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# Research on High Frequency SWISS Rectifier based on Digital Control

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## Abstract

**SWISS rectifier has the characteristics of high output power, adjustable output voltage, easy high-frequency, etc., which is very suitable for high-power conversion occasions such as high-power charging of electric vehicles, data centers, communication base stations, etc. In this paper, a design scheme of SWISS rectifier controlled by STM32G474 single chip microcomputer is proposed. The voltage and current PI double closed-loop control strategy is used to realize the accurate control of output voltage, and the control algorithm is designed to realize the power factor correction function of the system. This paper introduces the working principle of SWISS rectifier, and gives the calculation method of key component parameters. The simulation model of 750V/20kW is built by PLECS simulation software to verify the proposed scheme. The results show that the power factor of the system can reach 0.999 at rated power, the output voltage ripple is about 0.2V after stability, and the THD is 3.1%, and the system has a fast response speed, which verifies the feasibility of the scheme.**

## Keywords

**SWISS Rectifier; PI Closed-loop Control; STM32; CNC Power Supply.**

## 1. Introduction

SWISS rectifier was first proposed by Professor Kolar in 2011. It is a unidirectional step-down three-phase PFC rectifier with controllable output DC bus voltage, wide output voltage range, low input current harmonic content and high conversion efficiency[1]. The rectifier is very suitable for occasions with high power requirements, and has broad application prospects in electric vehicle charging, data center power supply and other fields.

As the topology structure of SWISS rectifier was proposed relatively late, the related research content is few, there is no dedicated control chip to realize its functions, and the analog control has shortcomings such as difficult loop design, complex circuit design, and difficult function expansion. The digital control method can realize the loop control of the system through the program, which has the advantages of short development cycle, flexible control, simple circuit design, convenient data monitoring and so on. In order to verify the feasibility of SWISS rectifier adopting digital control scheme, this design uses STM32G474 controller as the control core of SWISS rectifier, proposes a design scheme with output voltage of 750V and power of 20kW, and simulates this scheme through PLECS simulation software.

## 2. Hardware Circuit Design

The main topological circuit of the SWISS rectifier is shown in Fig. 1. The main parameters of the system are the input three-phase AC phase voltage of 380V, the system switching frequency of 150 kHz, and the output DC voltage range of 0~750 V adjustable.

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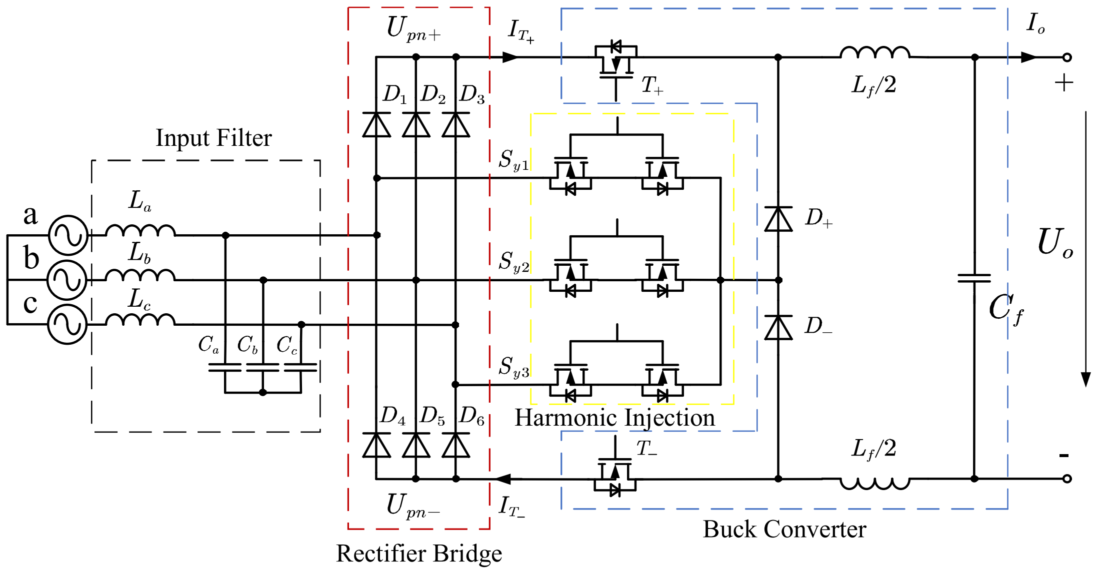


