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Excitation Effect Analysis of a Novel HTS Controllable Reactor with Orthogonal Configured Core Based on Dynamic Inductance Matrix

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Abstract **—The controllable reactor is one of the most effective methods for compensating reactive power. A novel type of HTS controllable reactor with orthogonally configured core has been proposed, analyzed, and developed. However, for the controllable reactor with dynamic inductance, the excitation analysis based on field circuit coupled method is inefficient and the excitation parameters optimization is more difficult. In this paper, an excitation system containing voltage source converter (VSC) and Buck-Boost converter is established. The reactor is built as a self-defined nonlinear element in system model based on the dynamic inductance. The inductance matrix, core saturation, leakage magnetic field at HTS winding, and total magnetic flux in the excitation core are included in the self-defined element. The parameters of the excitation system have been optimized easily. The simulation result of the output characteristic of the reactor is consistent with the experimental observations of the prototype. The dynamic inductance method is proved to be fast and effective.**

1. Structure and Local Linearization Method

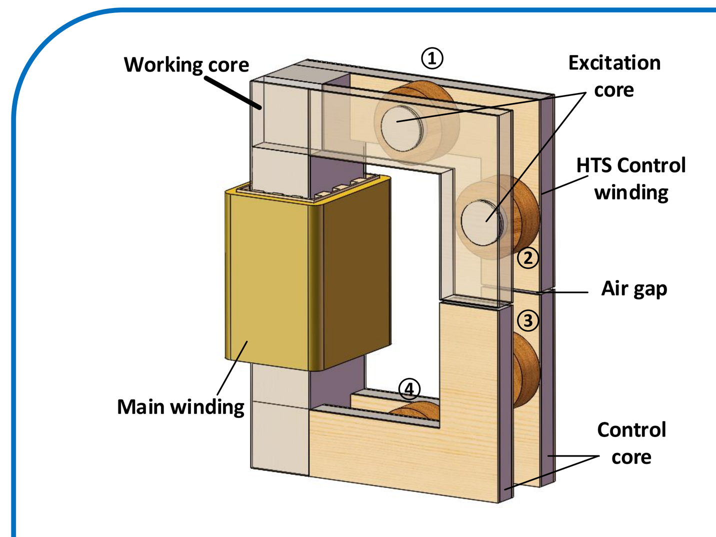


Fig. 1. Basic structure of HTS Controllable Reactor with Orthogonally Configured Core.

The main winding is wound around the working segment and connected to the power grid. The control segment contains two parallel D-shaped magnetic yokes and four excitation cores between the two yokes, on which four DC control windings are wound with HTS tapes and connected in series.

The total tangent matrix form the nonlinear solution (base analysis) is used in the linear perturbation analysis to capture the linear and nonlinear magnetic effects at the operating point of the nonlinear analysis.

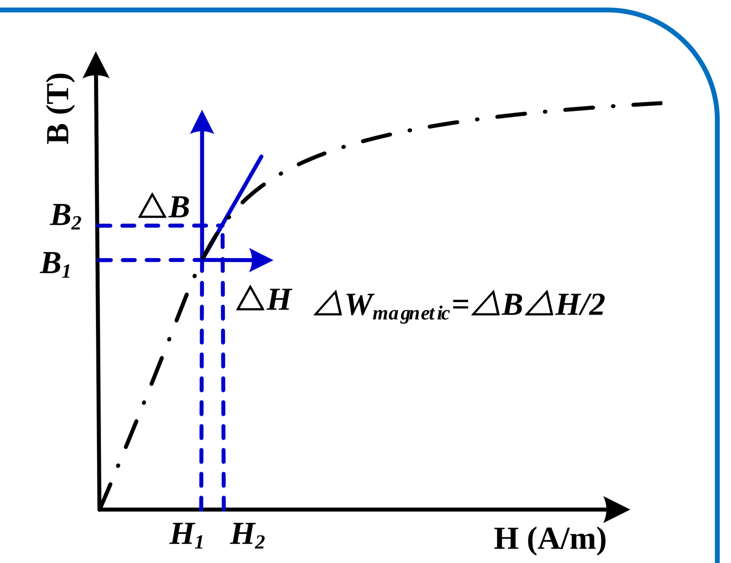


Fig. 2. Local linearization method of magnetic energy

2. Inductance matrix calculation

the transient response equation of the equivalent circuit is :

$$u=\frac{d\psi}{dt}=\left(\frac{dL_S}{di}+L_s\right)\frac{di}{dt}=dL_D(i)\frac{di}{dt}$$

There are one work winding and four excitation windings in the reactor. The dynamic inductance can be represented by a 5×5 matrix.

