The Field Excitation Adjustment Characteristic of the Parallel Magnetic Circuit Hybrid Excitation Machine

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Abstract — The hybrid excitation machine (HEM) has two kinds of excitation sources, one is the permanent magnet and the other is the field current. The mathematic model of the HEM based on DQ frame is presented in this paper. Different from the conventional Permanent Magnet Synchronous Motors (PMSM), the d-axis armature current and the dc excitation current can be both used to perform the field-weakening operation, the optimal control strategy of the dc excitation current and the stator current are analyzed. The novel field weakening method and its incidental excellent performance will be shown in this paper.

I. INTRODUCTION

The PMSM are widely used in hybrid electric vehicles (HEV) and battery electric vehicles (HEV), for its high efficiency, high power and torque density [1, 2]. The vehicles have great requirements on high starting torque and wide constant power operation range. The PMSM's starting torque is mainly constrained by the flux provided by the permanent magnets and the current limited by the controller and constant power operation range is mainly determined by the d-axis armature reaction. At high speed, the armature reaction will lead to high order harmonics of flux which will cause high core losses in the silicon steel sheet. High starting torque and wide constant power operation range are difficult to balance in the PMSM design for the fixed excitations provided by PMs. In order to overcome this problem, the hybrid excitation machine was proposed and studied. In HEM, the PMs provide the invariable component of the total flux duo to its constant coercive force and the field windings provide the variable counterpart which can be adjusted by the dc field current [3,4,6]. HEM is able to achieve high torque, wide constant power range avoiding low power factor and efficiency at high speed working, thanks to field excitation adjustment.

T.J.E. Miller and W.L. Soong studied the key parameters in the PMSM. The normalized power against speed characteristics can be expressed by the saliency ratio and the normalized magnet flux linkage, and the parameter plan will guide the machine's design [5]. Although the HEM has been developed for decades, most researchers are focusing on the structures of the machine, the parameters of HEM are rarely studied. In this paper, the algorithm of the field and the armature current adjustment is studied based on the normalized parameters of HEM.

Based on the types of magnetic circuit, HEMs fall into two categories: the parallel magnetic circuit HEM and series magnetic circuit HEM [12]. PMs of the series ones have the risk of demagnetization, and the PMs are large magnetic reluctance in field winding magnetic path, the required ampere-turns is bigger than the parallel ones' with the same flux adjustment ratio. So in this paper, the parallel magnetic circuit HEM is studied.

II. MATHEMATIC MODEL OF HEM

A. Mathematic Model

The first order harmonic model for HEM based on the synchronous d-q reference frame is adopted to express the voltage and the torque. In the model, the phase resistances and the mutual inductances between all the windings are ignored. The steady state equations can be expressed as:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} 0 & -wL_q \\ wL_d & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \psi_{exe} \end{bmatrix} \tag{2-1}$$

$$U = \sqrt{v_d^2 + v_q^2} \tag{2-2}$$

$$Is = \sqrt{i_d^2 + i_q^2} \tag{2-3}$$

$$\psi_{exe} = \psi_{pm} + \psi_e \tag{2-4}$$

$$k_e = \frac{\psi_e}{\psi_{pm}} \tag{2-5}$$

$$\begin{aligned} T_{em} &= p[(\psi_{pm} + \psi_e)i_q + (\varepsilon - 1)L_d i_d i_q] \\ &= p[(\psi_{pm} i_q + (\varepsilon - 1)L_d i_d i_q] + p\psi_e i_q \\ &= p[\psi_{pm}(1 + k_e)i_q + (\varepsilon - 1)L_d i_d i_q] \end{aligned} \tag{2-6}$$

v_d, v_q: d and q-axis components of terminal voltage;
i_d, i_q: d and q-axis components of armature current;
L_d, L_q: d and q-axis components of synchronous inductance;
ε : saliency ratio
ψ_{exe} : total excitation flux linkage;
ψ_{pm} : flux provided by PMs;
ψ_e : flux linkage provided by field current;
k_e : field excitation coefficient

