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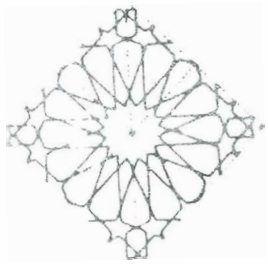

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THE ACCELERATION CHARACTERISTICS OF THE TRAPIZOIDALLY RAILED LINEAR HOMOPOLAR SYNCHRONOUS MOTOR AS COMPARED TO THE ZIG-ZAG VERSION FOR MAGLEV APPLICATIONS

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ABSTRACT

The Zig-Zag Linear Homopolar Synchronous Motor, ZZLHSM, is a machine that provides a combined lift and thrust for maglev vehicles. A meglev vehicle is a vehicle that is supported by magnetic attraction between controlled electromagnets fixed to its chassis and a pair of iron tracks. The magnet of ZZLHSM is U-shaped and acts as a two-pole machine in which each pole is split into two sub-poles. Each sub-pole is surrounded by a coil fed by an inverter such that the field could be distorted among the four sub-poles. The rail of the ZZLHSM is zig-zag shaped and will move relative to the sub-poles to minimise reluctance, hence propulsion is obtained. The ZZLHSM machine version was modified by changing the shape of the rail to a trapezoidal one, and hence obtaining a Trapizoidally Railed Linear Homopolar Synchronous Motor, TRLHSM.

This paper describes in theory the acceleration characteristics of the TRLHSM machine version that could be used for maglev transport utilizing integrated lift & thrust. It first establishes the basic principle of operation whereby the various machine relationships are derived for TRLHSM. Few assumptions are made before finding out these relationships which include: the relationships of fluxes, flux densities, vertical force, horizontal force, open circuit voltages, vertical & horizontal accelerations. Maximum thrusting conditions are then found.

A review is then made for the ZZLHSM version with same winding and excitation conditions, whereby the corresponding relationships are briefed.

The paper concludes with a comparison between the characteristics of TRLHSM and ZZLHSM.

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THE TRAPIZOIDALLY RAILED
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KEYWORDS

Zig-Zag, Trapizoidal, Linear, Homopolar, Synchronous, Machine, Maglev, Suspension, Propulsion & Transportation.

INTRODUCTION

Fig. 1 shows the ZZLHSM magnet within a maglev vehicle boggie. The main poles of ZZLHSM are excited by field current through dc coils. Each of the main poles is split into two sub-poles that are surrounded by ac coils. McLean[1,2] and West[1] have chosen a rail shape shown in Fig. 2a. Hence, with the ac coils around sub-poles excited such that the field is forced through sub-poles 1&3, the rail will move assuming constant air gap, z, to link sub-poles 1&3. When field is forced through sub-poles 2&4, the rail will move again to link sub-poles 2&4. As the switching of sub-pole coil-excitations synchronizes to rail position, a continuous motion is obtained. The ZZLHSM is unable, due to symmetry, to start motion when the rail completely links sub-poles 1&3 or sub-poles 2&4 at a stop. This may be avoidable by another ZZLHSM pair placed half pole-pitch away.

Now for the same magnet, if a trapizoidally shaped rail like the one shown in Fig. 2b is used, the ac coils around sub-poles can be excited to force field through sub-poles Hence, the rail will move assuming constant air gap, z, to link sub-poles 1&3. The field is then forced through sub-poles 2&3. Hence, pulling the rail to link sub-poles 2&3. Forced through sub-poles 2&4, the field then pulls the rail to link sub-poles 2&4. Finally, when field is forced into sub-poles 1&4, the rail will move to link them both. This completes one cycle and as excitations of sub-pole ac coils are synchronized to rail position, a continuous motion is obtained.

This Trapizoidally Railed Linear Homopolar Synchronous Motor, TRLHSM, is noted to have no symmetry position throughout its cycle. Hence, no need for a starter exists. Another feature is that the switching frequency is half that of the ZZLHSM for same speed, since the rail cycle length of the TRLHSM is twice that of the ZZLHSM.

