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Single-winding Regulation Mode of Controllable Reactor of Transformer Type

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Abstract
It is an important part to select the regulation mode in the design and manufacture of a controllable reactor of transformer type (CRT). Based on the circuit equations expressed by the self and mutual inductance, the piecewise expressions of the instantaneous current in work winding in the single-winding regulation mode are obtained, and then the formula for calculating the RMS of each harmonic current in work winding is derived by Fourier series decomposition. At last, the control characteristics of CRT and the curves of the RMS of harnonic currents with reference to the output power in three typical single-winding regulation modes are presented and their advantages and disadvantages are compared in the sample, which provides a reference for the design of CRT.

Keywords: *controllable reactor of transformer type, single-winding regulation mode, harmonic current*

1. Introduction

Reactive balance is very important for the secure and economical operation of the power systems[1]. By now, due to the long-term efforts of many scientific workers at home and abroad, there are various kinds of reactive-load compensation equipments have come into use [2-4], In 1995, G.N.Aleksandrov, a Russian expert, came up with the basic circuit diagram of CRT[5], after that many scholars do further research on it [6-9], and point out that CRT has the advantages of fast response and controllable harmonic contents, which is a reactive-load compensation equipment that can applies to EHV transmission lines.

The key reason the harmonic contents of CRT can be controlled is that there is a restriction among regulation mode, control steps, capacity of each step and harmonic contents. Reference [7] presented 3 regulation modes: step-single-branch mode, fixed-single-branch mode, transfer-single-branch mode, since all of them allow only one control winding to be regulated, they can be called as single-winding regulation mode. Reference [7] did research on the 3 modes in case of neglecting the coupling of the control windings. However, the non-ignorable inductive coupling always exists among the control widings, and each of the control winding current will seriously affect the others, this leads to a great difficulty for the selection of the rated capacity of each control winding.

In this paper, taking into account of the inductive coupling among the control widings, the formulas for calculating the RMS of each harmonic current and the current harmonic coefficients are given, and then the variation trends of the output power and the curves of the RMS of harnonic currents with reference to the output power in the three typical single-winding regulation modes are presented, this will provides a reference for the design of a CRT.

2. Instantaneous Current of Working Winding

The basic circuit diagram of a CRT is illustrated in Figure 1, where, W_1 is the high-voltage work winding, and W_2 , W_3 ,…, W_n are control windings. In addition, each control winding is equipped with a current-limiting reactor (X_2 , X_3 ,…, X_n) and a thyristor switch (T_2 , T_3 ,…, T_n)which consists of two thyristors in parallel but in opposite directions. Assume that the voltage of

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the grid is shown as $u_1=\sqrt{2}U_1\cos(\omega t)$, and the starting point during each period is the time when the voltage of the grid reached maximum.

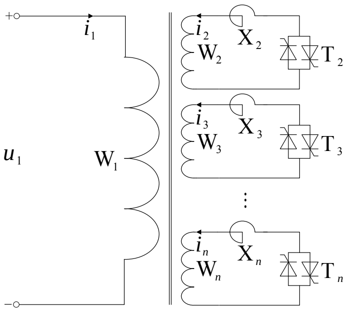


Figure 1. Basic Circuit Diagram of CRT

Including W_1 ,There are n windings in the CRT illustrated in Figure 1. Assume that all the parameters of all windings are referred to W_1. Neglecting the iron saturation and all resistance, the instantaneous circuit equations for all of the windings while all the n–1 control windings are short-circuited are given by (1), where, L_k is the self-inductance of W_k ($1\le k\le n$), M_{kq} is the mutual-inductance between W_k and W_q , $L_{\mathrm{x}k}$ is the inductance of X_k , while X_k is the current-limiting reactor connected with W_k as mentioned above.

$$\boldsymbol{L}_n(p\boldsymbol{i}_n)=\boldsymbol{u}_n \tag{1}$$

Where, $\boldsymbol{L}_n=\begin{bmatrix} L_1 & M_{12} & M_{13} & \cdots & M_{1n} \\ M_{21} & L_2+L_{\mathrm{x}2} & M_{23} & \cdots & M_{2n} \\ M_{31} & M_{32} & L_3+L_{\mathrm{x}3} & \cdots & M_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ M_{n1} & M_{n2} & M_{n3} & \cdots & L_n+L_{\mathrm{x}n} \end{bmatrix}$, $p=\mathrm{d}/\mathrm{d}t$, $\boldsymbol{i}_n=[i_1\ \ i_2\ \ i_3\ \ \cdots\ \ i_n]^{\mathrm{T}}$, $\boldsymbol{u}_n=[u_1\ \ 0\ \ 0\ \ \cdots\ \ 0]^{\mathrm{T}}$.

