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Research Article

Optimal Calculating on Working Point of the Permanent Magnet

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Abstract: Confirming about the working point of the permanent magnet is an essential premise in the calculating of the permanent magnetic circuit. In this study, the choosing methods about the working point of the permanent magnet are analyzed overall. The calculating formulas of the optimal calculating are deduced using the conception of magnetic energy density. The conclusions can give some guidance to the permanent magnetic circuit calculating and design.

Keywords: Permanent magnet, optimal calculating, working point

INTRODUCTION

With the wide application of permanent magnetic material, the calculating of permanent magnetic circuit is more and more important. The choosing of working point of permanent magnetic is the base of calculating of permanent magnetic circuit. Permanent magnet is working based on remanence of magnetic material and has much larger coercive force. In the analysis of permanent magnetic circuit, the permanent magnet is corresponding as a magneto-motive force and provides with magnetic resistance. There are two kinds of working states, one kind is that the permanent magnet works at demagnetization curve and magnetic resistance keeps constant, the other is permanent magnet works at reverting line and magnetic resistance is variable. The optimal calculating of permanent magnet working point can improve the efficiency of magnetic circuit. In this study, the working points of the two kinds of working state for permanent magnet are analyzed and some correlative calculating formulae are deduced. Tong and Zai (2000) analyze the low voltage electrical equipment relay and control system. Zhang (1990) study the electrical equipment theory base. Liu (2002) make an analysis and calculation of permanent magnetic working points of polarity magnetic system. Cai (1996) have a study of the vehicle ignition system reliability test bench. Gong *et al.* (2005) have a research of the electronically controlled motorcycle engine fuel injection and ignition control modeling and simulation. Song and Jia (2010) make a study of the development of electronic ignition system for ignition chamber GDI engine.

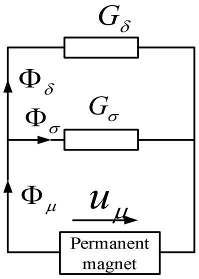

Fig. 1: Model of permanent magnetic circuit

OPTIMAL CALCULTING OF PERMANENT MAGNET

The working point of permanent magnet has connection with techniques of magnetization. Because of the lower magneto conductivity of permanent magnet and the much influence of leakage magnetic flux, the leakage magnetic flux phenomenon must be considered. The permanent magnetic circuit model is shown as Fig. 1. The leakage magnetic coefficient is defined as:

$$\sigma = \Phi_\mu / \Phi_\delta = b_\mu / b_{\delta\mu} \tag{1}$$

where,

Φ_μ = Main magnetic flux
Φ_δ = Air gap magnetic flux
Φ_σ = Leakage magnetic flux
b_μ = Magnetic induction intensity
$b_{\delta\mu}$ = Converting air gap magnetic induction intensity
G_δ = Air gap magneto conductivity

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G_σ = Leakage magneto conductivity

Magnetic field energy of air gap is:

$$A_\delta = 0.5\Phi_\delta \mu_\delta = 0.5\left(\frac{b_\mu}{\sigma} S_\mu\right)(-H_\mu L_\mu) = -0.5B_r H_c\left[-\frac{1}{\sigma}\frac{b_\mu}{B_r}(-\frac{H_\mu}{-H_c})\right]V_\mu$$

$$\ldots = -0.5B_r H_c(-\frac{1}{\sigma}bh)V_\mu = -\frac{B_r H_c}{2} w_\delta V_\mu \tag{2}$$

where, $w_\delta = -bh/\sigma$ is converting magnetic energy density. $b = b_\mu/B_r$, $h = -H_\mu/H_c$, B_r and H_c are remanence and coercive force of permanent magnetic material. H_μ is permanent magnetic field intensity.

Calculating of working at demagnetization curve: When permanent magnet is magnetized at the state of complete assembly and no demagnetizing effect occurs, the permanent magnet works at demagnetization curve. When working point changes, the leakage magnetic coefficient σ changes slightly and σ can be approximately constant. Then, $\sigma = b\mu/b_\delta$ and air magnetic induction intensity $b_\delta = b_\mu - b_\sigma$. The converting air gap magnetic energy density is:

$$w_\delta = -b_\delta h_\mu = -\frac{b_\mu}{\sigma} h_\mu \tag{3}$$

According to experiential formula of demagnetization curve, then:

$$b_\mu = \frac{1+h_\mu}{1+ah_\mu}, \quad a = \frac{\sqrt[2]{r-1}}{r}$$

where, r is bulge coefficient of magnetic material.

