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Design of Ripple Power Supply for Aging Test of DC Arrester

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Abstract. The reliability of DC arresters is one of the basis of safe operation for HVDC transimission system, the aging test is the main measure to obtain the reliability of arresters, and therefore, is of great importance. The test voltage with ideal waveforms had not been produced before by any of the test equipment when it is loaded. The paper introduces a method to produce the aging test ripple voltage waveforms of 6 pulses and 12 pulses converter which fully considers the influence of trigger angle and commutation angle. The paper designed a kind of ripple voltage power source which can series, and produce the ripple waveform of any trigger angle and commutation angle, the output voltage of one module is up to 1kV. The device went through 1000 hours of testing, and commutation process can be seen in the oscillograph clearly, including stable commutation overshoot. The oscillograph also show that the fundamental frequency of the waveform is stable, and waveform distortion is small and can be ignored. The output voltage meets the requirements of aging test for various types of DC arresters.

1. Introduction

The DC arrester is the key equipment for over voltage protection of HVDC system. Its reliable operation is directly related to the safe and reliable operation of HVDC system. Metal oxide resistors, the main component of DC arresters, are aging in long-term operation, which affects the stability and reliability of arresters. Usually, the aging performance of arresters is studied by accelerated aging test[1-3].

The working voltage of HVDC arresters, especially converter arresters (including valve arresters and bridge arresters), is the superposition of DC voltage and ripple voltage. The ripple voltage contains various high-order harmonic, the working voltage of valve arresters also contains fundamental component of power frequency[4]. In addition, the commutation of the converter valve will lead to commutation overshoot, the working voltage waveform of the converter arrester is complex. The amplitude of commutation overshoot is not only related to the trigger angle(α) and commutation angle(μ), but also related to the parameters of the damping circuit and leakage inductance of the converter transformer[2-4]. The voltage waveform shown in Figure 1 is 6 pulses converter valve arrester and bridge arrester waveform. Only under this voltage waveform can accelerated aging test truly reflect the aging performance of converter arrester[5].

At present, the test voltage with ideal waveform had not been produced before by any of the test equipment when it is loaded. Based on the mathematical model of 6 pulses converter valve voltage and



bridge voltage waveform, this paper analyzed and summarized the variation rule of voltage waveform, fully considered the influence of commutation angle and trigger angle on voltage waveform, and proposed a method to generate the ripple voltage. A ripple power supply module which can be series with small waveform distortion, stable working voltage and frequency under any arrester resistor (reference voltage is not more than 8kV) is developed.

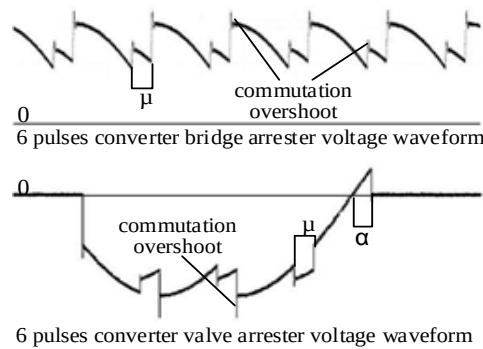


Figure 1. HVDC 6 pulses converter voltage waveform

2. The mathematical model of 6-pulse converter voltage

The basic principle of 6 pulses converter is that under the action of AC voltage and trigger pulse of thyristor, according to the turn-on and turn-off conditions of thyristor, AC converted to DC(rectifier), or DC is converted to AC(inverter)[4-6]. This paper takes rectifier as an example to analyze the basic principle, as shown in Figure 2.

