Analysis and Design of Power Electronic Transformer for Smart Grid Application

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Abstract. With the development of smart grid and energy Internet, power electronic transformer has become one of the key equipment in power system. Its characteristic research and structure design have become a hot topic in related research fields. In order to take into account, the access of traditional AC motor system and renewable energy system, a three-stage power electronic transformer simulation model based on Simulink platform is built in this paper, and the key characteristics are analyzed and verified. With the application of power electronic transformer, the AC voltage can be adjusted quickly, and the AC/DC interface can be taken into account in the transmission system.

1. Introduction

1.1 Research background and significance

China is a big country of electric energy production and use. Improving the security, stability and quality of power supply has become one of the key issues in the use of electric energy [1]. Fossil energy and other non-renewable energy are facing the problem of exhausted use and unfriendly to the environment [2]. With the continuous emergence of alternative energy, the power system has also developed new technologies, such as the large-scale grid connection of new energy generation, the development of large-scale energy storage technology and the use of new energy transportation [3].

Power transformers appeared in the 19th century. At present, the mainstream transformers adopt the core oil immersed structure, which plays the role of voltage level transformation and electrical isolation in the power supply system [4]. The traditional transformer is simple in manufacture, stable in operation and strong in practicability, but it also has many inherent defects, such as large volume and quality, which limits the use of occasions; the insulating oil in the transformer will cause environmental pollution; when the transformer core is saturated, it will bring a lot of harmonics, which will seriously affect the power quality; when the grid side voltage fluctuates, it will be transmitted to the load through the transformer, etc. [5].

Traditional transformers cannot meet the requirements of flexible load management in smart grid construction [6]. With the gradual maturity of power electronic technology, people put forward the power electronic transformer (PET) structure. Pet is mainly composed of converter and high-frequency transformer, with the help of power electronics technology, voltage level conversion and energy transmission [7]. Compared with the traditional transformer, the power electronic transformer is stable, flexible in energy transmission, can control the power flow in the power grid in real time, and greatly improve the stability and power quality of power grid operation. Figure 1 shows a typical topology of a power electronic transformer (PET).
1.2 Research status

The combination of transformer technology and power electronics technology has gone through two main stages, the first is the power electronics of on load tap changer of power frequency transformer, and the second is the birth and evolution of power electronic transformer [8].

The concept of power electronic transformer was put forward by General Electric in 1970s. Power electronic transformer becomes an important part of new energy generation and energy Internet construction by interconnecting the main subnet ports in the new power system to realize power directional and quantitative transmission.

The topology of the first-generation power electronic transformer was developed by FREEDM center of North Carolina State University. Its structure is shown in Figure 2, including rectifier stage, isolation stage and output stage. It basically meets the functional requirements of power electronic transformer. However, there are some problems such as low switching frequency of components, large volume and weight of transformer, poor dynamic response of system and serious noise. The second-generation solid-state transformer developed by FREEDM center improves power quality through reactive power compensation, voltage support and harmonic improvement. Researchers from Zurich Polytechnic University in Switzerland, Nottingham University in the UK and Rometorvergata University in Italy have given power electronic transformer topologies. In 2009, American Electric Power Research Institute proposed IUT structure, which makes the system switching frequency up to 50 kHz.

The emergence of smart grid concept also attracted the attention of a large number of domestic scholars, and then participated in the research of pet [9]. The Institute of electrical engineering of Chinese Academy of Sciences and Huazhong University of science and technology jointly put forward a kind of MMC power electronic transformer structure, which can adjust the power quality on the basis
of retaining the basic functions of the transformer, and show good performance in the case of load balance. At present, the domestic research on power electronic transformer mainly focuses on the control method, and different scholars have given a variety of solutions from the perspective of magnetic circuit and coordinated operation with microgrid [10].

1.3 Application of power electronic transformer
Pet has the basic functions of transformer, and many new functions have been developed for the development of energy industry, which can effectively alleviate the impact of load side fault on power supply voltage, limit the harmonic flow in the power grid and the impact of grid side voltage change on load. Figure 3 is a practical application example of power electronic transformer.

