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Design and verification test of a HTS leakage flux-controlled reactor

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Abstract **—Controlled reactors can adjust the output capacity to stabilize system voltage, control reactive power and improve system stability according to operating conditions. The design of reactance and control system determines whether a controlled reactor can meet the requirement of stable operation. In this paper, the operating principle of a high temperature superconducting leakage flux-controlled reactor (HTS-LFCR) is introduced. The design of the reactance and the initial turn-on angle of the control system are discussed. A HTS-FLCR is fabricated and tested. The experimental results show that: the reactance design values are basically consistent with the experimental tests; when the initial turn-on angle of the control system is 90°, the reactor can achieve a smooth transition from one operating mode to another.**

1. Structure and operating principle

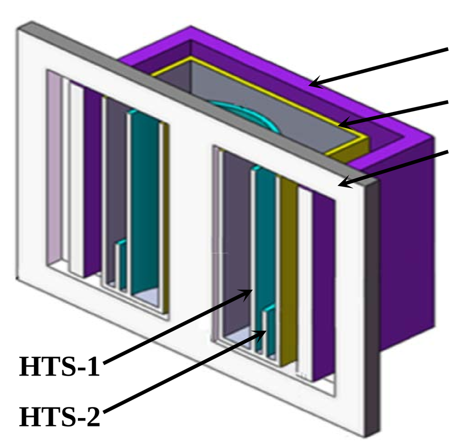


Fig. 1. Basic structure of a HTS-LFCR with two HTS control coils.

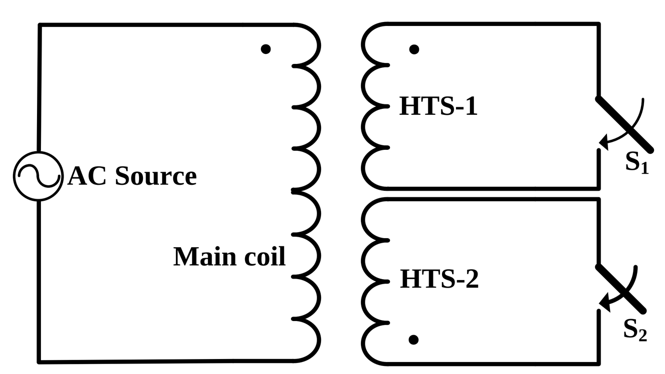


Fig. 2. The equivalent circuit of the HTS-LFCR.

TABLE I THE OPERATION MODES OF HTS CONTROL COILS

Operation mode	Mode 1	Mode 2	Mode 3	Mode 4
HTS-1 (S_1)	Open	Short	Open	Short
HTS-2 (S_2)	Open	Open	Short	Short

The HTS-LFCR realizes the controlled reactance regulation by opening or shorting the HTS control coils. When the operating states of HTS control coils are changed, the main flux path of the reactor is changed, thus causing the change of the reactance value.

2. Calculation and Analysis of Reactance

A. Reactance under Mode 1 and Mode 4

$$X_L = 2\pi f N^2 \mu_r \mu_0 \frac{A_c}{l_c}$$

B. Reactance under Mode 2 and Mode 3

$$X_L = \frac{4\pi^2 f N^2 \mu_0 \rho_1 R D}{H_0}(1+k)$$

$$k = 1 + \rho_2 H_0^2 (a^2 + 4ab^2 + b^2) \big/ (3\tau D \rho_1 \times 10^4)$$

$$\tau = d_0 + d_2 + d \quad D = d + (d_0 + d_2)/3 \quad a = H / H_0$$

$$b = h / H_0 \quad 2H = H_0 - H_2 \quad 2h = h_2 - h_1$$

$$\rho_1 = 1 - (1 - e^{-\pi H_0/\tau})\tau \big/ (\pi H_0)$$

$$\rho_2 = 1 - H_0(1 - e^{-2\pi\tau/H_0}) \cdot \frac{1 - 0.5e^{-4\pi\delta/H_0}(1 - e^{-2\pi\tau/H_0})}{2\pi\tau}$$

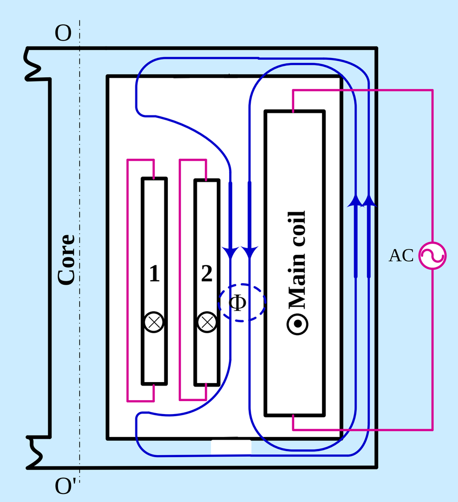


Fig. 3. Model of the reactance calculation under Mode 4.