**Fig.1** SWISS rectifier topology diagram

SWISS rectifier is composed of three-phase bridge, harmonic injection circuit and Buck conversion circuit. The harmonic injection circuit is composed of three sets of bidirectional switching tubes, and each bidirectional bridge arm is composed of two enhanced N-channel MOS tubes with common source connection. It operates by switching the current path of the network at twice the power supply frequency (100Hz), providing the system with a path to inject low-frequency current[4]. Each end of the DC output side of the three-phase rectifier bridge is connected with a fully controlled high-speed switching tube ($T_+$ and $T_-$), and the current flowing through $T_+$ and $T_-$ is $I_{T_+}$ and $I_{T_-}$, respectively, which is proportional to the voltage at both ends of the output side of the three-phase uncontrolled rectifier bridge. The difference current of $I_{T_+}$ and $I_{T_-}$ flows into the power phase with the lowest absolute voltage through the harmonic injection circuit, thus realizing the function of adjustable output DC bus voltage and active power factor correction[5].

## 2.1 Input LC Filter Design

Due to the characteristics of the SWISS rectifier topology, LC low-pass filter needs to be added at the input end to suppress the interference of higher harmonics of the input current on the circuit. LC filter design should comply with the following requirements: (1) the cut-off frequency should be much lower than the switching frequency of the system; (2) The minimum reactive power at the grid frequency; (3) The volume and weight of the filter capacitor are as small as possible under the condition that the high-frequency current harmonics can be effectively filtered; (4) The voltage drop of the filter inductor at the rated current is as small as possible[6]. In order to reduce the reactive power introduced by the filter capacitor as much as possible, its parameters should be as small as possible, and the selection range should be from 3uF to 10uF.

After the filter capacitance is determined, the filter inductance parameter can be calculated by the filter cutoff frequency and filter capacitance. Usually the cut-off frequency of the filter is not greater than 0.1 times the switching frequency of the system. Then the filter inductance can be obtained by the following formula (1).

$$L_x \geqslant \frac{1}{(2\pi \cdot f_{off})^2 \cdot C_x} \tag{1}$$

Where: $L_x$ is the inductance value of the input filter; $C_x$ is the capacitance value of the input filter; $f_{off}$ is the cut-off frequency of the input filter.

### 2.2 Output LC Filter Design

In order to avoid introducing common-mode noise into the system, the output filter inductor is divided into upper and lower equivalent inductors, and the current flowing through the inductor can be divided into DC bus current and ripple current. When the switching frequency is fixed, the ripple current is negatively correlated with the inductor size, and the ripple current is usually 0.1 to 0.3 times of the rated DC bus current [10]. This design takes the inductance current ripple coefficient $K_{RF}$=0.2, then the inductance value is calculated by formula (2).

$$L_f \geqslant \frac{U_o}{2 \cdot K_{RF} \cdot I_o}\left(\frac{1-D_{\min}}{f_s}\right) \tag{2}$$

Where: $L_f$ is the inductance value of the output filter inductance; $D_{\min}$ indicates the minimum system duty cycle.

After determining the inductor current ripple, the size of output voltage ripple is negatively correlated with the capacitance value. When the ripple current is constant, the larger the capacitance value is, the smaller the output voltage ripple will be. However, at high frequencies, the equivalent series resistance (ESR) should be considered in addition to the capacitance capacity when aluminum electrolytic capacitors are used to influence ripple voltage [11]. The voltage ripple of the output voltage is generally not higher than 1% of the rated output voltage. Then the capacitance value of the DC side capacitance can be calculated by formula (3).

$$C_f \geqslant \frac{U_o}{2L_f} \cdot \left(\frac{1-D_{\min}}{8f_s^2 \cdot \Delta u_{C_f,pp} - \Delta i_{L_f,pp} \cdot R_{ESR}}\right) \tag{3}$$

Where, $\Delta u_{C_f,pp}$ is the peak-to-peak value of the output capacitance voltage, and $\Delta i_{L_f,pp}$ is the peak-to-peak value of the output inductance current.

