Design and Implementation of Digital Control of Photovoltaic Power Inverter

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Abstract

Inverter grid-connected PV system as a network interface with the main equipment, the control technology has become a research hotspot. Based on the theoretical analysis, a brief introduction of photovoltaic grid-connected inverter system structure and working principle, a linear control model of the inverter, the focus of the working conditions of its control grid design and Digital Realization process. Proposed to achieve zero steady state error conditions for sinusoidal current control, the use of band-pass filter type BPFM (Band-Pass Filter Mode) controller and inverter output current control, achieve high performance inverter Grid . Digital signal processor with TMS320LF2407A (DSP) as the controller design and simulation of the system parameters to achieve the small photovoltaic inverter good control.

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1. Introduction

With coal, oil and other fossil fuels are depleted, solar energy as a clean, safe, green, renewable energy, is becoming a highly polluting fossil fuels one of the major alternative energy sources. In recent decades, solar photovoltaic technology has been an unprecedented development, including photovoltaic power generation technology using solar energy has become one of the main ways. Grid inverter for renewable energy and power generation in key equipment [1], and as a photovoltaic power generation system and grid interface to the main equipment, photovoltaic power inverter control technology has become a research hotspot. Digital control design of control systems is the development trend, it has a simple design, flexible control, high reliability, strong anti-interference ability and ease of maintenance and testing and so on.

Is connected under the outer grid, solar power stations are divided into independent and network type and type two. Inverter compared with the general, whether stand-alone or grid type solar photovoltaic power plants. Inverter solar PV power plant has the following different characteristics [2]: one for high
efficiency: because the general matrix of the photovoltaic conversion efficiency of solar cells is very low, less than 15% and therefore requires high efficiency inverter; Second, small waveform distortion, high power factor: grid type solar power plant output to be associated with the external power grid, the inverter output waveform must be consistent with the external power grid. Requirements of the waveform distortion <5%, high harmonic content of "3%, power factor close to 1; third is the use of complex environment, the stability require high: for use in remote mountainous areas and islands of the independent-type solar power plant, the environment is relatively poor. And for families and-grid photovoltaic power also called electromagnetic interference is small, does not affect other living environment. Inverter based on the characteristics of recovery, the current study a variety of ways.

2. Analysis of digital control scheme

Compared to traditional analog control, digital control of inverter has many advantages to implement complex control algorithms. Such as parameter identification, intelligent control, deadbeat control, network control, improve system performance, control is more flexible; gain bandwidth control parameters are set through software, easy adjustment; standardized hardware structure, fewer number of components; avoid the existence of analog temperature drift, aging; improve system accuracy and stability; detailed system logs, easy to repair and maintenance.

It is because of digital control technology has so many advantages, the use of digital control of electrical equipment increasing. The field of digital control in power transmission has been popular, but in the power field, the current mainstream products on the market are still analog control. This is caused by two reasons: First, power transmission equipment, mechanical load is the load, while the load is the electrical power supply of the load. The latter time constant to several orders of magnitude lower than the former, therefore, sampling for digital control to maintain links and control delay is more sensitive. Simple traditional discrete analog controller, the control performance will lead to a significant decline. Second, the power supply for a large number of small and medium, DSP's price was too high, increasing the number of control cost pressures.

However, in recent years, advances in technology programs and hardware costs decline, so that the performance of digital control has been greatly improved in the power inverter has made a variety of control options: the main digital PID control, deadbeat control, repeat control, hysteresis current control. These control methods have advantages and disadvantages: PID control widely used in industry, has accumulated rich experience, the digital PID control is simple and practical, easy to implement. Drawback is that the dynamic properties are still not ideal. System state equation based on deadbeat control method with fast dynamic response speed, but the system stability and robustness of the poor. Internal model principle based on the system for repetitive control system with periodic load, but for the poor performance of random immunity. In addition, the inverter control methods have variable structure control, fuzzy control and neural network control.

