Dynamic Demagnetization Model of Permanent Magnets for Finite Element Analysis

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Abstract — this paper presents a linearized demagnetization model taking into account temperature dependence. At the same time, an efficient searching algorithm is proposed to properly identify the new worst working point and update the recoil line during the entire transient solution process if a working point is discovered below the knee point of the current recoil line. This model is extended to take into account the temperature dependence of demagnetization behaviors.

I. Introduction

Recently, different demagnetization modeling techniques based on finite element analysis (FEA) have been discussed in the literature. Kang *et al.* presented a two-step approach to first determine the worst load condition from transient solutions, and then apply this worst load condition to the irreversible demagnetization analysis using 2D magneto-static FEA[1]. The demagnetization has also been modeled by the classical Preisach-type hysteresis model to analyze the demagnetization states of permanent magnets during fault conditions in large synchronous motors [2]. Ruoto *et al.* have introduced an exponential function based model to take into account the temperature dependence of demagnetization behavior [3]. Clearly, the two-step approach ignored the demagnetization impact on transient solutions, thus the discovered worst working point may not represent the true operating condition. Therefore, it is necessary to check the working point of each element at each time-step. If the working point is too far from the curve given by the demagnetization model, the remanence of that element has to be adjusted so that the working point is brought back to the BH curve [3]. On the other hand, how a new worst load point is identified will have a direct impact on modeling accuracy, computation efficiency and convergence.

This paper introduces a linear model that handles the complete demagnetization curve and temperature dependence of demagnetization behaviors. At the same time, an efficient searching algorithm is proposed to iteratively search for a new worst working point along the gradient direction from time to time during the entire transient solution process if a working point is discovered below the knee point of the current recoil line. Then, this model is further extended to take into account the temperature dependent demagnetization behaviors.

II. Irreversible Demagnetization Model

If the working point a of permanent magnet material goes below the knee point K by an external field H_a, even after the external field H_a is reduced or totally removed, the subsequent working point will no longer along the original B-H curve, but along the recoil line L_a. As long as the subsequent applied external demagnetization field intensity does not exceed H_a, the permanent magnet will work along the recoil line L_a. If, however, greater external demagnetization field H_b is applied,

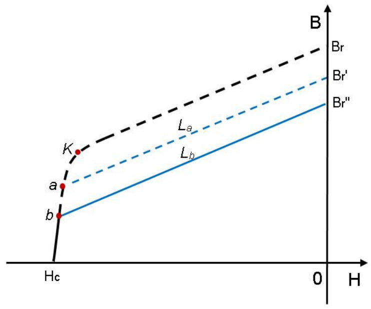

Fig. 1 Irreversible demagnetization due to working point below the knee point

a lower knee point b associated with a new recoil line L_b will be established as indicated in Fig. 1.

During FE analysis, the permanent magnet represented by the coercivity H_c is treated as an additional source contributing to the right-side hand of the FE formulation. The proposed approach is based on a linearized model characterized by the recoil line passing through the latest identified demagnetization point. This point will be updated from time to time when a new worst working point is discovered. In the model, the value of coercivity used in the FE formulation is H_c', the intersection of the recoil line with H-axis, as shown in Fig. 2, not H_c, directly from the original demagnetization curve. At the same time, the linear permeability with the value of the slope of the recoil line is used. Clearly, this linear model is valid only when the working point is above the worst point K on the recoil line such as the point P_1. This suggests that it is necessary to check the validity of the working point on the recoil line for every element at each time step. If a working point is discovered below the point K on the recoil line as the point P_2, a new and lower point K' corresponding to a new worst working point has to be identified from the original demagnetization curve during the transient process. The key issue here is how to efficiently identify this new worst working point K' from the original demagnetization curve. This will be described in detail as follows.

Assume that the point K_0 in Fig. 3 is the worst working point so far during the transient FE analysis, and the working point P_1 is derived based on H_{c0} associated with the recoil line L_0 passing through the point K_0. Since the working point P_1 is

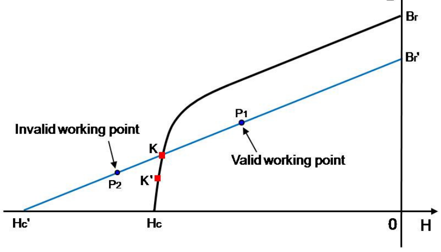

Fig. 2 Linearized demagnetization model

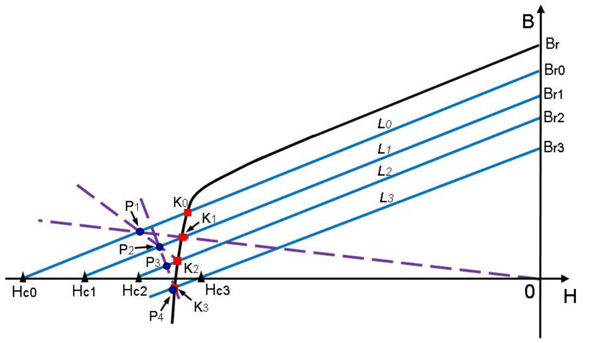

Fig. 3 Search for the new worst working point

below the point K_0, this linear model is no longer valid and a new and lower worst working point has to be identified. Clearly, this new worst working point should also reside on the original demagnetization curve. To this end, let us first to draw a line linking the origin with the working point P_1. The intersection between this line and the original demagnetization curve, the point K_1, is the candidate of the new worst working point to be searched for. It follows that after the FE analysis at the same time instant based on H_{c1} associated with the recoil line L_1, a new working point P_2 can be derived. Since the working point P_2 does still not reside on the original demagnetization curve, the searching process has to continue.