![Diagram of power electronic transformer application](image)

The power electronic transformer is especially suitable for the occasions with high power quality requirements, which can significantly improve the overall power consumption level of the industry, enhance productivity and economic benefits.

1.4 Introduction of main research contents
In this paper, AC / DC / AC three-phase power electronic transformer is studied and designed. On the premise of familiar with the application background of power electronic transformer, the topology structure, main working principle, operation mode and control method of power electronic transformer are deeply understood. Finally, the electromagnetic transient simulation of power electronic transformer is built through electromagnetic transient simulation software SIMULINK.
2. Structure and working principle of power electronic transformer

Power electronic transformer consists of three parts, DC-DC converter, rectifier and inverter. DC-DC converter is the core part. The structure and working principle of the three parts are introduced in turn.

2.1 Introduction of structure and working principle of DC-DC converter

DC-DC converter is composed of high-frequency transformer and high-low-voltage full bridge circuit. Its working principle can be briefly described as follows: the upper level of DC is converted into high-frequency square wave by inverter, coupled with secondary side through high-frequency transformer, and then the alternating current is restored to direct current through rectifier. Figure 4 and Figure 5 are the schematic diagram and equivalent circuit diagram of DC-DC converter respectively. Among them, T is the high-frequency transformer, n is its transformation ratio; Q1-Q4, S1-S4 are two groups of switch tubes connected with the primary and secondary sides of the high-frequency transformer respectively, which are complementary in groups when working; L is the inductance in series on the primary side of the transformer.

![Figure 4 Schematic diagram of DC-DC converter](image)

![Figure 5 Equivalent circuit diagram of DC-DC converter](image)

DAB converter controls the IGBT of the high voltage test full bridge circuit to turn on alternately, and reverses the DC current into AC square wave, then transforms the voltage through the high-frequency transformer, and then rectifies the output through the low-voltage side. The whole working process is: in the initial state, the high voltage Q1 and Q4 are on, the low voltage side S1 and S4 are on, and the primary capacitance stores energy for the transformer through the inductance L. Then, due to the phase shift angle between the primary and secondary sides, the primary side leads the secondary side, switches to Q2 and Q3, the primary side transformer resets and the secondary side capacitor is charged. After that, the secondary side switches to S2 and S3 conduction, the transformer stores energy, and then the primary side switches to Q1 and Q4 conduction, and the secondary side capacitor is charged, thus completing one cycle of work and entering the next working cycle. The waveform of primary and secondary side voltage and inductance current in a cycle is shown in Fig. 6. Vab, Vcd and iL are the voltage of primary and secondary side of transformer and the current flowing through inductance L respectively.
It can be seen from figure 6 that the average power of DC-DC converter in a working cycle is as follows:

\[ P = \frac{1}{2\pi} \int_{0}^{2\pi} V_{ab}(\theta) i_L(\theta) d\theta \]  

(2.1)

By substituting \( V_{ab} \) and \( i_L \) into equation 2.1, the following results are obtained:

\[ P = \frac{\phi(\pi - |\phi|) nV_1 V_2 T}{2\pi^2 L} \]  

(2.2)

According to equation 2.2, the relationship between average power \( P \) and phase shift angle \( \phi \) is drawn in MATLAB as follow:

It can be seen that the maximum transmission power can be obtained when the phase shift angle is 90° in figure 7.

2.2 Introduction of rectifier structure and working principle

The rectifier circuit adopts three-phase bridge full control rectifier circuit, and its structure is shown in Fig. 8, in which T1-T6 is the switch tube, C is the capacitor, a, b and c are the three-phase AC interface. When it is put into operation, two thyristors are required to turn on at the same time to supply power to the load, and they must be one common anode group and one common cathode group with different phases. Six thyristors trigger conduction according to the sequence of T1-T6. The difference of trigger pulse is 60° in sequence. The difference of trigger pulse between three thyristors in common anode group and common cathode group is 120° and that of two tubes on the same bridge arm is 180° respectively. Finally, the difference of two-phase voltage corresponding to conduction is output at the load side.
Figure 8 Schematic diagram of three phase bridge full control rectifier circuit

From the AC input side, the rectifier circuit can be reduced to the circuit shown in Figure 9.