Then:

$$w_\delta = -\frac{h_\mu(1+h_\mu)}{\sigma(1+ah_\mu)} \tag{4}$$

The extremum condition of w_δ is $dw_\delta/dh_\mu = 0$, then:

$$\begin{cases} h_{\mu m} = \frac{1}{\alpha}(\sqrt{1-\alpha} - 1) \\ b_{\mu m} = \frac{1+h_{\mu m}}{1+\alpha h_{\mu m}} = \frac{1-\sqrt{1-\alpha}}{\alpha} \end{cases} \tag{5}$$

Thus, the slope of line between working point of permanent magnet and coordinate origin is:

$$\mu_* = \frac{b_{\mu m}}{h_{\mu m}} = \frac{b_{\delta m} + b_{\sigma m}}{h_{\mu m}} = \mu_{\delta *} + \mu_{\sigma *} \tag{6}$$

or

$$\mu_* = B_r/H_c \tag{7}$$

The max magnetic energy density is:

$$w_{\delta m} = -\frac{b_{\mu m} h_{\mu m}}{\sigma} = \frac{2(1-\sqrt{1-\alpha}) - \alpha}{\sigma\alpha^2} \tag{8}$$

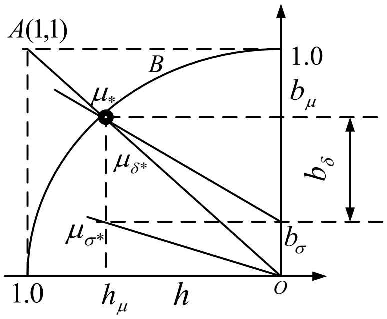

Fig. 2: Permanent magnet works at demagnetization curve

Therefore, the conclusion can be achieved: the optimal working point of permanent magnet is point of intersection between the line of coordinate origin and $A(B_r, -H_c)$ and demagnetization curve when permanent magnet works at demagnetization curve. The conclusion of Eq. (5) to (7) is denoted as Fig. 2

Calculating of working at reverting line: In order to keep the working point of permanent magnet from the affected by outside magnetic field, some AC magnetic field is needed to demagnetize a certain extent and make the permanent magnet works at a steady reverting line. Two kinds are classified: one kind is magnetized at the state of assembling partially and its leakage magneto conductivity. Is equal to that of assembling completely, namely that $\mu_{\sigma *} = \mu_{\sigma * 0}$. The other is magnetized at the state of assembling partially and its leakage magneto conductivity. Is not equal to that of assembling completely, namely that $\mu_{\sigma *} \neq \mu_{\sigma * 0}$. The confirming of working point is determined by the intensity of outside interferential magnetic field and the working point of permanent magnet should not transfer to demagnetization curve in the instance of intense outside interferential magnetic field. Otherwise, the start point of reverting line will change when outside interferential magnetic field is wiped off and the B value of working point will decrease

- The optimal working point of $\mu_{\sigma *} = \mu_{\sigma * 0}$. Supposing the start of reverting line is $A_1(h_1,b_1)$ and working point is $A_2(h_2,b_2)$, as Fig. 3. Leakage magnetic coefficient is given at assembling partially

$$\sigma = b_1/b_{\delta 0} \tag{9}$$

where, $b_{\delta 0}$ is air gap magnetic induction intensity, $b_1 = b_{\delta 0} + b_\sigma$, b_σ, is leakage magnetic induction intensity, shown as Fig. 3.

According to engineering experiential formula, equivalent expressions of demagnetization curve is $b = (1 + h)/(1 + \alpha h)$, reverting coefficient $\mu_{R*} = 1 - \alpha$.

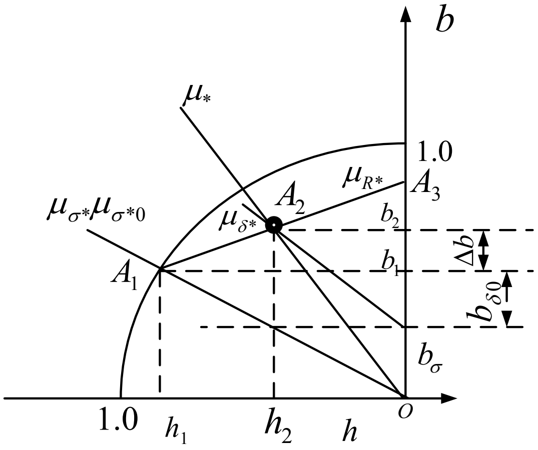

Fig. 3: Working at reverting line ($\mu_{\sigma*}/\mu_{\sigma*0}$)

When working point transfers from $A_1(h_1,b_1)$ to $A_2(h_2,b_2)$, air magnetic induction intensity is:

$$\begin{aligned} b_\delta &= b_{\delta 0} + \Delta b = b_1/\sigma + \mu_{R*}(h_2 - h_1) \\ &= \frac{1+h_1}{\sigma(1+ah_1)} + (1-\alpha)(h_2 - h_1) \end{aligned} \tag{10}$$

The converting magnetic energy density of air gap is:

$$w_\delta = -h_2 b_\delta = -h_2(1-\alpha)(h_2-h_1) - h_2 \frac{1+h_1}{\sigma(1+\alpha h_1)} \tag{11}$$

where, - $h_2 b_{\delta 0}$ = -h_2 1+$h_1/\sigma(1+\alpha h_1)$ is convert-ing value of magnetic energy density with starting air gap of working point. – $h_2(1 - \alpha)(h_2 - h_1)$ is converting value of magnetic energy density increment from assembling partially to assembling totally.

