# Magnetic Circuit Analysis of Claw-Pole Permanent Magnet Generator of Vehicle based on Equivalent Magnetic Circuit Method

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Abstract: The structure of claw-pole permanent magnet generator is introduced in the paper; Major magnetic flux circuit of claw-pole permanent magnet rotor is analyzed. In calculation method of permanent magnet volume and armature winding turns, determination of important parameters is researched. The magnetic circuit model is built by equivalent magnetic circuit method. Permeance and flux are calculated. The performance of the generator was tested, it is proved that the generator has the characteristics of high efficiency and high reliability.

## 1. Introduction

Nowadays, in national economic the vehicle industry has become one of industries. The generator is considered an important part of vehicle. There are two kinds of generator recently in vehicle, in Hsilicon rectifying generatorH, excitation current in excitation winding produces the magnetic field, only a few electrical energy can be converted to magnetic energy for Hsilicon rectifying generator, so utilization of energy is very low; the excitation winding is easy to be broken, at the same time maintenance cost will be increased. However, there is not excitation winding in permanent magnet generator, so brush and slip ring which are easy to appearing failure are not used, it is a generator which has not brush. Meanwhile, it's structure is simple, operation is reliable and it has the characteristics of small size, low loss and light weight. So, permanent magnet generator is future development direction of generator for vehicle application.

## 2. The Design of Structure of Magnet Generator

The structure of rotor is claw-pole type,which is made up of two flanges on which there is some claw, there is an axial magnetized annular permanent magnet between flanges, axial flux is converted to the radial flux through claw-pole, and toe polarities on adjacent claw-pole are opposite. The shape of permanent magnet is very simple, so it has good magnetic properties, magnetization is even, and utilization is high, too. In addition, its production process is very simple, it has high productivity,the cost of product is reduced. The claw-pole permanent-magnet generator is mainly made up of stator, rotor and regulator. Rotor is composed of front claw-pole and rear claw-pole, an annular permanent magnet and a shaft. Stator is composed of armature windings, stator core, a front cover. The structure of the generator is shown in Figure 1. Because NdFeB material is a rare earth permanent magnet materials which has character of high coercivity, high remanence, and high magnetic energy product, under the normal temperature, the remanence intensity *Br* is up to 1.47T, the coercivity *Hc* is up to 992KA/m, and the maximum magnetic energy product is up to 397.9KJ/$m^3$[1], Therefore, the axial size of NdFeB is smaller, however it can product greater magnetomotive force.

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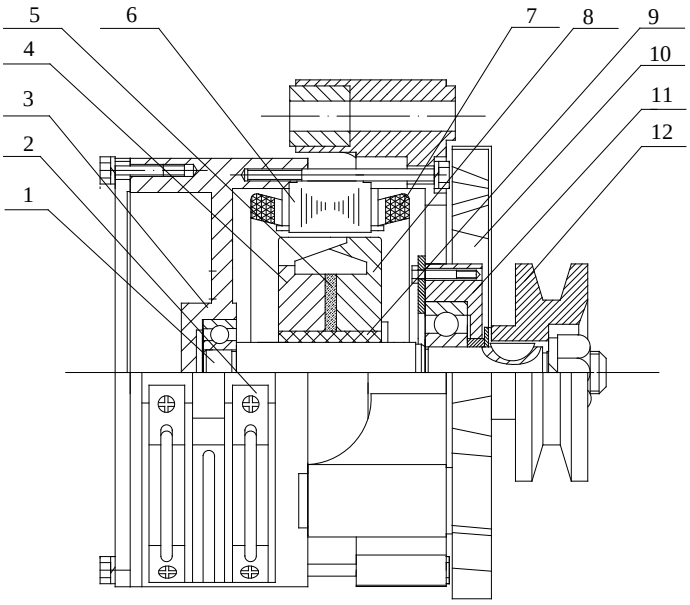
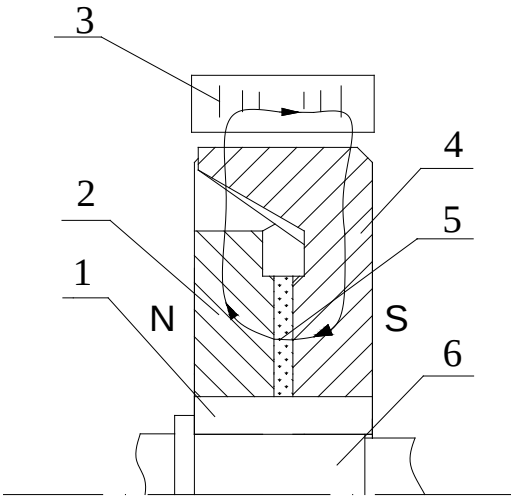



