Parameter Calculation and Working Characteristic Analysis of a New Type of Magnetic Integrated CRT

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ABSTRACT The working characteristic of an electromagnetic equipment is an important reference standard for measuring its working performance. In this paper, we take a new type of magnetic integrated controllable reactor of transformer type (CRT) as the research object, establish its equivalent mathematical model and deduce its calculation short-circuit impedance and winding current formulas. On this basis, the relationship between the working winding instantaneous current, harmonic current coefficient and equivalent impedance of the new magnetic integrated CRT and the thyristor trigger angle is quantitatively analysed, and the working characteristic curves, such as the instantaneous current waveform, harmonic characteristic curve, control characteristic curve and volt-ampere characteristic curve of the working winding, are obtained. On the basis of the MATLAB/Simulink simulation platform, a new magnetic integrated CRT simulation model is established to simulate the working winding current under different trigger angles to verify the established formulas. Meanwhile, the response speed of the CRT is simulated and analysed. Results show that the analytical calculation results of the winding current of the magnetic integrated CRT are consistent with the simulation results. The new type of magnetic integrated CRT has the characteristics of hierarchical smooth regulation and low harmonic current and the advantages of fast response speed and high sensitivity. Furthermore, the CRT’s volt-ampere characteristic is approximately linear. This study is expected to provide some theoretical guidance for the in-depth understanding of the working characteristics of the magnetic integrated CRT and the structural design and optimisation of the CRT.

INDEX TERMS Magnetic integrated CRT; Mathematical model; Parameter calculation; Working characteristics

I. INTRODUCTION

In recent years, with the centralised access of large-scale new energy power generation, the power system presents new characteristics of high new energy penetration proportion at the source side and AC/DC hybrid connection at the grid side [1–2]. The operation characteristics of high proportion renewable energy are different from those of the traditional power supply. Its power supply fluctuation exceeds the load fluctuation and becomes the main source of power system uncertainty [3]. To cope with the increasingly complex power grid structure and the drastic power flow changes, meet the power demand of different regions, realise the optimal allocation of energy resources nationwide and ensure the reactive power balance and voltage control of the power system, extra high voltage (EHV), long-distance and high-capacity transmission put forward high requirements for controllable reactance [4–5]. As a new type of dynamic reactive power compensation device for realising a smooth inductive reactance output on the basis of the magnetic flux control principle, a controllable reactor of transformer type (CRT) has the advantages of small current harmonic, fast response and...
continuous adjustable capacity. With the development goal of lightweight and miniaturised electromagnetic equipment, the introduction of magnetic integration technology into the structural design of controllable reactors has become a new direction of the controllable reactor research.

A study [6] first introduced magnetic integration technology into the structural design of CRT and proposed an array magnetic integration CRT on the basis of the principle of magnetic flux offset. However, the proposed CRT’s structure is complex, the number of windings is difficult to expand, and the universality is poor. To solve this problem, a previous study [7] proposed a magnetic integrated CRT with multiple magnetic conductive materials on the basis of the combination of multiple magnetic conductive materials. Although the structure is simplified, it cannot realise complete decoupling between windings, and the no-load current is large. Therefore, another study [8] proposed a split magnetic integrated CRT to address the above problems. However, to achieve high short-circuit impedance, discus is set between the iron core of the working winding and the control winding, increasing the difficulty of process manufacturing. A work [9] proposed a multi basic independent unit magnetic integrated CRT by setting a leakage magnet core column between the working winding and the control winding to replace the discus in the CRT structure in the previous study [8]. However, the setting of multi basic independent units increases the volume, weight and material cost of the equipment. Therefore, on the basis of the multi basic independent unit magnetic integrated CRT, several works [10–11] integrated two basic independent units and proposed a dual control-winding basic unit magnetic integrated CRT to reduce the volume, weight and cost of the CRT. Meanwhile, aiming at minimising the cost and loss, a study [12] established a structural parameter optimisation model for the dual control winding basic unit magnetic integrated CRT and optimised its structural parameters. Obviously, the dual control winding basic unit magnetic integrated CRT is the most superior magnetic integrated structure of CRT [10]. However, although the above research shows the effectiveness of the structure by establishing its equivalent magnetic circuit model and circuit model, the harmonic, magnetisation, control and other working characteristics were not analysed. In fact, the working characteristics of an electromagnetic equipment are an important reference standard for measuring its working performance.

