Development of a High Temperature Superconducting Controllable Reactor Based on Finite Element Method

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***Abstract*-A new 40kVA, 400V high-temperature superconducting (HTS) controllable reactor of transformer type has been designed, built and tested. The reactor has totally 3 windings and utilize Bi2223 HTS materials to wound the inside two windings which are responsible for the adjust of the reactor's reactance. A finite element model was developed and simulation was conducted to predict its performance, such as capacity, harmonic and response. Then experiments were carried out and results are compared.**

Keywords- high temperature superconducting (HTS); finite element model; controllable reactor

I. INTRODUCTION

Since control of reactive power is important and significant for a transmission network, many kinds of devices are developed to cater for such demand [1]. However, most of them are characterized by one or more demerits as high harmonics component, slow response, complex control and high cost etc.[1]-[4].While Thyristor Controlled Reactor(TCR) injects lots of harmonics into the system[2], Magnetically Controlled Reactor(MCR) responses slowly and reactors of transformer type have relatively large losses[3][4].

Meanwhile, as superconducting technology develops, superconductor power equipment is expected to make a significant impact [5]. Till now, some superconducting reactors have been devised, but almost all of them are confined to fault current limiters [6][8].

Combining the technology of controllable reactor and superconductivity, this paper proposes a novel High Temperature Superconducting (HTS) controllable reactor of transformer type, which is mainly applied for reactive power compensation.

This paper applies a finite element analysis method to the computation of the reactance of the HTS reactor. A prototype of HTS reactor is built and experiments are carried out. Some discrepancies between computation and experimental results and possible causes are analyzed.

II. BASIC PRINCIPLE

Structure of the HTS reactor can be simplified as in fig.1. It has a three-limb core. The primary winding, i.e. the outside winding which is made up of aluminum wire, is designed to provide reactive power for system when at work, while the inside two HTS windings (secondary and tertiary winding) control the capacity of the reactor.

The primary winding being given a sinusoidal voltage, the flux traversing the HTS loop will stay invariant when HTS coil is closed according to the conservation of flux in a superconducting loop. The variant flux can only pass through the gap between the closed HTS coil and ordinary coil. Reactance changes as a result of the change of flux.

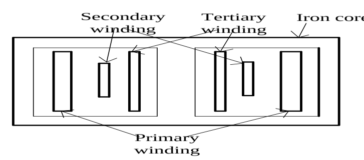

FIGURE I. STRUCTURE OF HTS REACTOR.

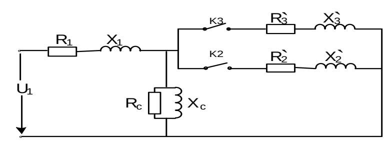

FIGURE II. EQUIVALENT CIRCUIT.

Since its structure is similar to that of a three-winding transformer, its equivalent circuit can be depicted in Fig 3. By short circuiting secondary or tertiary winding, i.e. closing switch K2 or K3, the equivalent inductance (of the primary) will vary. Its working modes are listed in Table. I.

TABLE I. WORKING MODE OF HTS REACTOR.

Working mode	Switch status	Impedance
S1	K2、K3 open	X1+Z0
S2	K2 opened,K3 closed	X1+X3
S3	K2 closed,K3 opened	X1+X2
S4	K2、K3 closed	X1+X2//X3

III. COMPUTER MODELING AND SIMULATION

Literature [9][10] proposed a finite element method, as shown in Fig.4, to calculate the reactance components of the Steinmetz exact transformer equivalent circuit. However, it is only possible for a two-winding transformer. In order to acquire the reactance components in Fig.2, we need to simulate for 3 times.

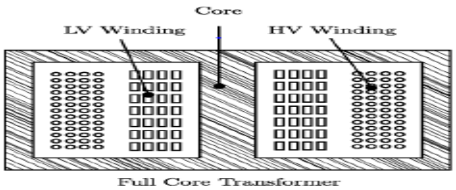

FIGURE III. FINITE ELEMENT ANALYSIS OF A FULL CORE TRANSFORMER.

