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Research Article

The Design of AC Regulated Power Supply Based on PWM Chopping Series Compensation Technology

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Abstract: Area for the fast load variation, the power grid voltage fluctuations is very serious. In order to supply stable voltage for the small power user, a unipolar chopping compensation AC regulated power supply is designed based on bidirectional H PWM chopping bridge which can realize the bidirectional flow of energy when the voltage is boosted and step-down. It adopts voltage feedback control. The initial chopping duty ratio is determined by proportion regulation according to difference of the input voltage and the standard voltage; it can improve the voltage response speed. The initial duty ratio is corrected according to digital PID regulation based on the output voltage feedback, which ensures the stability of the output voltage. The STC12C5A62AD single chip is adopted for the regulated power supply that have 8 AD inputs and PWM output, it make the system structure simple. The 12.8 kHz sampling frequency and high precision voltage sampling technology ensures the precision of sampling. The 10 kHz frequency of the chopper reduces the harmonic component and it is easy to filter. Experimental results show that dynamic response speed of the regulated power supply is fast and precision of it is high. It has great practical value.

Keywords: AC regulated power supply, feedback control, PWM control, series compensation

INTRODUCTION

The grid voltage drops off sharply in many areas at peak power, but it rises sharply at power trough. It is low for a long time in some outlying areas and it fluctuates sharply in load change faster areas (Lin *et al*., 2008). Especially in agricultural areas, agricultural facilities voltages are extremely instability. Therefore, high stability AC regulated power supply has a very broad application prospects.

There are many AC regulated power supply types, in which the series compensation regulated power supply is utilized to achieve stable output voltage by the compensation transformer (Zhang, 1999; Zhao *et al*., 2011; Wang *et al*., 2009). The compensation transformer is equivalent to the autotransformer, which has the advantages of small volume and high efficiency. Therefore, the series compensation type regulated power supply is the new direction of development of AC power control technology. The chopping series compensation regulated power supply that is designed in this study can achieve compensation from inductive electromotive force and phase of transformer's secondary side based on fully controlled power electronic devices. And it has the advantages of simple structure of regulated power supply, high stabilizing voltage precision, fast response speed, can be applied to a variety of different types of low power load below 5k W.

STRUCTURE AND PRINCIPLE

- **Main circuit structure of the regulated power supply:** Main circuit structure of chopping cascade compensation type regulated power supply is shown as Fig. 1. It is used a full bridge bidirectional chopper, which each bridge arm is composed of 2 inverse parallel diode and IGBT devices. The primary side of the compensating transformer and the bridge arm output are connected in series, secondary side connected in power network and loads. Because unipolar chopper control is adopted that enable power factor of the compensation circuit AC input to be 1 and when the chopping frequency is higher, the harmonic voltage is very small. And the output filter is composed of Lf and Cf in order to reduce the harmonic wave.
- **Principle and equivalent circuit:** It works in a different state when input voltages of power network are different. If the compensation transformer is an ideal transformer, its

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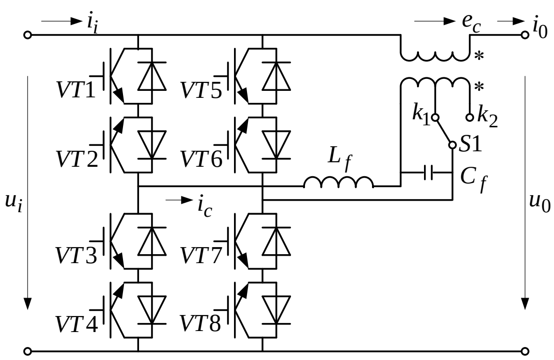

