Calculation Method for Commutation Overshoot Voltage in DC Converter Valves Based on Piecewise Fitting of Thyristor Reverse Recovery Current - Postprint

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Abstract

Thyristors, RC damping circuits, and valve arresters are the principal components of the primary circuit in UHV DC converter valves. Determining the parameter matching among these three device types constitutes the main task in the electrical design of UHV DC converter valves. This paper reveals the generation mechanism of commutation overshoot voltage in converter valves, determines the interaction laws governing the parameters of the three device types, establishes the differential equations for the converter valve operating circuit, solves these equations through a piecewise fitting approach for thyristor reverse recovery current, and verifies the accuracy of the calculation method through experimental testing.

Full Text

Study on the Calculation of the Commutation Overshoot of HVDC Valve Based on the Piecewise Fitting of Reverse Recovery Current of Thyristor

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ABSTRACT

Thyristors, RC damping circuits, and valve arresters constitute the primary components of the main circuit in UHVDC converter valves. Determining the parameter matching among these three types of devices is a primary task in the electrical design of UHVDC converter valves. This paper reveals the generation mechanism of commutation overvoltage in converter valves, identifies the interactive influence patterns among the parameters of the three device types, establishes the differential equations for the converter valve operating circuit, solves these equations through piecewise fitting of the thyristor reverse recovery current, and validates the accuracy of the proposed calculation method through experimental testing.

KEY WORDS: UHVDC; converter valve; commutation overshoot; RC damping parameters

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High-voltage direct current (HVDC) transmission is an important technology for large-capacity, long-distance power transmission. The DC converter valve is the core equipment of HVDC transmission projects. Since the core device, the thyristor, is not an ideal switching component, the HVDC converter valve generates commutation overvoltage during turn-off, subjecting the valve to excessive voltage stress [1-2]. The voltage stress during converter valve turn-off is not only an important test criterion for type tests and factory tests [3-4], but also a significant aspect of valve electrical characteristic research and electrical design [5-8]. Therefore, it is necessary to conduct a detailed analysis of the turn-off voltage stress of converter valves, which are the core equipment of HVDC transmission, and to determine the parameter matching of main circuit components such as thyristors and RC damping circuits.

To date, several publications have introduced and explained the turn-off voltage stress of DC converter valves and its importance [6-8], but few have provided detailed analysis. References [8-10] address this issue but do not consider the effects of thyristor reverse current and reverse recovery charge, which deviates significantly from actual conditions. Reference [11] presents a thorough simulation analysis of turn-off voltage stress under the special operating condition of γ=90°, but this condition represents a transient state with no practical significance for converter valve electrical parameter design.

This paper reveals the mechanism of commutation overvoltage generation based on analysis of the converter valve operating circuit; establishes a second-order non-homogeneous linear differential equation for the converter valve operating circuit after adding an RC damping circuit; solves the differential equation through piecewise linearization of the thyristor reverse recovery current and fitting the current change rate with a parabola; and for the first time derives an analytical expression for valve commutation overvoltage, revealing the variation pattern of overvoltage peak with damping parameters. On this basis, the accuracy of the calculation method is verified through comparison with test results. Since rectifiers experience significantly higher reverse voltage stress than inverters, this paper uses the rectifier circuit as the converter valve operating circuit.

The 6-pulse converter is the basic conversion unit of HVDC converters. A typical 6-pulse converter operating circuit is shown in Figure 1 [Figure 1: see original paper], consisting of six converter valves V1~V6.

Taking the commutation from valve 6 to valve 2 as an example to illustrate the commutation overvoltage generation process, the corresponding voltage and current waveforms are shown in Figure 2 [Figure 2: see original paper]. At time t0, valve 2 receives the trigger signal, and commutation between valve 2 and valve 6 begins. The current through valve 2, i2, starts to increase from 0, while the current through valve 6, i6, begins to decrease from the load current Id.