In this model, the PMs and the field windings provide the total excitation flux ψ_{exe}. ψ_{exe} and ψ_e alternate with the field current correspondingly, the ψ_{pm} keeps constant. k_e is defined as the ratio of ψ_e to ψ_{pm}, it does not hold the constant value, but is varying with the field current. The positive current will produce the positive field flux, enhance the total flux, and the negative current will give negative field flux, the total flux also decrease, which is used at field weakening operation. The maximal absolute value of k_e reflects the hybrid degree of the excitation. $k_e=1$ means the field flux equal to the flux produced by the PMs, and the EMF doubles at the same speed, and high starting torque can be achieved; $k_e=-1$ means that all the PM flux goes through the field excitation circuit, doesn't link with armature windings, which can be used at field weakening operation.

B. Per-Unit System

For obtaining a general conclusion, a per-unit system is used. The PM flux linkage, , maximal current limited by the controller and rated speed are chosen as the base values. The normalized model is expressed as:

$$\begin{bmatrix} v_{dn} \\ v_{qn} \end{bmatrix} = \begin{bmatrix} 0 & -w_n \varepsilon L_{dn} \\ w_n L_{dn} & 0 \end{bmatrix} \begin{bmatrix} i_{dn} \\ i_q n \end{bmatrix} + w_n \begin{bmatrix} 0 \\ 1+k_e \end{bmatrix} \tag{2-7}$$

$$\begin{aligned} T_n &= (1+k_e) i_{qn} + (\varepsilon - 1) L_{dn} i_d i_q \\ &= (1+k_e) I_{sn} \cos\theta + (\varepsilon - 1) L_{dn} I_{sn}^2 \cos\theta \sin\theta \end{aligned} \tag{2-8}$$

III. The Field Excitation Adjustment Characteristic

A. Optimum Current Vector Control of the HEM

The negative d axis current is applied in the conventional PMSM operation when $U>U_{lim}$, HEMs have two adjustable values, one is the armature current vector angle, and the other is the field current and the two values give more freedom to get better performance. At the same time, some conclusions in HEM are different with those in PMSM because of k_e.

Based on the normalized model described above, the armature current vector angle with $I_{sn}=1$ at which the maximum torque per ampere (MTPA) is produced can be derived as (3-1). This angle changes with k_e, Fig.1 shows the MTPA line at different k_e.

$$\theta_{opt} = \arcsin\left(\frac{(1+k_e) - \sqrt{(1+k_e)^2 + 8L_d^{*2}(1-\varepsilon)^2}}{4L_d^*(1-\varepsilon)}\right) \tag{3-1}$$

In PMSM, L_{dn} is a key parameter which affects the field weakening operation. The three operation regions [8] are related to the value of L_{dn}. When machine is working along the line CD, it can produce maximal torque with the limited voltage, this is called voltage limited maximum-output trajectory, or MTPV trajectory (maximal torque per Voltage). In HEM, the MTPV trajectory is varying with k_e, the current vector can be expressed as (3-2). The center of ellipse is the character current which is defined as the ratio of ψ_{exe} to L_d, and moves towards to the positive direction of i_d with k_e decreasing. So different from PMSM, the HEMs don't have fixed MTPV trajectory which is varying with k_e. Fig 3 shows several MTPV trajectories at different k_e. The ellipse center of limited voltage moves toward to the positive direction of i_d, it gives the possibility to get more excellent performance at high speed operation.

$$\begin{cases} id = -\dfrac{(1+k_e)}{L_d^*} + \dfrac{\varepsilon(1+k_e) - \sqrt{\varepsilon^2(1+k_e)^2 + 8(\frac{U_{\lim}^*}{w^*})^2(\varepsilon-1)^2}}{4(\varepsilon-1)L_d^*} \\ iq = \dfrac{\sqrt{(\frac{U_{\lim}^*}{w^*})^2 - \left(\frac{\varepsilon(1+k_e) - \sqrt{\varepsilon^2(1+k_e)^2 + 8(\frac{U_{\lim}^*}{w^*})^2(\varepsilon-1)^2}}{4(\varepsilon-1)}\right)^2}}{\varepsilon L_d^*} \end{cases} \tag{3-2}$$