1.shaft 2.regulator 3.rear cover 4.front-claw pole 5.permanent magnet 6. stator core 7.armature coil 8.rear-claw pole 9.magnetic shield10. fan 11.pulley

Fig.1 Structure of magnet generator with claw-pole




1.magnetic shield 2.claw-pole of N pole 3.stator core 4.claw-pole of S pole 5.permanent magnet 6.shaft

Fig.2 Main magnetic flux of rotor

## 3. Determination of Major Parameters

### 3.1 Power, Rotate Speed and Range of Voltage

The generator is used for supplying DC for the entire electrical system of the vehicle. and charging for battery[2], current needed by electrical equipment is approximately34.3A, so rated current output is designed as 35.7A, at this time, rated power is 500W. when speed is between 2000 r/min and 4800 r/min, the output voltage must be between 12V to 14.5V.

### 3.2 Calculating Permanent Magnet Volume

Based on short-circuit triangle method [3] ， the formula for calculating permanent magnet volume of is as follows:

$$V_M = \frac{(p_N)_{\cos\varphi=0}\sigma_0 C_F K_{\alpha d}}{3.54 k_B f B_{M0} H_{Mh}} \cdot \frac{k_i^2}{k_i - 1} \times 10^8 , \quad (1)$$

In the type: $P_N$ is rated capacity ；$\sigma_0$ is magnetic leakage factor, there, the value of` $\sigma_0$ is 1.4; $C_F$ is magnetic potential coefficient, When the magnet circuit is not up to saturated, value of $C_F$ is between 1.1 to1.5, in the design, $C_F$ is taken as1.1; $K_{\alpha d}$ is direct-axis armature reaction magnetic potential equivalent coefficient, $K_{ad} = \frac{\alpha\pi + \sin\alpha\pi}{4\sin\frac{\alpha\pi}{2}}$, where, $\alpha$ is arc coefficient, $\alpha = 0.8$; $k_i$ is short circuit current multiple, $k_i = 4$, $k_i = I_n / I_N$, $I_n$ is short circuit current, $B_{M0}$ is magnetic induction intensity at no-load operating point, $B_{M0} = 0.85 B_r$, $B_r$ is remanence intensity, $H_{Mh}$ is magnetic field intensity on steady-state short-circuit, $H_{Mh} = 0.65 H_c$, $H_c$ is magnetic field intensity.

### 3.3 Calculation of Number of Armature Turns of Per Phase

According to electromagnetic principium, the formula for calculating number of armature turns is as follows [4,5]:

$$W = \frac{E_0}{4fK_B K_w \phi_0}, \tag{2}$$

In the type: $E_0$ is electrodynamic potential on no-load, $K_B$ is waveform coefficient, when the form of magnetic field in gap is sinusoidal field, $K_B = 1.11$; $f$ is frequency, $f = pn/60$, $p$ is number of pole-pairs,a claw pole has 6 claws, $p$ =6, $n$ is speed, $k_w$ is winding coefficient of armature turns, $k_w = 0.92$, $\phi_0$ is the effective magnetic flux which goes through stator winding, $\phi_0 = \phi_\delta / \sigma_0$, $\phi_0 = \frac{S_M B_{M0}}{\sigma_0}$, where, $\sigma_0$ is magnetic leakage factor,the value of $\sigma_0$ is between 1.2 and 1.5, there, $\sigma_0$ =1.3, $S_M$ is component of cross-sectional area of magnet at each pole, $S_M = \frac{1}{P}\sum S_{M0}$, $S_{M0}$ is cross-sectional area of annular magnet, $B_{M0} = 0.85B_r$.