The vector diagram is drawn from the equivalent circuit (as Figure 10), and the following phasor equation can be obtained from it:

\[ \dot{U}_N = \dot{U}_S + j\omega L_N I_N \]

When \( U_N \) is constant, the amplitude and phase of \( I_N \) are completely determined by the amplitude of \( U_S \) generated by inverter and its phase with \( U_N \). By controlling the phase angle between \( U_N \) and \( U_S \) and the amplitude of \( U_S \), the magnitude and phase of current \( I_N \) at AC side can be controlled, and then in-phase operation of \( I_N \) and \( U_N \) can be realized. That is, through control, the rectifier operates under the condition of power factor of 1. In actual operation, the phase of \( U_S \) is controlled to make \( U_N \) and \( I_N \) in-phase, so as to realize power conservation. And according to:
\[ u_d i_d(t) = u_a(t) i_a(t) + u_b(t) i_b(t) + u_c(t) i_c(t) \]
\[ = \sqrt{2} U_N \sin(\omega t) \cdot \sqrt{2} I_N \sin(\omega t + \frac{2\pi}{3}) \cdot \sqrt{2} I_N \sin(\omega t - \frac{2\pi}{3}) \]
\[ + \sqrt{2} U_N \sin(\omega t + \frac{2\pi}{3}) \cdot \sqrt{2} I_N \sin(\omega t + \frac{2\pi}{3}) = 3 U_N I_N \]

Obviously, \( i_d(t) = \frac{3U_N I_N}{u_d} = \frac{3U_N I_N}{u_d} \), furthermore, it is found that there is no energy ripple in the DC side, and a constant output voltage can be obtained directly.

### 2.3 Introduction of inverter structure

The inverter circuit adopts three-phase voltage type inverter circuit, and its structure is shown in Fig. 11. Among them, V1-V6 is the switch tube, N is the neutral point, N’ is the imaginary neutral point, and all three phases are connected with resistive load. Each bridge arm modulates each group of driving signals unipolar, and reverses DC into square wave to control phase difference for power transmission.

![Figure 11 Schematic diagram of three phase inverter circuit](image)

![Figure 12 Working waveform of three phase inverter circuit](image)

The three-phase inverter circuit has six working modes in a working cycle. Under each working mode, there are three bridge arms and one switch tube in each working mode. Figure 12 shows the working waveform of the three-phase inverter circuit, while Table 1 shows the switching conditions of each switch tube corresponding to the six working modes. It can be seen that the three tubes are on in each working state, and the maximum voltage output of \( \pm \frac{2}{3} U_d \) can be achieved.

| V1 | V2 | V3 | V4 | V5 | V6 |
|----|----|----|----|----|----|
| 0-60° | on | off | off | off | on | on |
In addition, for the numerical design of resistive load, the inductance of inductive load is required to be much greater than the resistance of resistance load at carrier frequency, and much less than resistance at fundamental frequency. Therefore, the partial voltage of inductance under high frequency can be increased without affecting fundamental signal as much as possible, so as to improve the filtering performance of inductance.

3. Introduction to control methods

3.1 Introduction of rectifier control method

Figure 13 is the block diagram of rectifier control circuit. Firstly, the rectifier output voltage $U_{dc1}$ is compared with the given value, and the difference signal generated is used as PI input signal, and the output signal of PI controller is the amplitude of AC current. In order to prevent PI controller from over integration and difficult to recover, the flag bit of delayed start is set, and it starts after 0.1 second. The three-phase voltage $V_{ABC}$ collects its angular frequency $\omega t$ by PLL, then calculates the voltage drop on resistance and inductance, and uses indirect current control method to reduce the voltage $U_a$ of the grid and the voltage $UL$ on the inductance resistance to obtain the final control signal of the rectifier. The rectifier adopts PWM control method, so that the output is more stable, and the unit power constrained operation of the network side can be realized. The single-phase PWM control signal is obtained by modulating the above-mentioned control signal with triangular wave. The control signals of the other two phases can be obtained by shifting the control signals of phase a by $120^\circ$ and $240^\circ$ respectively, and then modulating with triangular wave.

