A high-efficiency micro-grid simulation system based on STM32

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Abstract. A high-efficiency micro-grid simulation system based on STM32 is designed. The hardware circuit includes two three-phase half-bridge inverter circuits, AC voltage and current sampling circuits, and LC filter circuits. STM32F407 is used as the main controller, and outputs SVPWM waves. The main inverter has low THD when running on its own, so that can stably convert DC power into three-phase AC power. When working in parallel, the system realizes that the output power ratio of the two inverter circuits is adjustable. Through theoretical analysis and testing, the micro-grid has high efficiency, and the circuit also performs well when testing the load regulation rate. In addition, the system uses OLED screens and matrix keyboards to achieve human-computer interaction, and has overcurrent and overvoltage protection functions.

1. Introduction

As fossil fuels are on the verge of exhaustion and people pay more and more attention to environmental protection, clean energy is driving the transformation and upgrading of the energy structure. Because micro-grid can be organically combined with wind power generation, photovoltaic power generation, etc. and exist huge application potential, various countries have launched related research. Among them, the United States first proposed the concept of micro-grid and established the Mad River micro-grid demonstration project. Faced with the reality of domestic energy shortages and increasing loads, Japan has set out to vigorously develop micro-grid. Compared with developed countries, China’s research on micro-grid started late. In terms of grid operation, my country’s power grids still have problems such as low reliability and high investment costs. At the technical level, the main gap lies in the intelligent control and high efficiency of coordinated operation technology for micro-grid. Coordinated operation technology, but now the country has planned to actively promote and encourage the development of renewable energy as one of the national strategies, so the research on micro-grid will surely make great progress. Hu Ping uses wind energy and solar energy to generate electricity as DC power input of the micro-grid with intelligent control to reduce energy waste [1]. Cai Changchun, Cheng Shucheng, etc. proposed the use of fuzzy RBF neural network to equivalent modeling the DC micro-grid-connected with improved bacterial foraging algorithm, which provides a new method for microgrid modeling. However, the stability of the method in practical application has not been verified by experiments [2].

Traditional switching power supply circuits are generally complex in control and bulky and poor in maintainability. To solve the problems of high investment and operation and maintenance costs in my country's micro-grid technology, the research focus of this system is how to improve the efficiency and
stability of the micro-grid simulation system, simplify the circuit structure and control scheme, and optimize various parameters (such as load regulation rate). In order to improve the control performance of the system, the control of the three-phase inverter circuit adopts a fully digital control scheme, using STM32F407 to complete the system's feedback signal detection and SVPWM wave output, and adopts a simplified algorithm to shorten the calculation time of SVPWM. The system can also realize independent and parallel operation, switch between the two states seamlessly, and adjust and distribute power according to demand. In order to ensure the stability of the system output, PID algorithm is used to achieve closed-loop control.

2. System overall design

Figure 1 shows a block diagram of the overall system design. The system simulates the DC micro-grid system, the DC power source is equivalent to wind power generation, solar power generation, etc., and provides DC power for two inverters. The core module of the system is two three-phase inverter circuits, whose main function is to realize the conversion of DC to three-phase AC. The function of the switch is to switch the mode. When the switch is off, the master inverter circuit operates independently; when the switch is closed, the master and slave inverter circuits operate simultaneously. The voltage and current transformer and AC sampler work together as the AC voltage and current acquisition module, which can realize the isolation and sampling of electrical signals, and send the sampled signals back to STM32F407. STM32F407 has fast calculation speed, high precision, short response time and rich functions. Therefore, in this system, its tasks include outputting multiple complementary SVPWM waves, processing and calculating feedback values, using PID algorithms to adjust SVPWM parameters, and connecting with OLED screens and matrix keyboards to realize human-computer interaction.

