

The Performance Optimization of A Novel Composite Soft Magnetic Material Based Three-Phase Saturated Core Fault Current Limiter

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In this paper, a Novel Composite Soft Magnetic Material Based Three-Phase SCFCL (NCTFCL) is proposed to limit the transient short-circuit current in three-phase HVAC system under different conditions. Firstly, the topology and working principle of the NCTFCL is introduced, and its equivalent electromagnetic model is established. Secondly, The current limiting performance, volume and cost of NCTFCL are optimized based on RSM-MOGSA algorithm. Finally, the FEA simulation results demonstrate the effectiveness of the current limiting method and the structure of the proposed NCTFCL in this paper.

Index Terms—Fault current limiter, Multi-Objective Optimization, Transient current, Finite Element Analysis.

I. INTRODUCTION

THE traditional three-phase saturated core fault current limiter uses silicon steel sheet as the its body core. And the core is alternately desaturated when the fault occurs. However, the silicon steel sheet has a high saturation point (1.9T~2.0T), which causes the excitation source to need a larger magnetomotive force to bias the silicon steel sheet to the saturation state during normal operation, which increases the overall cost. In addition, the dynamic performance of the silicon steel sheet is insufficient, the transient change speed of the permeability is not good at the moment when the fault occurs, and the current limiting effect of the transient short circuit current is poor, which is difficult to meet the requirements of the rapid protection of the system. Aiming at the above problems, a Novel Composite Soft Magnetic Material Based Three-Phase SCFCL (NCTFCL) is proposed and the performance optimization method is also designed.

II. MODELING METHOD

A. The working mechanism of the NCTFCL

The proposed Novel Composite Soft Magnetic Material Based Three-Phase SCFCL (NCTFCL) structure is composed of the three-phase iron core made of nano-amorphous, the NdFeB permanent magnet (PM), the AC and DC coils, the air gap and the yoke made of silicon steel sheet.

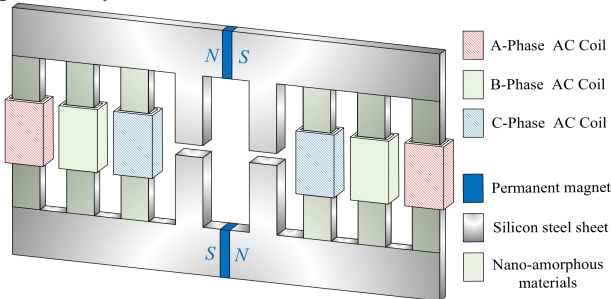


Fig. 1. The topology structure of NCTFCL.

The TEDFCL in Fig.1 working mechanism is as follows:

(1) Normal working state: The ABC-phase cores are in deep saturation state. And output inductance is small.

(2) Fault working state: When the fault occurs, the fault phase current surges, fault magnetomotive force in AC coils offsets the DC magnetomotive force. The cores on both sides are alternately desaturated, and the core inductance increases to complete the fault current limiting.

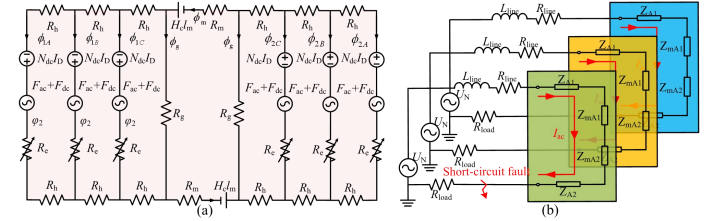


Fig. 2. The electromagnetic circuit model. (a) The electrical circuit model. (b) The magnetic circuit model.

A. The Parameter Design Criteria of The NCTFCL

Fig.2 shows the TEDFCL equivalent magnetic circuit. When the fault occurs, the circuit equation is shown in Eq. (1).

$$\begin{cases} \phi_N = \phi_{2N} = \frac{\pm \nu (2\gamma\theta + 12\zeta\gamma R_m + 3\zeta\theta) N_{ac} I_X}{R_{cs} (2\gamma\theta + 12\zeta\gamma R_m + 3\zeta\theta) + \theta^2 + 6\theta R_m} + \frac{3R_g H_c I_m}{R_{cs} R_m + R_{cs} R_g + 3R_g R_m} \\ \left\{ \begin{aligned} \zeta &= \frac{1}{3} R_{cs} + R_g, \gamma = \frac{1}{2} R_{cs} + R_g, \theta = R_{cs} \times R_g, \nu = \frac{R_g}{2\gamma} + \frac{R_g \theta + 6\zeta R_m R_g}{2\gamma\theta + 12\zeta\gamma R_m + 3\zeta\theta} \end{aligned} \right. \\ \phi_m = \frac{3H_c I_m (R_m + R_g)}{R_{cs} R_m + R_{cs} R_g + 3R_g R_m} \quad \phi_g = \frac{H_c I_m R_m}{R_{cs} R_m + R_{cs} R_g + 3R_g R_m} \end{cases} \quad (1)$$

