Simulation Analysis for Controllable Reactor of Transformer Type with Multifold Magnetic Materials Integration

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Abstract: - This paper presents a construction of a controllable reactor of transformer type (CRT) with multifold magnetic materials, and the construction based on the magnetic-integration techniques is used to weaken the magnetic coupling effect among control windings and eliminate requirement of series current limiting reactance. At last, based on the proposed equivalent circuit of integrated magnetic structure, a simulation model is fabricated by MATLAB/SIMULINK. Simulation analysis of winding current and control characteristic show that this construction meets the design requirements of “high impedance and weak coupling”, the harmonic content of the work winding is small, also the construction can realize the smooth reactive power regulation and react with a high speed. The validity of the construction and the correctness of the simulation model are proved by the results of simulation. This multifold magnetic materials integration method offers a reference to the integration of complex electromagnetic equipment.

Key-Words: - Controllable Reactor of Transformer Type, Magnetic Integration, Magnetic Coupling, Equivalent Circuit, Simulation Model, Simulation Analysis.

1 Introduction

Reactive power balance is a key to guarantee stable operation of electrical power system. Controllable reactor is a reactive compensation device which can achieve dynamic compensation of reactive power. Therefore, the research of the controllable reactor has become a hotspot. With the increasing of net capacity, voltage level and the capacitive reactive power of transmission line, researching of controllable reactor of high voltage and large capacity has more important significance [1,2]. Controllable reactor of transformer type (CRT) is an important reactive power compensation device of EHV and UHV transmission lines which can realize swift and smooth regulation with small harmonics in a broad range [3].

The essentiality of the CRT is a multi-winding transformer whose control winding works under short circuit states in orderly. It achieves the quick and smooth adjust by controlling conduction angle of anti-parallel thyristors which cascaded in control winding loops. In order to keep short circuit current of each control winding near the rated value and subsequent control windings affect a little to current of control windings when they have been taken into operation when CRT is working, Reference [4] proposes the design rule of CRT is “high impedance and weak coupling”, which means the big-enough short circuit impedance between work winding and control winding and small-enough magnetic coupling among control windings. In previous research, cascading current limiting reactor in the control winding loop is equivalent to increase the short circuit impedance between the work winding and control winding, it is also equivalent to decrease the magnetic coupling among control windings [5]. However, cascading current limiting reactor in the control winding circuit increases the number of magnetic devices and makes the structure to be complicated. Also, the installed capacity is twice over the actual compensating capacity of transmission lines.

Reference [6] and [7] show that technology of magnetic integration not only achieves integration of inductance and transformer, but also realizes decoupling of multifold wildings. Reference [8,9] propose that the general method is increase magnetic reluctance of core column wound around wildings by opening the air-gap in them in order to realize decoupling of wildings, thus, the magnetic flux caused by wildings comprises close loop through its own core and public magnetic circuit of low magnetic resistance which has no air-gap. This method weakens the magnetic coupling among wildings. Another way is that splitting the wildings on structure of array core to achieve the same purpose [10, 11]. But no-load current of the device and wastage will increase obviously when the core has the air-gap is applied in the structure of CRT. The structure of the array core will also increase volume and complexity of CRT.

This paper proposes a construction of CRT with multifold magnetic material integration based on technology of magnetic integration. It builds an equivalent circuit of this structure. The paper also has completed simulation analysis for work winding current, control characteristic and transient process. Results of the simulation show that this structure can meets the design requirements of “high impedance and weak coupling”, in the same time, it simplifies the construction and decreases the no-load current. The current of work winding can meet the requirements of harmonic. This structure also achieves adjusting quickly and smoothly. The method proposed in the paper offers a reference for the integration between complex electromagnetic devices, it also expands the method and application of the technology of magnetic integration.

2 Magnetic Integrated Structure of CRT

The figure of CRT working principle is shown in Fig.1.

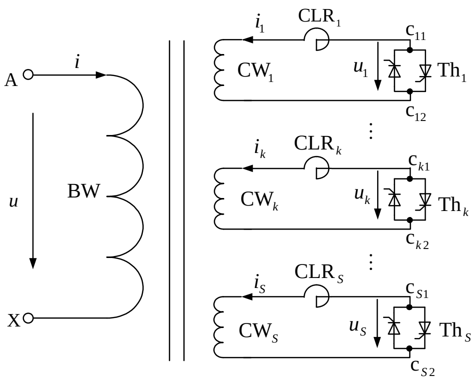

Fig.1 The figure of CRT working principle

In Fig.1, A and X are two ports of work winding connected to power grid. c_{k1} and c_{k2} are two ports of control winding CW_k. Anti-parallel thyristors are connected between them. BW is work winding; S is power-step number; CW_k is k-th (k=1,2,…,S) control winding; CLR_k is the current limiting reactor cascaded in the k-th control winding loop; Th_k is the anti-parallel thyristors cascaded in the k-th control winding as well; u, i are voltage and current of the work winding respectively; u_k is the k-th voltage of the anti-parallel thyristors; i_k is current of the control winding CW_k. CRT achieves adjusting quickly and smoothly of reactive power by controlling the conduction angle of the anti-parallel thyristors.