3. System hardware circuit design

3.1. Three-phase inverter circuit and MOS drive circuit

The core of the micro-grid simulation system is two parallel three-phase inverter circuits. The two parts of the three-phase inverter circuits are exactly the same. The circuit shown in Figure 2 is one of the three-phase inverter circuits. The driver circuit of the MOS tube uses the IR2104 chip, which is a full-bridge driver chip, with a dead time to prevent the MOS tubes on the same half-bridge from being turned on at the same time. The voltage can be increased by the bootstrap capacitor to achieve the lower tube driving of the half-bridge. And the chip has the advantages of high integration, strong anti-interference ability, simple design circuit, strong stability, etc., which meets the design of this circuit. The circuit topology selected for the three-phase inverter circuit is a three-phase half-bridge inverter circuit. The circuit structure is simple and consists of three half-bridges. The center point of each half-bridge arm is taken as the output point, and then connected to the LC filter. The circuit can realize three-phase inverter. The drain source of each MOS tube is connected to a buffer circuit, which can prevent the sudden change of the voltage at both ends from damaging the MOS tube according to the characteristics of the capacitor.
The switching method adopted by this circuit is zero voltage switching (ZVS), which can further reduce the switching loss.

Figure 2. Three-phase inverter circuit and MOS drive circuit

3.2. Design of AC sampling circuit
The AC sampling scheme is AD sampling calculation. The output voltage and current signals are connected to the voltage transformer and the current transformer respectively to realize the isolation of strong and weak currents. At the same time, the output signal of the three-phase inverter circuit is reduced for easy collection. After the active filter circuit, the collected signal is more accurate and reliable, and finally transmitted to the AD chip for sampling. The following figure shows the AC voltage sampling circuit.

Figure 3. AC voltage sampling circuit

3.3. Hardware circuit efficiency improvement scheme
The MOS tube model selected by this system is CSD19536, and its withstand voltage is 100V, with low on-resistance and gate-drain capacitance. Low on-resistance can reduce the power dissipated in the form of heat energy. When the capacitance of the gate and drain capacitor is small, the charge stored in the capacitor will be less, and the gate charge loss and drain capacitance loss will be reduced, which can
further reduce the circuit loss.

The filter circuit is an LC circuit. In order to achieve high efficiency, it is necessary to reduce the core loss and winding loss of the filter inductor. In the choice of magnetic core, the use of ferrite material core with higher resistivity can effectively reduce the inductance eddy current loss. In order to reduce the leakage inductance, the winding is more compact, and multiple thin wires are used instead of a single thick wire to wind the inductance, so as to reduce copper loss and reduce the proximity effect and skin effect. The selected model of filter capacitor is MKP capacitor. Compared with general CBB capacitor, MKP capacitor has a higher starting point of withstand voltage, small internal temperature rise, and low lead loss.

4. System software design

4.1. Programming block diagram

Figure 4 is the programming flow chart of the system. After system initialized, it goes into mode selection module. When selecting the stand-alone operation mode, only inverter 1 works: STM32F407 controls the advanced timer to generate SVPWM wave, and SVPWM wave further controls the on and off of the MOS tube, and the inverter outputs three-phase AC power. The AC voltage is collected by the sampling circuit and sent back to STM32F407 for processing and calculation. The feedback value is compared with the preset value, and then the output SVPWM wave is adjusted by PID algorithm. The sampled data will be updated and displayed on the OLED screen in real time. When selecting the parallel operation mode, the split ratio, that is, the ratio of the output currents of inverters 1 and 2 need to be set. In this mode, the output voltage and current need to be sampled at the same time, and the feedback value will be displayed on the OLED screen.

![Figure 4. Block diagram](attachment:image.png)
4.2. SVPWM algorithm
SVPWM is called space vector pulse width modulation. Through this technology, any vector in 360° space can be synthesized by eight basic voltage vectors. The figure below shows the voltage sector diagram. Compared with SPWM, the 3rd harmonic is injected into the modulation wave of SVPWM, which greatly improves the utilization rate of the DC bus voltage, while reducing switching losses and making it easier to realize digitization. The goal of SVPWM technology is to approximate the output voltage vector \( U_{out} \) in real time by combining the switching states corresponding to the basic space vector. The composite relationship of the vector is:

\[
U_{out} = \frac{2}{3}U_{dc}\left(S_a + S_b e^{\frac{2\pi}{3}} + S_c e^{-\frac{2\pi}{3}}\right)
\]  

Where \( S_a, S_b, S_c \) represent the switching status of each half bridge, \( U_{dc} \) is the DC bus voltage. It can be obtained from the formula that \( U_{out} \) is the same size and the phase changes constantly, so the trajectory of the vector is approximately a circle. The basic principle of SVPWM modulation is to do orderly switching control of the six MOS tubes in the three-phase half-bridge inverter circuit, so that the composite vector of the three-phase voltage output by the inverter simulates this circle. The SVPWM simplified algorithm is realized by establishing a new three-phase reference system perpendicular to the sector boundary, and judging the sector where the synthesized voltage space vector \( U_{out} \) is located according to the sign of each axis component of the new reference system; Calculate and set the duty cycle of the PWM module corresponding to a, b and c under the seven-segment SVPWM modulation method for the sector where the unitary component and \( U_{out} \) are located [7].