The equivalent circuit of the commutation process is shown in Figure 3 [Figure 3: see original paper]. In the commutation process, within the commutation angle , both valve 6 and valve 2 conduct forward current, and both valves remain in the conducting state. Therefore, Uv6=0, the value of di6/dt is negative, and the converter transformer output voltage Ubc is entirely borne by the converter transformer leakage inductance Llk.

When i6 decreases to 0, commutation ends. Since the thyristor is not an ideal switching device, it undergoes a reverse conduction process after current zero-crossing. During this reverse conduction process, the reverse current through the thyristor increases from 0 to the reverse current peak IRM, then decreases from IRM to 0 [12~13], as shown in Figure 4 [Figure 4: see original paper].

Between t1 and t3, the current change rate di6/dt of valve 6 is the same as during the commutation process, and valve 6 still does not withstand voltage. After time t3, the magnitude of di6/dt gradually decreases, and valve 6 begins to withstand reverse voltage. At time t4, i6 reaches the reverse peak current IRM, at which point di6/dt=0 and UV6=-Ubc. After time t4, the value of di6/dt changes from negative to positive, and the induced voltage of Lsr superimposes with the converter transformer output voltage Ubc, causing the voltage borne by valve 6 to be higher than Ubc. At time t5, di6/dt reaches its peak, and the reverse voltage borne by valve 6 reaches its peak. This process generates the commutation overvoltage.

Taking t0 as the time reference point, let the effective value of the converter transformer valve-side voltage be Utr-v, and the angular frequency of the AC grid be ω. The voltages borne by the four valves in the blocking state are respectively:

From the above formulas, when valve 6 recovers blocking, the overvoltage generated due to the converter transformer leakage inductance Llk is applied not only to valve 6 but also affects the voltages of other valves in the blocking state. Valve 3, which is in the same phase as valve 6, bears a line voltage close to 0, thus its reverse voltage is minimal. Valves 4 and 5, which are in different phases from valve 6, bear the same peak reverse voltage.

The peak reverse voltage depends on the converter transformer valve-side voltage effective value Utr-v, converter transformer leakage inductance Llk, firing angle α, and commutation angle .

First, let us discuss the amplitude of overvoltage generated by the converter transformer leakage inductance Llk. For conventional thyristors used in HVDC transmission, factory test data show that during the thyristor blocking recovery process:

Where: k depends on the thyristor's inherent recovery characteristics.

In the time period from t4 to t6, the current variation is linearized:

Where: t is the duration of the commutation process.

From equations (5)~(8), the voltage stress borne by the converter valve during operation can be calculated. For a certain UHVDC transmission project, Utev=172kV, Llk=12.2mH, and the 6-inch high-power thyristor used has k=1.5. The peak reverse voltages of different valves corresponding to different firing angles are shown in Figure 5 [Figure 5: see original paper].

The valve voltage waveforms corresponding to Figure 5 are shown in Figure 6 [Figure 6: see original paper].

From Figure 5, the peak reverse voltage borne by valve 3 is much smaller than that of valves 6 and 4. When the firing angle is less than 17°, the peak reverse voltage of valve 6 is less than that of valve 4. When the firing angle is greater than 17°, the peak reverse voltage of valve 6 exceeds that of valve 4. Under normal operating conditions, the rectifier firing angle varies from 15° to 20°. Within this range, the peak reverse voltages of valves 6 and 4 are between 330kV and 350kV, while the converter transformer output voltage peak is 243kV. The reverse overvoltage multiplication factor is between 1.36 and 1.44. The PCOV (Power Frequency Continuous Overvoltage) limit withstand level of the valve arrester is typically 1.2 times the CCOV (Continuous Converter Operating Voltage), meaning the overvoltage generated during valve operation must not exceed 291.6kV. Excessive peak reverse voltage will cause excessive leakage current in the valve arrester, leading to overheating and damage during long-term operation.

2 Establishment of Valve Circuit Equations After Adding RC Damping Circuit

To reduce commutation overvoltage during converter valve turn-off, an RC damping circuit must be connected in parallel across each thyristor in the converter valve [14]. The commutation circuit model after paralleling the RC damping circuit is shown in Figure 7 [Figure 7: see original paper].