We could repeat the above scheme by drawing a line linking the origin with the working point P_2 to obtain a new candidate of the worst working point. But the convergence is very slow. Instead, searching in the gradient direction along the line passing through both the previous working point P_1 and the current working point P_2 is much more efficient. The intersection between this line and the original demagnetization curve, K_2, provides an improved candidate for the new worst working point. Consequently, a new working point P_3 can be derived after FE analysis based on the updated recoil line L_2 with H_{c2}. Even though P_3 has not moved onto the original demagnetization curve yet, the new point P_3 is much closer compared to the previous point P_2.

Similarly, by searching in the gradient direction along a line passing through both the previous working point P_2 and the current working point P_3, the intersection between this line and the original demagnetization curve, K_3, provides a new linear model characterized by the recoil line L_3 with H_{c3}. The subsequent FEA simulation will provide a new working point P_4. As the working point P_4 has converged onto the original demagnetization curve within a pre-specified tolerance, K_3 is the new worst working point. Since the searching algorithm converges along the gradient direction, only a very few iterations are required to find the new worst working point.

III. Temperature Dependent Demagnetization Model

For a better representation of any type of magnet, it is advantageous to work on intrinsic flux density $\boldsymbol{B_i}$ *vs* $\boldsymbol{H}$ curve, instead of flux density $\boldsymbol{B}$ *vs* $\boldsymbol{H}$ curve. Once the temperature dependent B_i-H curve is derived, it is straightforward to convert B_i-H characteristic into B-H characteristic in terms of

$$B = B_i + \mu_0 H \tag{1}$$

In the model, two temperature dependent parameters are remanent flux density B_r, the value of B_i (or B) at $H = 0$, and intrinsic coercivity H_{ci}, the value of H at $B = 0$. Both B_r and H_{ci} can be described using second order polynomials as

$$B_r(T) = B_r(T_0)\left(1+\alpha_1(T-T_0)+\alpha_2(T-T_0)^2\right) = B_r(T_0)\,P(T) \tag{2}$$

$$H_{ci}(T) = H_{ci}(T_0)\left(1+\beta_1(T-T_0)+\beta_2(T-T_0)^2\right) = H_{ci}(T_0)\,Q(T) \tag{3}$$

where T_0 is the reference temperature, and α_1, α_2, β_1 and β_2 are coefficients which can be identified from supplier datasheets.

The B_i-H curve up to the intrinsic coercivity H_{ci} can be described by the following function:

$$B_i(H,T) = P(T)\left(b_0 \tanh\left(\frac{H+Q(T)H_{ci}(T_0)}{Q(T)h_0}\right) + b_1 \tanh\left(\frac{H+Q(T)H_{ci}(T_0)}{Q(T)h_1}\right)\right) \tag{4}$$

Here $P(T)$ and $Q(T)$ are defined by (2) and (3), respectively. They are both unit at the reference temperature T_0. As a result, all coefficients b_0, h_0, b_1 and h_1 can be identified by a nonlinear curve fitting based on B_i-H curve at the reference temperature T_0. It can be easily verified that (4) has automatically satisfied the constraint of (2): $B_i(0,T) = B_r(T)$. Consequently, once the model is constructed at the reference temperature T_0, any B_i-H curves at other temperature can be dynamically reconstructed in terms of the temperature dependence of $B_r(T)$ and $H_{ci}(T)$. Finally, the B-H curve in the second and third quadrants can be further derived through (1), and the temperature dependent slope of the recoil line is derived from (1) and (4) as

$$\mu(T) = \left.\frac{\partial B(H,T)}{\partial H}\right|_{H=0} = \left.\frac{\partial B_i(H,T)}{\partial H}\right|_{H=0} + \mu_0 = \frac{P(T)}{Q(T)}\mu_i(T_0) + \mu_0 \tag{5}$$

IV. Benchmark Example

The proposed model is applied to 3D FE analysis of a 8-pole, 48-slot Toyota Prius IPM motor [4]. Fig. 4 shows the torque derived without considering demagnetization of NdFeB magnets, and with considering demagnetization of NdFeB magnets at temperatures of 25° and 90°, respectively. More results will be provided in the full paper.

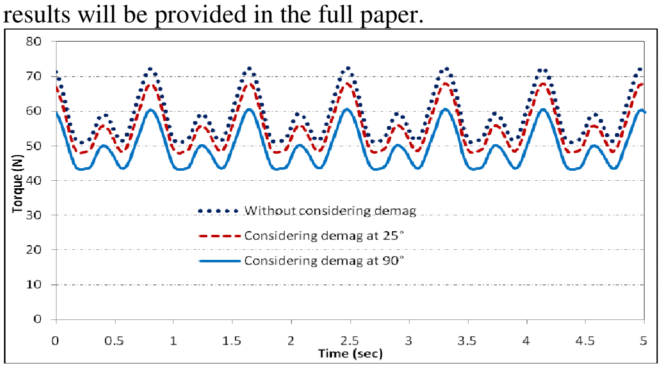

Fig4. Torque profiles showing temperature dependent demagnetization effects

V. References

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