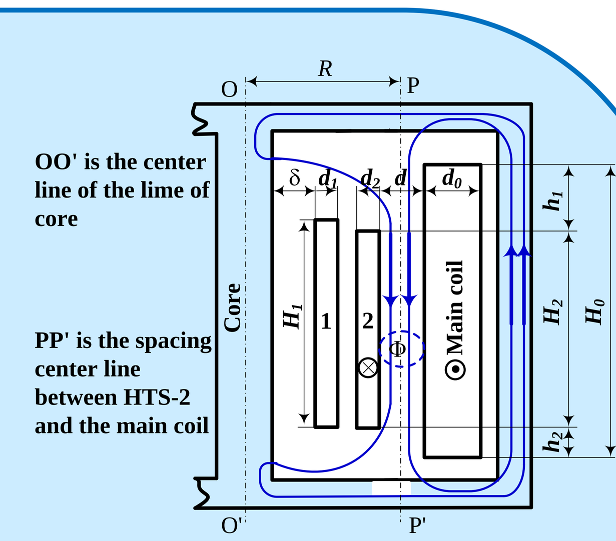
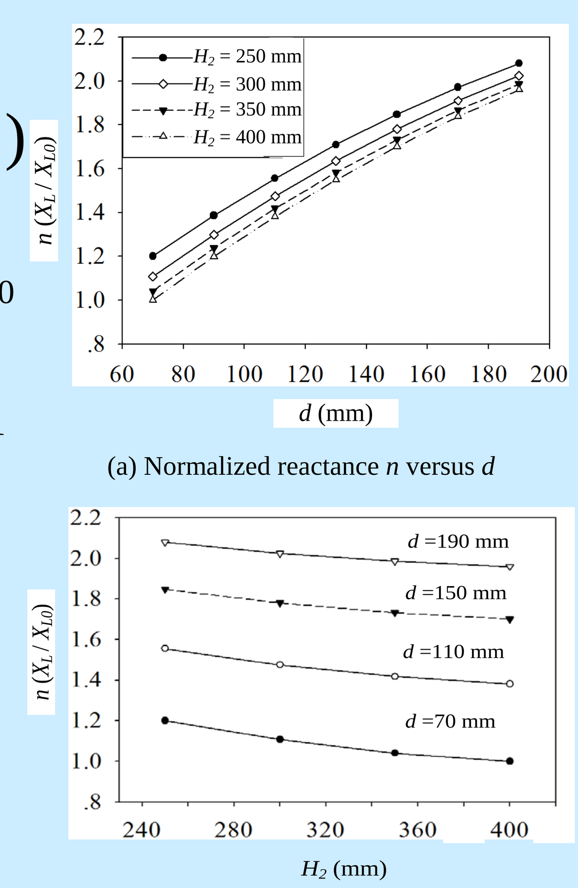


Fig. 4. Model of the reactance calculation under Mode 3.



(a) Normalized reactance n versus d

(b) Normalized reactance n versus H_2

Fig. 5. The normalized reactance n versus d and H_2.

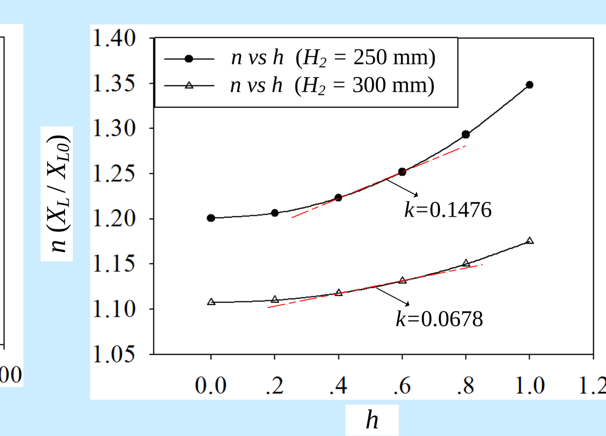


Fig. 6. The normalized reactance n versus h.

The influence of h on n is less than that of H_2 on n. Among the three parameters, d has the greatest influence on reactance X_L, and h does the least one.