From geometrical connection of Fig. 3, if $A_1(h_1,b_1)$ is decided, μ_{R*} will be decided. The conduction of the max inner connected rectangle area of ΛOA_1A_3 is $h_2 = 0.5h_1$. To meet this conduction, $b_\sigma = 5b_1$ and leakage magnetic coefficient $\sigma = b_1/b_{\delta 0} = 2$, then converting value of air gap magnetic energy density is:

$$w_\delta = -\frac{h_1}{2}\left[(1-\alpha).0.5h_1 + \frac{1+h_1}{2(1+\alpha h_1)}\right] \tag{12}$$

Obviously, the location of $A_1(h_1,b_1)$ has influence on w_δ and there is a h_{1m} value to maximize w_δ. If the method of derivate to w_δ is used to solve the h_{1m}, a cubic equation will be got and difficult to solve. If α is given and draws the chart of $w_\delta = f(h_1)$, it is convenient to find h_{1m}.

In the actual engineering, σ is always bigger than 2, the change of b_2 is very little and approaches to b_m for different α value. The optimal working point is solved as:

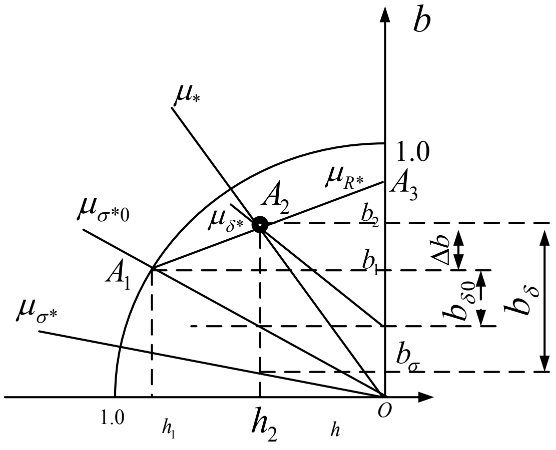

Fig. 4: Working at reverting line ($\mu_{\sigma*} \neq \mu_{\sigma*0}$)

$$\begin{cases} b_2 = \frac{1-\sqrt{1-\alpha}}{\alpha} \\ b_1 = \frac{1+h_1}{1+\alpha h_1} \\ \frac{b_2}{b_1} = \frac{h_2\mu_*}{h_1\mu_{\sigma*}} = \frac{h_2}{h_1}\frac{\sigma}{\sigma-1} \end{cases} \tag{13}$$

- The optimal working point of $\mu_{\sigma*} \neq \mu_{\sigma*0}$. Making the coefficient $k_y = \mu_{\sigma*}/\mu_{\sigma*0}$ and leakage magnetic coefficient $\sigma = b_1/b_{\delta 0}$, the w_δ is not dicided by inner connected rectangle area of ΔOA_1A_3 and a apex is lies at $\mu_{\sigma*}$ line, as Fig. 4.

From Fig. 4, it is difficult to get:

$$\begin{cases} \mu_{\delta*} = b_\sigma/h_2 \\ \mu_{\sigma*0} = (b_1 - b_{\delta 0})/2 \end{cases} \tag{14}$$

Then

$$k_y = \mu_{\sigma*}/\mu_{\sigma*0} = b_\sigma/(b_1 - b_{\delta 0})$$

accordingly:

$$b_\sigma = k_y\,(b_1 - b_{\delta 0}) = k_y b_1[(\sigma-1)/\sigma] \tag{15}$$

and

$$b_\delta = b_2 - b_\sigma = b_1 - b_\sigma + \Delta b \tag{16}$$

therefore,

$$b_\delta = b_1\left(1 - k_y\,\frac{\sigma-1}{\sigma}\right) + (1-\alpha)(h_2 - h_1)$$

Making

$$\sigma_p = \frac{\sigma}{\sigma - k_y(\sigma-1)}$$

Then:

$$b_\delta = b_1/\sigma_p + (1-\alpha)(h_2-h_1) = b_1/\sigma_p + \mu_{R*}(h_2-h_1) \tag{17}$$

Equation (17) is similar with (10), the difference is σ_p and σ.

CONCLUSION

The optimal calculating of permanent magnet working point is presented under different working conditions. The calculating equations are applicable to nonlinear demagnetization curve of permanent magnet, such as AlNiCo. Moreover, for the thulium permanent magnet, the calculating method is much simple because of their line demagnetization curve.

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