Fig. 1: Main circuit of the regulated power supply

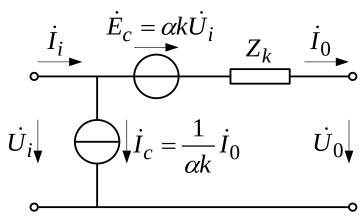

Fig. 2: Equivalent circuit

Table 1: Work state table of switch tube

	$U_i<U_N$		$U_i>U_N$	
Switch	$u_i>0$	$u_i<0$	$u_i>0$	$u_i<0$
VT1	on	off	off	off
VT2	off	PWM	on	off
VT3	off	on	PWM	off
VT4	off	off	off	on
VT5	off	off	on	off
VT6	on	off	off	PWM
VT7	PWM	off	off	on
VT8	off	on	off	off

homonymous ends is shown as Fig. 1. Input voltage of power network is u_i, output voltage of regulated power supply is u_0, the compensation transformer two times electromotive force is e_c, positive directions are shown as Fig. 1. If it is represented by phasor, then $\dot{U}_0 = \dot{U}_i + \dot{E}_c$. If the rated output voltage is U_N, when $U_i<U_N$, the transformer is compensated positively, the output voltage is increased, that is $U_0 = U_i + U_c$. And when $U_i>U_N$, it is compensated negatively, output voltage is reduced. The working state of switch tube is shown as Table 1 (Ma, 2011; Wang and Zhang, 2008; Deng *et al*., 2004).

Because of the constraints of IGBT device turn-on and turn-off time, duty ratio can not be too small. In order to ensure the 1% stabilization accuracy of the regulated power supply, the number of windings of primary side of the transformer are designed for k_1 and k_2 class and $k_1 > k_2$. When U_N-10≤U_i≤U_N+ 10, the k_2 is switched to k_1. In PWM chopper control, E_c = $\alpha k U_i$,αk is equivalent ratio. When compensation is positive, α>0, on the contrary, α<0.

If the actual compensation transformer magnetizing branch is ignored, short circuit impedance is converted to the secondary side of it that is represented by Z_k, then equivalent circuit is shown in Fig. 2. When the load current is I_0, there is:

$$\dot{U}_0 = \dot{U}_i - \dot{E}_c - \dot{I}_0 Z_k\,,\ \dot{I}_i = \dot{I}_0 + \dot{I}_c \tag{1}$$

In which, $\dot{I}_c = \frac{1}{\alpha k} = \dot{I}_0$, $\dot{E}_c = \alpha k \dot{U}_i$.

If output voltage U_0 is equal to U_{0N}, the compensation voltage is shown as followed:

$$\Delta\dot{U} = \dot{U}_{0N} - \dot{U}_i = \alpha k \dot{U}_i - \dot{I}_0 Z_k \tag{2}$$

That is:

$$\alpha = \frac{\Delta\dot{U} + \dot{I}_0 Z_k}{k\dot{U}_i} \tag{3}$$

The duty ratio of the next cycle is calculated that not only needs detecting voltage and current in the last cycle, but also phases. The phases detection are difficult when the load power factor is higher, so the formula (3) cannot be used for calculation of duty ratio. As a result of transformer short circuit impedance Z_k is relatively small, the according voltage is small. Accordingly, in the first place, the duty ratio α can be calculated approximately as follow in order to increase rapid response of output voltage.

$$\alpha' = \frac{\Delta U}{kU_i} \tag{4}$$

In the sec place, actual output voltage need to be detected, the correction value Δα of duty ratio can be calculated by the digital PID closed-loop feedback control in order to improve the precision of regulated power supply (Sun *et al*., 2006; Zhang *et al*., 2008).

- **Principle of digital PID:** If U_{0n} is the output voltage of the No. n cycle, then:

$$U_{0n} = Pe_n + I\cdot\sum_{m=0}^{n} e_m + D(e_n - e_{n-1}) \tag{5}$$

The P is proportion coefficient, I is integration coefficient, D is differential coefficient, $e_n$is error of the No. n cycle, e_n -1is error of the No. n-1 cycle.