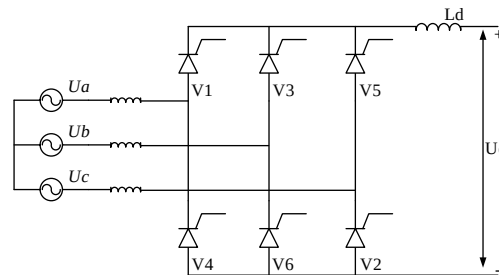


Figure 2. Schematic diagram of 6-pulse rectifier converter

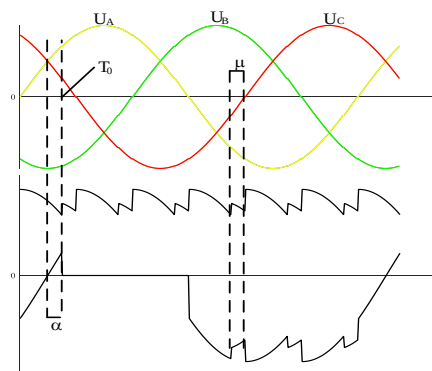


Figure 3. Typical waveform of 6-pulse rectifier converter

In normal conditions, the bridge voltage and V1 valve voltage of rectifier as shown in Figure 3. It is stipulated that the zero-crossing point of phase A voltage from negative to positive is the zero point of timing, and the opening time T_0 of V1 as the starting time in a period. According to the conduction rules, a cycle can be divided to 12 segments, the thyristor conduction status and mathematical model of each segment are shown in Table 1.

Table 1. Bridge voltage and valve voltage sub-function of 6-pulse rectifier converter

Time	V1	V3	V5	V4	V6	V2	U_d	U_f
$T_0 \sim T_1$	1	0	1	0	1	0	$U_{d1} = 0.5 * (u_a + u_c) - u_b$	$U_{f1} = 0$
$T_1 \sim T_2$	1	0	0	0	1	0	$U_{d2} = u_a - u_b$	$U_{f2} = 0$
$T_2 \sim T_3$	1	0	0	0	1	1	$U_{d3} = u_a - 0.5 * (u_b + u_c)$	$U_{f3} = 0$
$T_3 \sim T_4$	1	0	0	0	0	1	$U_{d4} = u_a - u_c$	$U_{f4} = 0$
$T_4 \sim T_5$	1	1	0	0	0	1	$U_{d5} = 0.5 * (u_a + u_b) - u_c$	$U_{f5} = 0$
$T_5 \sim T_6$	0	1	0	0	0	1	$U_{d6} = u_b - u_c$	$U_{f6} = u_a - u_b$
$T_6 \sim T_7$	0	1	0	1	0	1	$U_{d7} = u_b - 0.5 * (u_a + u_c)$	$U_{f7} = 0.5 * (u_a + u_c) - u_b$
$T_7 \sim T_8$	0	1	0	1	0	0	$U_{d8} = u_b - u_a$	$U_{f8} = u_a - u_b$
$T_8 \sim T_9$	0	1	1	1	0	0	$U_{d9} = 0.5 * (u_b + u_c) - u_a$	$U_{f9} = u_a - 0.5 * (u_b + u_c)$
$T_9 \sim T_{10}$	0	0	1	1	0	0	$U_{d10} = u_c - u_a$	$U_{f10} = u_a - u_c$
$T_{10} \sim T_{11}$	0	0	1	1	1	0	$U_{d11} = u_c - 0.5 * (u_a + u_b)$	$U_{f11} = 0.5 * (u_a + u_b) - u_c$
$T_{11} \sim T_{12}$	0	0	1	0	1	0	$U_{d12} = u_c - u_b$	$U_{f12} = u_a - u_c$

(a) u_a, u_b, u_c as instantaneous value of three-phase voltage;

(b) 1 means that the corresponding thyristor is on and 0 means that the corresponding thyristor is off.

According to Figure 3 and the conduction rules, the values at each time point in Table 1 conform to the following principles:

$$T_{2n+2} = T_{2n} + \frac{\pi}{3} \quad (1)$$

$$T_{2n+1} = T_{2n} + \frac{\mu}{180} \pi \quad (2)$$

$$T_0 = \frac{\pi}{6} + \frac{\alpha}{180} \pi \quad (3)$$

According to Table I, the mathematical model of bridge voltage can be summarized.

$$U_d = \frac{1}{N_{up}} (u_a * E_1 + u_b * E_3 + u_c * E_5) - \frac{1}{N_{down}} (u_a * E_4 + u_b * E_6 + u_c * E_2) \quad (4)$$

(a) $E_1 \sim E_6$ express existence function, when thyristor V_i closed, $E_i = 1$, else, $E_i = 0$.

