DC/DC half-bridge SST based on energy router

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Abstract. In this paper, a DC/DC half-bridge SST (Solid state transform) based on energy router is proposed. The structure mainly includes high-frequency transformer circuit, half-bridge circuit and control circuit. The DC side is converted to a high frequency AC signal through a half-bridge circuit. Then the high-frequency transformer circuit transmits the AC signal to the secondary side, and the secondary side is connected to the same half-bridge circuit for rectification to make electrical energy output in the form of DC. The whole circuit adopts symmetrical structure, which is beneficial to the bidirectional flow of energy. The simulation results verify the correctness and feasibility of the design scheme.

1. Introduction

The energy Internet has become a hot spot in the energy industry. As a key equipment of energy Internet, energy router can integrate information with new energy technology, so as to gradually ease people's dependence on fossil energy. The power network is the main carrier of the future energy Internet. However, the current power network operation is still characterized by dual structure, and the production, distribution and consumption are separated, so the energy is not fully utilized [1]. The main functions of energy router include power transmission function, energy storage function and intelligent communication function. Its core function is power transmission function relying on power electronics technology. The core of power transmission is to realize two-way power transmission. The key equipment for energy router to realize Power conversion is Solid State Transformer (SST), also known as Electronic Power Transformer (EPT), Power Electronic Transformer (PET) or Intelligent Universal Transformer (IUT) [2].

SST is an important part of the power energy router, which mainly relies on the power electronic transformation technology as the key technology, and then realizes the power transmission through the electromagnetic coupling of medium and high frequency transformers, which is an important device for energy transmission in modern power system [3]. After years of research, a variety of topological structures based on power electronic converter have been proposed, which can be divided into DC/DC type SST, AC/AC type SST and AC/DC/AC three-level SST. The input end of DC/DC transform SST structure topology is DC power supply, and the power electronic conversion circuit consists of four fully controlled devices to form the full bridge circuit. The input and output end parallel capacitance to increase the stability of power transmission to realize the power conversion better [4]. Literature [5] proposed three control modes: phase-shifting control strategy; frequency conversion control strategy; shift addition frequency conversion control strategy. Solid state transformer has many advantages. Due to the randomness and intermittently characteristics of distributed energy, the current literature on the...
design of SST has complex mathematical models, and the cross decoupling problem is serious when designing the input stage of solid state transformer. This control mode seriously restricts the reliability of the system. In view of the above reasons, due to the great potential value of solid state transformers, the current discussion, analysis and design are far from enough [6]. In this paper, this design of SST mainly uses DC/DC conversion circuit. In order to improve the efficiency of SST transmission and simplify the overall structure of SST, a DC/DC half-bridge SST based on energy router is proposed. The structure mainly includes high-frequency transformer circuit, half-bridge circuit and control circuit. The rated input voltage of the circuit is 36V dc, and the rated power is 300W. The DC power supply is converted to high frequency AC signal through a half-bridge circuit, The AC signal is transmitted to the secondary side by the high-frequency transformer circuit, and the secondary side is connected to the same half-bridge circuit for rectification, so that the electric energy is output in the form of DC. The whole circuit adopts symmetrical structure, which is beneficial to the bidirectional flow of energy.

2. Structure of DC/DC half-bridge SST

2.1. High-frequency transformer

In SST structure, the intermediate stage is connected by high-frequency transformer, whose main functions include insulation isolation of transformer circuit, magnetic energy conversion and voltage conversion. The basic structure of transformer mainly includes iron core and coil [7]. In order to carry out stable energy transfer, we choose the annular core as the main type of high-frequency transformer core. Its magnetic flux leakage and external magnetic field have little influence, and its magnetic properties are good, which can meet the requirements of energy transfer.

Since the core is made of magnetic materials, the magnetization curve of magnetic materials is an important parameter for the research and application of magnetic materials. The magnetization curve of magnetic materials is shown in Figure 1, its outer loop is a magnetization curve and the inner loop is a hysteresis loop. HC represents the coercive force, BS is saturation flux density:

\[
B = \begin{cases} 
0 & \text{if } H < -H_c \\
B_s & \text{if } H = -H_c \\
\mu_0 B_0 & \text{if } H > H_c 
\end{cases}
\]

\[\begin{align*}
\mu_i &= \frac{1}{\mu_0} \lim_{H \to 0} \frac{B}{H} 
\end{align*}\]  

Figure 1. Magnetic material magnetization curve.

Figure 2. Test circuit principle.

