Mansoura Engineering Journal

Volume 12 | Issue 2 Article 14

6-7-2021

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Recommended Citation
El-Drieny, Saad (2021) "A Design-Technique for the Prediction of Steady State Performance of a Homopolar Linear Synchronous Motor.," *Mansoura Engineering Journal*: Vol. 12 : Iss. 2 , Article 14.
Available at: https://doi.org/10.21608/bfemu.2021.175880

Mansoura Engineering Journal (MEJ), Vol. 12, No. 2, December 1987

A DESIGN-TECHNIQUE FOR THE PREDICTION OF STEADY STATE PERFORMANCE OF A HOMOPOLAR LINEAR SYNCHRONOUS MOTOR

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(Received Nov 18, 1987, accepted Dec. 1987)

خلاصة – من الاهداف الرئيسية التي يجب أن تراعى أثناء تصميم المحركات المتزامنة الخطية والمستخدمة في رفع وجر القطارات الكهربائية ، أن تكون قليلة الوزن ذات معامل قدرة وجودة عاليتين ما أمكن مع اعطاء قوة الجر وقوة الرفع المناسبتين لدورة تشغيل معينة . ومن المعروف أن قوتي الرفع والجر يعتمدان على كثافة المجال المغناطيسي بالثغرة الهوائية B والناشئ عن الامبيرلفات لكل من ملفات التغذية وملفات التيار المتردد ، لذا فانه بحسب حساب تلك الكثافة بدقة لتحقيق الأداء المستهدف ، يقدم البحث أسلوب تصميمي لحساب أداء الاله مستخدما طريقة (Finite difference method) في ثلاثة أبعاد وذلك لتحليل المجال المغناطيسي بالاله وحساب كثافة المجال الناشئ عن ملفات التغذية وملفات التيار المتردد كل على حدة في اتجاه محور القطب واتجاه محور التعادل (B_f ، B_d ، B) ويتم ذلك على ويتم ذلك على افتراض مائة أمبير لفة لكل من مجال التغذية والمجال الدوار بمركبتيه ، وكذا افتراض أبعاد مبدئية للمحرك طبقا للمواصفات المطلوبة ، بعدها يتم حساب مستويات الجهود الناشئة داخل الاله (E_f ، E_d ، E_q) لكل لفة . من ناحية أخرى يتم حساب تلك الجهود بمساعدة المخطط الاتجاهي (Phasor diagram) للآلة على أساس من الجهد المقنن لها وافتراض قيم مناسبة لزاوية الحمل ومعامل القدرة ، بعد ذلك يتم مناظرة هذه الجهود الناتجة من المخطط الاتجاهي بتلك التي تم حسابها من التحليل المغناطيسي ، وذلك للحصول على عدد اللفات لكل وجه وايجاد القيم الحقيقية للفيض المغناطيسي المناظر (ϕ_d ، ϕ_q : ϕ) والامبير لفات اللازمة لكل مجال . بالحصول على القيم الحقيقية للامبير لفات يمكن حساب كثافة الفيض المغناطيسي في الثغرة الهوائية وكذا قوى الرفع والجر المناظرة وفي حالة ما اذا كانت تلك القوى غير مناسبة لدورة التشغيل المقترحة يتم افتراض قيم أخرى لزاويا لحمل ومعامل القدرة وتعاد الخطوات السابقة وصولا الى قيم مناسبة لكثافة المجال المغناطيسي بالثغرة ومعرفة قيم الكثافة المغناطيسية المناظرة بالحديد وحساب أبعاد الآلة التي تحقق الحد الأدنى من وزن الحديد طبقا لدرجة التشبع المطلوبة . ولقد تم تطبيق هذا الأسلوب التصميمي المقترح في شكل برنامج للحاسب الآلي على احدى أربع محركات من النوع المذكور تستخدم في رفع وجر قاطرة كهربائية وزنها ٣ طن بسرعة ١٠ متر / ث وعجلة مقدارها ١ر٤٧ م/ ث٢ . وقد أظهرت النتائج الحسابية أن أقصى معامل قدرة يمكن الوصول اليه ٧ر متأخر كما أن الوزن الكلي للمحركات لا يتعدى ١/٦ وزن القاطرة . ويعد هذا الأسلوب التصميمي المقترح أداة مرنة في يد مصمم مثل هذه الآلة ، تمكنهم من الأخذ في الاعتبار العديد من متغيرات المصمم وظروف التشغيل .