(b) N_{up} express the total number of E_i equal to 1 in the upper half bridge at a time.

(c) N_{down} express the total number of E_i equal to 0 in the upper lower bridge at a time.

3. A method of generating ripple voltage

3.1 Calculate of 6-pulse converter voltage

The average DC voltage of the rectifier under normal operation condition is [4]:

$$U_{dc} = \frac{3\sqrt{2}}{2\pi} U_l [\cos \alpha + \cos(\alpha + \mu)] \quad (5)$$

In Table 1, the converter bridge voltage and V1 valve voltage are superimposed by DC voltage and ripple voltage. The ripple voltage of valve is:

$$U'_f = U_f + \frac{1}{2} U_{dc} \quad (6)$$

The ripple voltage of converter bridge is:

$$U'_d = U_d - U_{dc} \quad (7)$$

In normal condition, according to the Table 1, the length of each commutation period is μ , and that of non-commutation period is $60 - \mu$. Assume that a period (valve voltage) consists n points, so:

The waveform in commutation period is composed of $n\mu/360$ points;

The waveform in non-commutation period consists of $n(60 - \mu)/360$ points.

Take time $T_i \sim T_{i+1}$ as example, assume that the expression of the valve(or bridge) voltage during this period is $u = f(t)$, the sampling points is m , so:

$$m = n\mu/360 \text{ or } m = n(60 - \mu)/360 \quad (8)$$

The time interval of equal interval sampling is

$$\Delta t = \frac{T_{i+1} - T_i}{m - 1} \quad (9)$$

The voltage value at the j point is

$$u_j = f(T_i + (j - 1) * \Delta t) \quad (10)$$

Sampling value of ripple voltage after removing DC component is

$$\begin{aligned} u'_j &= u_j + \frac{1}{2}U_d \text{ (valve voltage)} \\ u'_j &= u_j - U_d \text{ (bridge voltage)} \end{aligned} \quad (11)$$

According to the above method, the m points voltage values can be obtained in turn. Similarly, the ripple voltage of each sampling point in a period can be calculated in turn, $u'_1, u'_2, \dots, u'_n$.

Next, the specific calculation steps to digitalize the voltage of ripple voltage are as follows:

(a) Finding the maximum ripple voltage

$$u'_{max} = \max\{u'_1, u'_2, \dots, u'_n\} \quad (12)$$

(b) Normalization

$$u''_i = u'_i / u'_{max}, \quad i = 1, 2, \dots, n \quad (13)$$

(c) Coordinate transformation

$$u_i^{(3)} = u''_i + 1, \quad i = 1, 2, \dots, n \quad (14)$$

(d) Digital conversion

$$u_i^{(4)} = u_i^{(3)} * (2^k - 1) \quad (15)$$

k is the digit numbers of microprocessor.

(e) Take the integer portion

$$U_i = [u_i^{(4)}], \quad i = 1, 2, \dots, n \quad (16)$$

Through above steps, the digital value of ripple voltage at each sampling point in a period of 6-pulse rectifier valve(or bridge) voltage can be obtained. According to different trigger angle and commutation angle, waveform is different, and the value of digital quantity is different.

3.2 Calculate of 12-pulse converter voltage

The 12-pulse converter is composed of two 6-pulse converters connected in series on the DC side, and its AC side is connected in parallel through the network winding of the converter transformer[1-4]. One side winding of converter transformer is star-shaped and the other is triangle-shaped, so that the commutation voltage with phase difference of 30 degrees can be obtained at the AC side of two 6-pulse converters.