## 3. Control Strategy and Algorithm Design

### 3.1 Control Strategy Design

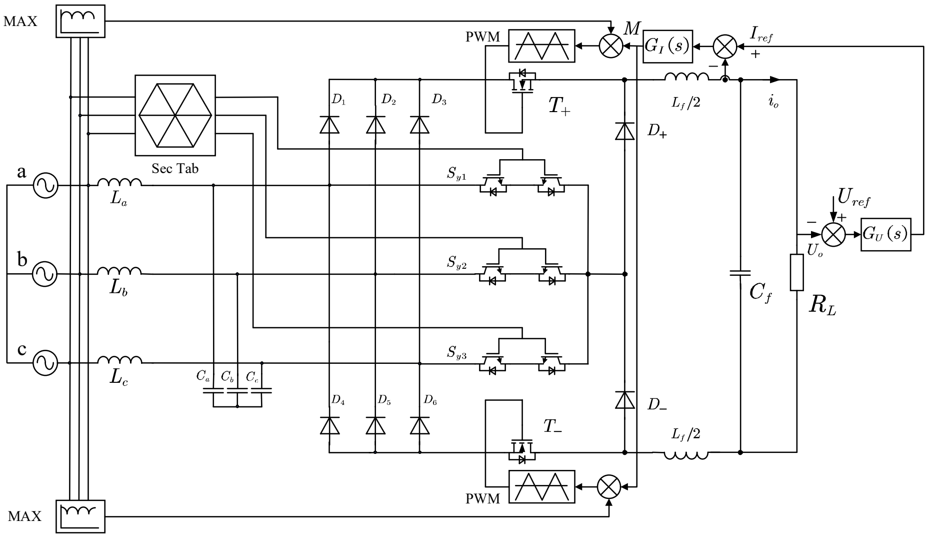


**Fig.2** SWISS rectifier control strategy block diagram

The closed-loop control strategy adopts the voltage outer loop controlled by PI and the current inner loop controlled by PI. The DC voltage is sampled as the feedback signal of the voltage outer loop,

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and the DC voltage is precisely controlled through the closed-loop control of PI controller. The output signal is the given current of the current inner loop, and the output inductance current is sampled as the feedback signal of the current inner loop. The output signal of the inner loop of current PI is the modulation ratio, which is multiplied with the output of three-phase maximum extractor, so as to realize the function of double closed-loop control of voltage and current and power factor correction. Where, $G_U(s)$ and $G_I(s)$ are PI regulators of the outer voltage loop and the inner current loop respectively, and their transfer functions are as follows:

$$\begin{cases} G_U(s) = k_{Up} + \dfrac{k_{Ui}}{s} \\ G_I(s) = k_{Ip} + \dfrac{k_{Ii}}{s} \end{cases} \tag{4}$$

$G_{id}(s)$ is the transfer function from the system duty cycle to the inductor current, and $G_{vi}(s)$ is the transfer function from the system inductor current to the output voltage. The formula is as follows:

$$\begin{cases} G_{id}(s) = \dfrac{U_{pn}}{R} \cdot \dfrac{sRC_f + 1}{s^2 L_f C_f + s\frac{L_f}{R} + 1} \\ G_{vi}(s) = \dfrac{R}{sRC_f + 1} \end{cases} \tag{5}$$

By setting the appropriate loop crossing frequency and phase Angle margin, the proportional coefficient and integral coefficient of the inner current loop and the outer voltage loop can be obtained.