According to operating principle of CRT, we apply the technology of magnetic integration into the design of the CRT, and then propose the CRT’s integrated structure of variety magnetic permeability material as shown in Fig.2.

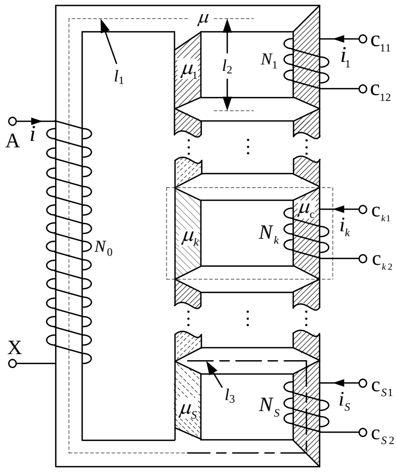

Fig.2 The CRT’s integrated structure of variety magnetic permeability material

As shown in Fig.2, the CRT’s integrated structure of variety magnetic permeability material is constituted by core column wound around the work winding, upper and lower yoke and control winding unit (parts in dashed box), the control winding unit includes core columns wound around control winding, the core paralleled with core columns wound around control winding, upper and lower yoke connect them. Magnetic material of different filled line type has different magnetic permeability in Fig.2, magnetic material of same filled line type has same magnetic permeability. N_0 is turns of work winding BW; N_k is turns of control winding CW_k, μ is permeability of core column wound around the work winding and yoke; μ_c is permeability of core column wound around the control winding; μ_k is the permeability of core column which paralleled with the core column wound around control winding. Every core column wound around the control winding has paralleled core column, which achieves the “high impedance” between control winding and work winding by distribute magnetic flux, i.e. which equivalent to achieves the integration of control winding and current limiting reactor. In order to meets the design requirement of the “weak-coupling” among control windings, $\mu > \mu_c$ and $\mu > \mu_k$. Thus, flux which is generated by control winding constitutes a closed loop through its own core and low magnetic resistance core which is wound around the work winding, this can decrease magnetic coupling among control windings and achieve the "weak coupling" purpose of CRT basically. This structure is needs not to cascade the current limiting reactor to loop of the control winding additionally, it not only meets the design requirement but also simplifies the whole device. Method of connection between different magnetic materials parts is same as column and yoke connection of regular transformer.

3 Equivalent Circuit of Integrated Magnetic CRT

According to the method of establishing transformer-inductance equivalent circuit for magnetic integrated structure in reference [12, 13], the equivalent circuit of magnetic integrated structure of Fig.2 is shown in Fig.3.

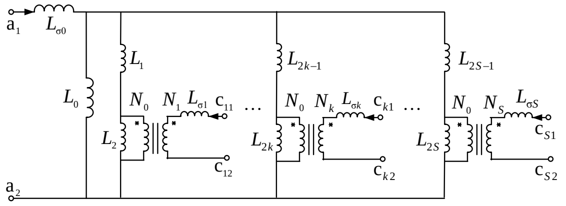

Fig.3 The equivalent circuit of integrated magnetic CRT

In Fig.3, $L_{\sigma 0}$ is leakage inductance of the work winding; $L_{\sigma k}$ is leakage inductance of the control winding CW_k; L_0 is magnetizing inductance corresponding to the core wound around work winding; L_{2k-1} is magnetizing inductance corresponding to the core which paralleled with the core wound around the control winding CW_k; L_{2k} is magnetizing inductance corresponding to the core wound around control winding CW_k. For N_0 as reference in equivalent circuit, the calculations of inductors are shown as following:

$$L_0 = N_0^2 / R_0 \quad (1)$$

$$L_{2k-1} = N_0^2 / R_{2k-1} \quad (2)$$

$$L_{2k} = N_0^2 / R_{2k} \quad (3)$$

Where, R_0 is magnetic resistance of core wound around work winding (including magnetic resistance of upper and lower yoke); R_{2k-1} is magnetic resistance of the core which paralleled with the core wound around the control winding CW_k; R_{2k} is magnetic resistance of core wound around control winding CW_k. The calculations of them are following:

$$R_0 = l_1 / (\mu A_1) \quad (4)$$

$$R_{2k-1} = l_2 / (\mu_k A_2) \quad (5)$$

$$R_{2k} = l_3 / (\mu_c A_3) \quad (6)$$

Where, $l_1=2(S+1)r_{co1}+2r_{co2}+2d+Sh$, $l_2=2r_{co1}+h$, $l_3=2(r_{co1}+r_{co2}+d)+2r_{co1}+h$; As shown in Fig.4, h is height of winding; r_{co1} is radius of the core wound around the control winding and the core wound around the work winding; r_{co2} is radius of the core which paralleled with the core wound around the control winding; $A_1=A_3=\pi\, r_{co1}^2$ □is cross sectional area of the core wound around the control winding and the work winding; $A_2 = \pi r_{co2}^2$ is cross sectional area of the core which paralleled with the core wound around the control winding; d is core window width.

4 The Winding Leakage Inductances Calculation of CRT

The winding leakage inductances calculation of the equivalent circuit which proposed in Fig.3 is shown as Fig.4.

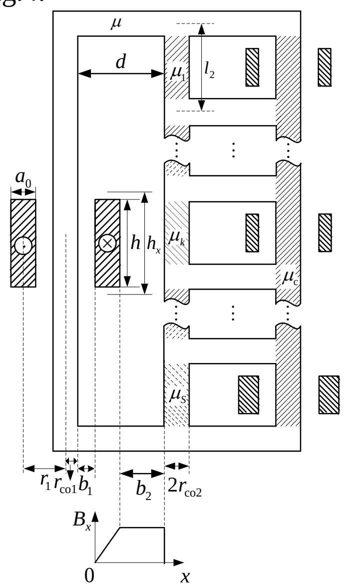

Fig.4 The calculation figure of leakage inductance integrated structure

Under the condition that neglecting the core magnetic saturation, choosing inside of winding as zero reference point, according to Ampere circuital theorem and relationship of the leakage inductance and leakage magnetic field energy[14], the work winding leakage inductance as following:

$$L_{\sigma 0} = \mu_0 \pi N_0^2 \rho (2 r_1 a_0 / 3 + 2 r_1 + a_0 b_2 + b_2^2) / h \quad (7)$$

In similar way, according to the (7), the control winding leakage inductance formula when normalized to turns of the work winding is following:

$$L_{\sigma k} = \mu_0 \pi N_0^2 \rho (2 r_{ck} a_k / 3 + 2 r_{ck} + a_k b_{k2} + b_{k2}^2) / h \quad (8)$$

Where, a_k is control winding CW_k thickness neglecting turn insulation; r_{ck} is distance of the control winding CW_k and its core columns between the centerline; b_{k2} is distance from lateral of control winding CW_k to parallel core column.

5 The Simulation Analysis Based on MATLAB of CRT

The CRT of magnetic integrated structure composed of variety of magnetic materials shown as Fig.2, the grid voltage is U=500/$\sqrt{3}$ kV, its rated current is I_e=208A, S=4, power increment coefficient β_{st}=2.1, rated current of every level (the current of work winding BW) should be 22.46A, 47.17A, 99.05A, 208A, frequency f=50Hz, turns of work winding is N_0=1600, other parameters are shown in Table 1 [15].

Table 1 The structural parameter

parameters	value	parameters	value(cm)
μ_ε	10000	a_0	12.0
$\mu_{1\varepsilon}$	2400	a_1	1.0
$\mu_{2\varepsilon}$	1300	a_2	1.1
$\mu_{3\varepsilon}$	460	a_3	2.4
$\mu_{4\varepsilon}$	100	a_4	5.0
$\mu_{c\varepsilon}$	1200	h	120.0
ρ	0.898	b_1	5.5
		d	32.8
		r_{co1}	35.4
		r_{co2}	6.5

In Table 1, μ_ε is the relative permeability of the core column wound around work winding and the yoke, according to the parameters, silicon steel sheet whose relative permeability is 10000 can been used as the core material. $\mu_{k\varepsilon}$ (k=1,2,3,4) is the relative permeability of the core column which paralleled with core column wound around control winding CW_k, according to the value of the relative permeability of ferromagnetic materials, Mn-Zn ferrite whose relative permeability is 1000-3000 can been used as the core material of core columns which paralleled with core column wound around control winding CW_1 and CW_2, Ni-Zn ferrite whose relative permeability is 10-500 can been used as the core material of core columns which parallel with core column wound around control winding CW_3 and CW_4; $\mu_{c\varepsilon}$ is the relative permeability of core column wound around control winding, its material can been used the Mn-Zn ferrite whose relative permeability is 1200, the meaning of the other parameters are exactly the same with Fig.4.