3. Prototype and Experimental Test

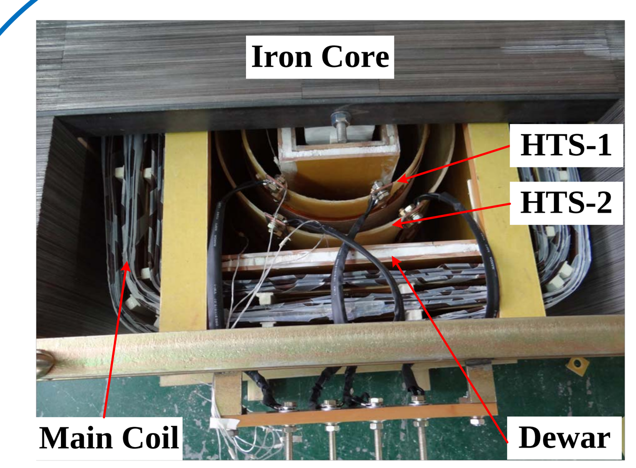


Fig.7. High leakage HTS reactor prototype

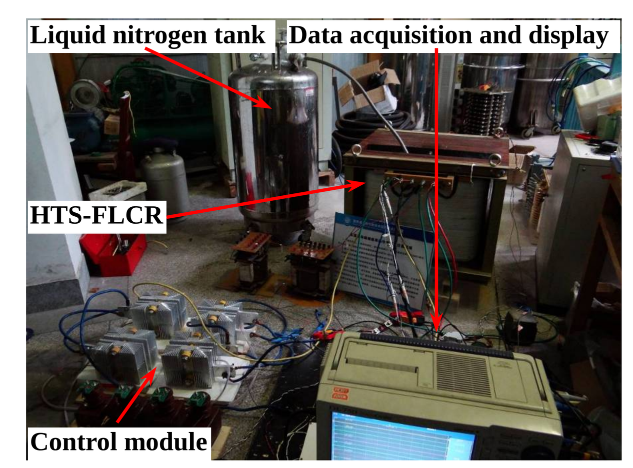


Fig. 8. Components of the HTS-FLCR prototype system.

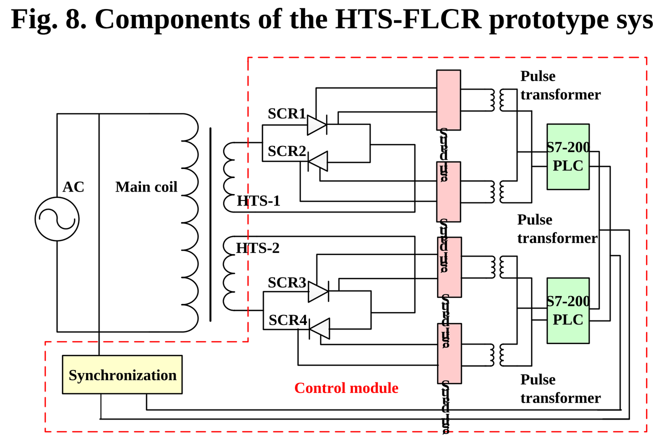


Fig. 9. Elementary diagram of the HTS-FLCR prototype system.

TABLE II. PARAMETERS OF THE HTS-LFCR

Parameter	Value (Design /Operation)	Parameter	Value
Rated voltage	380 V	Turns of main coil	170
Rated current	100 A	Turns of HTS-1	460
X_L @ Mode 1	261.9 Ω /244.3 Ω	Turns of HTS-2	352
X_L @ Mode 2	7.1 Ω / 6.8 Ω	Height of main coil	410 mm
X_L @ Mode 3	4.9 Ω / 5.3 Ω	Height of HTS-1	220 mm
X_L @ Mode 4	4.6 Ω / 4.8 Ω	Height of HTS-2	80 mm

TABLE III. THE DC COMPONENT BIAS RATIOS OF EACH COIL

α	Mode conversion	β = (I_{max} – I) / I		
		Main coil	HTS-1	HTS-2
0	Mode 1 to 2	0.940	0.903	
	Mode 1 to 3	0.954		0.916
30°	Mode 1 to 2	0.726	0.693	
	Mode 1 to 3	0.867		0.698
60°	Mode 1 to 2	0.443	0.410	
	Mode 1 to 3	0.457		0.432
90°	Mode 1 to 2	0.047	0.033	
	Mode 1 to 3	0.050		0.058