Inverter for photovoltaic characteristics, this paper established a linear grid-connected inverter control model, on the basis of the deficiencies of traditional PID control [3], proposed to achieve zero steady-state sinusoidal current control error conditions, the use of band-pass filter type BPFM (Band-Pass Filter Mode) controller and inverter output current control, achieve high performance inverter and network operation. In the analysis based on the principle of the control scheme selection, design and simulation of system parameters, with the DSP as a controller to achieve small-scale photovoltaic inverter control.

3. System structure and working principle

Photovoltaic power generation system block diagram shown in Figure 1. The system consists of PV
array, DC/DC (Boost step-up circuit), inverter circuit, sampling circuit, DSP controller and the six major sections isolation transformers. The system is a two-stage transformer isolated inverter system, according to actual needs and the net work to achieve independence and two modes of operation. Photovoltaic solar arrays will be collected into a DC power supply, the DC power and then by Boost boost circuit is transformed into 400V DC voltage source, and photovoltaic arrays to achieve maximum power point tracking (MPPT), so that helps improve system the overall efficiency, but also easy to implement full-bridge inverter circuit after the class and network control. And the inverter frequency is used in unipolar sinusoidal pulse width modulation (SPWM) method, without increasing the switching frequency of the premise, improves the harmonic frequency SPWM waveform, so that the harmonic components of the output voltage can be effective control. Filtering and switching full-bridge circuit can be high frequency SPWM inverter output by filtering the sine wave fundamental to provide to the local load and achieve stand-alone mode; also can be subjected to frequency isolation transformer to provide electricity to the grid, to achieve and network operation mode. Frequency isolation transformer (turns ratio KT = 1:1) to isolate the DC current component, and reduces the power grid and grid-connected inverter of electrical equipment and personal safety. The whole system mode selection, SPWM wave generation, grid lock, the processing and protection of the test parameters are unified by the DSP chip TMS320LF2407A completed.

![Figure 1, grid-connected PV system block diagram](image1)

4. Design of grid inverter

Grid inverter is grid-connected PV system, the core part of its solar array can be issued by the DC power into the grid against the same frequency and phase voltage alternating current, and ultimately out of the inverter AC current to unity power factor is fed into the grid. And inverter main circuit topology shown in Figure 2.

![Figure 2, grid inverter main circuit topology](image2)

Which, Ud for the PV array voltage to the circuit by Boost DC voltage source; selection switch IGBT inverter module; use of frequency isolation transformer leakage inductance and the composition of LCL pre-class structure of the output LC filter. Theoretical analysis shows that, LCL structure, LC structure is
better than the attenuation of high frequency components showed a high resistance state, can effectively restrain the impact of harmonic currents and current. And inverter main circuit topology is shown in Figure 3 equivalent. Ug-grid voltage; L2-isolation transformer; T-converted to the secondary leakage inductance, the inverter is used as the grid inductance.

![Figure 3 grid inverter main circuit topology](image)

4.1 Grid-Connected Inverter Control Scheme

Inverter and network control and network technology as a key part of the study, the output control can be divided into two kinds of voltage control and current control. Grid-connected inverter of this article with instantaneous feedback current control scheme [4], the inverter output current by controlling the phase and size, in order to achieve unity power factor, energy output, greatly reducing the output current harmonic pollution on power. And inverter control system block diagram shown in Figure 4. The IGBT switching frequency set at 20kHz, well above the power frequency of 50Hz. Therefore, in order to facilitate the analysis of the impact of switching on the system can be approximated as a SPWM inverter unit ratio of links $K_m$.