To summarise, this paper takes the new magnetic integrated CRT, that is, the dual control-winding basic unit magnetic integrated CRT, as the research object, establishes its equivalent mathematical model and deduces the calculation formulas of short-circuit impedance and winding current. On this basis, the relationship between the instantaneous current, harmonic current coefficient and equivalent impedance of the working winding of the new magnetic integrated CRT and the thyristor trigger angle is quantitatively analysed, and the working characteristic curves, such as the instantaneous current waveform, harmonic characteristic curve, control characteristic curve and volt ampere characteristic curve of the working winding, are obtained. On the basis of the MATLAB/Simulink simulation platform, a new magnetic integrated CRT simulation model is established, and the working winding current under different trigger angles is simulated to verify the established formulas. Meanwhile, the response speed of the CRT is simulated and analysed. This study is expected to provide some theoretical guidance for the in-depth understanding of the working characteristics of the magnetic integrated CRT and the structural design and optimisation of the CRT.

II. WORKING PRINCIPLE OF A NEW MAGNETIC INTEGRATED CRT

Figure 1 shows the fundamental diagram of the new magnetic integrated CRT.

![Fundamental diagram of the new type magnetic integrated CRT](image)

In Figure 1, BW is the working winding, and its terminal AX is connected to the high-voltage bus; \( i_0 \) is the working winding current of the CRT; \( CW_1, CW_2, \ldots \) are the control windings; \( T_1, T_2, \ldots, T_n \) are the anti-parallel thyristor valve group that are connected in series in the control-winding circuits. The design principle of ‘high impedance and weak coupling’ shall be met in the structural design of the CRT [13]. Therefore, the working winding and control winding of the CRT shall meet the high impedance with short-circuit impedance of approximately 100%. \( M_{ij} \) (\( i \neq j \)) refers to the mutual inductance between the control windings at all levels. If weak coupling shall be realised between the control windings at all levels, then \( M_{ij} \approx 0 \).

To realise stepless continuous smooth regulation, the CRT has single branch regulation modes of sequential, fixed and transfer single branches and multi branch regulation mode [14]. Taking the sequential single branch regulation mode as an example, this paper introduces the basic working principle of the CRT. Figure 2 shows the
structural diagram of the dual control-winding basic unit magnetic integrated CRT that is composed of multiple independent dual control-winding basic units, and each basic unit contains one working and two control winding units. Under the regulation mode of the sequential single branch, by regulating the turn-on of anti-parallel thyristors \( T_1, T_2, \ldots, T_s \) that are connected in series in the control winding circuits at all levels, the control windings at all levels (\( CW_1, \ldots, CW_s \)) are short circuited in turn to gradually increase the current of working winding \( BW \) and meet the transition of the CRT from no load to full load. The single branch regulation mode of the CRT is based on the harmonic dilution principle, that is, the harmonic current generated by only one regulation winding is diluted through the short circuit of multiple control windings to suppress the harmonic current of the CRT [15]. Therefore, the number of stages of CRT control winding should be greater than 1; otherwise, a large number of harmonics will be injected into the power grid under light load [13].

\[ \begin{align*}
&\text{FIGURE.2 Structure diagram of dual control-winding basic unit magnetic integrated CRT}

\text{III. MATHEMATICAL MODEL OF NEW MAGNETIC INTEGRATED CRT}

The dual control-winding basic unit magnetic integrated CRT is composed of multiple independent dual control winding basic units. Any basic unit (\( k \)) of the dual control winding is selected as the analysis object, and its structural diagram is shown in Figure 3. If the winding resistance is ignored, then its equivalent circuit model can be established, as shown in Figure 4.