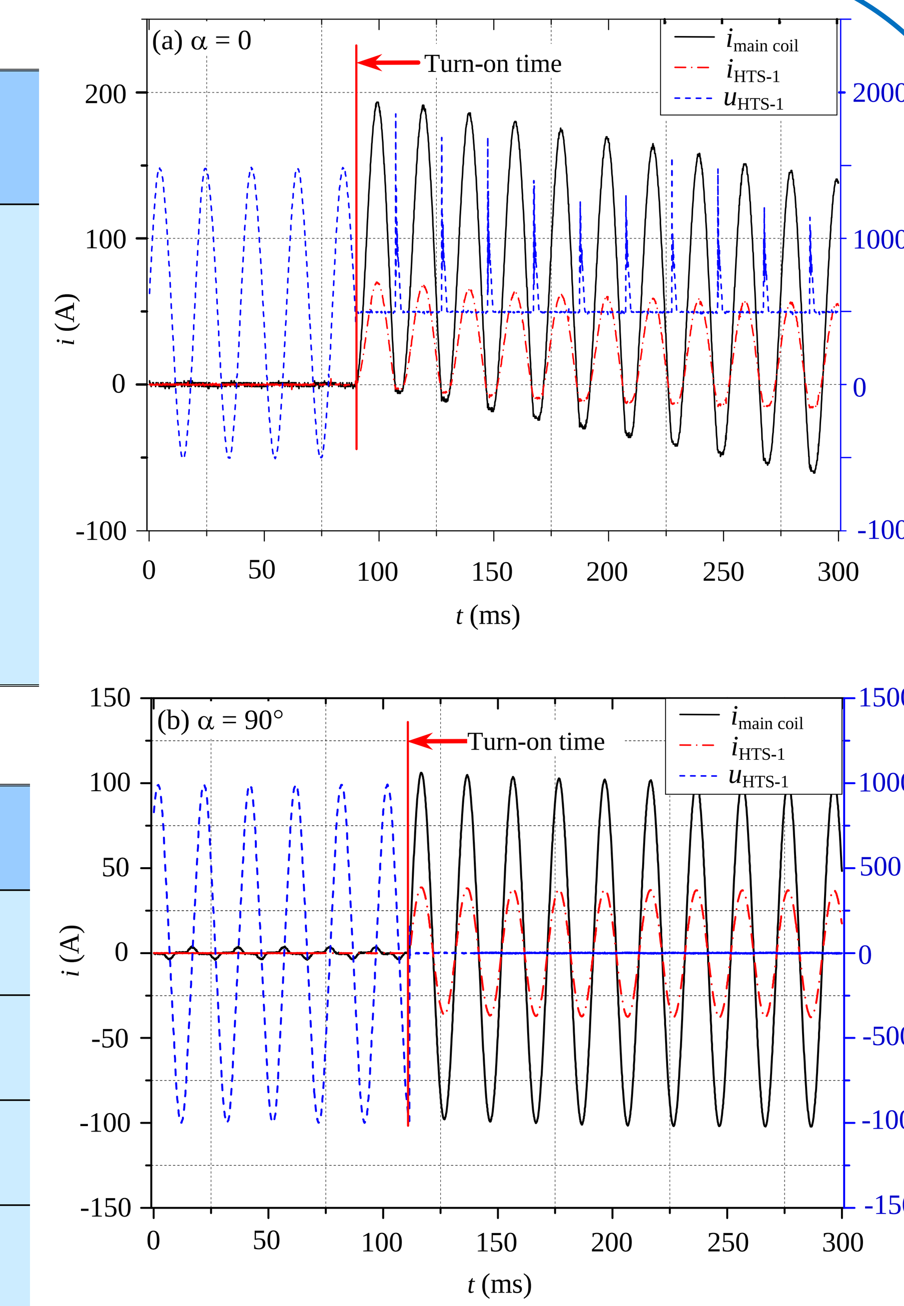


Fig. 10. The voltage and current waveforms of coils (Mode 1 to 2).

When α is increased from 0 to 90°, β decreases accordingly. When α is 0, β is the highest. When α is 90°, β is close to 0 and is the lowest. This shows that when the FLCR is switched from Mode 1 to Mode 2, if α is 90°, no transient DC component will be produced, and thus a smooth transition can be achieved.

4. Conclusion

(1) The calculated value of reactance is basically consistent with the measured value, and the error is less than 8.5%.

(2) According to the influence of the coil parameters on the reactance, the reactor structure should be designed to a flat type, which is beneficial to increase the reactance regulation range of the reactor.

(3) The selection of initial phase can be realized by control system. When the initial phase of the voltage over the main coil is 0 while the mode conversion is carried out, the transient voltage and current components of each coil are the largest. When the initial phase of the voltage is 90°, the HTS-FLCR is directly transferred to steady operation.