## 4. Analysis of Magnetic Circuit of the Generator

The total magnetic flux of the generator is made up of major magnetic flux and leakage magnetic flux. Main flux passes armature turns which can generates electromotive force. Leakage flux doesn't pass armature turns. Equivalent magnetic circuit of major magnetic flux is shown in the Fig. 2, it sets out from the N-pole, passes left claw on N pole, gap, stator teeth, also passes the armature turns in stator slot, stator yoke, neighbouring stator teeth, and then enters gap again, reaches the right claw of S pole, goes back S pole permanent magnet.

Because of effect of flange and claw pole shoe and magnetic potential drop generated by additional gap between magnet and flange, the leakage flux can be divided into three parts,there are $\phi_{sc}$ which is between adjacent claw), $\phi_{sf}$ which is between two flanges and $\phi_{sM}$ which is magnet itself , leakage flux is also divided into $\phi_{sc}$ (between adjacent claw) and $\phi_{sM}$ (magnet itself) two parts, equivalent magnetic circuit is established using equivalent magnetic circuit method, it is shown in Figure 3. In Figure 3, $G_c$ is magnetic conductivity of each claw pole, $G_{01}$ is magnetic conductivity of additional gap between magnet and flange(single pole), $G_f$ is magnetic conductivity of each flange, $G_\delta$ is magnetic conductivity of gap between stator teeth and each claw, $G_{sc}$ is leakage magnetic conductivity between each antipole which is converted to both ends of a claw), $G_{ZS}$ is magnetic conductivity of each stator teeth, $G_{as}$ is magnetic conductivity of stator yoke[6].

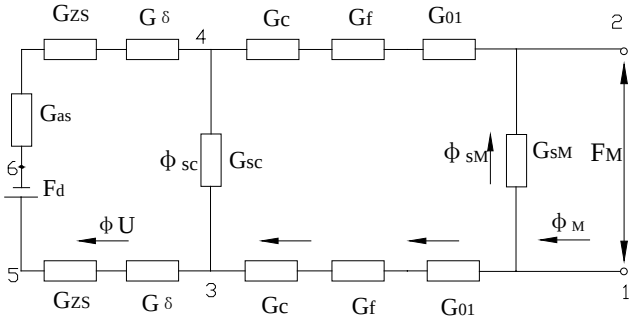



Fig.3 Equivalent circuit of the generator

After analyzing Figure. 3, the synthesized magnetic conductivity is calculated from Eq 3, from Eq 4,the synthesized leakage magnetic conductivitycan be calculated, no-load magnetic flux leakage coefficient is calculated from Eq 5.

$$G_0 = G_{sM} + \frac{1}{\frac{2}{G_c}+\frac{2}{G_f}+\frac{2}{G_{01}}+\frac{1}{G_{sc}}+\frac{1}{\frac{2}{G_b}+\frac{2}{G_{ZS}}+\frac{1}{G_{aS}}}}, \tag{3}$$

$$G_s = G_{sM} + G_{sc} \times \left[ \frac{\frac{2}{G_\delta}+\frac{2}{G_{ZS}}+\frac{1}{G_{as}}}{\left(\frac{2}{G_c}+\frac{2}{G_f}+\frac{2}{G_{01}}+\frac{2}{G_b}+\frac{2}{G_{ZS}}+\frac{1}{G_{aS}}\right)+G_{sc}\left(\frac{2}{G_c}+\frac{2}{G_f}+\frac{2}{G_{01}}\right)\left(\frac{2}{G_b}+\frac{2}{G_{ZS}}+\frac{1}{G_{aS}}\right)} \right], \tag{4}$$

$$\sigma_0 = 1+\left(G_{sM}+G_{sc}\right)\left(\frac{2}{G_\delta}+\frac{2}{G_{ZS}}+\frac{1}{G_{aS}}\right)+G_{sM}\left(\frac{2}{G_c}+\frac{2}{G_f}+\frac{2}{G_{01}}\right)\left[1+G_{sc}\left(\frac{2}{G_\delta}+\frac{2}{G_{ZS}}+\frac{1}{G_{aS}}\right)\right]. \tag{5}$$

When generator is no-load running,at this time, $F_d = 0$, shorting out between point 5 and point 6.introducing label '0', it means no-load. Using Kirchhoff's first law and ohm law of magnetic circuit, the total flux, effective flux and leakage flux can be worked out.