Assume that there are $h-1$ ($1\le h\le n$)control windings are involved in the operation, and only one of them is being regulated, whose triggered angle is equal to α ($0<\alpha<\pi/2$), while the other $h-2$ are short-circuited during the period. Since the symmetry of current waveform in W_1 , we just have to work out the expression for the instantaneous current in $[0,\pi/2]$.

The circuit equations for all of the windings in $(0,\alpha]$ can be rewritten as:

$$\boldsymbol{L}_{h\text{-}1}(p\boldsymbol{i}_{h\text{-}1})=\boldsymbol{u}_{h\text{-}1} \tag{2}$$

Where, $\boldsymbol{L}_{h-1}$, $\boldsymbol{i}_{h-1}$, $\boldsymbol{u}_{h-1}$ are the submatrixes of $\boldsymbol{L}_n$, $\boldsymbol{i}_n$, $\boldsymbol{u}_n$ respectively, which can be obtained by removing the elements of $\boldsymbol{L}_n$, $\boldsymbol{i}_n$, $\boldsymbol{u}_n$ that corresponding to the regulated and open-circuited windings.

From(2), the differential equation for the work winding current is derived as:

$$\frac{\mathrm{d}i_1}{\mathrm{d}t}=\frac{u_1}{L_{1,h-1}} \tag{3}$$

Where, $1/L_{1,h\text{-}1}$ is the first element of the first column of $\boldsymbol{L}_{h\text{-}1}^{-1}$, and $\boldsymbol{L}_{h\text{-}1}^{-1}$ is the inverse matrix of $\boldsymbol{L}_{h\text{-}1}$. Since the initial condition in this time segment is $i_1|_{\omega t=0}=0$, from (3), i_1 is figure out as (4).

$$i_1=\frac{\sqrt{2}U_1}{\omega L_{1,h\text{-}1}}\sin(\omega t) \quad (4)$$

In the same way, the circuit equation for work winding current in $(\alpha,\pi/2]$ can be rewritten as:

$$\frac{\mathrm{d}i_1}{\mathrm{d}t}=\frac{u_1}{L_{1,h}} \quad (5)$$

Where, $1/L_{1,h}$ is the first element of the first column of $\boldsymbol{L}_h^{-1}$, and $\boldsymbol{L}_h^{-1}$ is the inverse matrix of $\boldsymbol{L}_h$, and $\boldsymbol{L}_h$ is the submatrixes of $\boldsymbol{L}_n$,which can be obtained by removing the elements of $\boldsymbol{L}_n$ that corresponding to the open-circuited control windings. Since the final value of the former time segment is the initial condition of the current time segment,from(5), i_1 can be figure out as (6).

$$i_1=\frac{\sqrt{2}U_1}{\omega L_{1,h}}\sin(\omega t)-(\frac{\sqrt{2}U_1}{\omega L_{1,h}}-\frac{\sqrt{2}U_1}{\omega L_{1,h\text{-}1}})\sin\alpha \quad (6)$$

3. Formulas for Calculating Harmonics

The waveform of i_1 is symmetric among 4 quarter periods, which contains only fundamental and odd harmonics. Hence, i_1 can be expressed as a Fourier series like this.

$$i_1=\sum_{k=1}^{\infty}\{b_{2k-1}\sin[(2k-1)\omega t]\} \quad (7)$$

Where,

$$\left.\begin{array}{c} b_{2k-1}=\frac{4}{\pi}\int_0^{\frac{\pi}{2}}i_1(\omega t)\sin[(2k-1)\omega t]\mathrm{d}(\omega t) \\ (k=1,2,3,\cdots) \end{array}\right\} \quad (8)$$

From (4), (6), (8), the RMS of the $2k-1(k=1,2,3,\cdots)$th harmonic current in the work winding can be derived as (9):

$$I_{2k-1}=\frac{U_1}{\pi\omega}\left|\frac{1}{L_{1,h}}f_k(\pi/2)+(\frac{1}{L_{1,h-1}}-\frac{1}{L_{1,h}})f_k(\alpha)\right| \quad (9)$$

Where,

$$\left.\begin{array}{c} f_1(\alpha)=2\alpha+\sin 2\alpha \\ f_k(\alpha)=\frac{1}{2k-1}[\frac{\sin 2(k-1)\alpha}{k-1}+\frac{\sin 2k\alpha}{k}] \\ (k=2,3,4,\cdots) \end{array}\right\} \quad (10)$$

The formula(9) clarifies the relationship not only between the RMS of each current harmonic and triggered angle, but also between the harmonic components and the parameters of self and mutual inductance,which is very important for the design of CRT.