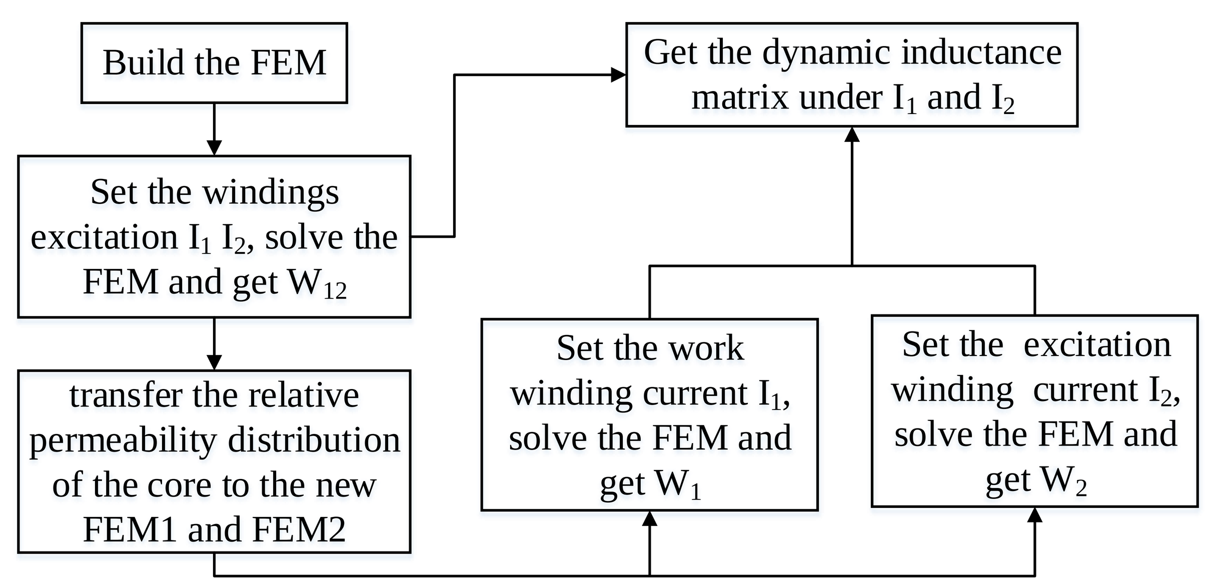
$$L_D=\begin{bmatrix} L_1(\mathrm{i}) & M_{12}(\mathrm{i}) & M_{13}(\mathrm{i}) & M_{14}(\mathrm{i}) & M_{15}(\mathrm{i}) \\ M_{12}(\mathrm{i}) & L_2(\mathrm{i}) & M_{23}(\mathrm{i}) & M_{24}(\mathrm{i}) & M_{25}(\mathrm{i}) \\ M_{13}(\mathrm{i}) & M_{23}(\mathrm{i}) & L_3(\mathrm{i}) & M_{34}(\mathrm{i}) & M_{35}(\mathrm{i}) \\ M_{14}(\mathrm{i}) & M_{24}(\mathrm{i}) & M_{34}(\mathrm{i}) & L_4(\mathrm{i}) & M_{45}(\mathrm{i}) \\ M_{15}(\mathrm{i}) & M_{25}(\mathrm{i}) & M_{35}(\mathrm{i}) & M_{45}(\mathrm{i}) & L_5(\mathrm{i}) \end{bmatrix}$$

To reduce the size of the inductance matrix, the excitation windings are equivalent to one winding.

