Analysis and Design Based on the Operation Mode of Power Electronic Transformer in Smart Grid

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Abstract. Power electronic transformers (PET) are the key energy conversion equipment in the operation of modern smart grids, the main function of PET is to achieve the conversion of AC voltage to AC voltage, while taking into account the DC ports. This article mainly studies three-stage power electronic transformers based on three-phase uncontrolled rectifier, full-bridge isolated DC-DC converter and three-phase inverter. The operation mechanism and actual working process of the three parts of the PET are analyzed respectively, and the transformer is simulated and analyzed based on the Matlab/Simulink simulation platform. The rectifier converts the AC voltage on the grid side into a rippled DC voltage; the DC-DC converter transforms the obtained DC voltage, taking into account the access of the DC ports; the inverter converts the obtained DC voltage into AC voltage through unipolar modulation and connects to the grid. The experimental results show that the PET constructed in this way can operate safely and stably, which has good voltage conversion and electrical isolation functions, and can be connected to DC loads.

1. Introduction

In the modern society, electricity is essential to people's lives. The transformer is an important part of the power distribution system, the main function of the transformer is electrical isolation and voltage conversion. With the continuous development of technologies such as active distribution networks, smart grids, and new energy power generation, traditional power frequency transformers can no longer meet the demand of smart power generation[1].

With the in-depth study of power electronic technology, PET have emerged as a new type of smart transformer. Power electronic transformer, also known as solid-state transformer, is composed of two parts, namely power electronic converter and high-frequency transformer, which realize the function of voltage conversion through electronic components. Compared with traditional transformers, which have some disadvantages such as large size, heavy weight, and single transformation function, PET have the following advantages[2-4]:

1. Small size, light weight, and will not use insulating oil, will not pollute the environment;
2. PET have DC and AC links and can be connected to AC power grids and DC loads, new energy equipment that can be connected to DC power supplies power to the grid;
3. Higher reliability, more accurate and flexible adjustment of the power output terminal.

The concept of PET was first proposed by American W. McMurray, and the AC-AC converter he proposed is the embryonic development of today's PET[5]. When the concept of "smart grid" was proposed, power electronic technology has made great development and progress, and PET have also been widely studied and paid attention by more countries and enterprises. Literature [6] proposed a PET that can be used in medium and high voltage distribution networks. The structure of this PET is three-phase structure, which is divided into three parts: high voltage, medium voltage, and low voltage. This
method effectively verifies the accuracy and validity of the PET topology and has a wide range of application prospects in smart grids.

In addition to the functions of traditional transformers, they can also control current and voltage and improve power quality[7]. In today's era, new energy power generation has become a new trend. The world is advocating the concept of energy saving, environmental protection, and green power generation. PET can also connect the new energy power generation system with the power system and input the generated electrical energy into the power system[8]. Literature [9] proposed a three-level PET, in the topology of this PET, a three-phase and three-level topology is used. In this type of transformer, the voltage that the switch components bear is only one-half of the voltage that the two-level circuit bears, which increases the range of input voltage levels and is better suited for high-voltage power distribution. At present, the application of PET in power systems includes two aspects: distributed power grid connection and improvement of power quality[10].

2. Rectifier

PET are mainly divided into three parts: AC-DC rectifier, DC-DC converter and DC-AC inverter, in order to realize AC-DC-AC voltage conversion[11]. The rectifier is the input part of the entire pet. Since the input voltage is three-phase voltage during the operation of the power grid, a three-phase three-wire structure is adopted, and the inside of the rectifier adopt an H-bridge full bridge structure. The bridge arm connected by each phase voltage is composed of two diodes in series, and a capacitor and a resistor are connected in series with the three bridge arms[12]. The topological structure of the rectifier is shown as in Figure 1.

![Figure 1. Topological structure diagram of rectifier](image)

In Figure 1: $E_a(t)$, $E_b(t)$, $E_c(t)$ are the three-phase voltage of the three-phase power supply, $D_a$, $D_b$, $D_c$ are the upper diode of each corresponding bridge arm in the three-phase power supply, $D_a'$, $D_b'$, $D_c'$ are the lower diode of each corresponding bridge arm in the three-phase power supply, C is the filter capacitor for output DC voltage, R is the equivalent load. The goal is to output 1000V direct current, the input three-phase power is 730 volts, C is 0.0033 farads, and R is 10 ohms.