### 3.2 Algorithm Design

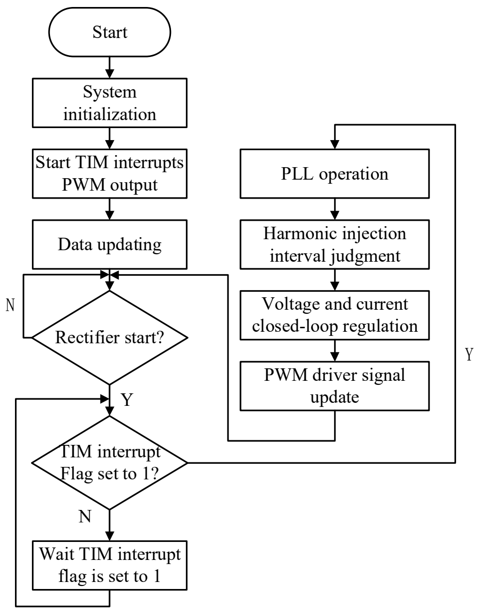


**Fig.3** SWISS rectifier closed-loop algorithm flow chart

The controller samples the voltage and current of the input side and the output side, and converts them into the actual value by using the program. The three-phase input voltage is phase-locked through the input voltage signal, which provides the phase signal for the harmonic injection interval judgment algorithm, and makes the output response drive signal control the harmonic injection circuit

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channel. The output voltage signal, inductive current signal and phase signal are taken as the input of PI double closed-loop control algorithm respectively, and a new control duty cycle is calculated to achieve output voltage stability and power factor correction. The system control flow chart is shown in Fig.3.

## 4. Emulation Proof

In order to verify the feasibility of the digital control scheme of SWISS rectifier based on STM32G474 controller, a prototype with three-phase voltage RMS 380V input, DC output voltage 750V and rated output power 20kW was built through PLECS. The specific parameters of the SWISS rectifier prototype are shown in Table 1.

**Table 1.** Parameters of SWISS rectifier prototype

| Parameter | Value |
|---|---|
| AC Input Voltage $u_{in}/V$ | $U_{ac}$=380$V_{rms}$ |
| AC Input Frequency $f/Hz$ | $f$=50Hz |
| DC Output voltage $U_o/V$ | $U_o$=750V |
| DC Output Power $P_o/W$ | $P_o$=20kW |
| DC Link Inductance $L_{f1},L_{f2}/mH$ | $L_f$=300μH |
| DC Link Capacitance $C_f/\mu F$ | $C_f$=990μF |
| AC Filter Inductance $L_{inx}/\mu H$ | $L_x$=47μH |
| AC Filter Capacitance $C_{inx}/\mu F$ | $C_x$=3.3μF |
| Switching Frequency $f_s/kHz$ | $f_s$=150kHz |

The SWISS rectifier starts at rated power and produces a stable output waveform, as shown in Fig. 4.

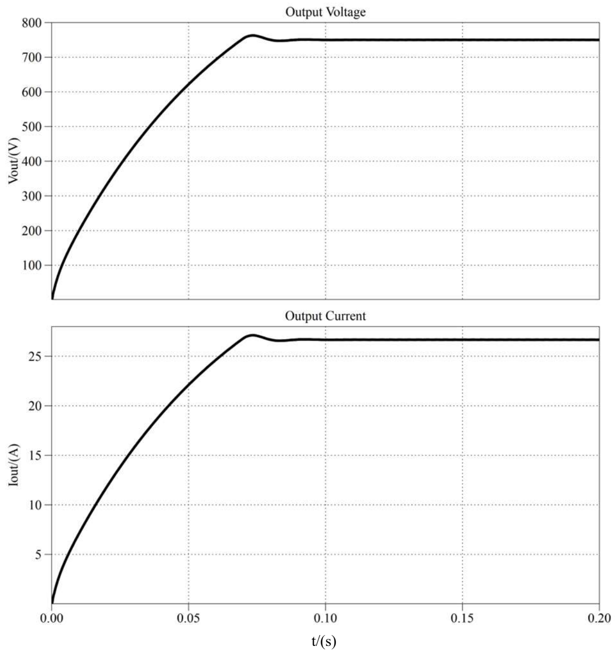


**Fig.4** Simulation waveform of output voltage and current at rated power

As can be seen from the simulation waveform in FIG. 2, it takes about 100ms for the output voltage to maintain stability from 0V to 750V when the system is started, and the DC voltage is constant 750V without obvious fluctuations when the system is output stabilized. The ripple peak value of the ripple voltage is about 190mV when the ripple is amplified and observed. It mainly consists of 300Hz harmonics and 150kHz switching harmonics. The peak value of the ripple current is about 7mA, which is negligible. Thus, the accuracy and stability of the bidirectional SWISS rectifier control strategy in rated power rectifier mode can be verified.