Figure 4 shows the equivalent circuit diagram of the basic unit of the double control winding reduced to the working winding side. In Figure 4, \( N_0 \) is the number of turns of the working winding (\( BW_k \)) of any double control winding basic unit \( k \). \( N_1 \) and \( N_2 \) are the turns of control winding \( CW_{2k-1} \) and \( CW_{2k} \), respectively. \( L_{51} \) is the leakage inductance of the working winding. \( L_{62} \) and \( L_{63} \) are the leakage inductances of control windings \( CW_{2k-1} \) and \( CW_{2k} \), respectively. \( L_4 - L_6 \) are the excitation inductors corresponding to magnetic circuits ab, ahgf, af, fe, be and bcde, respectively. The calculation method and formula of each parameter are discussed in detail in reference [11] and thus not presented in this paper.

\[ \begin{align*}
&\text{FIGURE.3 Structure diagram of dual control-winding basic units}

&\text{FIGURE.4 Equivalent circuit model of dual control-winding basic unit } k \]
According to the equivalent circuit model of dual control winding basic unit shown in Figure 4, the calculation formula of impedance between the windings reduced to the working winding side under different working conditions can be deduced, as shown in Equation (1).

\[
Z_{k} = \omega \frac{L_{3i} + L_{4}}{L_{3} + L_{4}} \left/ \frac{L_{3} + L_{4}'}{L_{3} + L_{4}'} \right. \right/ \left( L_{3} + L_{4} \right) = \omega \frac{L_{3i} + L_{4}(L_{3} + L_{4} + n_{1}^{2} L_{32})}{(L_{3} + L_{4})\left( L_{3} + L_{4} + n_{1}^{2} L_{32} \right)} \right/ \left( L_{3} + L_{4} \right) \right/ \left( L_{3} + L_{4} \right)
\]

(1)

where \( \omega = 2\pi f \) is the operating angular frequency of the CRT.

When the dual control winding basic unit is in no-load, that is, \( CW_{1} \) and \( CW_{2} \) are in open circuit. The impedance \((Z_{0k})\) between the working and control windings is shown in Equation (2).

\[
Z_{0k} = \omega \frac{L_{3i} L_{4}(L_{3} + L_{4} + n_{1}^{2} L_{32})}{(L_{3} + L_{4})(L_{3} + L_{4} + n_{1}^{2} L_{32}) + L_{1} L_{2} L_{12}}
\]

(2)

When the dual control winding basic unit is in half load, that is, \( CW_{1} \) is in short circuit and \( CW_{2} \) is in open circuit, then,

\[
L_{2}' = L_{2} / (n_{1}^{2} L_{32}) = \frac{n_{1}^{2} L_{2} L_{32}}{L_{2} + n_{1}^{2} L_{32}}
\]

\[
L_{6}' = L_{6}
\]

where \( n_{1} = \frac{N_{0}}{N_{1}} \). At this time, the short-circuit impedance \((Z_{1k})\) between the working winding and control winding \( CW_{1} \) is shown in Equation (3).

\[
Z_{1k} = \omega \frac{L_{3i} L_{4}(L_{3} + L_{4} + n_{1}^{2} L_{32})}{(L_{3} + L_{4})\left( L_{3} + L_{4} + n_{1}^{2} L_{32} \right) + L_{1} L_{4} L_{12} L_{32} + L_{1} L_{2} L_{12}}
\]

(3)

where

\[
L_{32} = n_{1}^{2} L_{2} L_{32} + L_{3} (L_{2} + n_{1}^{2} L_{32})
\]

