sqd} = \begin{bmatrix} u_{Sq} & u_{Sd} \end{bmatrix}^T, \tag{19}$$

$$i_{Fqd} = \begin{bmatrix} i_{Fq} & i_{Fd} \end{bmatrix}^T, \tag{20}$$

$$i_{Sqd} = \begin{bmatrix} i_{Sq} & i_{Sd} \end{bmatrix}^T, \tag{21}$$

$$i_{Lqd} = \begin{bmatrix} i_{Lq} & i_{Ld} \end{bmatrix}^T. \tag{22}$$

The dq rotating reference frame model of a three-phase UPS inverter with multiple-filter output is obtained using (9)-(12). The q and d sub-circuits have coupled voltage and current sources. Transfer functions for the various feedback control schemes are used to compare their anticipated performance characteristics, before proceeding to detailed simulation. The channels must be viewed a multiple input and multiple output (MIMO) system, so the system has the four following transfer functions:

$$H_{dd}(s) = \frac{U_{Fd}(s)}{U_{ds}(s)}, \tag{23}$$

$$H_{qd}(s) = \frac{U_{Fq}(s)}{U_{ds}(s)}, \tag{24}$$

$$H_{qq}(s) = \frac{U_{Fq}(s)}{U_{qs}(s)} = H_{dd}(s), \tag{25}$$

$$H_{dq}(s) = \frac{V_{Fd}(s)}{V_{qs}(s)} = -H_{qd}(s). \tag{26}$$

Therefore, all four transfer functions have the same resonance frequency and damping factor. By ignoring coupling of the power stages, the cross coupling transfer function in $H_{qd}(s)$ and $H_{dq}(s)$ would be zero. Equations system can be represented by equivalent circuits shown in Fig. 7. The equivalent series resistances of the filters capacitors are not considered in the model.

4. Simulation results

In power electronic systems, simulations are mainly performed to analyze and design the circuit configuration and applied control strategy. A three-phase UPS has been simulated to verify the operation of the proposed control method. Fig.8 shows the simulation results including load current, load voltage and modulation index, under three-phase inductive load. Fig.9 show the simulated waveforms of the output voltage and output current of the system with non-linear load when multiple LC output filter is employed. The THD of the voltage is less than 5% and the regulation is less than 3%.

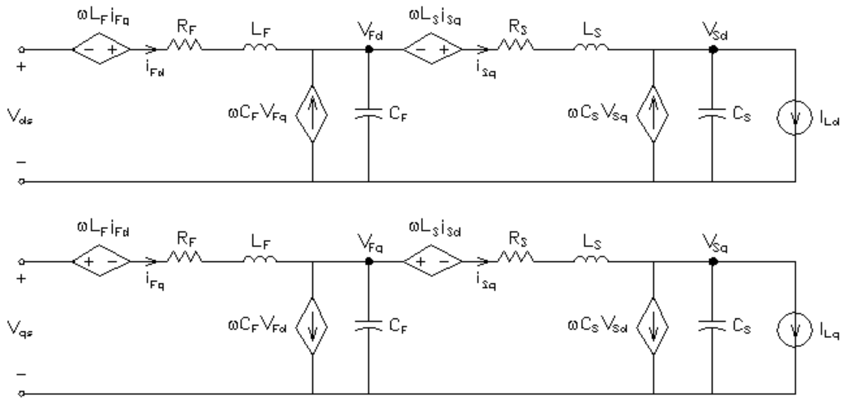


Fig.6. Equivalent dq model of three-phase UPS inverter with multiple filters.

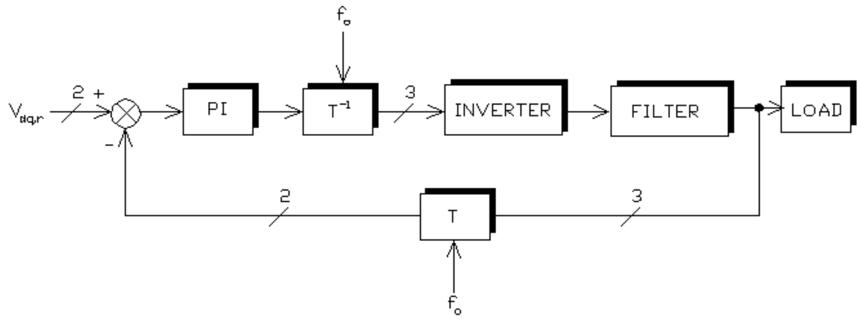
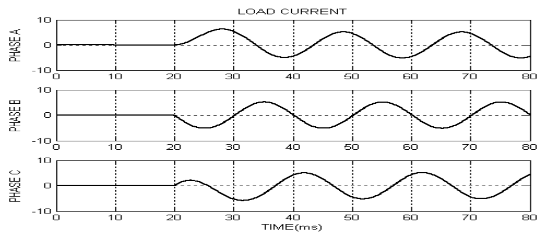
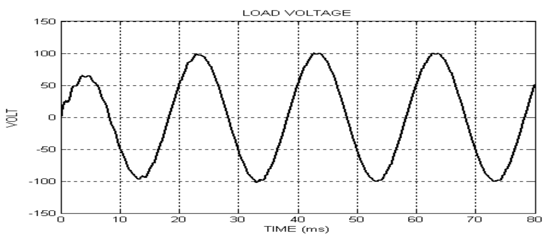


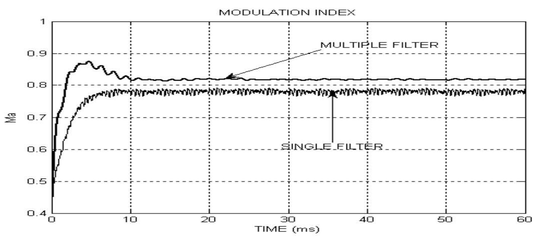
Fig.7. Block diagram of dq rotating frame controller



(a) Load current



(b) Load voltage



(c) Modulation index

Fig.8. Simulation results under three-phase inductive load.

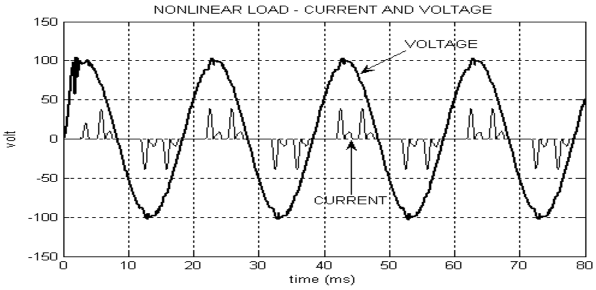


Fig.9. Voltage and current of the non-linear load.

5. Conclusion

A mathematical modeling of a system for analysis and design of the proposed control system was described. The mechanism of output waveform distortion of three-phase PWM inverter with nonlinear loads through detail theoretical analysis was explained. To eliminate the harmonic components transferred to the load, a multiple-filter was used at the output of UPS. This filter enables to reduce THD of the output voltage about 5% and voltage regulation 3%.

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