3.2 Introduction of DC-DC converter control method

The DC-DC converter adopts the current feed-forward control method. It can be seen from equation 2.2 that the transmission power $P$ is related to the phase shift angle $D$, and has nothing to do with the initial inductance current $i_0$ when the input and output voltages remain unchanged in one control cycle. In fact, when the bias current exists in the inductor, the calculation of the transmission power $P$ is changed from the formula 2.1 to:
\[ P = \frac{1}{2\pi} \int_0^{2\pi} U_{ab} (\theta) (i_L(\theta) - I) d\theta = \frac{1}{2\pi} \int_0^{2\pi} U_{ab} (\theta) \cdot i_L(\theta) - U_{ab} (\theta)I d\theta \quad (3.1) \]

In the above formula, \( I \) is the bias of inductance current in dynamic change compared with that in steady state. Since the value of \( U_{ab} \) is positive and negative in each working cycle, the integral term corresponding to DC bias current is 0. From equation 2.2, the equivalent inductance parameter \( L \), transformer transformation ratio \( n \) and working period \( T \) of the converter can be considered as unchanged. Moreover, it is considered that the input voltage of the energy conversion system conforms to the general situation and changes relatively slowly, which is also regarded as a constant value. Then, the final output power of the system can be simplified as follows:

\[ p = \frac{V_p \phi (\pi - \phi)}{\pi^2} \quad (3.2) \]

According to the above formula, it can be obtained that the value of phase shift angle \( \phi \) is:

\[ \phi = \left( \frac{1}{2} - \frac{1}{\sqrt{4 - \frac{p}{V_0}}} \right) \pi \quad (3.3) \]

In this current feedforward control method, the simplified quantity \( p \) of the transmitted power can be expressed as:

\[ p = V_p^2 i_0^* \quad (3.4) \]

Among them, \( V_p^* \) is the given value of virtual output voltage generated by the difference between output voltage and its given value through PI controller, \( i_0^* \) is the given value of load current and satisfies:

\[ i_0^* = \frac{V_0^*}{V_0} i_0 \quad (3.5) \]

To sum up, the phase shift angle \( \phi \) can be expressed as:

\[ \phi = \left( \frac{1}{2} - \frac{1}{\sqrt{4 - \frac{i_0^* V_0^*}{V_0^2}}} \right) \pi \quad (3.6) \]

Therefore, the load current feedforward control can be designed according to the final formula (3.6). The structure diagram is as follows:

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Figure 14 Load current feedforward control circuit block diagram
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The corresponding delay time of the flag bit of the control circuit is set to 0.3s. The load current feedforward control method has better dynamic response performance, and the change of operating environment has little influence on the operation of the system. Moreover, the control method has no dependence on the circuit design parameters such as inductance, and does not need to consider the accurate value of the system components parameters. Therefore, it has higher compatibility and portability.
3.3 Introduction of inverter control method

The inverter adopts PWM control mode to control the effective value of the output voltage of the whole system. The single-phase output voltage is sampled at the output end of the inverter, and the unit value of the error signal is taken as the input of the PI controller. This standardization can ensure that the input and output signals of the PI controller are matched in magnitude, which is convenient for setting PI parameters. In addition, the flag is set to 0.3s to ensure the smooth start. Single phase PWM control signal is obtained by modulating PI output signal with triangular wave. The control signals of the other two phases can be obtained by shifting the control signals of phase a by 120° and 240° respectively, and then modulating with triangular wave.

![Control circuit block diagram of inverter](image)

4. Experimental results and analysis

In order to verify the effectiveness of the power electronic transformer structure mentioned above, a 100kW power electronic transformer simulation model is built based on the Simulink platform in MATLAB. The key waveforms and parameters of each part are described and explained below.