When the dual control winding basic unit is in full load, that is, both \( CW_{1} \) and \( CW_{2} \) are short circuited, then,

\[
L_{2}' = L_{2} / (n_{1}^{2} L_{32}) = \frac{n_{1}^{2} L_{2} L_{32}}{L_{2} + n_{1}^{2} L_{32}}
\]

\[
L_{6}' = L_{6}/n_{2}^{2} L_{63} = \frac{n_{2}^{2} L_{6} L_{63}}{L_{6} + n_{2}^{2} L_{63}}
\]

where \( n_{2} = \frac{N_{0}}{N_{2}} \). At this time, the short-circuit impedance \((Z_{2k})\) of the dual control winding basic unit is expressed as Equation (4).

\[
Z_{2k} = \omega \frac{L_{3i} L_{4}(L_{3} + L_{4} + n_{2}^{2} L_{32}) + L_{22}(L_{2} + n_{2}^{2} L_{32})}{(L_{3} + L_{4})(L_{3} + L_{4} + n_{2}^{2} L_{32}) + L_{22}(L_{2} + n_{2}^{2} L_{32}) + L_{22}(L_{1} + L_{4})}
\]

(4)

Where

\[
L_{22} = n_{2}^{2} L_{6} L_{32} + L_{3} (L_{6} + n_{2}^{2} L_{32})
\]

For a magnetic integrated CRT with \( k \) independent dual control winding basic units and \( s = 2k \) control winding stages, given that control windings \( CW_{1} - CW_{m} \) \((1 \leq m \leq s)\) are short circuited in turn, the magnetic integrated CRT impedance of the dual control winding basic unit magnetic integrated CRT is as shown in Equation (5).

\[
Z_{4} = \frac{1}{\sum_{j=1}^{k} Z_{0j}} \left( \sum_{j=1}^{k} Z_{0j}^{-1} \right) + \frac{1}{\sum_{j=1}^{k} Z_{0j}^{-1}} \sum_{j=1}^{k} Z_{0j}^{-1} \left( \sum_{j=1}^{k} Z_{0j}^{-1} \right)
\]

(5)

In Equation (5), \( Z_{0j} \), \( Z_{1j} \), and \( Z_{2j} \) represent the short-circuit impedance of the j-th dual control winding basic unit under the no-load, half load and full load states, respectively, and their calculation formulas are expressed as Equations (1)–(4). In \( \sum_{j=1}^{k} Z_{0j}^{-1} \), if \( i > k \), then

\[
\sum_{j=i}^{k} Z_{0j}^{-1} = 0
\]

According to Equation (5), when control windings \( CW_{1} - CW_{m} \) \((1 \leq m \leq s)\) is short circuited in sequence, the working winding current \((I_{0d,m})\) of the dual control winding basic unit magnetic integrated CRT can be calculated using Equation (6).
\[ I_{0,m} = \frac{U_N}{Z_{0,m}} \]  

(6)

Where, \( U_N \) is the rated voltage of the working winding.

IV. WORKING CHARACTERISTICS ANALYSIS OF NEW MAGNETIC INTEGRATED CRT

A. CALCULATION OF INSTANTANEOUS CURRENT AND HARMONIC CURRENT OF WORKING WINDING

The single branch regulation mode of the CRT means that except for the control branch where the thyristor is in the regulation state, the thyristors of the other control branches of the CRT are in full operation or off state [16]. Obviously, except for the control branch in the regulation state, other control branches will not introduce harmonics to the power system [14]. For the CRT with S-level control winding, the compensation capacity of the CRT increases gradually with the sequential input of control windings \( CW_1 - CW_m \) in the sequential single branch regulation mode. If the excitation current is ignored, assuming that the \( m \)-th stage control winding of the CRT with rated voltage 

\[ u = \sqrt{2}U_N \sin(\omega t + \frac{\pi}{2}) \]

of the working winding is in regulation state (i.e. \( CW_1 - CW_{m-1} \) are in full short circuit) and the trigger angle of the thyristor is \( \alpha \), the calculation formula of the CRT working winding current is as shown in Equation (7).