Substituting structural parameters shown in Table 1 into (1)-(8) can be calculated the inductance in equivalent circuit of Fig.3 shown in Table 2.

The MATLAB simulation model of CRT based on the equivalent circuit shown in Fig.3 is shown as Fig.5.

Table 2 The inductance value be calculated

parameters	value (H)	parameters	value (H)
L_0	1.2873×10^3	$L_{\sigma0}$	1.6851
L_1	53.7105	$L_{\sigma1}$	2.2108
L_3	29.0932	$L_{\sigma2}$	2.2066
L_5	10.2945	$L_{\sigma3}$	2.1507
L_7	2.1379	$L_{\sigma4}$	2.0338
L_2	446.7383	L_4	446.7383
L_6	446.7383	L_8	446.7383

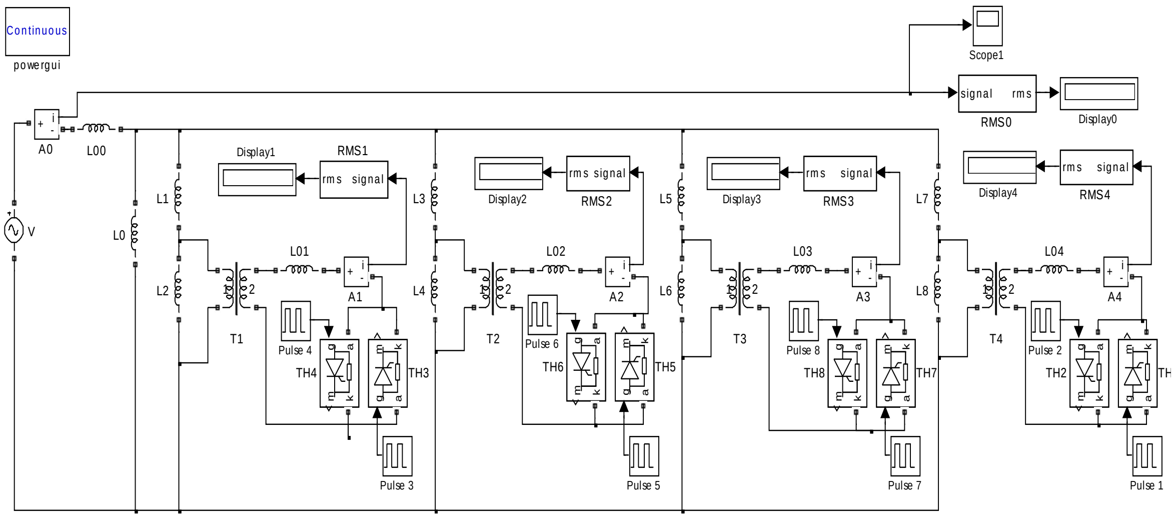

Fig.5 Simulation model of CRT by MATLAB/SIMULINK

5.1 The Winding Current Simulation and Harmonic Analysis

In Fig.5, which set the value of the component parameters according to the inductance values in Table 2, by controlling the conduction of anti-parallel thyristors cascade in control winding loops, the control winding can be short-circuited in orderly, it can get the short-circuit current of windings as shown in Table 3.

It can be concluded from Table 3 which the short-circuit current of the control windings remains near the rating (the number of bold is rated value), and with the follow-up control windings input, the current of the control windings have been put into operation decreases a little. For example, when the control winding CW_1 is short-circuited, the current RMS of control winding CW_1 is 15.66A, when all the windings are shorted, its current RMS is 10.12A, reduces 35.4%, the decrease of other control windings current is smaller, In reference [4], the maximum decreasing extent of current is 66.2% under the condition that a current limiting reactor is in series in loop of every control winding. Simulation data shows that the magnetic integrated structure composed of variety of magnetic materials shown as Fig.2 can achieve the CRT "high impedance" purposes. This structure also reduces the magnetic coupling among control windings, basically meets the design requirements of the CRT "weak coupling", at the same time, it is equivalent to integrated the control winding and current-limiting reactor together. The structure also simplifies the entire device. In addition, the CRT no-load current is only 4.5% of the rated current.

Table 3 The short-circuit current RMS of windings

	No-load current	Th_1 fully conduct	Th_1-Th_2 fully conduct	Th_1-Th_3 fully conduct	Th_1-Th_4 fully conduct
BW current I/A	9.36	22.88	46.71	100.20	207.90
CW_1 current I_1/A	0	**15.66**	14.95	13.35	10.12
CW_2 current I_2/A	0	0	**26.71**	23.84	18.07
CW_3 current I_3/A	0	0	0	**60.00**	45.48
CW_4 current I_4/A	0	0	0	0	**132.70**

According to the simulation model shown in Fig.5, the waveform of work winding current can be simulated when the fourth series control winding is in the adjusting state as Fig.6.