Above the Figure 1, it can be seen that magnetic materials will gradually tend to saturation magnetic induction intensity with the increase of magnetic field intensity. We call the limit value of the permeability at the beginning of the magnetization curve the initial permeability, whose value is as follow (1):
\( \mu_r \) represents permeability of vacuum \((4\pi \times 10^{-7} \text{ H/m})\); \( B \) is AC magnetic induction intensity (T); \( H \) is alternating current field intensity (A/m). In the closed magnetic circuit, the effective permeability can be obtained (2):

\[
\mu_e = \frac{L_e}{4\pi N^2} \times \frac{1}{\Delta e} \times 10^7
\]  

(2)

\( L_e \) is self-inductance of coil (Mh); \( N \) is Number of wire loops; \( \frac{1}{\Delta e} \) is magnetic core constant, meaning the ratio of magnetic circuit length to core cross-sectional area (mm\(^{-1}\)).

The selection or design of the transformer must go through some necessary technical parameters, including: Rated power frequency, phase number, load voltage and load current, load or rectifier circuit properties, voltage regulation, coil average temperature rise, transformer efficiency, environmental conditions, safety requirements and other special requirements [8].

According to the steps of transformer design, the high frequency transformer of this design requires the transmission power of about 300W, and the peak voltage of the primary side of the transformer is 36V, and the peak voltage of the secondary side is 36V, the frequency is 20kHz, the efficiency is 95%, the adjustment rate is 5%, and the temperature rise target is 30°C.

In order to verify the reliability of the design, corresponding tests are carried out on the designed transformer, mainly testing the saturated voltage value when it is open and the saturated current value when it is short. The test circuit principle is shown in Figure 2: (a) is open circuit test principle to get the maximum voltage that the transformer can transmit; (b) is principle of short circuit test to get saturation current, which the maximum power of the transformer can be obtained by multiplying by the maximum transmission voltage.

According to the above principle, the sinusoidal signal is used as the input signal to test the transformer. Firstly, the open circuit voltage value of the transformer is tested, and the test results are shown in Figure 3: (a), (b), (c) are test results of transformer primary side with 25 turns; (a) shows that the unsaturation voltage is 25V, (b) shows the voltage value is 36V at critical saturation. At this point, the output voltage starts to distort, and the voltage drops rapidly from the peak, and the waveform is in a straight line. (c) shows the voltage value at supersaturation is 45V. At this time, waveform distortion is obvious, the whole waveform gradually deviates from the sine wave. (d), (e), (f) are test results of transformer primary side with 35 turns; (d) is similar to (a), and (e) is similar to (b). But the critical saturation voltage at 35 turns is about 42V; (f) is similar to (c), waveform distortion is obvious when voltage value is 45V. By comparison, in order to meet the requirement of voltage peak of 36V and retain a certain voltage preload, the primary side winding of the transformer is 35 turns.

![Figure 3. High frequency transformer open circuit test.](image-url)

Then, the short-circuit current of high-frequency transformer is tested. Through the open-circuit test, the high-frequency transformer with 35 turns on the primary side is selected as the test target. The open-circuit test results are shown in Figure 4: (a) shows that when unsaturated, the output current is 5A, and the output waveform is sinusoidal wave, which is relatively stable on the whole. (b) shows
that when the critical saturation occurs, the current is 16A. At this time, the output waveform starts to be distorted. The output harmonic content increases, and the waveform contains bulges. (c) shows when oversaturated, the output current is 18A. At this time, the overall output waveform is distorted greatly, and the electromagnetic performance of high-frequency transformer magnetic ring is poor.

![Figure 4. High frequency transformer short circuit test.](image)

According to the relevant tests on the electromagnetic performance of high-frequency transformer's magnetic ring, when the primary side is 35 turns, the peak saturation voltage of the transformer is 36V and the peak saturation current is 16V, so the overall power of the transformer is about 288W, which meets the requirements of transformer design.

2.2. **Half-bridge circuit**

This SST bridge circuit mainly adopts the form of half bridge, and the design principle of half bridge circuit is shown in Figure 5. The half-bridge circuit consists of two fully controlled power electronic switches. The gate of the switch is connected to an optical coupler. The optical coupler is composed of light-emitting diode and push-pull output photoelectric three-stage tube. The light-emitting diode is controlled by the control chip, and photoelectric triode with push-pull output can drive the power supply more stably to control the opening and closing of the switch tube with +15V and -9V; Two capacitors and two large resistances are connected in parallel at both ends of the switch tube to balance the half-bridge voltage and filter; The bridge circuit has 4 ports. SST adopts DC/DC conversion structure, so Por1 and Por2 are connected to high-frequency transformer, Por3 and Por4 are connected to DC power or load.