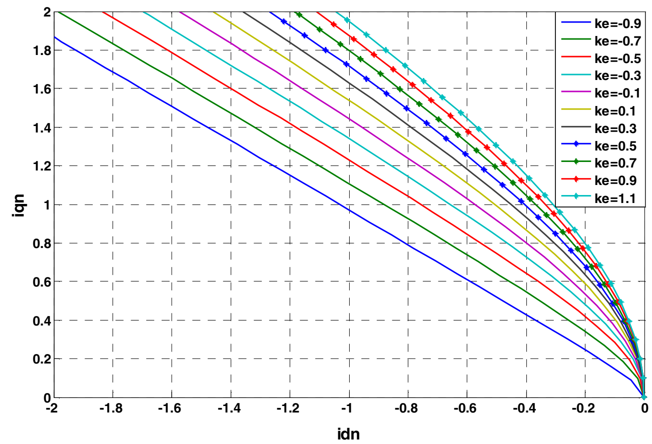

Fig. 1. MTPA trajectory at different k_e

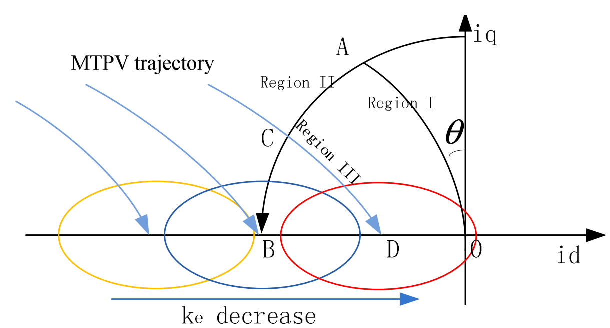

Fig. 2. Voltage-limit ellipse at different k_e

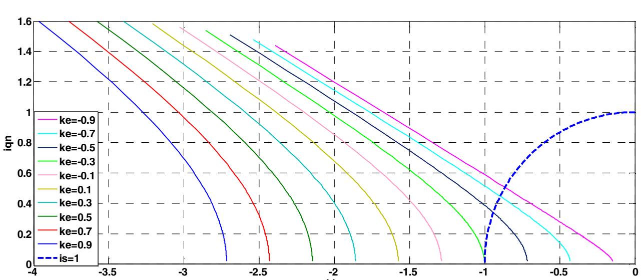

Fig. 3. MTPV trajectory at different k_e

B. The Field Excitation Adjustment Characteristic of HEM

Section A discussed the MTPA and MTPV operations at different k_e, the optimized field excitation adjustment can be used to achieve maximal torque under voltage and current limited at determined speed. The baseline machine's parameters are shown in table I.

TABLE I
MACHINE'S PARAMETERS

PARAMETER	VALUE
ψ_e	-0.9 ~ 0.9
L_{dn}	0.7
ε	1.9

With different k_e, the power against speed characteristics is shown as Fig 4, k_e increases on the direction of arrowhead. According to this figure, the optimal output characteristics is achieved with reasonable variation of k_e, and the machine is hard to achieve high starting torque and wide constant power operation range with fixed excitation.

It is easy to confirm the current vector at constant torque region. As (3-1) expressed, the maximal torque will be got with maximal k_e. Bigger starting torque can be got with bigger value of k_e. However, the saturation and copper losses caused by k_e should be considered during practical application.

Once the terminal voltage exceeds the limited value, the current vector angle should increase or k_e should decrease. The theoretic constant power is able to achieve to extraordinary high speed, as shown in Fig. 4. With the current and terminal voltage limited, the constant torques hyperbola and constant voltage curve is shown as Fig. 5. The voltage curve is plotted at rated speed, so the low voltage value at rated speed means the machine can working at higher speed with the armature current angle and k_e. The maximal torque at the limited voltage is the located on the tangential point.