The waveform of work winding current shown in Fig.6, waveform 1,2,3,4,5 respectively corresponding to the firing angle is 0, π/8, π/4, 3π/8, π/2 of thyristors cascaded in the fourth control winding loop. It can be seen from figure that the current waveform distortion is small with the change of the triggering angle, therefore the harmonic current content is small [16].

Therefore, the magnetic integrated structure composed with variety of magnetic materials can meets the requirements of harmonic, under the condition of the same capacity of CRT, it can reduce power series and simplify the structure of CRT.

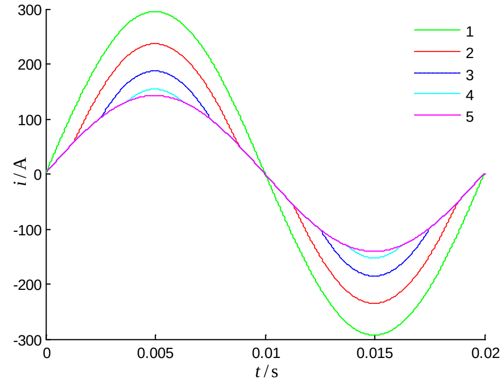

Fig.6 Current waveform of working winding in the forth step

5.2 Simulation analysis of control characteristic and the transition process Analysis

The control characteristic of CRT is shown as Fig.7.

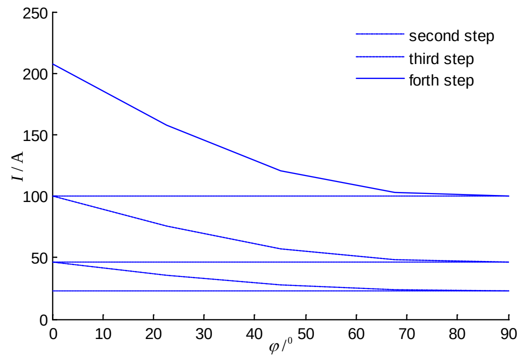

Fig.7 Control characteristic of CRT

Obviously, it can been seen that the CRT is smooth adjustment with classification from Fig.7, in order to reduce the harmonic, first series (0-11%) is direct transitions, while other three can achieve the smooth adjustment by controlling the anti-parallel thyristors of each one. The work winding current transition process of CRT with load changing is shown as Fig.8.

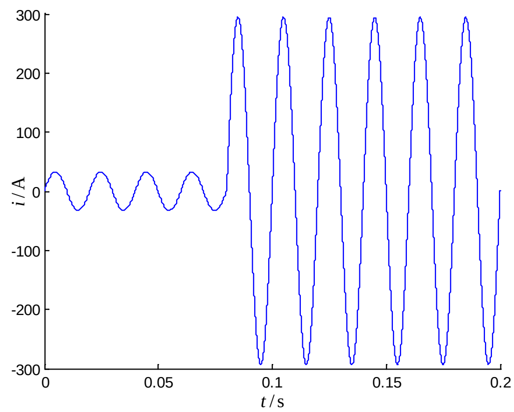

Fig.8 Transition waveform of a CRT

Fig.8 is the transition process which is load changed from 11% to 100%, it can be seen from Fig.8 that the transition process of CRT is very quick, the structure of Fig.2 can be achieved a direct transition from one steady state to another steady state.

It can be seen that the simulation results are identical of simulation model in this paper with the polygon equivalent circuit model of CRT in reference [4] from the above simulation analysis, this shows that the correctness of the simulation model established in this paper.

6 Conclusion

Based on the magnetic integration technology, the magnetic integrated structure composed of variety of magnetic materials of CRT is proposed. The MATLAB simulation model of CRT is established by the integrated magnetic equivalent circuit model. And the winding current and control characteristic of CRT are analyzed by the simulation. The results of simulation show that the magnetic integrated structure composed of variety of magnetic materials of CRT not only satisfies the “high impedance, weak coupling” design requirements, but also simplifies the structure of the entire device and reduces the no-load current. The work winding current harmonic content is small, the power control characteristic is smooth regulation with classification, and the response speed is rapid. Those advantages verify the effectiveness of this structure and the correctness of the simulation model. The magnetic integrated structure composed of variety of magnetic materials provides a new method to integrate the complex electromagnetic equipment and broadens application of magnetic integration technology.

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