4.3. Software efficiency improvement methods
The frequency of the switching power supply is a major factor affecting the efficiency of the circuit, so it is particularly important to select the appropriate switching frequency. When the switching frequency is too small, the volume of the filter will increase significantly. Otherwise, the low frequency harmonics will not be filtered out, resulting in waveform distortion and large total harmonic distortion (THD) value. Gradually increase the switching frequency, although the volume of the filter circuit can be reduced, it will increase the switching loss of the power switch MOSFET, which can even be compared with the conduction loss. According to the formula:

\[
P_{on} = \frac{1}{2}U_D I_{o_{on}} f_s
\]

\[
P_{off} = \frac{1}{2}U_D I_{o_{off}} f_s
\]

It can be obtained that the power loss of the power switch tube MOSFET rises linearly with the increase of the switching frequency. After comprehensive consideration, 20kHz is used as the switching frequency of this system.
4.4. Control strategy of parallel operation mode

4.4.1. Voltage stabilization strategy in dq rotating coordinate system

The output voltage of the three-phase inverter is three-phase alternating current. Three output voltages with the same amplitude but 120° phase difference can be projected from the three-phase stationary coordinate system to the two-phase rotating coordinate system through matrix conversion, that is, the Parker transformation. In order to facilitate the Parker inverse transformation, the 0-axis coordinates and \( U_0 \).

\[
U_0 = \frac{1}{3} (U_a + U_b + U_c) \tag{4}
\]

\[
\begin{pmatrix}
U_a \\
U_b \\
U_c
\end{pmatrix} = \frac{2}{3} \begin{pmatrix}
\cos(\omega t) & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right)
-\sin(\omega t) & -\sin\left(\omega t - \frac{2\pi}{3}\right) & -\sin\left(\omega t + \frac{2\pi}{3}\right)
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{pmatrix} \begin{pmatrix}
U_a \\
U_b \\
U_c
\end{pmatrix} \tag{5}
\]

The Parker transformation is equivalent to the projection of \( U_a, U_b, U_c \) on the \( \alpha - \beta \) axis to the dq0 axis. After a certain angle rotation transformation, the rotating vector is transformed into a quantity in the stationary rectangular coordinate system. When the three-phase inverter circuit enters the steady state, the value of the d-axis component in the dq0 coordinate system is equal to the peak value of the output voltage, and the components of the q-axis and the 0-axis are both zero. According to this, when the main inverter is running alone, a single-loop voltage control is performed in the dq0 coordinate system to achieve output stabilization. When the A-phase vector is aligned with the q-axis, matrix transformation is performed, and the waveform before and after transformation is shown in Figure 6.

![Waveform comparison before and after](image)

Figure 6 Waveform comparison before and after

4.4.2. Power distribution adjustment in parallel operation

When two inverters are operating in parallel, the output voltage supplies power to the load at the same time. Record the output voltage of inverter 1 as \( \hat{U}_1 \angle \phi_1 \) and the output voltage of inverter 2 as \( \hat{U}_2 \angle \phi_2 \). Calculate the vector difference of the two output voltages:

\[
\Delta \hat{U} = \hat{U}_1 \angle \phi_1 - \hat{U}_2 \angle \phi_2 \tag{6}
\]

When \( \Delta \hat{U} \neq 0 \), it means that the output voltage phase and other parameters of each module are inconsistent, and a circulating current will be generated between the modules. Under the action of circulating current, the output current \( I_{o1}, I_{o2} \) is not consistent, so that the active power and reactive power of the two inverters are different. It can be seen that when the inverters are connected in parallel, their output power has a consistent relationship with their output current. Therefore, the power...
distribution can be adjusted by changing the value of \( \phi_1, \phi_2 \) to make \( \Delta \Phi \neq 0 \). When two inverters are needed to realize current sharing output, the current sharing control scheme adopted is master-slave control. When the slave inverter is not connected to the main circuit, first use the PLL phase-locked loop control to ensure that the phase angle of the output voltage of the slave inverter is consistent with the phase angle of the master inverter, and then close the switch to let the slave inverter connect to the main circuit. This control method requires that the output voltage of the main inverter remains stable and controls the output voltage of the parallel inverter. According to the split ratio 1:1, the current reference value of each module is obtained, and the output current from the inverter is constant and the current value is close to the current reference value, and the overall current sharing is realized.