That is the three windings are named i, j and k respectively, three permeance matrixes for an n layer HTS reactor of transformer type are defined as

$$P_A = \begin{bmatrix} P_{A11} & & & P_{A1n} \\ & \bullet & & \\ & & \bullet & \\ & & & \bullet \\ P_{An1} & & & P_{Ann} \end{bmatrix} \tag{1}$$

Where $P_{Aij} = P_{Aji}$

$$P_B = \begin{bmatrix} P_{B11} & & & P_{B1n} \\ & \bullet & & \\ & & \bullet & \\ & & & \bullet \\ P_{Bn1} & & & P_{Bnn} \end{bmatrix} \tag{2}$$

Where $P_{Bik} = P_{Bki}$

$$P_C = \begin{bmatrix} P_{C11} & & & P_{C1n} \\ & \bullet & & \\ & & \bullet & \\ & & & \bullet \\ P_{Cn1} & & & P_{Cnn} \end{bmatrix} \tag{3}$$

Where $P_{Cjk} = P_{Ckj}$

Each P is obtained from finite-element software by performing n simulations. In each simulation, a single winding layer, assigned with a unity number of turns, is excited with unit current, and a row of is calculated by

$$P_{ij} = \frac{\lambda_i}{i_j} \tag{4}$$

Where λ_i is the flux linkage of layer due to an excitation current i_j in winding i. And,

$$P_{ik} = \frac{\lambda_i}{i_k} \tag{5}$$

$$P_{jk} = \frac{\lambda_j}{i_k} \tag{6}$$

The winding section inductance matrix L can then be obtained from P. The elements of are calculated as [11]

$$L_{ij} = N_i N_j P_{ij} \tag{7}$$

$$L_{ik} = N_i N_k P_{ik} \tag{8}$$

$$L_{jk} = N_j N_k P_{jk} \tag{9}$$

Each time, two windings are selected and we call one of them primary and the other secondary. The primary and secondary windings are formed via series connections of one or more layer sections. Assume W is the set of winding layer sections (numbered from the inside) while P and S be subsets of containing and elements, respectively. Let P(i) and S(j) denote the ith and jth element of P and S. The self-inductances of primary and secondary winding are then given by [12]

$$L_{Pa} = \sum_{i=1}^{nP_a} L_{Pa(i)Pa(i)} + \sum_{i=1}^{nP_a} \sum_{\substack{j=1 \\ i\neq j}}^{nP_a} L_{Pa(i)Pa(j)} \tag{10}$$

$$L_{Sa} = \sum_{i=1}^{nS_a} L_{Sa(i)Sa(i)} + \sum_{i=1}^{nP_a} \sum_{\substack{j=1 \\ i\neq j}}^{nP_a} L_{Sa(i)Sa(j)} \tag{11}$$

$$L_{Pb} = \sum_{j=1}^{nP_b} L_{Pb(j)Pb(j)} + \sum_{j=1}^{nP_b} \sum_{\substack{k=1 \\ k\neq j}}^{nP_b} L_{Pb(j)Pb(k)} \tag{12}$$

$$L_{Sb} = \sum_{j=1}^{nS_b} L_{Sb(j)Sb(j)} + \sum_{j=1}^{nP_b} \sum_{\substack{k=1 \\ k\neq j}}^{nP_b} L_{Sb(j)Sb(k)} \tag{13}$$

$$L_{Pc} = \sum_{k=1}^{nP_{ac}} L_{Pc(k)Pc(k)} + \sum_{k=1}^{nP_c} \sum_{\substack{i=1 \\ i\neq k}}^{nP_c} L_{Pc(k)Pc(i)} \tag{14}$$

$$L_{Sc} = \sum_{k=1}^{nS_c} L_{Sc(k)Sc(k)} + \sum_{k=1}^{nP_c} \sum_{\substack{i=1 \\ i\neq k}}^{nP_c} L_{Sc(k)Sc(i)} \tag{15}$$