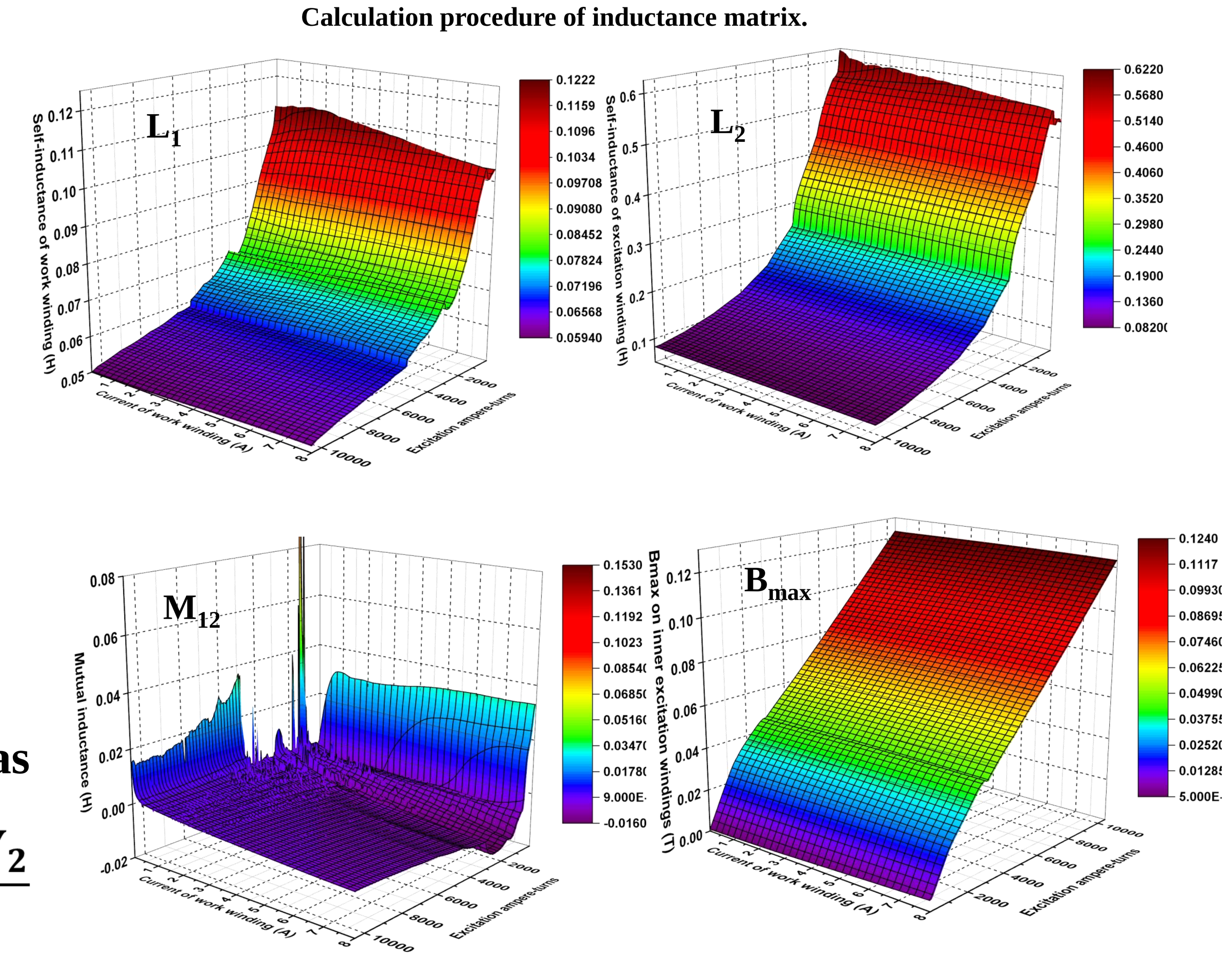
$$\begin{bmatrix} L_1 & M_{12} \\ M_{12} & L_2 \end{bmatrix}\begin{bmatrix} d\,i_1/d\,t \\ d\,i_2/d\,t \end{bmatrix}+\begin{bmatrix} R_1 & \\ & R_2 \end{bmatrix}\begin{bmatrix} i_1 \\ i_2 \end{bmatrix}=\begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