ABSTRACT- Linear synchronous motors appear to have particular advantage when used for combined traction and levitation of urban transport vehicles. The usual problems of this application are :-

(i) The coming together of the exact traction force with the correct levitation force at all times of duty cycle of transport vehicle. Hence, the correct air-gap flux density and identification of operating conditions, which meet the traction and levitation force requirements, should be investigated.

(ii) The weight of the motors.

In order to predict the motor behaviour over the range of operating conditions, 3-field solutions based on 3-dimensional finite-difference method for m.m.f's, arising from d.c. excitation and from d, q axes armature current, have to be calculated. These solutions when superimposed with their relative strength obtained from a phasor diagram, relating the currents of the equivalent circuit to the voltages, will produce the air-gap flux density which exactly corresponds to the required traction and levitation force. This combination between the 3-field solutions (magnetic circuit) and the phasor diagram (electrical circuit) is the basis of a design-technique presented in this paper. This technique is applied for the prediction of the steady-state performance of a homopolar E-core linear synchronous motor capable of lifting and driving a 3-tonne vehicle, with 10 m/sec. and an acceleration of 1.47 m/sec^2 .

1- INTRODUCTION

Homopolar linear synchronous motors (HLSM) have been proposed as a propulsion system for both high speed and urban transport tracked vehicles [1,2,3,4]. The simplest form of HLSM is the E-core type as shown in the schematic diagram in figure (1). This diagram shows that the field and armature coils lie in planes perpendicular to one another. As a result, the magnetic circuit path for the constant homopolar flux is transverse to the direction of motion. In contrast, the fundamental component of the alternating flux, partly generated by salient poles and partly by time varying armature current, develops longitudinally. So, the field distribution for m.m.f's arising from the d.c. excitation component and the two components of both d, q axes of the armature current (reaction) have to be solved in 3-dimensional. The finite-difference method is used to calculate the node potentials for 100 AT for each of the above components. Any field pattern can then be represented in terms of these 3-components in certain proportions.[6] .

The paper presents a detailed design process involving the use of the 3-component field solutions together with an unscaled phasor diagram, which is finally scaled to the desired terminal voltage by adjusting of the winding turns proportionality

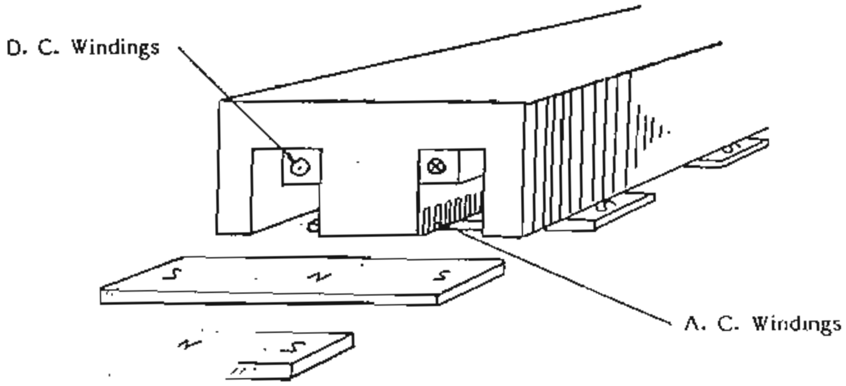


Figure 1: Homopolar linear synchronous motor.

2- EXCITATION FIELD AND ARMATURE-REACTION FIELD CALCULATION

The vertical force is greatly influnced by the d.c. excitation m.m.f. which varies considerably with operating conditions. For a given (track) pole shape and stator dimensions the spacial distribution of magnetic scalar potential is calculated for each of three separate conditions :-

(i)- 100 Amper turns per pole in the armature alone with the pole axis under the peak of m.m.f. (d-axis distribution).