![Figure 4 grid inverter control system schematics](image)

Based on the above analysis can be grid-connected inverter control block diagram shown in Figure 5. Where, $G(S)$ for the LCL filter transfer function, namely:

$$G(S) = \frac{i_o(S)}{u_{ab1}(S)} = \frac{1}{S(L_1 + L_2 + L_1L_2CS^2)}$$  \hspace{1cm} (1)

$G_c(S)$ - the system controller transfer function; $H(s)$ - current sensing circuit of the transfer function; $I_{ref}(S)$ - synchronized with the grid voltage and net current reference signal.
At present, current-mode control strategy to achieve a lot, typically a hysteresis current tracking control and constant switching frequency current control of two [5]. This paper is to overcome the shortcomings hysteresis current control of the triangular wave comparison control, it is a constant switching frequency control scheme, the control block diagram shown in Figure 6. Among them, the sinusoidal current reference value $i_{\text{ref}}$ and output transient current $i_{\text{o}}$ error comparisons of the amount adjusted by the controller is sent to the comparator, obtained with triangular wave comparison SPWM signal to control the main circuit power control and end the turn. In this control mode, the power switching device switching frequency is fixed, is the carrier frequency, which is more convenient high-frequency filter design, the output current harmonic components contained less [6]. In this study, the controller uses a simple, reliable PI control module.

### 4.2 Design of Filter Parameters

Since the inverter is used independently LC filter structure, and net work, on the basis of the LC filter inductor $L_2$ in series and then into the grid, that uses a LCL filter structure, so the design parameters of $L_1$ and $C$ design by independent work requirements:

1) the selection of the inductor $L_1$. Inductor current ripple to take 20% of the rated current, the inverter output 220V/1000VA conditions required to design by $\Delta I_{\text{max}}$ to 0.909 A.

In the unipolar SPWM modulation frequency, the output voltage of the carrier frequency $f_c$ is the switching frequency $f_s$ 2 times, then the inductor current ripple and inductor $\Delta I_{\text{max}}$ the relationship between the expression of $L_1$ is:

$$L_1 \geq \frac{U_d}{8f_s \Delta I_{\text{max}}} \quad (2)$$

Actual take L1 = 3.05 mH.

2) the selection of filter capacitor C. Assuming the filter inductor current ripple absorbed by the filter capacitor, the maximum output voltage ripple:

$$\Delta U_{\text{om}} = \Delta I_{\text{max}} \times \frac{1}{4\pi f_s C} = \frac{U_d}{32\pi f_s^2 L_1 C} \quad (3)$$

Therefore, to limit the voltage ripple requirements:
\[ C \geq \frac{U_d}{32\pi f_s^2 L_i \times \Delta U_{in}} \quad (4) \]

If the output voltage ripple of 1.5% or less, there are:

\[ C \geq 0.988 \mu F \]

Actual take \( C = 1.6 \mu F \).

3) the selection of the grid inductance \( L_2 \). The work of the inverter when the grid current source, \( L_2 \)'s role is to suppress high-frequency ripple current grid. \( L_2 \) different choices for different documents, and generally \( L_2 = kL_1 \) [7] [8]. different values of \( k \), the resonant frequency will only affect the size of high frequency (smaller \( k \) value of its resonant frequency becomes larger, the larger the \( k \) value of the resonant frequency will make it smaller), without affecting the characteristics of its low frequency. In this design, the \( L_2 \) by the isolation transformer secondary leakage inductance as, taking into account the actual situation of isolation transformers used in the final selection of the inductor \( L_2 \) is 9.6 mH.

4.3 Digital Control Implementation Based on DSP

TMS320LF2407A TI's chip processing speed 40MI/s, with a strong internal peripheral functions. The high-performance DSP cores and powerful peripheral units and the inverter can achieve the requirements of real-time network and high precision control. Using its event management module (EV) in the full compare unit can produce 4 full-bridge inverter controlled power tube voltage pulse. In the DSP program space in the pre-stored sine table to achieve the sinusoidal current reference generation. Since the data length of \( N \) in the value table with equal frequency modulation ratio \( mf \), I used a switching frequency of 20kHz, the frequency modulation wave 50 Hz, therefore, \( N = 400 \). 20 kHz digital SPWM principle occur as follows:

T3 of the timer prescaler is set to \( X / 1 \), count mode set to continuous change mode, the corresponding period register value is set to 1000 so that it can register and set the dead zone to avoid the occurrence of straight leg. In each cycle (timer underflow interrupt), according to look-up table pointer, DSP sine wave to obtain the corresponding program from the digital reference and assign it to compare register CMPRx, while adding a look-up table pointer, in a sinusoidal cycle will be reset to a reference sine wave lookup table pointer of the first address. Thus, in the corresponding PWM output port to generate SPWM waveform.