The equivalent inductance matrix can be calculated as

$$L_1=\frac{2\times W_1}{I_1^2}\quad L_2=\frac{2\times W_2}{I_2^2}\quad M_{12}=\frac{W_{12}-W_1-W_2}{I_1I_2}$$

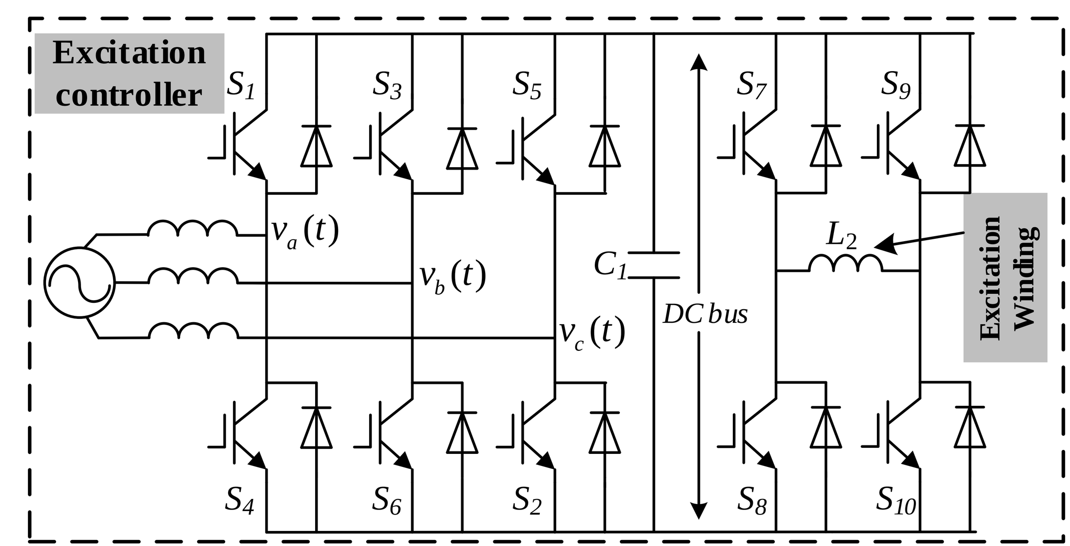


Calculation procedure of inductance matrix.



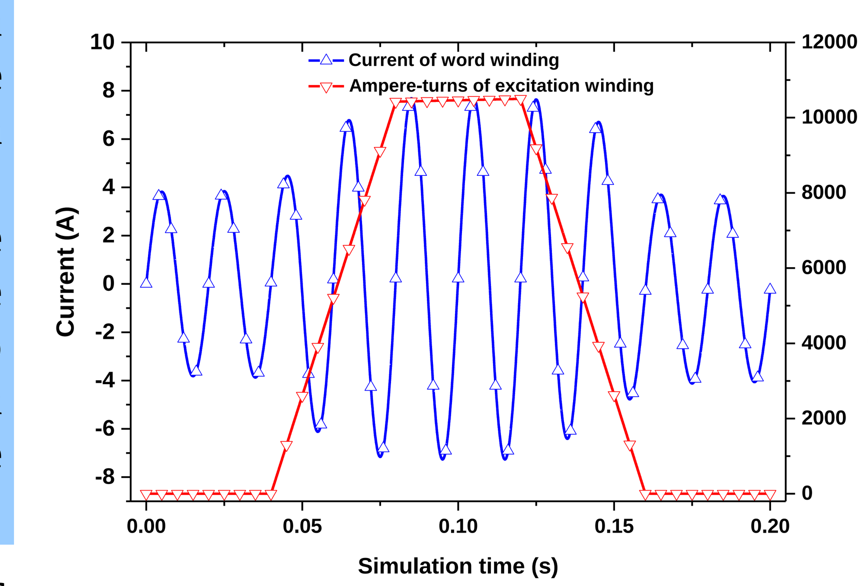
Inductance and magnetic flux density matrix.