Table 2 shows the names and corresponding values of the main parameters in the simulation model.

| Parameter name                              | Parameter value |
|---------------------------------------------|-----------------|
| Effective value of grid side phase voltage Va/V | 230.94          |
| Grid side resistance Ra/ Ohms                | 0.1             |
| Grid side inductance La/mH                   | 1               |
| Given value of DC side voltage Udc1*/V       | 1000            |
| Starting time of rectifier ts1/s             | 0.46            |
| Energy storage inductance L/mH               | 0.1             |
| Transformer ratio n                          | 1               |
| Given value of DC-DC converter output voltage Uo1*/V | 1000            |
| Starting time of DC-DC converter ts2/s       | 0.15            |
| Given value of effective value of phase voltage Urms*/V | 300             |
| Inductance LN/mH                             | 3               |
| Resistance RN/ Ohms                          | 2.5             |
| Starting time of inverter ts3/s              | 0.14            |
| Total transmission power P/kW                | 108             |
Next, the waveform of single-phase voltage and current at grid side, voltage waveform at DC side of rectifier, voltage waveform at both ends of high-frequency transformer and current waveform of energy storage inductor, DC voltage waveform of inverter, resistance component waveform of inverter output voltage and inverter output voltage waveform will be introduced in turn.

The waveform of single-phase voltage and current at the network side is shown in Figure 16. Taking phase, a as an example, the blue solid line is the phase a voltage, and the red solid line is the phase a current. From the waveform, it can be seen that the voltage and current at the network side meet the same phase condition, thus meeting the power conservation condition.

The DC side voltage waveform of rectifier is shown in Figure 17. The control circuit is not put into operation before 0.1s, and the rectifier is in uncontrolled rectifier working state. When 0.1s, the mark position is the effective bit, and the full bridge rectifier is in operation. According to the waveform, the response speed of the rectifier after switching the working state is fast, and the overshoot of the rectifier system is within the acceptable range, and the stable operation with output of 1000V can be realized in a short time.

Figure 18 shows the voltage Uab and Ucd waveforms at both ends of the high-frequency transformer and the current waveform of the energy storage inductor. The yellow solid line is the Uab waveform of the primary voltage of the transformer, the blue solid line is the Ucd waveform of the secondary voltage of the transformer, and the red solid line is the current waveform flowing through the energy storage inductor of the transformer in series. It can be seen from the partial waveform images in Fig. 19 that the voltage signals at both ends of the high-frequency transformer are square waves. Therefore, it is proved that the working principle of the DC-DC converter is to convert the DC signal into the square wave signal first, and then recover the DC signal through rectification.
Figure 18 Waveform of voltage and energy storage inductance current at both ends of high frequency transformer

Figure 19 Partial waveforms of voltage and energy storage inductance current at both ends of high frequency transformer

Figure 20 shows the voltage waveform at the input side of the inverter. It can be seen that the DC-DC converter can achieve fast response and stable output of 1000V DC voltage.

Figure 20 DC side voltage waveform of inverter

Figure 21 Waveform of resistance component of inverter output voltage

The waveform of resistance component of inverter output voltage is shown in Fig. 21, and the waveform of inverter direct output voltage is shown in Fig. 22. It can be seen that the output voltage of inverter without filtering is discontinuous level signal with amplitude of $0, \pm \frac{2}{3}U_d$ and $\pm \frac{2}{3}U_d$. Therefore, an inductor is used to filter to obtain a continuous sinusoidal signal on the resistor.
The whole power electronic transformer system can be equivalent to a resistor. The system will not inject reactive energy in the process of operation. It can realize the constrained operation of unit power and ensure the power quality.

5. Conclusion
In order to take into account, the requirements of traditional energy and new energy power generation, this paper proposes a structure model of power electronic transformer, and carries out simulation analysis based on the model built on Simulink platform

1) The power electronic transformer can realize the constrained operation of unit power on the grid side, and the whole system can be equivalent to resistance during operation, and the grid side current has good sinusoidal, which effectively reduces the harmonic injected into the power grid, so it will not affect the power quality.

2) Power electronic transformer can realize flexible and fast voltage regulation and power control.

3) Power electronic transformer can take into account the different requirements of traditional energy and new energy power generation, and realize its simultaneous access, so it has higher flexibility and is suitable for more extensive applications.

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