The machine's working point is determined by the intersection of the current and voltage limited curve in PMSM. HEMs have two controllable parameters, the moveable voltage ellipse and the current circle have more than one intersection point which provides the possibility to optimize the machine's performance on torque, power factor and so on. The field excitation adjustment characteristic is coordinated control of the k_e and armature current. The control strategy can be got by solve the maximal value of the output power, the results is expressed as (3-3).

$$k_e = \frac{\varepsilon L_{dn}(\cos\theta)^2}{\sin\theta} - 1 + L_{dn}\sin\theta \qquad (3\text{-}3)$$

According (3-3), we can obtain the following conclusions:

1) The requirement of k_e is decided by L_{dn} and ε. On the current circle, any current vector has a unique k_e, the practical application is simple.
2) The minimal k_e is got when $i_d = I_{sn}$ and expressed as (3-4). If $L_{dn} \leqslant 1$, the minimal $k_e \leqslant 0$; if $L_{dn} > 1$, the minimal $k_e > 0$. So HEMs don't have Region III which simplified the control strategy, and improves the system's stability.

$$k_e = L_{dn} - 1 \qquad (3\text{-}4)$$

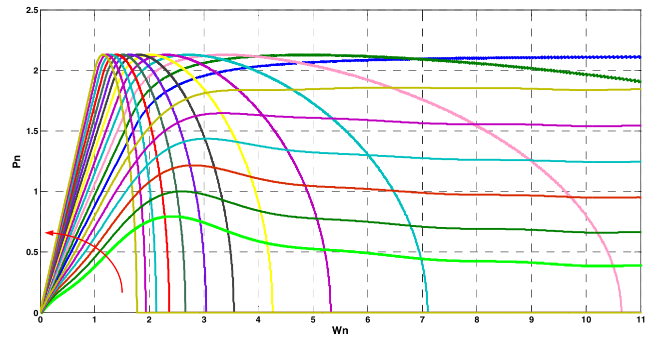

Fig. 4. Power against speed characteristics

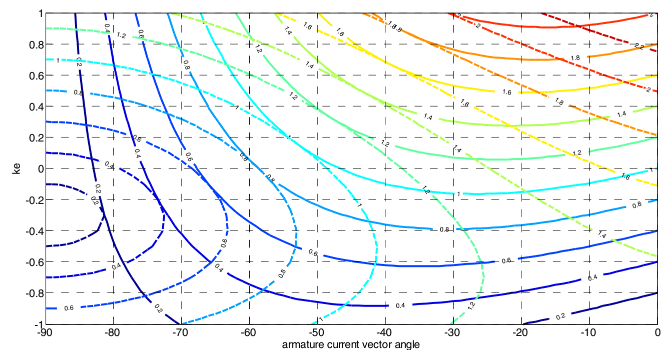

Fig. 5 Constant Torques Hyperbola (solid line) and Constant Voltage Curve (dashed line)

