A Piecewise Linear Hysteresis Model for NdFeB Considering Temperature Effects

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In this paper, based on experimental result of 14 grades of NdFeB magnet under various temperatures, a simpler and more practical hysteresis model is proposed for coupled field analysis, taking the magnetic field and temperature into account. The piecewise linear model is helpful to accelerate the FEM simulation speed, and decrease the iteration times in each time step.

***Index Terms*—Demagnetization, hysteresis model, neodymium magnet, rare earth permanent magnet, temperature dependent.**

I. Introduction

Nowadays, neodymium(NdFeB) is the strongest magnet at room temperature, featuring the biggest magnetic power, making magnetic device more compact and lighter, replacing other types of magnets in the many applications.

However, different from samarium cobalt magnet(SmCo), NdFeB is more sensitive to temperature. One of hazards for its industrial application is the demagnetization due to high temperature and strong inverse magnetic field during the operation. For motor designer, not only electromagnetic field but also thermal field needs to be paid attention to. Coupled field analysis could be a proper choice to validate the design and inspect the PM status, if a dynamic and temperature dependent PM magnet model is available.

From perspective of hysteresis, demagnetization is intrinsic phenomenon for all magnetic material. Turning point of demagnetizing curve is just one of points on hysteresis loop, and demagnetization curve is merely part of whole loop in second quadrant of J-H plane. Preisach and Jiles-Atherton(JA) model are two of the most popular hysteresis model capable of describing nonlinear and hysteretic property of magnetic material. Preisach model succeeds in describing the first order reversal curves, but with a lookup table for interpolation. JA model only needs fives coefficients, but its mathematical expression is complicated and nonlinear, involving iterative algorithm when applied in electromagnetic field computation, which of cause increases the solution time. Furthermore, its model parameters are hard to determine.

Previously, there some works about temperature dependent models[1-2]. Apart from nonlinear models, in this paper, a piecewise linear hysteresis model is proposed for NdFeB magnet, taking the effect of temperature and magnetic field into account.

II. A Piecewise Linear Hysteresis Model Without Considering Temperature Effect

We have tested 14 grades of NdFeB specimens made in China, including N, M, H, SH and UH series.

Fig. 1 shows measured demagnetizing curves of NdFeB at various temperatures from RT(25℃)~100℃.

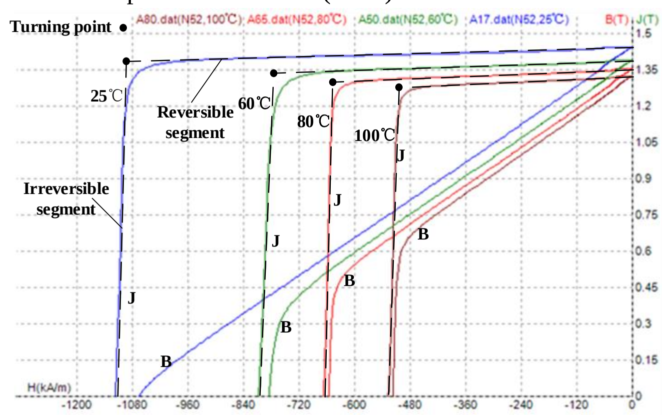

Fig. 1. Measured demagnetizing curves of NdFeB magnet(N52)

Different from other PM materials, NdFeB exhibits a special nonlinearity. In the second quadrant, each demagnetizing curve can be treat as two piecewise linear segments. Considering the symmetry, in the whole J-H plane, we can assume that limiting hysteresis loop is composed of four piecewise linear segments. This idea will provide a way to reduce the complexity of hysteresis model. No doubt, a linear material model would accelerate the FEM simulation, and decrease the iteration times in each time step.

According to the idea above mentioned, at certain temperature, three points are needed to determine the limiting loop shown in Fig. 2, that is remanence point(0, B_{r1}), coercivity point(H_{cj}, 0) and turning point(H_g, J_g). Here we assume the slope of reversible segment $\mu_0(\mu_r-1)$ is the same at various temperatures. Finally, such four parameters(B_{r1}, H_{cj}, H_g, μr) are needed to determine the limiting loop at given temperature.

Limiting loop is composed of 2 irreversible and 2 reversible segments, connected by turning points in each of 4 quadrants. Local loops have the same coercivity as limiting loop, same slope of reversible segment but with lower remanence($|B_{rk}|<|B_{r1}|$). Here we give an example for movement of working point at giving temperature. Mathematical deduction will be elaborated in the full paper, where only linear calculus is involved.

(a) Magnetize the NdFeB from fully demagnetized status, working point moves along the initial magnetization curve with remanence B_{rk}=0.

(b) When working point reaches P, continue to increase the field, working point moves to Q along the irreversible segment, remanence of the local loop B_{rk} changes, whose value can be determined by simple linear computation. Otherwise, it moves along reversible segment(PO), remanence of the local loop doesn't change(B_{rk}=0).