(ii)- 100 Amper turns per pole in the armature alone with the pole axis under the zero of spacial m.m.f. (q-axis distribution).

(iii)- 100 Amper turns per coil in the d.c. excitation coils.

The flux per armature pole and the peak flux density due to 100 AT of each component m.m.f. can then be calculated from this data. For any given component of air-gap flux density (B_f for example) or flux, it is hence possible to calculate the amount of m.m.f. required in the appropriate winding (N_f I_f). It is also possible to determine by direct proportion, the actual components of magnetic potential due to individual sources of m.m.f. The total potential at any node is hence the sum of potentials at that node. Vertical force and thrust are calculated from the Maxwell stresses derived from the field of net potentials. When the field equations are solved numerically it is often convenient to determine the forces by surface integration of Maxwell's second stress tensor [5], in air, over any surface enclosing the part on which the force is produced. The stresses consist of a tension along the lines of force, $1/2\ \mu_0 H^2$, and an equal pressure at right angles to them. Resolving in the normal and tangential directions relative to an arbitrarity chosen surface as shown in figure (2). The component of the stress directed away from the surface is :-

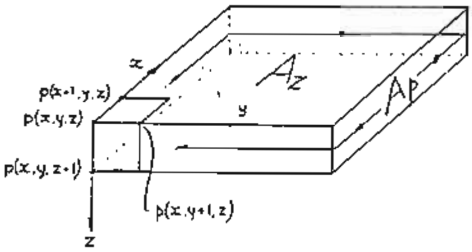


Figure 2: Surface of integration to calculate tangential and normal stresses.

$$F_n = 1/2\ \mu_o\ (H_n^2 - H_t^2)$$

and the tangential stress is

$$F_t = \mu_o H_n H_t$$

where :

$$H_n = H_z = P(x, y, z_s) - P(x, y, z_{s+1})$$

$$H_x = 0.5\ [\ P(x+1, y, z_s) - P(x, y, z_s) + P(x+1, y, z_{s+1}) - P(x, y, z_{s+1})\ ]$$

$$H_y = 0.5\ [\ P(x, y+1, z_s) - P(x, y, z_s) + P(x, y+1, z_{s+1}) - P(x, y, z_{s+1})\ ]$$

$$H_t^2 = H_x^2 + H_y^2\ ;$$

$$\text{Thrust} = \sum_{A_z} F_t$$

$$\text{Vertical force} = 1/2\ \mu_o\ [\ \sum_{A_z} H_n^2 - \sum_{A_p} H_{x,y}^2\ ]$$

This approach is written into a computer subroutine which calculates the thrust, vertical force and flux density distribution from the armature current and the number of turns per pole per phase (armature m.m.f.), load angle and power factor angle (pole position), and excitation m.m.f. Also the induced E_f, E_{ad} and E_{aq} per phase per turn of the armature turns for a given speed can be calculated.(where the indices f, ad and aq denote field and armature direct and quadrature windings respectively). The values of X_d and X_q the d- and q, axis reactances, can also be calculated from this data per (turn)^2 of the armature turns

3- SPECIFIC DESIGN CONSIDERATION

For a given thrust, frequency and applied voltage, the following design procedure based on :-

(a) An unscaled phasor diagram, which is finally scaled to the desired terminal voltage by adjusting the armature winding turns proportionally.

(b) The previous estimation of HLSM parameters (E_f, E_{ad}, E_{aq}) per turn of the armature turns and X_d, X_q per $(\text{turn})^2$ of armature windings.

is used to identify the possible operating conditions and the levitation force as the following steps :-

(i) Assume that the motor has no armature winding resistance or leakage reactance so that the e.m.f. induced in the armature at the air-gap (E_g) may be considered equal to the terminal voltage for the moment. Let this voltage be 1 Volt (or 1 p.u.). The values of the power factor angle ϕ' and load angle δ' are assumed, and the diagram of figure (3-a) is drawn. This shows the voltage $E_g = \bar{1}$ and the directions in which the current and the q-axis line.