5. Test plan and test results

5.1. Test plan and test results

(1) Only supply 50V DC to the main inverter, and provide Y-connected symmetrical load. Test the effective value of line voltage, effective value of line current, frequency, AC bus voltage total harmonic distortion (THD) and efficiency.

| Parameter          | Value  |
|--------------------|--------|
| \( U_{in}/A \)     | 50.00  |
| \( I_{in}/A \)     | 1.76   |
| \( U_{o1}/V \)     | 24.01  |
| \( I_{o1}/A \)     | 2.01   |
| THD                | 0.42%  |
| \( \eta \)%        | 94.99% |
| \( f/Hz \)         | 50.00  |

(2) The main inverter supplies power to the load, and when the effective value of the load line current changes between 0~2A, test the load regulation rate \( S_l \).

| Parameter          | Value  |
|--------------------|--------|
| \( I_{o1}/A \)     | 0.2399 |
| \( U_{o1}/V \)     | 2.09   |
| \( I_{o2}/A \)     | 24.02  |
| THD                | 0.13%  |

(3) Inverter 1 and 2 output power to the load together, when the effective value of load line current \( I_o \) changes between 1 and 3A, set the shunt ratio K by pressing the button (the ratio K is 1:2~2:1), and measure the reverse the output line currents of inverters 1 and 2 are calculated. Finally, the absolute value of the difference between the converted values of the output line currents of the two inverters is calculated.

| Parameter          | Value  |
|--------------------|--------|
| \( I_{o1}/A \)     | 1.03   |
| \( I_{o2}/A \)     | 0.351  |
| \( I_{o1}/A \)     | 0.702  |
| \( I_{o2}/A \)     | 0.679  |
| Converted value    | 0.679  |
| Difference          | 0.023  |
| \( I_{o1}/A \)     | 1.97   |
| \( I_{o2}/A \)     | 0.981  |
| \( I_{o1}/A \)     | 0.981  |
| \( I_{o2}/A \)     | 0.989  |
| Converted value    | 0.989  |
| Difference          | 0.008  |
| \( I_{o1}/A \)     | 2.51   |
| \( I_{o2}/A \)     | 1.426  |
| \( I_{o1}/A \)     | 1.426  |
| \( I_{o2}/A \)     | 1.084  |
| Converted value    | 1.445  |
| Difference          | 0.019  |
| \( I_{o1}/A \)     | 3.04   |
| \( I_{o2}/A \)     | 1.007  |
| \( I_{o1}/A \)     | 2.014  |
| \( I_{o2}/A \)     | 2.033  |
| Converted value    | 2.033  |
| Difference          | 0.019  |

5.2. Test result analysis

The two operation modes have been tested. The test results show that when working in stand-alone operation mode, the output line voltage of inverter 1 is 24V, the line current is 2A, the frequency is 50Hz, and the system efficiency can reach 94.99%. AC The total harmonic distortion (THD) of AC bus voltage is only 0.42%, and the load regulation rate is 0.13%. In parallel operation mode, the output current of inverter 1 and inverter 2 can be automatically distributed according to the set value within the specified range (ratio K is 1:2~2:1), and the difference is less than 0.1 A.

6. Conclusions

This system simulates the micro-grid, using two inverters, and there are two operating modes: stand-alone mode and parallel mode. The working efficiency of inverter 1 can be as high as 94.99%, the
frequency is stable at 50Hz, the load regulation value is low, and the total harmonic distortion (THD) of the AC bus voltage is only 0.42%. In parallel mode, automatic power distribution can be realized. In addition, this system uses a simplified algorithm to achieve SVPWM modulation, so it has the advantages of simple structure, high efficiency and stability of the circuit. The system also has overcurrent protection and overvoltage protection, which enhances the stability and safety of the system.

Acknowledgments
Wuhan University of Technology Independent Innovation Research Fund undergraduate project (2020-ZDH-B1-08).

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