The rectifier is controlled by the conduction characteristics of the diode. The upper diode of the bridge arm connected to the phase with the higher phase voltage is turned on, and the diode below the bridge arm of the phase with the lower phase voltage is turned on, thereby converting the input three-phase sinusoidal AC voltage into DC voltage.

The voltage ripple obtained in this way is relatively large, and an inductor connected in parallel with the bridge arm needs to be added for filtering. The existence of capacitor can eliminate the pulsation of DC voltage, thereby ensuring that the conversion can obtain a stable DC voltage. In order to get an output voltage of 1000V, after experiments, the input voltage needs to be adjusted to 730V. The voltage waveform after filtering is shown as in Figure 2.
3. DC-DC Converter

As the secondary transmission path of the PET, the DC-DC converter adopts a full-bridge isolated DC-DC converter, and each part on both sides has an H-bridge structure[13]. Its topological structure is shown as in Figure 3.

![Figure 2. Inverter output voltage waveform after filtering](image)

![Figure 3. Topological structure diagram of full-bridge isolated DC-DC converter](image)

In Figure 3: $U_{in}$ is the input power supply voltage, $i_{out}$ and $U_{out}$ are load current and output side voltage respectively, $S_1 - S_8$ are mosfet switch tubes, $L$ is auxiliary inductance, $i_L$ is the current on the inductor side, $U_1$ and $U_2$ are the output voltages of the H bridge at both ends of the DC-DC converter, $C_1$ and $C_2$ are the buffer capacitors on the power supply side, $R$ is equivalent load. $U_{in}$ is 1000 volts, $C_1$ and $C_2$ both are 0.0033 farads, $L$ is 0.001 Henry, and $R$ is 10 ohms.

The equivalent circuit diagram of the full-bridge isolated DC-DC converter is shown in Figure 4.

![Figure 4. The equivalent circuit diagram of a full-bridge isolated DC-DC converter](image)

In Figure 4: $V_1$ and $V_s$ are respectively represent two AC power sources, $L$ is the inductor, $V_L$ and $i_L$ are respectively represent the voltage and current of the inductor.

Assuming that the phase of AC power $V_1$ leading $V_s$ is $\theta$, calculate the current $I_L$. By $V_L = V_1 e^{j\theta}$, $V_s = V_s e^{j0}$, then introduce the formula $e^{jx} = \cos x + i \sin x$, then can get: $I_L = \frac{V_s - V_1}{jX}$, where $X$ is the inductive reactance of the inductor, $X = \omega L$, $\omega = 2\pi f$.

From the formula: $I_L = I_p + jI_Q$, where $I_p$ is the active power current and $I_Q$ is the reactive power current, then can get: $I_p = \frac{V_1 \sin \theta}{X}$, $I_Q = \frac{V_s - V_1 \cos \theta}{X}$, calculated active power: $P_s = V_s I_p = \frac{V_1 V_s \sin \theta}{X}$.
Due to $V_i$ and $V_o$ are both positive values, so it can be seen from the calculation result that the positive or negative of active power $P_\theta$ depends on $\sin \theta$. When the value of $\theta$ is 0-180 degrees, the power is positive, and it reaches the maximum when $\theta$ is equal to 90 degrees. From the characteristic curve of the sine function, it can be concluded that when two power supplies are connected, the power supply with the leading phase is charged and the power supply with the lagging phase is discharged. The input signal of the converter is a square wave signal, and the phase difference is controlled by the square wave inverter. On the output side of the DC-DC converter, it is also necessary to add a filter capacitor. The voltage output waveform of the DC side is shown in Figure 5.

4. Inverter

The inverter is the last stage of the PET. The function of this part is to convert the DC voltage into the AC voltage that can be used in the grid system.

The input end of the inverter is a DC voltage, and it needs to be output as an AC voltage, which requires adding a suitable input signal. Input a sine wave (modulation wave) and a triangle wave (carrier wave), and compare the amplitudes of the two waveforms. When the amplitude of the sine wave is large, the output is high level 1, and when the amplitude of the triangular wave is large, the output is low level 0. That is, Pulse Width Modulation (PWM modulation).

PWM modulation is to adjust the switches in the inverter circuit to make the multiple pulses obtained at the output of the circuit have the same amplitude, so that the equivalent voltage of each pulse is the waveform of a sine wave, which is used instead of generating a sine wave. Due to the PET is to be connected to the power grid for work, the three-phase voltage at the output must conform to the law of phase difference, which is "360 /N" degrees. As it is three-phase, so N is 3, then the phase difference is 120 degrees, and three input signals are obtained after offsetting 120 degrees and 240 degrees.