The Y bridge valve arrester working voltage waveform of 12-pulse converter is the same as that of 6-pulse converter. The difference between the working voltage waveform of Δ bridge valve arrester and that of Y bridge valve arrester is only in the phase angle. Therefore, the aging test voltage waveform of 12-pulse converter valve arrester can be replaced by the aging test voltage waveform of 6-pulse converter valve arrester[7-8].

The bridge voltage of 12-pulse converter is the sum of the bridge voltage of two 6-pulse converters. The DC voltage waveforms of the two bridges are identical, and the phase angle difference is 30 degrees. Therefore, the discrete ripple voltage of 12-pulse converter bridge arrester can be calculated by the following method.

The ripple voltage of 6-pulse converter bridge voltage in one cycle is $u'_1, u'_2, \dots, u'_n$, assume that its the Y bridge ripple voltage, the Δ bridge ripple voltage is $u'_{n/12+1}, u'_{n/12+2}, \dots, u'_n, u'_1, u'_2, \dots, u'_{n/12}$, thus the discrete ripple voltage of 12-pulse converter is:

$$(u'_1 + u'_{n/12+1}), (u'_2 + u'_{n/12+2}), \dots, (u'_n + u'_{n/12}) \quad (17)$$

4. Design of ripple power supply

DC arrester aging test power supply includes DC voltage generator and ripple power supply. This paper only introduces the design of ripple power supply[7]. The overall system diagram is shown in Figure 4 below.

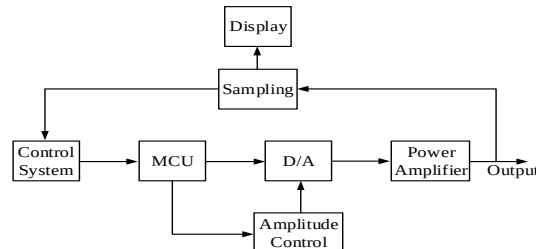


Figure 4. System chart of ripple power source

4.1 Control System

The aging test voltage is mainly determined by four parameters: reference voltage, chargeability, trigger angle and commutation angle. It calculates the ripple voltage and DC voltage, and according to the hardware circuit parameters to calculate the ripple voltage amplitude and DC voltage amplitude. The sampling module is to display the real-time output waveform.

4.2 Ripple Generator

The main function of the ripple generator is to process the control commands sent by the control system, mainly including D/A digital-to-analog conversion circuit and amplitude control circuit as show in Figure 5. At the beginning and end of commutation, the voltage waveform will appear voltage step, which requires the D/A conversion speed to be fast and the conversion accuracy to be high. In addition, the influence of non-linearity and digital noise should also be considered when selecting the D/A chip.

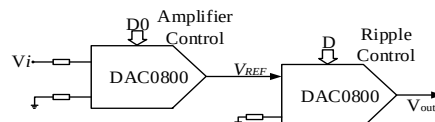


Figure 5. The ripple signal circuit diagram

Taking DAC0800 as example, the relationship between output voltage and control variable as follows.

$$V_{out} = V_{REF} * \frac{2D - 255}{256} \quad (18)$$

$$V_{REF} = V_i * \frac{2D0 - 255}{256} \quad (19)$$

By changing the values of reference voltage V_i and amplitude control $D0$, the value of DAC reference voltage V_{REF} in ripple generation circuit can be changed, so as to achieve the purpose of changing the amplitude of output ripple voltage. The ripple control D and amplitude control $D0$ are calculated by the control system.

4.3 Power Amplifier Module

The power amplifier boosts and amplifies the signal, and then transforms it into a ripple high voltage with a certain power output. Boost transformer involves high voltage output and self-insulation, and attention should also be paid to the influence of transformer core on ripple waveform, which needs to be specially developed. The ripple power supply designed in this paper uses three-winding boost transformer. The first winding is connected with the output of power amplifier, the second winding is high voltage output winding, connected with DC generator and arrester test piece. During the aging test, a certain leakage DC current will flow through the high voltage winding of boost transformer, which

may lead to DC bias and distortion of ripple waveform. Therefore, boost transformer increases the third winding and accepts controlled DC current source to offset the influence of DC leakage current.