$$\phi_{M0} = F_{M0}G_{sM} + \frac{F_{M0}}{\frac{2}{G_c}+\frac{2}{G_f}+\frac{2}{G_{01}}+\frac{1}{G_{sc}}+\frac{1}{\frac{2}{G_b}+\frac{2}{G_{ZS}}+\frac{1}{G_{aS}}}}, \tag{6}$$

$$\begin{aligned}\phi_{s0} &= \phi_{sc} + \phi_{sM0} \\ &= F_{M0}G_{sM} + F_{M0}G_{sc} \times \left[ \frac{\frac{2}{G_\delta}+\frac{2}{G_{ZS}}+\frac{1}{G_{as}}}{\left(\frac{2}{G_c}+\frac{2}{G_f}+\frac{2}{G_{01}}+\frac{2}{G_b}+\frac{2}{G_{ZS}}+\frac{1}{G_{aS}}\right)+G_{sc}\left(\frac{2}{G_c}+\frac{2}{G_f}+\frac{2}{G_{01}}\right)\left(\frac{2}{G_b}+\frac{2}{G_{ZS}}+\frac{1}{G_{aS}}\right)} \right]\end{aligned}, \tag{7}$$

$$\phi_{U0} = \phi_{M0} - \phi_{s0} = F_{M0}\left(G_0 - G_s\right) = F_{M0}G_U = F_{M0}\frac{1}{\frac{2}{G_c}+\frac{2}{G_f}+\frac{2}{G_{01}}+\frac{1}{G_{sc}}+\frac{1}{\frac{2}{G_b}+\frac{2}{G_{ZS}}+\frac{1}{G_{aS}}}} -$$

$$F_{M0}G_{sc} \times \left[ \frac{\frac{2}{G_\delta}+\frac{2}{G_{ZS}}+\frac{1}{G_{as}}}{\left(\frac{2}{G_c}+\frac{2}{G_f}+\frac{2}{G_{01}}+\frac{2}{G_b}+\frac{2}{G_{ZS}}+\frac{1}{G_{aS}}\right)+G_{sc}\left(\frac{2}{G_c}+\frac{2}{G_f}+\frac{2}{G_{01}}\right)\left(\frac{2}{G_b}+\frac{2}{G_{ZS}}+\frac{1}{G_{aS}}\right)} \right], \tag{8}$$

In the type:$G_0$ is synthesized magnetic conductivity,$G_u$ is effective conductivity, $G_s$ is synthesized leakage magnetic conductivity,$F_{M0}$ is magnetic motive force of permanent magnet on no-load.

## 5. Prototype Test

The rotor adopts claw-pole with 6 pairs, rated voltage, rated power, and rated speed respectively are 14V, 500W and 4800r/min. When load is respectively set to be 480W, 500W and 520W, test results are shown in Table 1.

Table 1 The results of test

| Speed(r/m) | 2000 | | | 4000 | | | 4800 | | |
|---|---|---|---|---|---|---|---|---|---|
| Power(W) | 480 | 500 | 520 | 480 | 500 | 520 | 480 | 500 | 520 |
| Voltage(V) | 13.92 | 13.86 | 13.70 | 13.97 | 13.90 | 13.81 | 14.35 | 14.24 | 14.16 |

It can be seen from table 1, when the speed is between 2000r/min and 4800r/min, the load is 480W, 500W and 520W, respectively,the maximum of output voltage is 14.16V, the minimum is 13.92V, performance indicators satisfy design requirements, reaches the national standard.

## 6. Conclusion

The claw-pole permanent magnet generator has the characteristics of simple permanent magne shape, uniform magnetization, high utilization, and simple manufacture process; operation is very reliable, failure rate of generator is low, too.

Based on the equivalent magnetic circuit method, magnetic circuit model of generator is built, synthesized magnetic conductivity, effective conductivity,synthesized leakage magnetic are calculated.

Based on permanent magnet motor theory, major parameters such as permanent magnet volume and number of armature turns are designed,at same time, prototype is made; test results show that when speed is between 2000r/min and 4800r/min, the load is 480W, 500W and 520W, respectively, The output voltage is higher than 13.92 and lower than 14.16, performance indicators reaches the national standard.

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