The input voltage and input current waveform of the SWISS rectifier under rated power output are shown in Fig. 5.

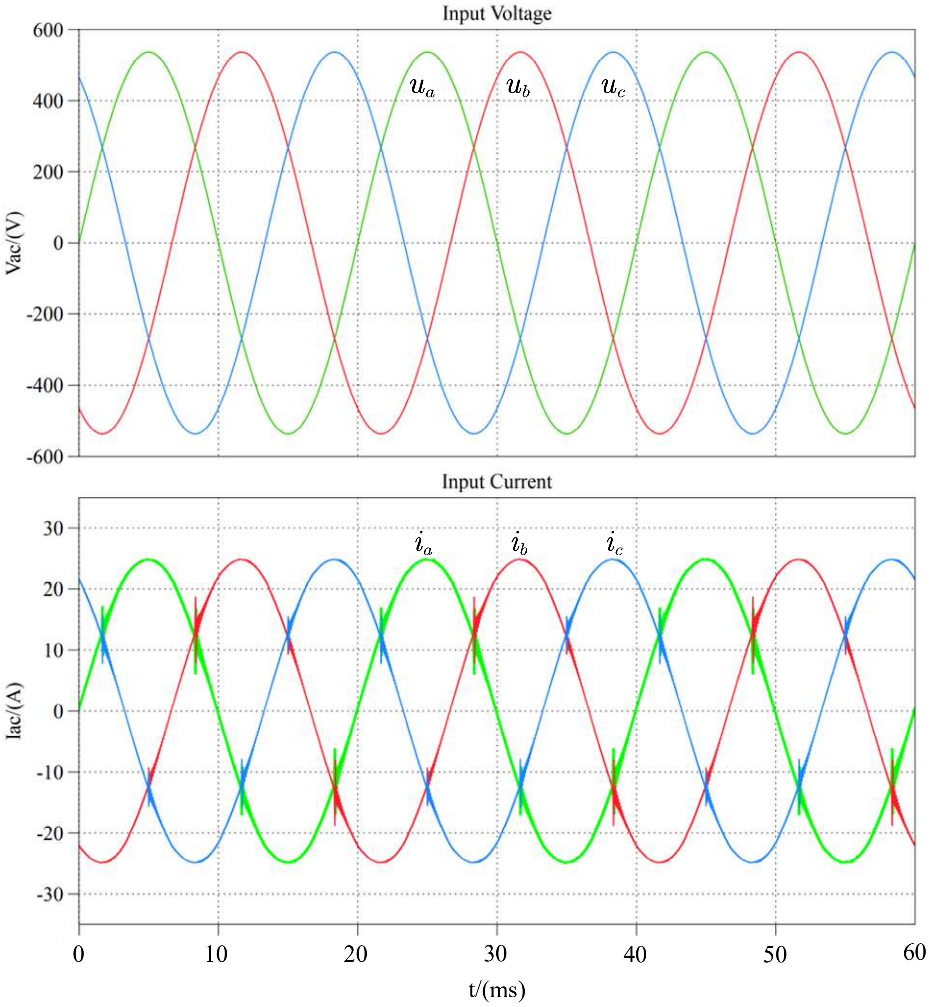


**Fig.5** Simulation waveform of output voltage and current at rated power

It can be seen from the AC input voltage and current waveform in Fig. 2 that the system basically realizes the function of power factor correction. The measured PF can reach 0.999, and the THD is 3.1%, which meets the requirements of the national standard. The maximum input current is about 24.8 A and the total input power is about 20kW. Due to the working characteristics of the SWISS rectifier, the input current distorts at the junction of the two-phase voltage, which is the main reason for the reduction of the THD.

## 5. Conclusion

In this paper, a SWISS rectifier design scheme based on digital control is proposed, and the key component parameter calculation and closed-loop control algorithm design of the SWISS rectifier are completed. The simulation model of 750V/20kW was built by PLECS simulation software for simulation verification. The simulation results show that the system has high power factor, high working efficiency, good dynamic adjustment performance and high output accuracy, which proves the feasibility and effectiveness of the digital control scheme for SWISS rectifier.

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