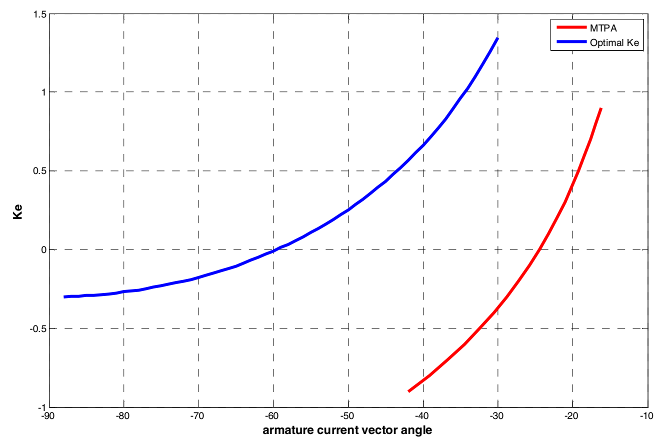

Fig. 6 Optimal Field Current against Stator Current Angle

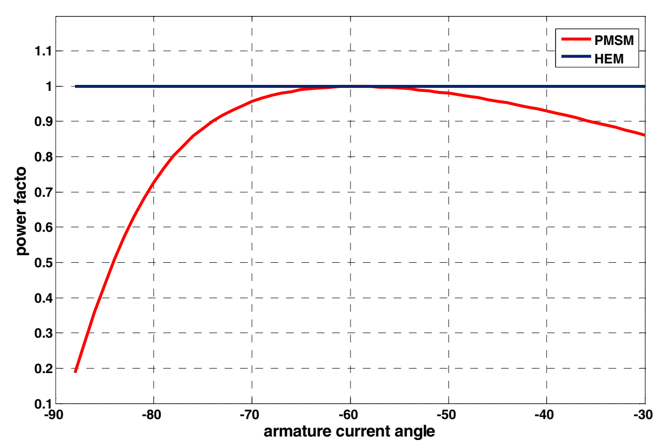

Fig. 7 Power Factor of PMSM and HEM

3) The variation of k_e is helpful to enhance the machine's power factor. The PMSM's power factor is decided by the working point on the i_d-i_q plant. The variation of k_e is inclined to high power factor. The Fig.7 shows the PMSM and HEM's power factor. The PMSM has high power factor when the armature current angle is small, but with the angle declining, the power factor decreases quickly, but HEM's power factor is able to keep high level at all region thanks to the variation of k_e.

4) All the conclusions are based on the first order harmonic model, and the core losses and the copper losses are not included in this paper. When HEMs are working at field weakening region, high order harmonics of flux caused by negative armature reaction will lead to high core losses. Contrarily, field current will realize field weakening with no increments of harmonics of flux, so ke will less than the theoretical value.

IV. EXPERIMENT RESULTS OF THE PROTOTYPE

The principle prototype of a 5kW parallel magnetic path HEM had finished as shown in Fig. 8, the experimental results about the effects of variation of k_e on MTPA is shown in Fig.9. At different field excitation currents, the maximal torque angle is varying. Some detail experiment will finish soon.

Fig. 8 5kW Prototype Machine

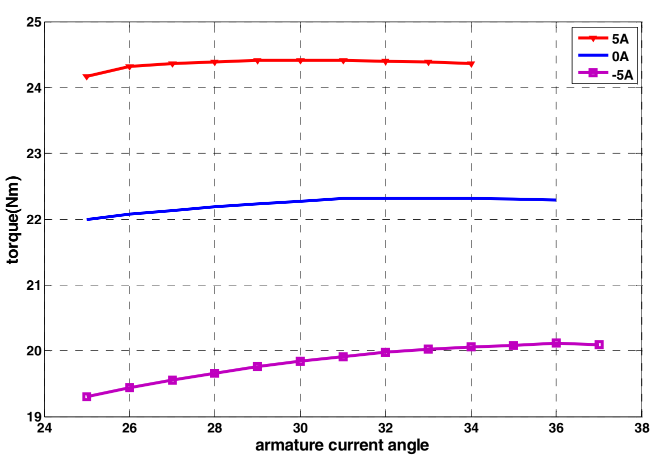

Fig. 9 Experimental Torque at Different Field Current

V. CONCLUSIONS

Based on the parallel magnetic circuit HEM, the field excitation adjustments characteristics are analyzed in this paper. The MTPA and MTPV lines are varying with k_e. The movable ellipses of limited voltage give remarkable field weakening ability. The field excitation adjustment characteristics discussed in section III reveal the relation between k_e and armature current vector angle. Based on the adjustment characteristics, the machine can obtain theoretic infinite field weakening speed, and the power factor automatically equal to 1 is an extra advantage.

The theoretical minimal value of k_e can guide the machine's design at the initial stage assisted the key parameter methods proposed by Fan Tao in [20].

All the conclusions are based on the first order harmonic model, the core losses and the copper losses should be included in future work, and the core losses affected by the field current should be balanced with the field windings' copper loose.

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