The magnetic flux of the NCTFCL under normal state and the fault flux are as Eq. (1). Where I_X is the ABC-phase current. Hence, the output impedance is in Eq. (2).

$$Z_F = \begin{cases} \frac{\omega 2\nu N_{ac}^2 (2\gamma\theta + 12\zeta\gamma R_m + 3\zeta\theta)}{R_{cs} (2\gamma\theta + 12\zeta\gamma R_m + 3\zeta\theta) + \theta^2 + 6\theta R_m} \\ \frac{\omega \mu_{cu} N_{ac}^2 S_{eq}}{l_{eq}} + \frac{\omega \nu N_{ac}^2 (2\gamma\theta + 12\zeta\gamma R_m + 3\zeta\theta)}{R_{cs} (2\gamma\theta + 12\zeta\gamma R_m + 3\zeta\theta) + \theta^2 + 6\theta R_m} \end{cases} \quad (2)$$

Where l_{eq} and S_{eq} is the equivalent magnetic length and cross-sectional area.

In order to ensure the core steady-state saturation and avoid transient reverse saturation, the parameter is shown in Eq (5).

II. PERFORMANCE AND STRUCTURE OPTIMIZATION

To verify the effect of the NCTFCL, a 500kV FEA model is built. The parameters in the FEA model are in Table I.

TABLE I
THE SPECIFIC PARAMETERS AND MATERIALS OF SIMULATION MODEL

Structure	Parameter	Structure	Parameter
Iron core	$l_c=16.0\text{m}; S_c=2.0\text{m}\times 2.0\text{m}$	Air gap	$l_g=0.4\text{m}; S_g=2.0\text{m}\times 3.0\text{m}$
PM	$l_m=0.2\text{m}; S_m=2.0\text{m}\times 8.0\text{m}$	Coil	$N_{ac}=60, N_{dc}=150$
Yoke	$l_h=33.0\text{m}; S_h=2.0\text{m}\times 8.0\text{m}$	EDB	$R=6\Omega, C=6\text{mF}$

A. The RSM Agent Model and MOGSA Optimization Result

TABLE II
THE FEA TRANSIENT CURRENT LIMITING EFFECT OF TEDFCL

Phase sequence	R^2	df	P-value	F-value	Adeq Precision
current limiting coefficient	0.9998	20	<0.0001	7.024×10^5	2742.4506

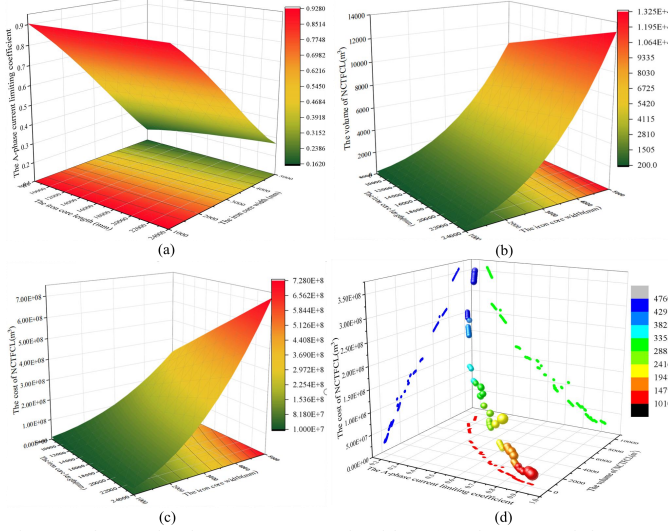


Fig. 3. The result of RSM-MOGSA algorithm. (a) The RSM of the current limiting performance. (b) The RSM of the volume. (c) The RSM of the cost. (d) The Pareto front of the MOGSA.

The current limiting coefficient, volume and cost of the NCTFCL are optimized. Fig.3 and Table II show the evaluation results of the *RSM-MOGSA* model. The R^2 of Y is 0.9998, its P is far less than 0.01, and the signal-to-noise ratio is 27.52, which is greater than 4, indicating a good degree of fitting and high model reliability.