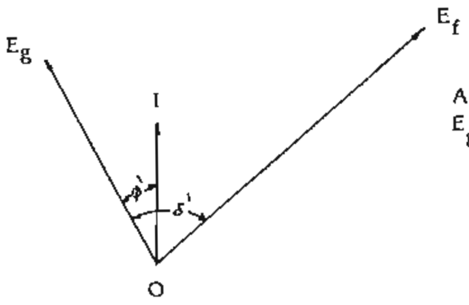


Figure 3-a

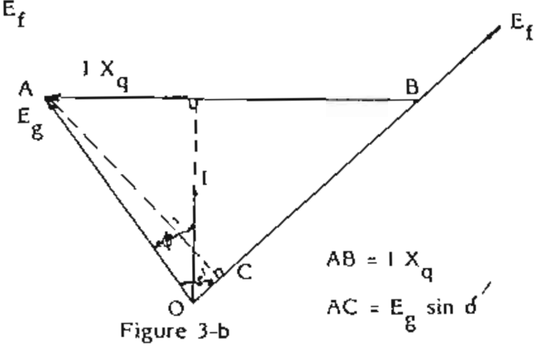


Figure 3-b

(ii) From known relationships in the d,q reference frame the following construction may be made in figure (3-b). Draw AB perpendicular to the reference I. AB has the voltage value $I X_q$ where X_q is the quadrature axis reactance. AC is perpendicular to OB.

(iii) Now make use of the relationship

$$E_g \sin \delta' = I X_q \cos(\delta' - \phi')$$

The equation of thrust in terms of specific magnetic loading and specific electric loading is given by :

$$F_T = B_g J A \cos \phi' \qquad \ldots(2)$$

where :

A : Active area under the armature = (pole pitch x core width)
F_T : The thrust
B_g : The air-gap magnetic loading
J : The electrical loading

For a given motor at a given speed

$$E_g = k N B_g$$
$$I X_q = k_1 N J$$

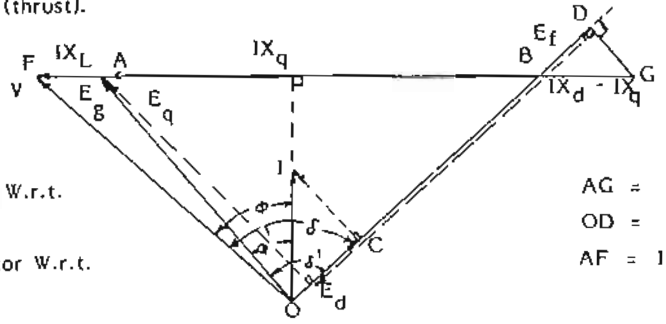
where k and k_1 have been computed and N the armature turns. The four unknown N, B_g, J, I X_q are calculated from equation (1) to (4) for a voltage E_g of 1 volt (1 p.u.)

(iv) Calculate the value of current I from the dimensions, number of turns N and the value of J. Calculate the quadrature axis reactance X_q from the field data and the number of armature turns N. Similarly calculate X_d and hence I X_d. Calculate the armature leakage rectance X_L from the number of turns N and the motor, slot and armature overhang dimensions. Calculate the voltage I X_L for this value of N.

(v) Extand the diagram of figure (3-c). A terminal voltage V is now shown corresponding to the current I, internal voltage E_g (= 1 volt) and N turns. The value of E_f is the theoretical voltage behind all the reactances (open circuit voltage). It requires a theortical flux density in the air-gap of B_f where proportionally $B_f = B_g E_f / E_g$. By referring to the file containing the field distribution due to 100 AT of field excitation it is a straight forward matter to calculate proportionally the total d.c. excitation required and all values of its scalar magnetic potential distribution. The flux densities B_d and B_q corresponding to the E_d and E_q voltages are similarly applied to the scaling of the computed d-and q-components. By adding the magnetic potentials of each component field, the net field is obtained. The vertical force and traction force may thus be calculated. The traction force should be equal to the value set for the design and agreement at this point serves to check the method.