The $2k-1$ th current harmonic coefficient for the work winding can be derived

$$k_{\mathrm{H},2k-1}=\frac{I_{2k-1}}{I_1}=\left|\frac{f_k(\alpha_h)}{\pi L_{1,h-1}/(L_{1,h}-L_{1,h-1})+f_1(\alpha_h)}\right| \quad (11)$$

4. Analysis of Examples

Taking CRT described in [7] as an illustration, the 3 single-winding regulation modes are analysed in the case of taking account of the coupling of the control windings in this paper. The CRT described in [7] has 6 windings(including W_1), the rated voltage is $U_N = 500/\sqrt{3}\mathrm{kV}$. Based on the self and mutual impedance which can be converted into the self and mutual inductance and the inductance of current-limiting reactors which can be calculated by the recursion algorithm, $\boldsymbol{L}_n$ can be expediently obtained,in this case, $n=6$,Hence, $\boldsymbol{L}_6$ is (unit:H)

$$\boldsymbol{L}_6=\begin{bmatrix} 452.83 & 451.40 & 451.36 & 451.27 & 451.17 & 450.98 \\ 451.40 & 538.36 & 452.67 & 452.57 & 452.41 & 452.16 \\ 451.36 & 452.67 & 524.34 & 452.64 & 452.48 & 452.22 \\ 451.27 & 452.57 & 452.64 & 482.61 & 452.57 & 452.32 \\ 451.17 & 452.41 & 452.48 & 452.57 & 462.89 & 452.48 \\ 450.98 & 452.16 & 452.22 & 452.32 & 452.48 & 453.99 \end{bmatrix}$$

Referring to [7], a 5-digit binary code is used to represent the state of each thyristor switch, there is a one-to-one correspondence between per bit of this code in sequence from high to low and each control winding of CRT from W_6 to W_2, where, "0"means the corresponding control winding is open-circuited, and the triggered angle of its thyristor is equal to 90°;"1"means short-circuited, and the triggered angle of the corresponding thyristor is equal to 0°; "$\overset{\frown}{1}$"means regulation, the corresponding triggered angle falls somewhere in between those two.

During the process that the output power of CRT changes from no-load to the rated, the variation range of output power can be divided into 5 steps in step-single-branch mode, 16 steps in fixed-single-branch mode, and 15 steps in transfer-single-branch mode in this case.

According to the above description, the regulating processes of the 3 operation modes are as follows. The double arrow in the processes indicates that the process is reversible, where, "$\leftrightarrow$" presents a instantaneously shifted process of winding currents, while "$\Leftrightarrow$" means a smooth power regulation due to the change of triggered angle of the thyristor switch.

(1) Step-single-branch mode

$$00000\overset{(1)}{\leftrightarrow}00001\overset{(2)}{\Leftrightarrow}00011\overset{(3)}{\Leftrightarrow}00111\overset{(4)}{\Leftrightarrow}01111\overset{(5)}{\Leftrightarrow}11111$$

(2) Fixed-single-branch mode

$$\overbrace{00000\leftrightarrow 00001}^{(1)}\leftrightarrow\overbrace{00010\Leftrightarrow 00011}^{(2)}\leftrightarrow\overbrace{00100\Leftrightarrow 00101}^{(3)}\leftrightarrow\overbrace{00110\Leftrightarrow 00111}^{(4)}\leftrightarrow\overbrace{01000\Leftrightarrow 01001}^{(5)}\leftrightarrow\overbrace{01010\Leftrightarrow 01011}^{(6)}$$

$$\leftrightarrow\overbrace{01100\Leftrightarrow 01101}^{(7)}\leftrightarrow\overbrace{01110\Leftrightarrow 01111}^{(8)}\leftrightarrow\overbrace{10000\Leftrightarrow 10001}^{(9)}\leftrightarrow\overbrace{10010\Leftrightarrow 10011}^{(10)}\leftrightarrow\overbrace{10100\Leftrightarrow 10101}^{(11)}\leftrightarrow\overbrace{10110\Leftrightarrow 10111}^{(12)}$$

$$\leftrightarrow\overbrace{11000\Leftrightarrow 11001}^{(13)}\leftrightarrow\overbrace{11010\Leftrightarrow 11011}^{(14)}\leftrightarrow\overbrace{11100\Leftrightarrow 11101}^{(15)}\leftrightarrow\overbrace{11110\Leftrightarrow 11111}^{(16)}$$