The mutual inductance is given by,

$$M_{PaSa} = \sum_{i=1}^{nPa} \sum_{j=1}^{nSa} L_{Pa(i)Sa(j)} \tag{16}$$

$$M_{PbSb} = \sum_{j=1}^{nPb} \sum_{k=1}^{nSb} L_{Pb(j)Sb(k)} \tag{17}$$

$$M_{PcSc} = \sum_{k=1}^{nPc} \sum_{i=1}^{nSc} L_{Pc(k)Sc(i)} \tag{18}$$

Then, the inductances are transformed into the reactance components of the Steinmetz exact transformer equivalent circuit using

$$Xa_1 = jw(L_{Pa} - xM_{PaSa}) \tag{19}$$

$$x^2 Xa_2 = jwx^2(L_{Sa} - \frac{1}{x} M_{PaSa}) \tag{20}$$

Then,

$$Xa = Xa_1 + x^2 Xa_2 = jw(L_{Pa} + x^2 L_{Sa} - 2xM_{PaSa}) \quad (21)$$

By the same way, it can be calculated that

$$Xb = Xb_1 + y^2 Xb_2 = jw(L_{Pb} + y^2 L_{Sb} - 2yM_{PbSb})$$

$$Xc = Xc_1 + z^2 Xc_2 = jw(L_{Pc} + z^2 L_{Sc} - 2zM_{PcSc}) \quad (22)$$

IV. MODELING RESULTS

The modeling of Section II was used to design a three-winding, single-phase, 380-V, 30-kVA HTS Reactor. Table II gives the physical dimensions and materials used in the design of the reactor.

The parameters of Table II and Table III were entered into a computer program written using the modeling methods of Section II. The program was able to determine the equivalent circuit parameters for the HTS reactor design.

TABLE II. MAIN PARAMETERS OF HTS REACTOR.

parameter	value	Unit
Rated voltage	380	V
Rated current	80	A
Capacity	30	kVA
Phase	Single	
Operating frequency	50	Hz
Iron core		
type	E core	
Magnetic flux density	1.6	T
Height	550	mm

TABLE III. SPECIFICS OF WINDINGS.

parameter	**Designed value**	**Unit**
Primary winding		
material	aluminum	
Diameter (inner/outer)	430/580	Mm
Number of turns	170	
Height	410	mm
Secondary winding		
material	BI-2223	
Winding type	Circle	
Diameter(inner/outer)	286/306	mm
Number of layer	10	
Number of turns	460	
Height	76	mm
Tertiary winding		
material	BISCCO	
Winding type	Circle	
Diameter(inner/outer)	240/260	mm
Number of layer	12	
Number of turns	352	
Height	208	mm

V. EXPERIMENTS AND DISCUSSION

Finally we built a prototype of a HTS reactor. However, in the process of manufacturing, the primary winding is built in a square shape. Experiments are carried out under 100V, 200V, 300V, 350V and 380V. Reactance under every experiment is calculated and listed in Table. IV.

FIGURE IV. PROTOTYPE OF HTS REACTOR.

FIGURE V. WINDINGS OF THE HTS REACTOR.

TABLE IV. REACTANCE (Ω) OF HTS REACTOR.

	Voltage						Average
	100V	200V	300V	350V	380V	400V	
S1	454	800	600	290	211	181	—
S2	6.25	6.17	6.42	6.24	6.09	6.23	6.23
S3	5.46	5.29	5.61	5.34	5.22	5.28	5.37
S4	5.03	4.87	5.17	4.92	4.8	4.87	4.94

TABLE V. COMPARATION OF CALCULATION SIMULATION AND EXPERIMENT (UNIT Ω).

	simulation	experiment
Xa	6.83	6.23
Xb	5.84	5.37
Xc	5.75	4.94

From Table.V, the results of simple calculation may have a quite large error as the size of the three windings are a little irregular.

The results of simulation and experiment are generally in consistent with each other. The discrepancy between simulation and experiment are due to that the actual size of the primary winding is different from that in the model.

VI. CONCLUSION

The inductance changing principle of high-temperature superconducting (HTS) reactor is illustrated, a finite element model is built. And electromagnetic simulation and computation is conducted and a 380V experimental HTS controllable reactor was designed, based on which an experiment is conducted. Small discrepancies appeared between the simulation and experiment and the cause was analyzed.

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