For the inverter output current and grid voltage tracking lock request, this digital PLL (Phase Locked Loop) control strategy. Periodic interrupt using timer T3 starts DSP's A / D port on the grid voltage and inverter output current is sampled, the sampling period of 50\( \mu \)s, the sampling control the timing diagram shown in Figure 7. Where, \( t_0 \sim t_4 \) for a switching cycle, the timer interrupt cycle time \( t_1 \), while start 2-way A / D converter, the voltage and current feedback amount of sampling, the sampling method of the control points relative to the extension of the sampling point is only half switching cycle time, control of real-time strong. \( t_2 \) time A / D conversion is completed, locked into the program, the size of the frequency of two times in the program is between the rising edge of the zero count signal to determine, that is used to represent the cycle count value. Count is started from the rising edge zero-crossing time of each interruption cycle, the representative of each counting unit 50\( \mu \)s, 20ms for the 400 unit, the phase difference is also obtained from the count.
Before doing phase-locked frequency of the grid voltage to determine whether the normal range, if in the normal range, then calculate the next cycle of the inverter output current cycle and the current look-up table pointer value points; and then look-up table with the grid access point to obtain the reference voltage tracking PLL current; Finally, the current PI control algorithm based on the implementation until the time t3. Timer underflow interrupt the moment t4, the comparison of the calculated value of PI to load compare register CMPrx. PI D control algorithm of the DSP program with the scope of failure of small and incremental computation to achieve, the block diagram shown in Figure 8.  

![Figure 7 Timing diagram of sampling control](image)

**5. Simulation and experiment**

In order to verify the design of the inverter with the correctness of the program, for the corresponding simulation and experimental validation, the specific parameter settings are as follows:

- Rated power $PN = 1 \text{ kW}$; DC bus voltage $U_d = 400 \text{ V}$; DC bus capacitance $C_d = 2200\mu\text{F/450 V}$; inverter output filter inductor $L_1 = 3.05\text{mH}$; inverter output filter capacitor $C = 1.6\mu\text{F/400V}$; power switch IGBT module type selection BSM20GP60, $I_d = 20 \text{ A}$, $V_{ces} = 600 \text{ V}$; isolation transformer parameters: excitation inductance is $340\text{mH}$, secondary side leakage inductance $L_2 = 9.6\text{mH}$, variable ratio $220\text{V}/220\text{V} = 1$.

Saber simulation software used to obtain the waveform shown in Figure 9, where the high amplitude voltage waveform for the power grid, the peak voltage is $311 \text{ V}$; amplitude of the inverter low grid current output, its peak current of $6.42 \text{ A}$.

System simulation and experimental waveforms are that the output of the inverter and net current frequency of $50 \text{ Hz}$, can track the grid voltage phase to achieve the unity power factor of the energy fed...
into the grid, the sinusoidal current waveform is high, the use of WaveStar its harmonic analysis, THD is 2.561%.

![Figure 9 inverter and network simulation waveforms](image)

6. Conclusion

This paper focuses on the solar PV system and inverter and the control condition when the network design and digital implementation process, and the use of simple design, flexible control, high reliability, strong anti-interference as a control DSP devices to achieve transient with fixed switching frequency current control and network programs. Finally, the simulation and experimental results show that the design can achieve a good grid inverter output current tracking voltage, and has a good degree and lower sinusoidal THD.

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