Nonlinear PWM-Controlled Photovoltaic Inverter with Reduced Number of Switches

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Abstract: A nonlinear pulse width modulation-controlled single-phase boost mode photovoltaic grid-connected inverter with limited storage inductance current is proposed in this paper. The circuit topology, control strategy, steady-state principle characteristic, and design criterion for the key circuit parameters of this kind of inverter are investigated in depth, and important conclusions are obtained. The inverter’s regenerating energy duty ratio $1-D$ which decreases with the decline of the grid-connected voltage is real time adapted by sampling and feeding back the inverting bridge modulation current, and the average value of the modulation current in each switching cycle tracks the reference sinusoidal signal to get high-quality grid-connected current. The active control of the energy storage inductance current and the balance of the voltage step-up ratio are realized by adding a bypass switch connected in parallel with the energy storage inductance and using two kinds of switching pattern namely boost pattern and freewheeling pattern.

Index Terms: Boost mode, limited storage inductance current, nonlinear pulse width modulation (PWM) control, photovoltaic (PV) grid-connected inverter, single-phase.

I. INTRODUCTION

The single stage inverter has become a research hotspot in the new energy power-generating field [1]–[8]. Compared with the buck mode inverter, the boost mode inverter has the advantages of single-stage voltage boosting, direct control of the output current and easy realizing the maximum power point tracking (MPPT) of the photovoltaic (PV) cell, long life of the energy storage inductors’ components, timely protection with over current and high system reliability, etc. In recent years, with the emergence of new type devices such as bidirectional blocking insulated-gate bipolar transistor (IGBT) and the development of superconducting technology, boost mode inverter will have a more important application value.

Based on the derived nonlinear modulation compensation function restraining harmonic waves of the grid-connected current, the proposed control strategy, respectively, extracts the dc and ac components of the energy storage inductance current and compares with the grid-connected current reference to get the nonlinear PWM signal which can inhibit third harmonic wave of the grid-connected current. The proposed control strategy can effectively suppress the third harmonic wave of the grid-connected current, but there are still defects such as large energy storage inductance (21 mH) and THD of the output current waveform up to 4.42%. A control strategy based on the inverter’s output current involving feedforward and feedback terms is proposed, which improves the quality of output waveforms, but the energy storage inductance $L$ is still as high as 10 mH; the conversion efficiency and THD of the output voltage are not given. A parallel resonator is connected in series between the input source and energy storage inductor connected voltage, namely a parallel resonator. The control principle based on the inverter’s output current involving feedforward and feedback terms is proposed, which improves the quality of output waveforms, but the energy storage inductance value of the inverter is 5 mH. Only light-load waveform is provided and the conversion efficiency is not provided. To overcome inherent defects of the traditional single-phase boost mode inverter, a nonlinear PWM-controlled single-phase boost mode PV grid-connected inverter with limited energy storage inductance current is proposed and deeply researched in this paper, and important conclusions are obtained.

II. NONLINEAR PWM CONTROL STRATEGY

Control Principle

In order to improve the quality of output waveform of the traditional single-phase boost mode inverter, a new idea that regenerating duty ratio $1-D$ of the inverter decreases with the decline of the grid-connected voltage $u_n$, namely a nonlinear

![Fig. 1. Circuit topology of traditional single-phase boost mode inverter and nonlinear PWM control strategy. (a) Circuit topology. (b) Control principle waveform. (c) Control circuit block.](image-url)
PWM control strategy based on inverting bridge’s modulation current is proposed in this paper, as shown in Fig. 1. This control strategy is that the inverter’s regenerating energy duty ratio \( 1-D \) is real time regulated by detecting and feeding back the modulation current \( im \) and high-quality grid-connected current is obtained. When the grid voltage \( un \) is less than the input voltage \( Ui \), \( im \) is greater than the expected value and the integral time \( (1-D) Ts \) of the feedback signal \( im \) to the reference value \( ir \) will become shorter, \( 1-D \) will be decreased; thus, the waveform quality of the grid-connected current \( in \) will be improved. Set the switching period is \( Ts \), and the integral circuit’s time constant is \( RcCs = Ts \). After the modulation current feedback signal \( im \) of the inverter through the integral circuit and the absolute value circuit, the average value \( iavg \) of \( im \) is obtained, and its absolute value \( |iavg| \) can be derived as follows:

\[
|i_{avg}| = \frac{1}{T_{sc}C_{sc}} \int_{0}^{(1-D)T_{s}} i_{m} \, dt = \frac{1}{T_{s}} \int_{0}^{(1-D)T_{s}} i_{m} \, dt \quad (1)
\]

The average value of harmonic current in CI within one \( Ts \) is zero; thus, the average value of output filtering capacitance current \( iCf \) within one \( Ts \) is the average value of its fundamental wave component \( iCf/1 \), namely

\[
\frac{1}{T_{sc}} \int_{0}^{T_{s}} i_{m} \, dt = \frac{1}{T_{s}} \int_{0}^{T_{s}} i_{m} \, dt \quad (2)
\]

Equations (1) and (2) show that the average value of harmonic current in CI is \( i_{m} \), and its absolute value \( |ir| \) is derived from (1)

\[
|i_{m} (1-D)| = |i_{avg}| = \left| \frac{ir}{im} \right| \quad 1-D = \frac{|ir|}{|im|} \quad (3)
\]

Equation (4) shows that \( 1-D \) is proportional to \(|ir / im|\) and is not proportional to the error current \( ir - im \). Therefore, the control strategy is called nonlinear PWM control strategy.