(3) Transfer-single-branch mode

$$\overbrace{00000\Leftrightarrow 00001}^{(1)}\leftrightarrow\overbrace{000\overset{\frown}{1}0\Leftrightarrow 00010}^{(2)}\leftrightarrow\overbrace{00\overset{\frown}{1}00\Leftrightarrow 00100}^{(3)}\leftrightarrow\overbrace{0\overset{\frown}{1}000\Leftrightarrow 01000}^{(4)}\leftrightarrow\overbrace{\overset{\frown}{1}0000\Leftrightarrow \underline{10000}}^{(5)}\underbrace{\Leftrightarrow}_{(6)}\underline{10001}$$

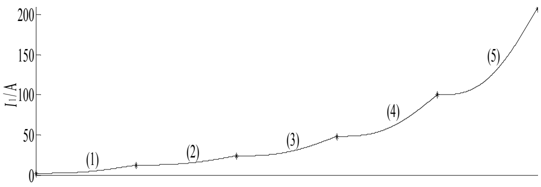
$$\leftrightarrow\overbrace{100\overset{\frown}{1}0\Leftrightarrow 10010}^{(7)}\leftrightarrow\overbrace{10\overset{\frown}{1}00\Leftrightarrow 10100}^{(8)}\leftrightarrow\overbrace{1\overset{\frown}{1}000\Leftrightarrow \underline{11000}}^{(9)}\underbrace{\Leftrightarrow}_{(10)}\underline{11001}\leftrightarrow\overbrace{110\overset{\frown}{1}0\Leftrightarrow 11010}^{(11)}\leftrightarrow\overbrace{11\overset{\frown}{1}00\Leftrightarrow \underline{11100}}^{(12)}\underbrace{\Leftrightarrow}_{(13)}\underline{11101}$$

$$\leftrightarrow\overbrace{111\overset{\frown}{1}0\Leftrightarrow \underline{11110}}^{(14)}\underbrace{\Leftrightarrow}_{(15)}\underline{11111}$$

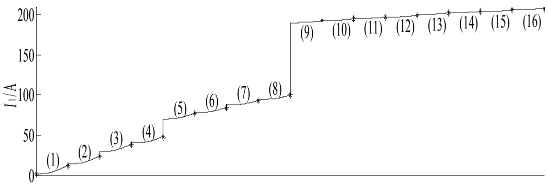
Figure 3 shows the piecewise curves of the RMS of fundamental current in work winding with reference to the triggered angle during each step,namely,the control characteristic. The number in each parenthesis in Figure 3 represents the step number, which is the same with what in the regulating processes metioned above. The corresponding triggered angle during each step reduces from 90° to 0° in both Figure 3(a) and Figure 3(b), which is different from Figure 3(c). In Figure 3(c), the triggered angle of the i th step reduces from a specific angle θ_i called as starting regulating angle that varies among different steps. In this case, the calculated values of θ_i are given in Table 1.

Table 1. Starting Regulating Angle of each Step in Transfer-single-branch Mode

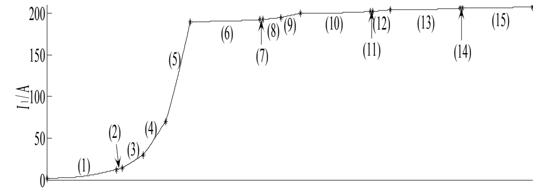
i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$\theta_i(^\circ)$	90.0	7.19	27.1	29.1	31.8	90.0	3.90	23.1	25.0	90	3.40	22.4	90.0	3.20	90.0



(a) step-single-branch mode



(b) fixed-single-branch mode



(c) transfer-single-branch mode

Figure 3. RMS of Fundamental Current vs Step Numbers

Figure 3(b) shows that the output power is intermittent when the CRT operating in fixed-single-branch mode, which is mainly due to that the capacity assignment of each control winding can't satisfy the design requirement for continuation, in fact, the capacity of each control winding mainly depends on the value of its current-limiting reactor. Hence, it is of great importance to select a appropriate value for each current-limiting reactor in order to satisfy the continuation of output power. Figure 3(a) and Figure 3(c) shows that the output power is continuous when CRT operating in step-single-branch mode and transfer-single-branch mode, but the regulation of output power mainly depends on the fourth and fifth step in this case, and the capacity of the regulating control windings in these two steps are larger than others,this is unreasonable in the practical application.