![Figure 5. Half-bridge circuit schematic.](image)

2.3. **Control circuit**

The control circuit is mainly for the control of optical coupler, and has the function of monitoring and protecting the whole circuit. The control circuit mainly USES STM32 series chips. The overall principle of the control circuit schematic diagram is shown in Figure 6.
Firstly, the whole control system is distributed, so the address of each bridge's STM32 chip needs to be set to facilitate the communication between the control chip and other controllers. This device sets the chip address through external hardware, and the address setting port is shown in Figure 6. A number of GPIO pins derived from STM32 are connected to the external terminal J1. The upper and lower ends of J1 are connected by series resistance grounding and V3.3 respectively. GND corresponds to input logic 0 and V3.3 corresponds to input logic 1. Generally, when input is 0 or 1, using the short connector to connect the upper and lower ports corresponding to J1 (such as port 1 and port 2, and ADD0 input is 1).

3. Simulation and analysis

![Figure 6. Control circuit schematic.](image1)

![Figure 7. DC/DC half-bridge SST.](image2)

In order to understand the running characteristics of SST better, we use Simulink to conduct simulation test on the SST structure. The model is shown in Figure 7: The circuit is composed of two bridge circuits and high-frequency transformers, with symmetrical structure at the left and right ends, which can realize the bidirectional flow of energy. The circuit can realize the zero-voltage switch and reduce the circuit loss. The simulation results are as follows:

Switching frequency is 10kHz, and parallel resistance is 200 kΩ. In the steady state, in order to simulate the actual situation, a certain amount of disturbance is added, and a circuit in series of small resistances is added as disturbance. In order to verify the circuit running characteristics, the control waveform is firstly tested. Figure 8 shows the waveform of different duty cycle, which is the influence of the control waveform on the circuit: (a) shows waveform output of primary side and secondary side of transformer when duty ratio is 50%; (b) shows waveform output of primary side and secondary side of transformer when duty ratio is 40%. As can be seen from the figure, when the duty cycle is 50%, the circuit quickly enters a stable state and the output is stable. When the duty ratio is 40%, the initial state of the circuit forms a 3-level output, and the circuit loss increases. Therefore, the duty ratio of
control waveform should be close to 50%, but the actual situation needs to set a dead zone time. If the duty ratio is 50%, it is easy to make the circuit short circuit.

![Waveform](image)

(a) 50% duty cycle                      (b) 40% duty cycle

Figure 8. Unipolar shift control waveform.

Figure 9 shows the voltage waveform of the primary and secondary side of the transformer. The parallel capacitance at both ends of MOSFET will affect the voltage of the circuit: Capacitance values in Figure 9, (a), (b), (c) are 0.01mF, 0.1mF and 1mF respectively. Known from above, when the capacitance is 0.01mF, the waveform fluctuates greatly, and the filtering effect of the capacitor in the initial state is not enough, increasing the circuit consumption; When the capacitance is 0.1mF, the initial state voltage waveform is distorted when the circuit is switched on, which is mainly caused by capacitive load of circuit and inductance of transformer. Then the primary side and secondary side form a square wave of +12V, and the circuit output is stable. When the capacitance is 1mF, the situation is similar to 0.1mF, but the output waveform distortion of the secondary side is large, which is mainly affected by parallel capacitance and consumes part of the electric energy. Therefore, 0.1mF capacitor is finally used in parallel. When the load 20 Ω, input power is 28.8W, and output power is 28.5W. The transmission efficiency of the circuit is about 98%, and the transmission efficiency is higher.

![Waveform](image)

(a) Parallel capacitance 0.01mF     (b) Parallel capacitance 0.1mF      (c) Parallel capacitance 1mF

Figure 9. Voltage waveform

4. Conclusions
SST (Solid state transform) can not only realize basic functions such as transformation of voltage grade, reactive power compensation and electrical isolation, but also realize two-way energy flow, improve power quality and power flow distribution. This paper analyzes the various components of SST circuit which include high frequency transformer circuit, half bridge circuit and control circuit and designs a kind of DC/DC half-bridge SST. The whole circuit adopts symmetrical structure, which is beneficial to the bidirectional flow of energy. Through test and simulation, the SST meets the requirements of circuit input rated voltage of 36V dc and rated power of 300W.
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