\[
i_{0,m} = \begin{cases} 
\sqrt{2}I_{0,m-1} \sin \omega t, & 0 < \omega t < \pi - \alpha < \omega t < \pi + \alpha; \\
\sqrt{2}I_{0,m} \sin \omega t - \sqrt{2}(I_{0,m-1} - I_{0,m-1}) \sin \alpha, & \omega t < \pi - \alpha \\
\sqrt{2}I_{0,m} \sin \omega t + \sqrt{2}(I_{0,m-1} - I_{0,m-1}) \sin \alpha, & \omega t < 2\pi - \alpha
\end{cases}
\]

(7)

If the capacity increasing coefficient \( \beta_m \) between two adjacent control windings is defined as,

\[ \beta_m = \frac{Q_{m-1}}{Q_m} = \frac{U_N I_{0,m-1}}{U_N I_{0,m}} = \frac{I_{0,m-1}}{I_{0,m}} \]

(8)

If

\[ i_{0,m} = \frac{i_{0,m-1}}{\sqrt{2}I_{0,m}} \]

(9)

The relative value of the amplitude of CRT working winding can be obtained by combining Equation (7)-(9), as shown in Equation (10).

\[
i_{0,m}^* = \begin{cases} 
\frac{1}{\beta_m} \sin \omega t, & 0 < \omega t < \pi; \\
\frac{1}{\beta_m} \sin(\omega t - \frac{\pi}{\beta_m}), & \pi - \alpha < \omega t < \pi + \alpha; \\
2\pi - \alpha < \omega t < 2\pi
\end{cases}
\]

(10)

By Fourier decomposition of Equation (10), the relative values of fundamental amplitude and \( n \)-th harmonic amplitude of CRT working winding current can be obtained, as shown in Equation (11) and Equation (12) respectively.

\[
i_{1,0,m} = \frac{1}{\pi} \int_0^{2\pi} i_{0,m} \sin n\omega t \, \text{d}t = 1 - \frac{1}{\pi \beta_m} (\beta_m - 1)(2\alpha + \sin 2\alpha)
\]

(11)

\[
i_{n,0,m} = \frac{1}{\pi} \int_0^{2\pi} i_{0,m} \sin n\omega t \, \text{d}t = \frac{2(1 - \beta_m)}{n\pi \beta_m} \left[ \sin((1-n)\alpha) + \frac{\sin((1+n)\alpha)}{1+n} \right]
\]

(12)

Thus, the \( n \)-th harmonic current coefficient \( k_{h,n} \) of CRT working winding can be obtained, as shown in Equation (13).

\[
k_{h,n} = \frac{i_{n,0,m}}{i_{1,0,m}} = \frac{I_{n,0,m}}{I_{1,0,m}} = \frac{2(1 - \beta_m)}{n\pi \beta_m} \left[ \sin((1-n)\alpha) + \frac{\sin((1+n)\alpha)}{1+n} \right]
\]

(13)

B. ANALYSIS OF CONTROL CHARACTERISTICS

The working form and operation sequence of the thyristor valve group in each control winding circuit of the CRT are called the regulation mode of the CRT [13]. Taking the sequential single branch regulation mode of the CRT as an example, this paper analyses its control characteristics.

For the sequential single branch regulation mode of the CRT in the regulation process of CRT from no-load to rated load (as shown in Figure 1), the trigger angle of thyristor \( T_1 \) in control winding \( CW_1 \) circuit starts to adjust until thyristor \( T_1 \) is completely turned on (at this time, the control winding circuit is in short circuit), while the thyristors of the other control winding circuits are completely turned off. Next, the trigger angle of thyristor \( T_2 \) in control winding \( CW_2 \) circuit starts to adjust until
thyristor T_2 is completely turned on. At this time, the CW_1 and CW_s circuits are completely short circuited, and the thyristors in the other control winding circuits are turned off. By analogy, when thyristor T_m of control winding CW_m circuit is in the regulated state, thyristors T_1−T_m−1 are in the conduction state and T_m+1−T_s+1 are turned off.