The modulation mode of the inverter is divided into unipolar modulation and bipolar modulation. The inverter is connected through an H bridge, and there are two switch tubes on each bridge arm. Bipolar modulation means that two bridge arms share the same input signal. When the upper switch tube of one bridge arm is turned on, the lower switch tube of the other bridge arm is turned on, so that the waveform obtained in this way has both positive and negative polarities within half a cycle. For unipolar modulation, each bridge arm connect an input signal, and the conduction of the switch tube on each bridge arm is independent of each other, which is not affected by other bridge arms. The waveform obtained in this way has only a single polarity in each half cycle[14].

Assuming that the frequency of the fundamental wave is 50Hz and the frequency of the carrier wave is 1000Hz, put them into the inverter of unipolar modulation and bipolar modulation respectively. Using the "Powergui" module in the Matlab/Simulink simulation platform to perform Fast Fourier Transform Analysis (FFTA) on the two methods. The results are shown in Figure 6.
THD represents the proportion of harmonic distortion, the large value means the great harmonics. The comparison shows that the unipolar modulation method is better than the bipolar modulation.

Since the output voltage needs to match the grid, a three-phase inverter is used in the PET to convert the constant DC voltage into AC voltage after filtering[15]. The topology of the inverter is shown in Figure 7.

\[ \text{In Figure 7: } U_{\text{out}} \text{ is the output voltage of the DC-DC converter, } S_9 - S_{14} \text{ are 6 mosfet switch tubes, } L_1 - L_3 \text{ is the three filter inductors, } R_1 - R_3 \text{ are the equivalent load resistances, } E_a(t), E_b(t), E_c(t) \text{ are the output three-phase power supply. The inductance } L_1 - L_3 \text{ are 0.005 farads, the resistance values are all 10 ohms, and } U_{\text{out}} \text{ is 1000 volts.} \]

In a three-phase inverter, each phase is connected by an H bridge arm, which is composed of two switch tubes in series. Each bridge arm is connected to an equivalent load resistor and an filter inductance, the inductance and resistance are connected in parallel, which will play a role in voltage division.

From the formula \( X = \omega L = 2\pi f L \) we can get the resistance of the inductor is proportional to the inductance. If \( L \) increases, the inductor’s partial voltage will increase, the generated harmonics will be smaller, and the output voltage curve will be smoother. However, an increase in the inductance voltage divider will cause the output voltage to decrease, and the voltage amplitude on the equivalent resistance will be reduced. The output voltage should also meet the voltage requirements for grid operation, so the inductance should be adjusted appropriately.

At high frequencies, the inductive reactance is bigger than the impedance, then the carrier frequency plays a major role. At low frequencies, the result is just the opposite. Therefore, the choice of inductance must meet two conditions: \( 2\pi f L \gg R \) and \( 2\pi f M L \ll R \). simplify and get \( \frac{R}{2\pi f_c} \ll L \ll \frac{R}{2\pi f_M} \). A suitable inductance can be obtained by taking an intermediate value within this range.

After being processed by the inverter, the output AC voltage waveform is shown in Figure 8.
Figure 8. Waveform diagram of inverter output AC voltage

The overall simulation system diagram of the PET is shown in Figure 9.
5. Conclusion
In order to build a PET with DC ports, this paper builds a three-stage PET based on a three-phase uncontrolled rectifier, a full-bridge isolated DC-DC converter, and a unipolar modulation three-phase inverter. And build the simulation system of this transformer through Matlab/Simulink simulation platform, carry on simulation analysis and verification to it. Theoretical analysis and experimental results show that:

1. Three-phase uncontrolled rectifier can convert the AC voltage on the grid side into DC voltage, and the resulting DC voltage has a small ripple, which is convenient to connect the full-bridge isolated DC-DC converter.

2. The full-bridge isolated DC-DC converter is mainly used for voltage conversion and electrical isolation. During operation, the power conversion, the charging and discharging functions are realized by controlling the phase difference of the voltage across the DC-DC converter.

3. The output voltage of the DC-DC converter is used as the input voltage of the three-phase inverter, the unipolar modulation method is adopted to adjust the inverter, which can make the AC voltage at the output end have smaller ripple, and the obtained voltage is suitable for connecting to the power grid.

4. When designing the inverter, it is necessary to add a filter inductance. The selection of the inductance is related to the frequency of the fundamental wave and the carrier wave. The value of the inductance is usually within the range of $\frac{R}{2\pi f_c} << L << \frac{R}{2\pi f_M}$.

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