(vi) The terminal voltage V, OF, is unlikely to be a practical value at this stage. Since the diagram consists of voltage phasors which are all proportional to the number of turns N it is however possible to choose the value of V and recalculated the others proportionally. The number of turns N are adjusted in proportion to the voltage increase.

(vii) Form the diagram of figure (3-c) and the final number of turns N required to give the desired terminal voltage it is hence possible to calculate the actual E_g, I, X_d, X_q, E_f, Φ, and δ of the motor under given coditions of internal load angle δ', internal power lactor Φ' and traction force (thrust).



δ : actual load angle W.r.t. terminal voltage

Φ: actual power factor W.r.t. terminal voltage

AG = I X_d
OD = E_f
AF = I X_L

Figure 3-C

4- PROTOTYPE DESIGN AND RESULTS

A design-technique has been examined theoretically for a wide range of operating conditions to design HLSM E-core type capable of lifting and deriving a 3-tonne vehicle, 10 m/sec with acceleration of 1.47 m/sec². The air-gap for this design was at 10 mm. The design steps are essentially iterative with the designer using trial values and subsequent refinements to bring it to an acceptable solution. It is outlined in the block diagram of figure (4). It shows two basic loops. The main loop, 1 involves the fundamental design calculations for dimensions and weight. The smaller loop 2 is concerned with a virtually