According to the relationship between the working winding fundamental current of the dual control winding basic unit magnetic integrated CRT and the trigger angle of the thyristor shown in Equation (11), the expression of the working winding current (i.e. the control characteristic expression) when the m-th control winding of the CRT is in the regulation state can be obtained, as shown in Equation (14).

\[
I_{0,m}(\varphi) = I_{d0,m} \left[ 1 - \frac{1}{\pi \beta_m} (\beta_m - 1) (2\alpha + \sin 2\alpha) \right]
\] (14)

To summarise, Equations (11)–(14) shows the interrelations among the working winding current, harmonic coefficient, thyristor trigger angle, capacity increasing coefficient, control winding technology, capacity of each control winding and regulation mode of the CRT. Therefore, the reasonable calculation and optimisation of the above parameters can control the harmonic current of the working winding effectively and improve the control characteristics.

C. ANALYSIS OF VOLT-AMPERE CHARACTERISTIC

The CRT is equivalent to a multi-winding transformer in graded short-circuit state, so the essence of its compensation inductance is the short-circuit impedance of the transformer. Therefore, having a good volt–ampere characteristic during operation is of great significance for the transformer. Therefore, having a good volt–ampere characteristic during operation is of great significance for the CRT [17]. The unit value of the CRT voltage is

\[ U^* = \frac{U}{U_m} \]

and the relative value of the fundamental current amplitude of the CRT working winding is known, as shown in Equation (11). Then, the unit value of the equivalent impedance of the CRT is as shown in Equation (15).

\[ Z^* = \frac{U^*}{I_{1m0,m}} \]

(15)

Given that the working winding of the CRT is directly connected in parallel to the high-voltage bus and the power system voltage is constant, that is, \( U^* = 1 \) (p.u.), according to Equation (15), the volt–ampere characteristic curve of the CRT in the regulation state can be obtained by changing the trigger angle of the thyristor.

V. EXAMPLE ANALYSIS

Assuming that the dual control winding basic unit magnetic integrated CRT has control winding stage s=4, it has two independent dual control winding basic units. For the convenience of analysis and calculation, the following are assumed: the rated voltage of the CRT is 220 V, the working frequency is 50 Hz, the rated current of the control windings at all levels is 10 A, and the turns of the working and control windings at all levels are 266. The inductance parameters in the equivalent circuit diagram of the dual control winding basic unit in Figure 4 are shown in Table 1. Given that the rated parameters of the two dual control windings’ basic unit structure are the same, their inductance parameters are also the same.

| TABLE 1 | INDUCTANCE PARAMETERS OF DUAL CONTROL WINDING BASIC UNIT |
|---------|----------------------------------------------------------|
| Inductance | Parameter/H | Inductance | Parameter/H |
| L_{s1} | 0.0073 | L_2 | 6.7573 |
| L_{s2} | 0.0073 | L_3 | 0.0486 |
| L_{s3} | 0.0073 | L_4 | 0.0486 |
| L_1 | 6.7573 | L_5 | 2.5124 |
| L_2 | 2.5124 |

According to the Figure 4 and Table 1, the simulation model of the dual control winding basic unit magnetic integrated CRT is established based on the MATLAB/Simulink simulation platform, as shown in Figure 5.