Figure 4 shows respectively the variation tendency of the RMS of the 5th, 7th, 11th, 13th harmonic current and the total harnonic current components (denoted as I_{H}) that poured into power system with reference to the RMS of the fundamental current in work winding.

The curves of the RMS of each harnonic current with reference to the output power have a trend of increase in both step-single-branch mode and transfer-single-branch mode, while they are steady in fixed-single-branch mode. Furthermore, the waveform distortion in transfer-single-branch mode is the most serious among 3 modes, and the waveform distortion in fixed-single-branch mode is much less than the other two. Analysing the trends of the above curves combining with each step, we can find that it will lead to larger harmonic current in work winding if a control winding of larger capacity is regulated.

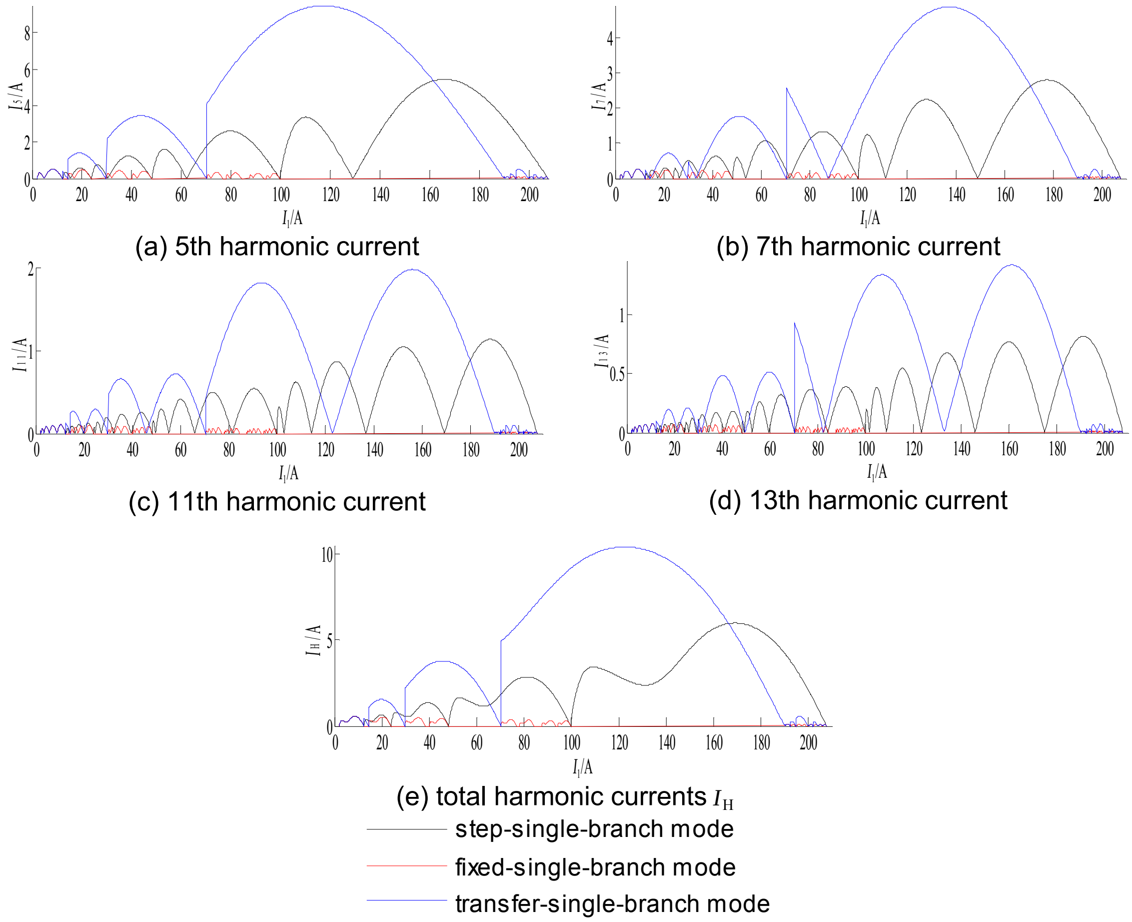


Figure 4. RMS of every Harmonic Currents and I_H vs output Power

4. Conclusion

(1) The RMS of harmonic currents in work winding of all kinds of single-winding regulation mode in the case of considering the coupling among control windings can be calculated by an unified formula.

(2) Operating in the single-winding regulation mode, the control winding of small capacity should be regulated to reduce the harmonic contents in the work winding on the premise that the continuation of the output power have been ensured.

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