Similarly, the output voltage of No.n-1 cycle is as followed:

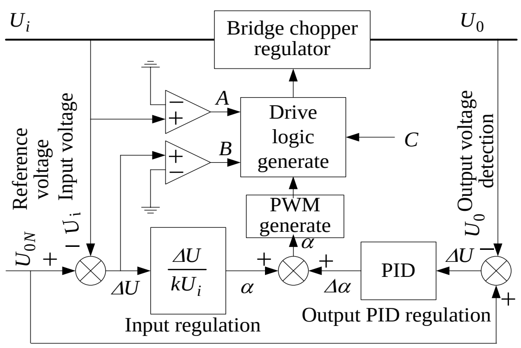

Fig. 3: Regulated power supply control diagram

$$U_{0n-1} = Pe_{n-1} + I \cdot \sum_{m=0}^{n-1} e_m + D(e_{n-1} - e_{n-2}) \tag{6}$$

If formula (5)-(6) is calculated, then:

$$U_{0n} - U_{0n-1} = P(e_n - e_{n-1}) + I \cdot e_n + D[(e_n - e_{n-1}) - (e_{n-1} - e_{n-2})] \tag{7}$$

If $U_{0n} - U_{0n-1} = \Delta U_n$ and $e_n - e_{n-1} = \Delta e_n$ and $\Delta e_n - \Delta e_{n-1} = \Delta^2 e_n$, then:

$$\Delta U_{0n} = P \cdot \Delta e_n + I \cdot e_n + D \cdot \Delta^2 e_n \tag{8}$$

when ΔU_{0n} is obtained, then correction value $\Delta\alpha$ of duty ratio can be calculated according to formula $\Delta\alpha = \frac{\Delta U_{0n}}{KU_i}$, finally, α can be calculated by $\alpha = \alpha' + \Delta\alpha$ so that precision of regulated power supply can be ensured. The principle of regulated power supply is shown as Fig. 3.

CIRCUIT SYSTEM DESIGN

The control circuit consists of a single chip, IGBT driving logic circuit and PWM drive circuit, an AC input voltage and current sampling, input voltage zero-crossing detection, alarm and displaying circuit, structure diagram of the system is shown in Fig. 4.

- **Singlechip circuit design:** In order to improve the accuracy of sampling, sampling is 128 times in half a cycle. The sampling frequency is 12.8 kHz at the frequency of 50Hz of input voltage, so the sampling interval is 0.078125 ms. During a sampling interval, the input, the output voltage and current sampling and the sampling data processing needed to be completed in a total of 2272 machine cycles. Thus the single chip crystal frequency is selected for 32MHz.A sampling interval is equal to 2400/ (32 × 1000000) = 0.075 ms, it can meet requirements of the design.

The STC12C5A60AD single chip is used for the design. Its speed (upper frequency 35 MHz) is high; it is convenient for improving sampling frequency. The P1 port has 8 PWM outputs, can also be used as a AD input port, which is convenient for sampling of input and output voltage with high precision.