A. WINDING CURRENT CALCULATION OF CRT

By introducing the inductance parameters of the dual control winding basic unit magnetic integrated CRT shown in Table 1 into Equations (1)–(6), the analytical calculation results of each winding current effective value of the dual control winding basic unit magnetic integrated CRT when control windings CW_1−CW_m (1 ≤ m ≤ s) are short circuited in turn can be obtained, as shown in Table 2. Bringing the working winding current shown in Table 2 into Equation (7), the instantaneous current waveform of the working winding under thyristor regulation can be obtained. Assuming that the 4th stage control winding (CW_4) of the CRT is in the regulation state, CW_1−CW_3 are completely short circuited. At this time, the analytical calculation results of the instantaneous current waveform of the CRT working winding under different trigger angles are shown in Figure 6(a). To verify the analytical calculation results of the winding current on the basis of the CRT simulation model shown in Figure 5, the simulation calculation results of each winding current of the CRT are shown in Table 3. By changing the thyristor trigger angle of the 4th stage control winding, the simulation result of the instantaneous current waveform of the working winding under different trigger angles can be obtained, as shown in Figure 6(b).
FIGURE 5  Simulation model of dual control-winding basic unit magnetic integrated CRT

TABLE 2  WINDING CURRENT CALCULATION IN ANALYTICAL METHOD

| Winding | No load | CW₁ is in full operation | CW₂-CW₃ are in full operation | CW₄-CW₅ are in full operation |
|---------|---------|--------------------------|-------------------------------|-------------------------------|
| BW      | 1.49    | 12.20                    | 20.74                         | 31.45                         | 39.99                         |
| CW₁     | 0       | 10.71                    | 9.54                          | 9.54                          | 9.54                          |
| CW₂     | 0       | 0                        | 9.54                          | 9.54                          | 9.54                          |
| CW₃     | 0       | 0                        | 10.71                         | 9.54                          | 9.54                          |
| CW₄     | 0       | 0                        |                               | 0                              | 9.54                          |

TABLE 3  WINDING CURRENT CALCULATION IN SIMULATION

| Winding | No load | CW₁ is in full operation | CW₂-CW₃ are in full operation | CW₄-CW₅ are in full operation |
|---------|---------|--------------------------|-------------------------------|-------------------------------|
| BW      | 1.36    | 12.06                    | 20.62                         | 31.32                         | 39.87                         |
| CW₁     | 0       | 10.95                    | 9.85                          | 9.85                          | 9.85                          |
| CW₂     | 0       | 0                        | 9.85                          | 9.85                          | 9.85                          |
| CW₃     | 0       | 0                        | 10.96                         | 9.85                          | 9.85                          |
| CW₄     | 0       | 0                        | 0                              | 9.85                          |

FIGURE 6  Instantaneous current waveform of CRT’s working winding of under different trigger angles: (a) Instantaneous current of working winding in analytical calculation; (b) Instantaneous current of working winding in simulation calculation

Tables 2 and 3 indicate that the working winding current of the dual control winding basic unit magnetic integrated CRT increases step by step with the sequential input of control windings, and the current of winding that has been put into operation hardly changes with the input of subsequent windings, that is, decoupling is realised among the control windings of the CRT. Combined with Figure 6, for any control winding, the current can be changed by regulating the trigger angle of the thyristor, and the current distortion is not serious.

In addition, the comparisons of the current of each winding shown in Tables 2 and 3 and the instantaneous current waveform of the working winding shown in Figures 6(a) and 6(b) show that the analytical calculation results of
the winding current of the dual control winding basic unit magnetic integrated CRT are consistent with the simulation results, verifying the validity of the CRT equivalent mathematical model, the analytical calculation formula of winding current and the CRT simulation model.

**B. HARMONIC CHARACTERISTIC ANALYSIS OF CRT**

By combining Equations (8) and (13) and the working winding current shown in Table 2, the variation law of each harmonic coefficient of the CRT under different trigger angles can be obtained, as shown in Figure 7.

![Figure 7](image1.png)

**FIGURE.7** Harmonic coefficient curve of CRT’s working winding

Figure 7 shows that among the harmonic components within the entire thyristor regulation range of the CRT, the harmonic coefficients of the 3rd, 5th, 7th, 9th and 11th harmonics are 3.39%, 1.18%, 0.59%, 0.35% and 0.23%, respectively, that is, within the entire regulation range of the thyristor trigger angle. The harmonic characteristics are good and meet the harmonic requirements of the reactor. Overall, the dual control winding basic unit magnetic integrated CRT has the characteristics of low harmonic current.