### III. STEADY PRINCIPLE CHARACTERISTICS

**A. Equivalent Circuit and Operating Modes in Low Frequency (LF) Output Period**

According to the relative value \( un/Ui \), the inverter’s switching pattern I or II, and the polarity of the modulation current \( im \), the proposed inverter has six kinds of equivalent circuits and A, B, C, D, E, F six operating modes within a LF output period \((0\rightarrow8)\), as shown in Fig. 4 and Table I.

**B. Operating Principle of Intervals**

There are eight operating intervals for the inverter within an LF output period \((0\rightarrow8)\), as shown in Fig. 2(g). \([0\rightarrow1]\): \(0 < un < Ui\), operating inMode A. L is freewheeling during \( DTs \) and magnetizing during \((1-D) Ts\). \( iL \) keeps rising, \( iL > IL \). The inverter operates in switching pattern II corresponding to the equivalent circuit, as shown in Fig. 2(e) and (c). Since \( 1-D \) is quiet small around \( un \)’s zero point, \( iL \) rises slowly. \( an \) rises to the \( UI \) and \( iL \) reaches its maximum value \( iL_{max} \) at the time \( t1 \).

\[
i_{L_{max}} = \frac{\alpha fis/\omega}{\omega} \frac{U_i - \sqrt{2}U_n |\sin(\omega kT_s)|}{L} [1-D(k)]T_s + I_L^L
\]

\[
= \int^{\alpha fis/\omega}_{-\alpha fis/\omega} U_i - \sqrt{2}U_n |\sin(\omega t)| \frac{U_i}{\sqrt{2}U_n} |\sin(\omega t)| \, dt + I_L^L
\]

\[
= \frac{U_i}{\sqrt{2U_n} \omega L} \left[ 2U_i (1 - \cos \alpha) + \frac{U_n (\sin 2\alpha - 2\alpha)}{\sqrt{2}} \right] + I_L^L
\]

The angle \( \alpha \) is the corresponding angle when \( un = Ui \), namely

\[
\alpha = \sin^{-1} \frac{U_i}{\sqrt{2U_n}} \quad (4)
\]

\([1\rightarrow2]\): \( an > Ui \), operating in Mode B. L is freewheeling during \( DTs \) and demagnetizing during \((1-D) Ts\). \( iL > IL \), the inverter operates in switching pattern II corresponding to the equivalent circuit, as shown in Fig. 2(e) and (c). After every \( Ts \) period, \( il \) is always higher than \( IL \) and decreasing, \( 1-D \) is increasing, and the drop rate of \( iL \) is increasing. At moment \( t2 \), \( iL \) rapidly drops back within \( IL \). The angle \( \beta \) is the corresponding angle of \( il \) from the maximum value at \( t1 \) to within \( IL \) at \( t2 \), namely \( \beta = \alpha t2 - t1 \). Set \( il(t2) = IL \), since the decline value of \( il \) from \( t1 \) to \( t2 \) is equal to the difference between \( iL_{max} \) and \( IL \), derived as

\[
\left( \frac{\alpha fis/\omega}{\omega} \right) \frac{U_i - \sqrt{2}U_n |\sin(\omega kT_s)|}{L} \frac{U_i}{\sqrt{2U_n} \omega L} |\sin(\omega kT_s)| \, T_s
\]

\[
= \frac{\alpha fis/\omega}{\omega} \frac{\sqrt{2}U_n |\sin(\omega kT_s)|}{L} \frac{U_i}{\sqrt{2U_n} \omega L} (1 - \sin 2\alpha) \quad (5)
\]
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Fig. 2. Equivalent circuit and steady principle waveform of the inverter. (a) Magnetizing state for $im > 0$. (b) Magnetizing state for $im < 0$. (c) Regenerating energy state for $im > 0$. (d) Regenerating energy state for $im < 0$. (e) Freewheeling state for $im > 0$. (f) Freewheeling state for $im < 0$. (g) Steady principle waveform within a LF output period.

Combination (13) with (18), the equivalent duty ratios of magnetizing and freewheeling states during each $Tes$, respectively, are

\[
\frac{\sum_{j=k}^{k+m-1} U_i}{L} D(j)T_s + \frac{\sum_{j=k}^{k+m+n-1} U_i - |u_n| [1 - D(j)] T_s}{L} = 0.
\]

The equivalent duty ratio of regenerating energy state during each $Tes$ meets (13). The corresponding equivalent circuits of the three kinds of state for this interval are shown in Fig. 2(a), (e), and (c). The angle $\gamma$ is the corresponding angle from $IL$ first dropping to $IL*$ at $t_2$ to $un$ decreasing to $Ui$ at $t_3$, namely

\[
\gamma = \pi - 2\alpha - \beta.
\]

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The previous equation shows that the double line frequency component of the input-side current of the inverting bridge mainly flows through $S_0$; thus, the energy storage inductor of the inverter can be greatly reduced.

### IV. SIMULATION RESULTS

Designed example: input dc voltage $U_i = 98 \, \text{-} 122 \text{V}$, grid voltage $U_n = 220 \text{V} \, 50 \text{Hz}$, rated power $P = 1 \text{kW}$, the switching frequency $f_s = 50 \text{kHz}$, current sampling frequency selected for $50 \text{kHz}$, energy storage inductor $L = 1 \text{mH}$, input filtering capacitor $C_i = 3 \times 1800 \mu \text{F}$, output filtering capacitor $C_f = 9 \mu \text{F}$, output filtering inductor $L_f = 0.5 \text{mH}$.

### REFERENCES