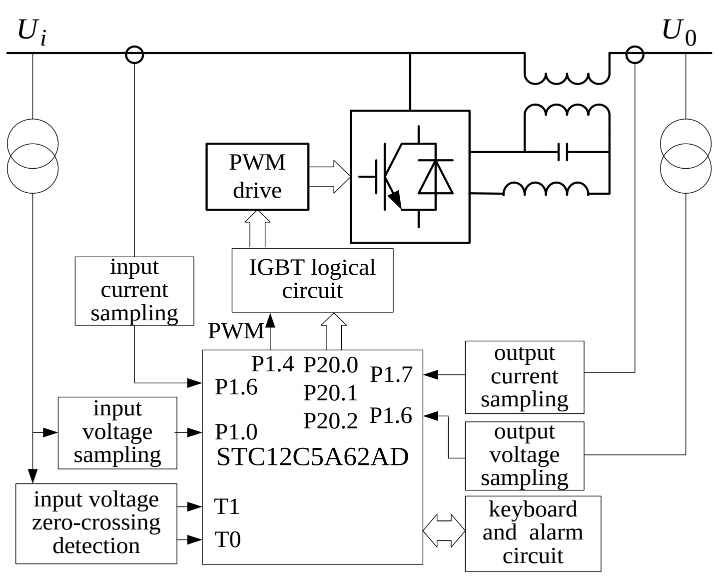

Fig. 4: Structure diagram of regulated power supply control circuit

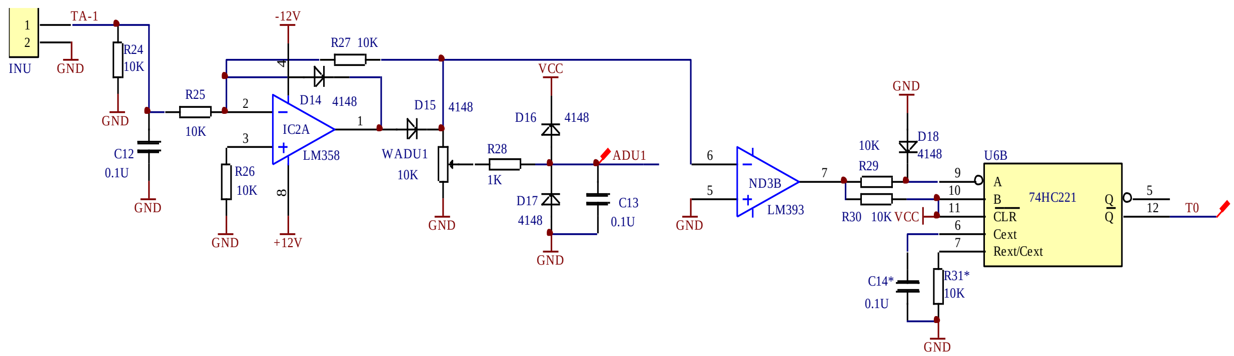

Fig. 5: Input voltage sampling and zero trigger circuit

Input and output voltage sampling and zero-crossing trigger: The input voltage sampling and zero-crossing detection circuit is shown as Fig. 5. After commercial power is connected by step-down, the positive half sine wave voltage can be obtained by an operational amplifier with half wave rectifier. Then through resistor divider, 0-5V voltage reaching to the single chip's P1.0, which is processed by AD conversion, sampling and calculating the voltage effective value. The sampling is 128 times in two voltages zero-crossing point in half a cycle, its frequency is 12.8 kHz. The voltage effective value can be derived as follow:

$$U_i \approx \left(\sum_{n=0}^{127} U_{in}^2 / 128 \right)^{1/2} \tag{9}$$

The commercial power is rectified by half wave and compared by the operational amplifier comparator; it will output synchronous square wave signals that can be used for polarity judgment of supply in half a cycle. The signal by the monostable circuit can be used for zero-crossing interrupt trigger.

The output sampling and zero-crossing detection circuits are same as above mentioned.

- **The design of IGBT driving logic circuit:** In order to reduce work pressure of the single chip, switch tube drive signals is composed of output PWM signal of single chip, half cycle polarity signal of input supply voltage, cascade compensation status signals and short-time reversing block signal when the upper and lower bridge arm reverse for preventing short circuit (Yang *et al*., 2004; Wang and Wei, 2005). Each signal state is shown as follows:

PWM: Pulse Width Modulation signal with adjustable duty ratio, output by the P 1.4 of the single chip.

- **Half cycle polarity signal of input power:** A = 1, power is a positive half cycle, A = 0, power is negative half cycle, output by P 2.0 of the single chip.
- **Cascade compensation state signal:** B = 1, is cascade boost compensation, B = 0, is cascade voltage step-down compensation, output by the P2.1 of the single chip.
- **The dead band control signal:** the 8 tubes are off when the upper and lower bridge arms reverse in order to prevent they are conducted simultaneously, output by the P 2.2 of the single chip.