**C. ANALYSIS OF CRT COST**

By introducing the working winding current shown in Table 2 into Equation (15), the control characteristic curve of the CRT can be obtained, as shown in Figure 8. For the CRT, to prevent the injection of a large number of harmonics under light load, the first stage control winding must jump directly [13]. In addition, with the continuous change of the thyristor trigger angle of the control winding at all levels, the working winding current of the CRT can realise a continuous and smooth transition. With the operation of each control winding in turn, the dual control winding basic unit magnetic integrated CRT exhibits the characteristics of hierarchical and smooth adjustment.

![Figure 8](image2.png)

**FIGURE.8** Control characteristic curve of CRT

**D. VOLT-AMPERE CHARACTERISTIC ANALYSIS OF CRT**

By combining Equations (11) and (15), the volt–ampere characteristic curve of the CRT in the regulated state can be obtained, as shown in Figure 9. Figure 9 shows that the volt–ampere curve of the dual control winding magnetic integrated CRT is approximately linear, indicating its good volt-ampere characteristics.

![Figure 9](image3.png)

**FIGURE.9** Volt-ampere characteristic curve of CRT

**E. VOLT-AMPERE CHARACTERISTIC ANALYSIS OF CRT**

On the basis of the CRT simulation model shown in Figure 5, the transition process of the CRT from 25% load to 100% load is shown in Figure 10. When \( t \in (0,0.1)\), only first stage control winding \( CW_1 \) is put into full operation, and the other control windings are not put into operation. When \( t = 0.1s \), all other control windings (\( CW_2 \)–\( CW_4 \)) are put into operation. At this time, the CRT reaches the rated capacity. Figure 10 shows that the dual control winding basic unit magnetic integrated CRT quickly enters the steady state at the moment of subsequent control winding input, which can not only realise the transition from steady state to steady state but also have a very fast response.
and approximately linear.

It has the characteristics of fast response and integrated CRT can realize the transition from steady state. It has the characteristics of hierarchical smooth regulation and dual control winding basic unit magnetic integrated CRT can be realized, and the current distortion is small. That is, the winding circuit, the smooth adjustment of the current can be realized, and the trigger angle of the thyristor in the control winding can be step with the sequential input of the control winding. By using the theoretical derivation.

According to the CRT's mathematical model, the MATLAB/Simulink simulation model is established, and the winding current and the response speed are simulated. Finally, its working characteristics are summarized and analyzed. The conclusions are as follows.

1. The analytical calculation results of the winding current of the dual control winding basic unit magnetic integrated CRT are in good agreement with the simulation results, which can verify the correctness and effectiveness of the theoretical derivation.

2. The working winding current of the dual control winding basic unit magnetic integrated CRT increases step by step with the sequential input of the control winding. By regulating the trigger angle of the thyristor in the control winding circuit, the smooth adjustment of the current can be realized, and the current distortion is small. That is, the dual control winding basic unit magnetic integrated CRT has the characteristics of hierarchical smooth regulation and low harmonic current.

3. The dual control winding basic unit magnetic integrated CRT can realize the transition from steady state to steady state. It has the characteristics of fast response and high sensitivity, and its volt-ampere characteristics is good and approximately linear.

VI. CONCLUSION

In this paper, a new type of magnetic integrated CRT, that is, the dual control winding basic unit magnetic integrated CRT, is taken as the research object, and the winding current, harmonic current, control characteristic and volt-ampere characteristic expressions are derived. According to the CRT's mathematical model, the MATLAB/Simulink simulation model is established, and the winding current and the response speed are simulated. Finally, its working characteristics are summarized and analyzed. The conclusions are as follows.

1. The analytical calculation results of the winding current of the dual control winding basic unit magnetic integrated CRT are in good agreement with the simulation results, which can verify the correctness and effectiveness of the theoretical derivation.

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