5. Test Result

The internal structure of ripple power supply designed in this paper are shown in Figure 6. Two boost transformers are output in series.

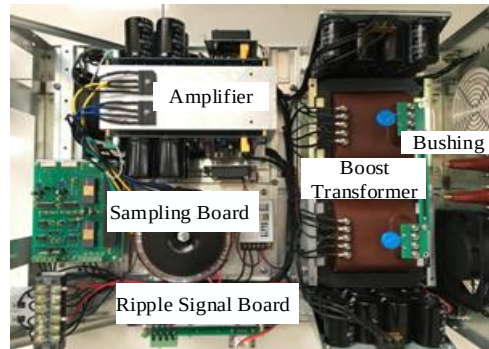


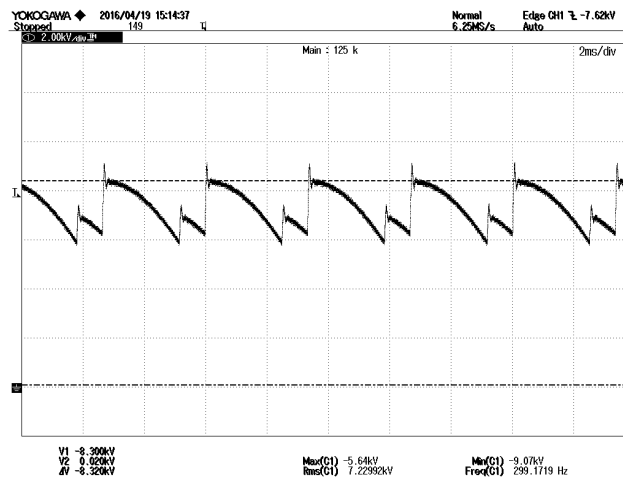
Figure 6. The ripple wave power source

In order to measure the stability of output waveform of ripple power supply, a 1000-hour continuous aging test was carried out. The trial product is QE36 produced by ETA, the DC reference voltage is 8kV, which is the highest DC reference voltage at home and abroad. In order to meet the aging test voltage requirements of arresters, the maximum effective output voltage of the ripple power supply module designed in this paper is 1kV. Four modules are used to output ripple waveform in series. The paper selects 15 degrees trigger angle and 15 degrees commutation angle as the typical test condition.

Figure 7 shows the aging test waveform of DC arrester. Without considering the commutation overshoot condition, the peak voltage reaches more than 8kV, the test voltage frequency of valve arrester is stable at 50Hz, the voltage frequency of 6-pulse converter bridge arrester is stable at 300Hz, and the frequency of 12-pulse converter bridge arrester is stable at 600Hz. The commutation process is clear and the amplitude of commutation overshoot is stable. The commutation overshoot, frequency and effective voltage of ripple voltage are stable during the test. Because of the leakage inductance of boost transformer and parasitic capacitance of arrester, the voltage waveform after boost transformer will have obvious commutation overshoot at the end of commutation, and a certain degree of voltage oscillation.



(a) Valve arrester aging test waveform of 6-pulse rectifier



(b) Bridge arrester aging test waveform of 6-pulse rectifier
Figure 7. Valve voltage of 6-pulse rectifier arrester

6. Conclusion

According to the mathematical model of 6-pulse converter valve and bridge arrester voltage, a method of dividing and discretizing voltage waveform is proposed in this paper. The method fully considers the influence of commutation angle and trigger angle, and can calculate the voltage waveform at any trigger angle and commutation angle. According to this method, a ripple power supply for aging test of DC arrester is developed in this paper. The power supply can generate ripple voltage waveform for aging test of 6-pulse converter arrester at arbitrary trigger angle and commutation angle. Multiple modules can be used in series to achieve higher output voltage. After more than 1000 hours of operation, the power supply has stable output voltage and frequency, stable amplitude of commutation overvoltage, and can fully meet the requirements of voltage waveform for aging test of various types of DC arresters.

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