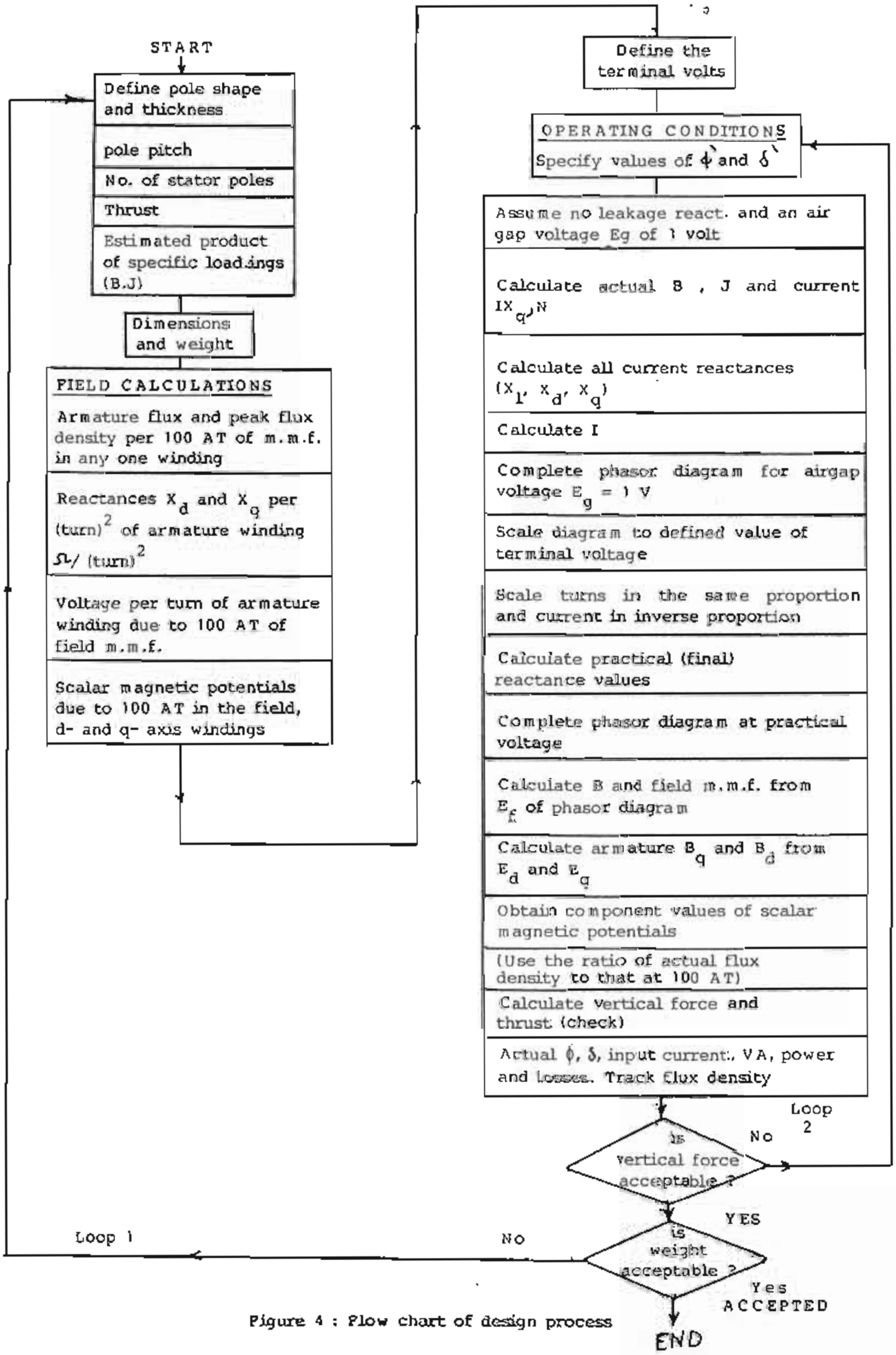


Figure 4 : Flow chart of design process

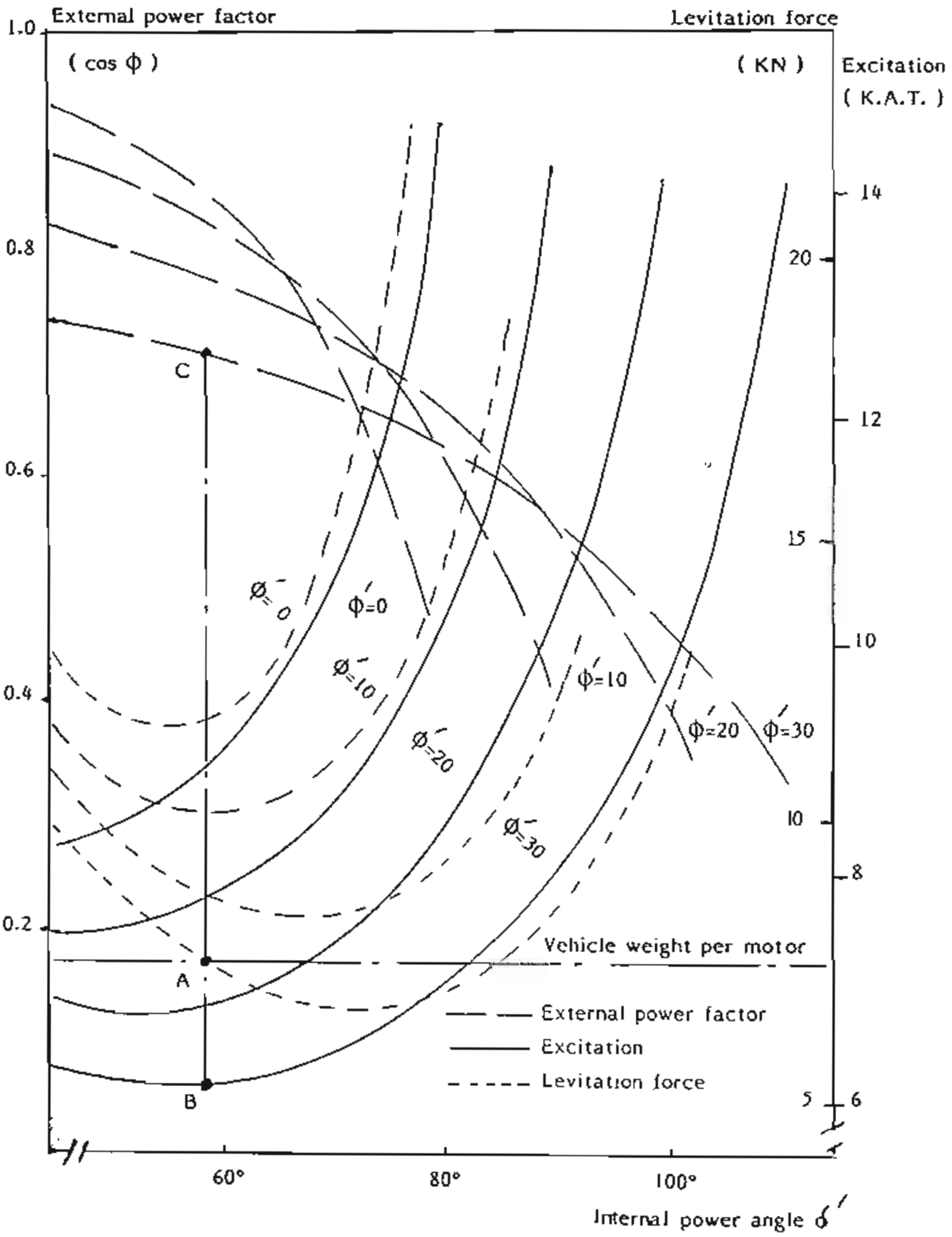


Figure 5: Levitation force, excitation and external power factor versus internal power angle δ' (at constant thrust and speed)

trail and error assessment of the design under different operating conditions indicated by choices of ϕ' and δ'. Many circuits of loop 2 are involved for one circuit of loop 1. Loop 2 is mostly computed as are the field calculations in loop 1. Figure (5) shows the levitation force, the excitation and the external power factor versus the internal power angle δ'. It indicates from the figure that only a narrow range of operating conditions meet the constraint of vertical force shown as a horizontal line. A "good" condition can be seen at 'A' at a load angle (internal δ) of about 60° and a power factor angle (internal ϕ) of 30°. The excitation required for this is shown at 'B' and is low. Also, the terminal power factor corresponding to this condition is shown at point 'C'. The predicted performance for one motor is shown in table 1. This motor representing one of four similar motors intended for mounting at the corners of a 3-tonne vehicle.

air-gap	10 mm
Weight of the motor	146 Kg
Efficiency	86 %
Power Factor	0.7
Output power	11.4 KW
Load angle	76°

Table 1 : Predicted performance

5- CONCLUSIONS

The proposed design-technique of a homopolar linear synchronous motor searches mainly for low weight, the best possible power factor, and the correct levitation force which meets the required traction force according to a duty cycle of a transport vehicle. This technique is based on the combination between the solutions resulting from the 3-field analysis, using finite-difference method in 3-dimensions , and that resulting from a proper phasor diagram.