B. The Multi-Objective Snake Optimization Algorithm

The response surface function of current limiting coefficient, volume and cost is in Eq. (3)-(4).

$$\begin{cases} \lambda = 0.956 + 6.51 \times 10^{-6} l_c + 3.5 \times 10^{-5} w_c - 5.25 \times 10^{-9} l_c w_c - 6.58 \times 10^{-10} l_c^2 \\ - 1.32 \times 10^{-7} w_c^2 + 1.01 \times 10^{-13} l_c^2 w_c + 3.62 \times 10^{-12} l_c w_c^2 + 5.21 \times 10^{-14} l_c^3 \\ + 3.74 \times 10^{-11} w_c^3 - 1.12 \times 10^{-16} l_c^2 w_c^2 + 4.10 \times 10^{-18} l_c^3 w_c - 4.90 \times 10^{-16} l_c w_c^3 \\ - 2.09 \times 10^{-18} l_c^4 - 5.99 \times 10^{-15} w_c^4 + 1.06 \times 10^{-21} l_c^3 w_c^2 + 5.48 \times 10^{-21} l_c^2 w_c^3 \\ - 7.74 \times 10^{-23} l_c^4 w_c - 3.80 \times 10^{-20} l_c w_c^4 + 2.99 \times 10^{-23} l_c^5 + 3.95 \times 10^{-19} w_c^5 \end{cases} \quad (3)$$

$$\begin{cases} V = 7.95 l_c w_c^2 + 48 w_c^3 + 96000 w_c^2 + 6 l_m w_c^2 \\ TC = (2 w_c^2 \rho_s p_s + 6 w_c^2 \rho_n p_n) l_c + (6 w_c^2 \rho_m p_m - 6 w_c^2 \rho_s p_s) l_m \\ + 6 w_c^2 \rho_s p_s (8 w_c + 16000 + l_m) - 0.05 w_c^2 \rho_s p_s l_c \end{cases}$$

$$\begin{cases} \min F(l_c, w_c) = [\lambda(l_c, w_c), V_2(l_c, w_c), TC(l_c, w_c)] \\ \text{s.t. } 8000 \leq l_c \leq 24000 \cap 1000 \leq w_c \leq 5000 \end{cases} \quad (4)$$

TABLE III
THE PARAMETER OPTIMIZATION RESULT OF THE NCTFCL

Case	The length of the iron core/mm	The width of the iron core/mm	The A-Phase current limiting coefficient of the NCTFCL		Volume /m ³	Cost /USD	λ predicted Error
			RSM Calculation	FEA Simulation			
Case 1	8181.76	3437.48	0.4654	0.4655	3888.06	1.46×10^8	0.06%
Case 2	14715.07	4460.72	0.3019	0.3017	8558.12	3.89×10^8	0.05%
Case 3	13980.85	2704.15	0.6256	0.6258	2485.83	1.29×10^8	0.42%
Case 4	9315.08	1662.15	0.8031	0.8032	698.53	3.42×10^7	0.28%

C. The Finite Element Simulation of the NCTFCL

In Fig. 4, using nano-amorphous material, the NCTFCL combines the advantages of low magnetic saturation point and the rapid transient change speed of the magnetic permeability. It can better play the role of limiting the transient current.

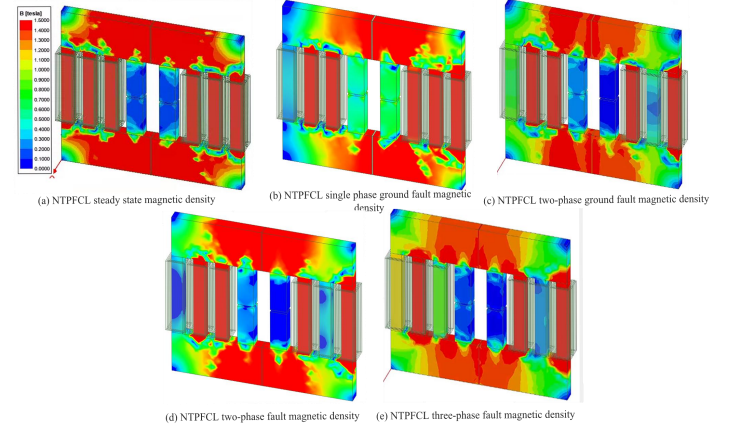


Fig. 4. The NCTFCL magnetic flux density. (a) The steady state magnetic flux intensity. (b) The single phase ground fault magnetic flux intensity. (c) The two phase ground fault magnetic flux intensity. (d) The two phase fault magnetic flux intensity. (e) The three phase fault magnetic flux intensity.

The FEA results show that the structure and function of NCTFCL are effective in transient demagnetization process.

III. CONCLUSION

This paper presents a Novel Composite Soft Magnetic Material Based Three-Phase SCFCL (NCTFCL). It can accelerate transient current attenuation and limit fault current amplitude significantly. The performance improvement of nano-amorphous materials and the details of multi-objective optimization methods are described in detail in the manuscript.

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