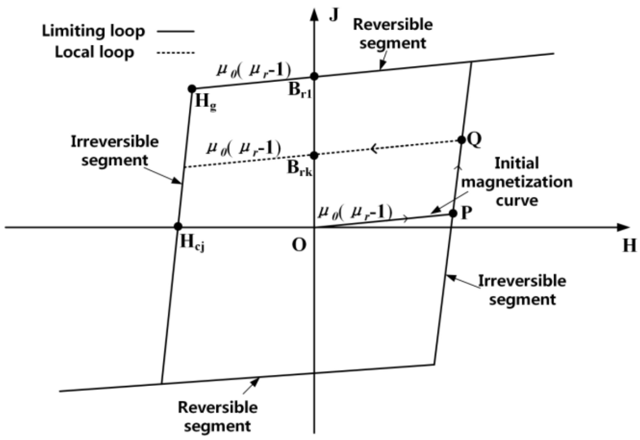

Fig. 2. Limiting hysteresis loop and branches of local loop

III. Temperature Dependent Hysteresis Model

A. Limiting loop, initial magnetization curve and local loop

In this section, remanence of limiting loop B_{r1} and intrinsic coercivity H_{cj} are generalized to be temperature dependent, both of which decrease with the rising temperature, expressed in (1) and (2). α and β are temperature coefficients of remanence and intrinsic coercivity. T and T_0 are the actual and reference temperature, respectively. Linear regressive analysis between B_{r1} H_{cj} and T was carried out for 14 grades of NdFeB, linear correlation degree is 99%.

$$B_{r1} = B_{r1}(T) = B_{r1}(T_0)\left[1-\alpha(T-T_0)\right] \tag{1}$$

$$H_{cj} = H_{cj}(T) = H_{cj}(T_0)\left[1-\beta(T-T_0)\right] \tag{2}$$

For magnetic strength of turning point H_g, the regressive analysis shows that exponential function is Ok to describe the temperature effect on turning point(see TABLE I).

TABLE I
Regressive Analysis of Turning Point Field Hg With Temperature

No.	Grade	$Hg=k_1*e^{-k2T}$		
		k_1/(kA/m)	k_2/(1/℃)	R^2
1.	N48	1316.9	0.010	0.9975
2.	N50	1352.1	0.012	0.9947
3.	N52	1434.3	0.011	0.9932
4.	N42M	1544.6	0.009	0.9911
5.	N50M	1513.1	0.010	0.9862
6.	N38H	1886.4	0.011	0.9807
7.	N40H	2040.1	0.010	0.9896
8.	N42H	1857.5	0.010	0.9895
9.	N48H	1661.8	0.009	0.9773
10.	N35SH	2117.8	0.009	0.9874
11.	N38SH	2168.4	0.010	0.9921
12.	N42SH	2101.3	0.009	0.9768
13.	N45SH	2138.7	0.008	0.9787
14.	N30UH	2249.9	0.008	0.9218

Initial magnetization curves of different temperatures are assumed to be collinear, starting from origin with the slope of $\mu_0(\mu_r-1)$. Each temperature corresponds to unique limiting loop, illustrated in Fig. 3.

B. Movement of working point when temperature changes

From Section III A, if the temperature is known, the temperature dependent limiting loop and possible branches of local loop are determined.

According to the piecewise linear hysteresis model introduced in Section II, each limiting loop is composed of four piecewise linear segments. Considering initial magnetization curve and local loops, there are only six possible segments for working point to reside. Since upper and right branches of limiting loop is symmetrical to lower and left branches, altogether four possible segments need to be considered.

Fig. 3 illustrates the movement of working point in four different situations, where T_k is the current temperature. When temperature increases from T_k to T_m(T_m>T_k), working point will move from K to M, when temperature decreases from T_k to T_n(T_k>T_n), working point will move from K to N.

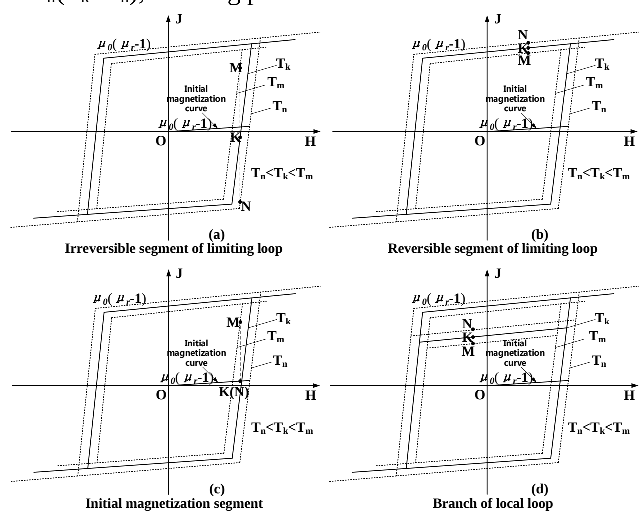

Fig. 3. Movement of working point with temperatures when current working point is on different branch of hysteresis loop

Look at Fig. 3(d), if the working point is on the local loop, when temperature changes, How does it move? Considering local loop approaches to limiting loop if B_{rk} approaches to B_{r1}, the polarization is expressed as (3) and (4) in this paper.

$$J(H,\ T_m) = J(H,\ T_k)\frac{B_{r1}(T_m)}{B_{r1}(T_k)} \tag{3}$$

$$J(H,\ T_n) = J(H,\ T_k)\frac{B_{r1}(T_n)}{B_{r1}(T_k)} \tag{4}$$

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