The traction and levitation forces depend on the resultant air-gap flux density which can be determined according to the resultant m.m.f's of both the field and the armature windings. To get this air-gap flux density the m.m.f's are superimposed according to their relative field strengths which are obtained from a proper phasor diagram. This diagram satisfies mainly the load operating conditions. As the majority of the total weight is due to the field winding and the associated iron, it is perferable to minimise the excitation requirements in a manner which does not affect the required levitation force. In this way the required levitation force may be attained on the cost of slightly low power factor.

The proposed design-technique has been applied to predict the steady-state performance of homopolar linear synchronous motor which is used for lifting and deriving a 3-tonne vehicle. The highest attainable power factor of the proposed motor is 0.7 lagging. This power factor is still better than that of a corresponding linear induction motor which is used only for the propulsion. The lowest attainable weight of the four motors which are used for mounting at the corner of that vehicle is about one-sixth of the vehicle weight. The proposed design-technique allows the designer to identify the most desirable operating conditions which meet the requirements of traction and levitation forces.

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LIST OF SYMBLOS:

B : Flux density
H : Magnetic field strength
H_t : Trangential component of magnetic field strength.
H_n : Normal component of magnetic field strength.
x, y, z : Model axes
P : Magnetic scalar potential
V : Terminal Voltage
J : Specific electrical loading
B : Specific magnetic loading
N : Number of turns per phase
E_f : Open circuit voltage
μ_o : Permeability of free space
B_g : The air-gap magnetic loading
ϕ, ϕ' : Phase angle between current and terminal voltage or gap flux
$\cos \phi$: External power factor
$\cos \phi'$: Internal power factor
δ : External load angle between the terminal voltage and the direct axis.
δ' : Internal load angle between the gap flux and the direct axis.