The unipolar control is adopted in chopping. When the dead band control signals is considered, the logical relationship of the switch tube driving signals and the input signals can be represented according to Table 1. The actual driving control circuit is completed by a programmable logic array GAL16V8D2, logic relation formula of each switch tube driving signal is shown by following:

$$\mathrm{VT1} = A \cdot B \cdot C\,,$$
$$\mathrm{VT2} = \left(\bar{A} \cdot B \cdot PWM + A \cdot \bar{B}\right) \cdot C$$
$$VT3 = \left(\bar{A} \cdot B + A \cdot \bar{B} \cdot PWM\right) \cdot C\,,$$
$$VT4 = \left(\bar{A} \cdot \bar{B}\right) \cdot C$$
$$VT5 = \left(A \cdot \bar{B}\right) \cdot C\,,$$
$$VT6 = \left(A \cdot B + \bar{A} \cdot \bar{B} \cdot PWM\right) \cdot C$$
$$VT7 = \left(\bar{A} \cdot \bar{B} + A \cdot B \cdot PWM\right) \cdot C\,,$$
$$VT8 = \left(\bar{A} \cdot B\right) \cdot C$$

- **Filter design:** According to the literature (Ma, 2011; Wang and Wei, 2005), the resonance frequency F_L can be obtained. If U_{imin} is the minimum input voltage of regulated power supply , T is chopper period, λ_i is the current ripple coefficient, ΔP_{max} is the maximum compensation power of the circuit, L_f is inductors of the LC series resonant filter, then:

$$L_f = U_{imin}^2 T / \left(4\sqrt{2}\lambda_i \Delta P_{max}\right) \tag{10}$$

If the load is rated value and the system is steady, the maximum power compensation of the circuit is derived as follow:

$$\Delta P_{max} = U_{cmax} I_{0N} = \left|U_i - U_{0N}\right|_{max} I_{0N} \tag{11}$$

U_{cmax} is the maximum compensation voltage, U_{ON}, I_{ON} is rated output voltage and current respectively. Accordingly, the capacitance of the filter can be determined by the formula $f_L = 1/(2\tau\sqrt{L_f C_f})$.

PROGRAM SYSTEM DESIGN

The regulated power supply is run by application program that is composed of main program, data acquisition and processing module, digital PID module, keyboard interrupt service module and interrupt service module etc.

- **Register configure:** The STC12C5A62AD single chip has 10 AD inputs, 8 PWM outputs. The duty ratio error of output pulse width is less than 1%, the sampling error of the input voltage is less than 1%.Thus they can ensure 1% accuracy of regulated power supply.

The PWM frequency is 10 kHz, the clock frequency of singlechip is 32MHz. The clock frequency of PCA is 256×10k = 2.56 MHz, it can be selected for Fosc/12, namely the CPS2, CPS1, CPS0 of CMOD register is 0, respectively, the actual PWM frequency is 10.4 kHz.

In the PCA module for PWM mode, the duty ratio can be regulated by CCAPnH and CCAPnL register. It is related to the capture register {EPCnL, CCAPnL}. When PCA CL SFR value is less than the {EPCnL, CCAPnL} value, the output of PWM is low. On the contrary, it is high. When the value of CL is overflow by FF into 00, the content of {EPCnH, CCAPnH} is loaded into {EPCnL, CCAPnL} when is changed the duty ratio of PWM output can be changed at the same time.

The PCA module is adopted in the design, it set the P1.4 for PWM output, set 4 bits of P1 port for input /output voltage, current.

- **Main program:** The main program is shown as Fig. 6. It includes as follow:
  - **Initialization:** it mainly includes setting the stack pointer; setting related control register of the timer/counter, A/D conversion, PAC/PWM and interrupt; opening interrupt.