3. Excitation System Design and Analysis



Topology of the excitation system

The topology of excitation system is composed of a three-phase voltage source converter (VSC) and a DC/DC chopper. The VSC is used to maintain the voltage of DC bus, while the DC/DC chopper is used to control the excitation current by adjusting the voltage of capacitor C_1.



The mathematical model of the VSC in synchronous rotating coordinates is:

$$\begin{cases} L\,di_d/dt=-Ri_d+\omega Li_q+u_{sd}-u_{rd} \\ L\,di_q/dt=-Ri_q-\omega Li_q+u_{sq}-u_{rq} \end{cases}$$

Ignore the impact of resistance of the winding the current of the windings can be expressed as:

$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix}=\begin{bmatrix} L_1 & M_{12} \\ M_{12} & L_2 \end{bmatrix}^{-1}\cdot\int\begin{bmatrix} u_1 \\ u_2 \end{bmatrix}dt$$

The inductance matrix is calculate under different current excitation and can be expressed as two-dimension table:

$$\begin{bmatrix} L_1 & M_{12} \\ M_{12} & L_2 \end{bmatrix}=\begin{bmatrix} L_1(i_1,i_2) & M_{12}(i_1,i_2) \\ M_{12}(i_1,i_2) & L_2(i_1,i_2) \end{bmatrix}$$

The mathematical model of DC/DC chopper is:

$$\begin{cases} L_2\dfrac{di}{dt}=(2d-1)u_{dc} \\ C\dfrac{du_{dc}}{dt}=i_{VSC}-(2d-1)i \end{cases}$$

State information of the HTS windings can also expressed as two-dimension table:

$$Ic_i=JcB\left(B\max(I_1,I_2)\right)$$

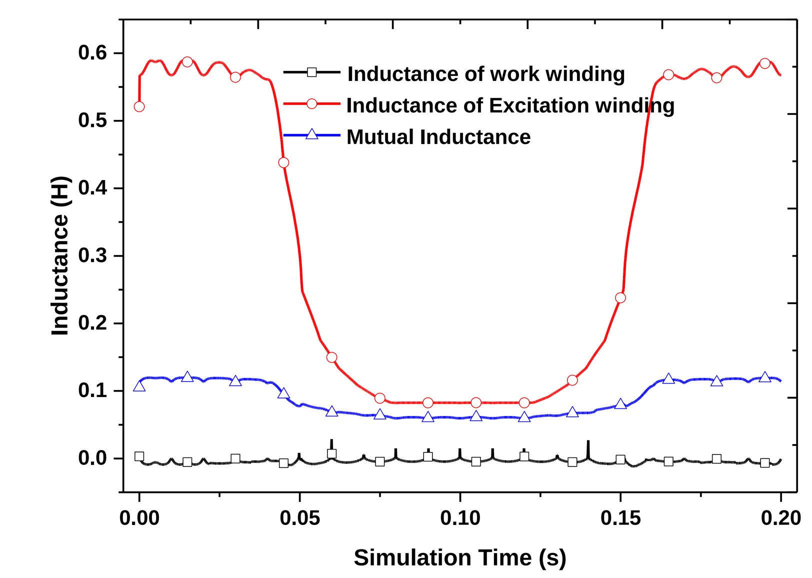


Fig. 10. Excitation effect of the reactor.

There are 10 cycles in this simulation. In the first two cycles, the excitation current is zero, and the equivalent inductance of the reactor reaches maximum value the peak value of the output current of the reactor is about 4.10A. Form 0.04s to 0.08s, the excitation current increases at the rate of 1.75kA/s, and the saturation of the core gradually deepened. In this process, the equivalent inductance of the reactor drops and the output current increases. At the end of excitation increase process, the peak value of the output current of the reactor is 7.70A.

4. Conclusion

In this paper, the excitation effect of the HTS reactor has been analyzed based on the self-defined element built by dynamic inductance matrix. The energy perturbation method is adopted to calculate the inductance matrix. An equivalent excitation winding has been used to reduce the calculation cost of the dynamic inductance. Combined with the built-in magnet state information, the self-defined element can guarantee the accuracy and greatly improve the computational efficiency which is helpful in analyzing the output characteristic of the magnets with dynamic inductance feature such as the reactors.