Considering only the commutation process, the commutation circuit in Figure 7 can be converted to the equivalent circuit shown in Figure 8 [Figure 8: see original paper].

Let $\Delta \geq 0$, that is:

By merging the damping circuits in Figure 8, the equivalent circuit shown in Figure 9 [Figure 9: see original paper] can be obtained.

From Figure 9, we can obtain:

From equations (9)~(10), we can obtain:

This equation can be equivalent to:

The characteristic equation of this second-order constant-coefficient non-homogeneous linear differential equation is:

Then the characteristic equation has two real roots, which can prevent oscillation of the entire circuit.

The two roots r1, r2 of equation (13) are respectively:

Let n1, n2 be arbitrary constants. The general solution of the homogeneous differential equation corresponding to equation (12) can be obtained as:

3 Application of Current Piecewise Fitting in Solving Circuit Equations

To solve equation (12), a particular solution of equation (12) must also be determined. The constant term in equation (12) contains the thyristor current change rate div/dt. Since the thyristor reverse current iv is a time-varying function, the thyristor current change rate div/dt is also a time-varying function. Therefore, the usual approach to determining the div/dt expression is to first determine the iv expression, then obtain the div/dt expression through differentiation.

Reference [15] proposes a method using the Logistic curve, which describes the natural growth process of animals and plants, to establish a thyristor reverse recovery time-varying resistance R(t) model. If this model is adopted to establish the iv expression, then:

Substituting equation (19) into equation (12) yields a complex second-order variable-coefficient non-homogeneous linear differential equation. The expression for UC cannot be solved through differential equation methods. Therefore, this model is only suitable for simulation software with real-time calculation capabilities.

References [16~21] propose using an exponential current source it to represent the thyristor reverse recovery current. This model is currently the most widely used, with the following expression:

If the model in equation (20) is adopted, an exponential function is introduced into the constant term of equation (12), making the solution extremely difficult. Therefore, other methods must be sought to fit iv.

Considering that div/dt is 0 at both t4 and t6 moments, and reaches its peak near the midpoint of the t4~t6 segment, the variation pattern of div/dt is similar to a parabola. Therefore, we can consider skipping the step of finding the iv expression and directly fitting div/dt in the t4~t6 segment with a parabola. Let:

Taking time t4 in Figure 4 as the time reference point (t=0), then at time t4, div/dt(t=0)=0. At time t6, div/dt(t=te=IRMt /kId)=0. At the midpoint of the t4~t6 segment, div/dt reaches its maximum value kId/t , i.e., div/dt(t=IRMt /2kId)=kId/t . Based on these boundary conditions, using the valve operating circuit in Figure 5 as the input condition, the reverse current model is established using both equation (20) and equation (21). The curve of div/dt changing with time t in the t4~t6 segment is shown in Figure (10) [Figure 10: see original paper].

From Figure 10, if the exponential current source model in equation (20) is used to simulate the variation pattern of div/dt with time t in the t4~t6 segment, div/dt decays according to an exponential law, and the initial value of div/dt is not 0. Obviously, this does not match the thyristor reverse current variation pattern shown in Figure 4 and will inevitably introduce significant deviation into the UC calculation results. In contrast, using the parabola model in equation (21), div/dt in the latter half of the t4~t6 segment approximately matches the exponential current source model, and can better simulate the variation pattern of div/dt throughout the entire t4~t6 segment.

Substituting equation (21) into equation (12), the constant term in equation (12) becomes a quadratic polynomial in t. Therefore, we can assume a particular solution of equation (12) as:

Then we can solve for:

Let n1, n2 be arbitrary real numbers. Then UC:

Taking time t4 as the time reference point (t=0), at this moment UC=0. When t=te, UC=−Ubc. From these initial conditions, we can obtain:

Thus, all coefficients in equation (12) are determined, and the functional relationship of Uc changing with time is subsequently determined.