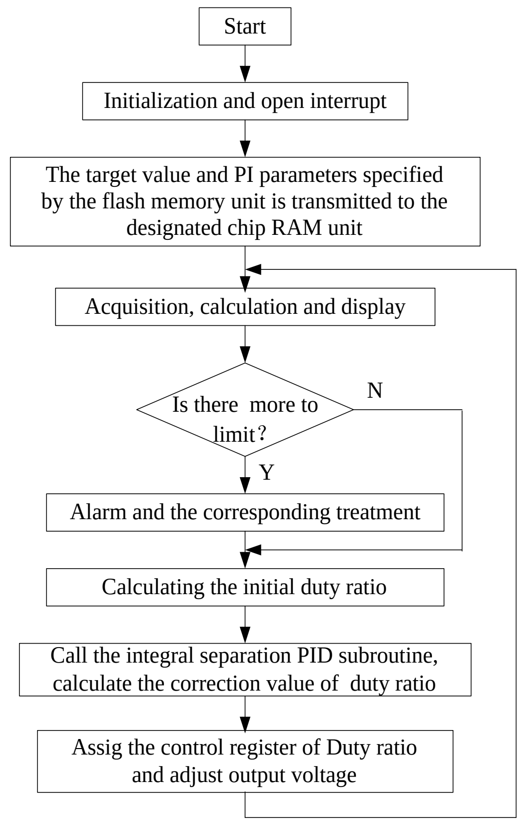

Fig. 6: Main program flow diagram

  - It moves the set value of output voltage and the limit values of input/output current, voltage and PID parameters written in the flash memory unit to the designated RAM unit.
  - It detects and displays input/output current, voltage and adjusts the output voltage.

- **The key program modules:** Whenever the zero-crossing synchronous signal is inputted into the single chip, it will trigger a interrupt. In the interrupt service module ,in voltage negative half cycle, input/output voltage are sampled; in the positive half cycle, the singlechip calculates duty ratio and compensation voltage polarity according to sample values of input/output voltage and standard voltage based on last half cycle of sampling values and the duty ratio is written to the PCA register. The digital PID module is the PID algorithm for calculating the duty ratio.

If only PID algorithm is adopted, the regulated power supply output will overshoot as result of Integration function when the grid voltage is fluctuated. The overshoot will make the system response bad. In

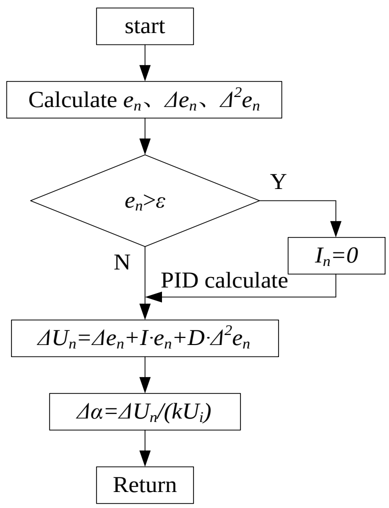

Fig. 7: The integral separated digital PID program flow diagram

order to overcome the phenomenon, firstly, initial duty ratio is determined roughly, secondly, the duty ratio correction value is obtained by the integral separation digital PID that can obtain a good control effect. The integral separation digital PID program flow diagram is shown in Fig. 7.

CONCLUSION

The trial manufacture and experiment had been done for the regulated power supply with capacity of 3kVA prototype. It is shown as following characteristics:

- The voltage high precision sampling and 10 kHz frequency of the chopper is the key for precision of regulated power supply.
- The closed loop is adopted for input/output voltage detection. The duty ratio can be determined roughly according to the input voltage ideal error that ensures the rapid response of output voltage. The stabilized voltage accuracy can be ensure according to integral separation digital PID according to the output voltage error. The output voltage tracing input voltage is only lag 20ms.The output voltage error is the maximum range of input voltage (220±4)V, but is less than 1%. The stability of the output voltage can be ensured when compensation power is only 25% of input rated power when input voltage U_i = 220×(1±20%)V.
- The single chip is used in the system with AD input and PWM output, which make the structure and control method simple.

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