Substituting equation (25) into equation (9), we can obtain:

Equation (28) is the function of reverse voltage changing with time during the blocking recovery process of the converter valve after adding the damping circuit, where the coefficients of UC are determined by equations (26) and (27). It can be seen that converter transformer parameters, damping circuit parameters, and thyristor parameters all affect the amplitude of Uv6.

Still using the circuit parameters of the UHVDC transmission project in Figure 5 as input conditions, the variation pattern of Uv6 with RS for different CS values is shown in Figure 11 [Figure 11: see original paper].

From Figure 11, within the te time period, for determined RS and CS, Uv6 increases from 0 to the reverse peak Uv6-max and then decreases to 0. If RS is constant, Uv6-max increases as CS decreases. If CS is constant, Uv6-max varies with te and RS in a "saddle" shape. When RS takes a certain value, the absolute value of Uv6-max can be minimized. It can be seen that selecting appropriate RS and CS values can make Uv6-max less than 291.6kV. In this way, the damping circuit effectively reduces commutation overvoltage and protects the valve arrester.

4 Comparison Between Calculation Model and Test Results

To further verify the accuracy of the above calculation method, calculation results must be compared with measured results under the same circuit conditions. The most intuitive comparison method is to directly input the circuit parameters of a certain DC project into the calculation formula and compare the measured valve voltage waveform with the calculation results. However, in actual engineering, the valve terminal voltage waveform cannot be measured directly. The valve voltage waveform can only be indirectly fitted from the measured voltage on the converter transformer valve side. Due to measurement sampling accuracy limitations, the resulting valve voltage waveform cannot display commutation overvoltage.

Therefore, experimental verification is considered. The thyristor-level equivalent test circuit shown in Figure 12 [Figure 12: see original paper] is established, where NS is the number of thyristor series stages in a single valve. Then Figure 12 can equivalently simulate the turn-off process of the converter valve in Figure 7.

Using the UHVDC transmission project parameters in Figure 5 as input conditions, setting the firing angle α=20°, and changing the damping parameters, the calculated UV6 results and test curves are shown in Figure 13 [Figure 13: see original paper].

The comparison between calculated and test results of Uv6-max corresponding to Figure 13 is shown in Table 1 .

From Figure 13, the variation pattern of the Uv6 curve obtained from equation (28) basically matches the test results. From Table 1 , when CS and RS take different values, the deviation between calculated and test results of Uv6-max does not exceed 4%. This indicates that the valve commutation overvoltage peak calculated by equation (28) can accurately reflect actual conditions, and demonstrates that the commutation overvoltage calculation method proposed in this paper has high practical value.

Conclusions

Through the research in this paper, the following conclusions can be drawn:

(1) Converter valve commutation overvoltage is generated by the change in thyristor reverse recovery current, which causes the converter transformer leakage inductance induced voltage to superimpose with the converter

transformer output voltage. Excessive commutation overvoltage will endanger the safe operation of the valve arrester.

(2) Paralleling an RC damping circuit across the converter valve can suppress commutation overvoltage, but adding RC damping changes the converter valve operating circuit structure. Based on the converter valve operating circuit, a second-order constant-coefficient non-homogeneous linear differential equation for the damping capacitor terminal voltage with respect to time can be derived.

(3) Using a parabola to fit the current change rate during the thyristor reverse recovery current process from reverse peak to 0 can skip the step of finding the iv expression and directly fit div/dt, avoiding the solution of variable-coefficient non-homogeneous differential equations.

(4) By solving the converter valve circuit equation through the piecewise fitting method of thyristor reverse recovery current, the variation pattern of valve reverse voltage with damping parameters can be obtained. When external circuit conditions are determined, the valve reverse voltage peak depends on the thyristor reverse recovery current peak, current change rate, damping capacitance, and damping resistance parameters.

(5) The deviation between calculated and test results of converter valve commutation overvoltage peak does not exceed 4%. The calculation method for valve commutation overvoltage proposed in this paper can accurately reflect actual conditions and has high practical value.

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