NOTATIONS

The symbols used in this paper are listed below:

A sub-pole surface area

A_i, A'_i overlap area of sub-pole i in TRLHSM, ZZLHSM respectively

a_{hp}, a'_{hp} horizontal pulsating acceleration relative to gravity in TRLHSM, ZZLHSM

a'_{hpz} maximum horizontal pulsating acceleration relative to gravity

a_{hs}, a'_{hs} horziontal steady acceleration relative to gravity in TRLHSM , ZZLHSM

a_{hs}, a'_{hs} maximum horizontal steady acceleration relative to gravity in TRLHSM, ZZLHSM

a_{vp}, a'_{vp} vertical pulsating acceleration relative to gravity in TRLHSM, ZZLHSM

a_{vpx}, a'_{vpx} maximum vertical pulsating acceleration relative to gravity in TRLHSM, ZZLHSM

B_i, B'_i flux density over sub-pole i in TRLHSM, ZZLHSM

E_X, E'_X open circuit induced voltage at phase X coil terminals in TRLHSM, ZZLHSM

F_h, F'_h horizontal thrust force in TRLHSM, ZZLHSM

F_v, F'_v vertical lift force in TRLHSM, ZZLHSM

ϕ_{ii} TRLHSM flux due to m_i which leaves sub-pole

ϕ_{ij} TRLHSM flux due to m_i which leaves sub-pole i to sub-pole j

ϕ_k, ϕ'_k flux due to all sub-polar mmfs that leaves sub-pole k in TRLHSM, ZZLHSM

i'_X current flowing in phase X ac coils of TRLHSM, ZZLHSM

I_D current flowing in the field of TRLHSM dc coils

λ_p, λ'_p peak flux linkage per ac coil in TRLHSM, ZZLHSM

λ_n, λ'_n flux linkage of ac coil around sub-pole n in TRLHSM, ZZLHSM

M_D, M'_D net dc mmf excitation of field winding per pole in TRLHSM, ZZLHSM

$\overline{M}_D, \overline{M}'_D$ optimum M_D, M'_D values for maximum thrust

m_X, m'_X ac mmf of phase X armature winding per sub-pole in TRLHSM, ZZLHSM

m, m' peak values of ac mmf excitation of any phase per sub-pole in TRLHSM,

$\overline{m}, \overline{m}'$ optimum m, m' values for maximum thrust

m_j, m'_j resultant mmf excitations around sub-pole j in TRLHSM, ZZLHSM

μ_0 permeability of air

N number of turns of ac coil around any sub-pole

N_D number of turns of dc coil around any pole

p pole pitch

T, T' time period to complete one cycle in TRLHSM, ZZLHSM

t time starting zero when rail completely links sub-poles 1&3

θ, θ' phase angles of ac excitations in TR

$\overline{\theta}'$ optimum phase angles at maximum

$\overline{\theta}_+, \overline{\theta}'_+$ optimum phase angles at maximum

$\overline{\theta}_-, \overline{\theta}'_-$ optimum phase angles at maximum

u speed of rail relative to magnet

W' weight of supported boggie

ω, ω' angular frequency of ac supply in T

z energized air gap

ASSUMPTIONS

For simplicity, the following assumptions we

1. All sub-poles have the same surface
2. AC coils around sub-poles are identi
3. Width of slot in the main poles is ne
4. Fringing and leakage are negligible.
5. Steel and copper losses are negligible
6. Air gap, z, is homogeneous over the su
7. The energized air-gap faces equal are net pole surface below it throughout tion 3 above. The rail of TRLHSM, for in Fig.3. Here, the total area above o the sum of the rectangle area and the constant and equals the sub-polar are
8. The energized area per pole is compo one of the two adjacent sub-poles wit sinusoidally between zero and A.
9. Speed of motor relative to track, u, is c
10. Track structure is rigid.
11. The motor does no rotation.

θ, θ' phase angles of ac excitations in TRLHSM,ZZLHSM

$\bar{\theta}, \bar{\theta}'$ optimum phase angles at maximum thrust conditions in TRLHSM,ZZLHSM

$\bar{\theta}_+, \bar{\theta}'_+$ optimum phase angles at maximum accelerations in TRLHSM,ZZLHSM

$\bar{\theta}_-, \bar{\theta}'_-$ optimum phase angles at maximum deceleration in TRLHSM,ZZLHSM

u speed of rail relative to magnet

W weight of supported boggie

ω, ω' angular frequency of ac supply in TRLHSM,ZZLHSM

z energized air gap

ASSUMPTIONS

For simplicity, the following assumptions were made in the analysis to come.

1. All sub-poles have the same surface area,A.
2. AC coils around sub-poles are identical.
3. Width of slot in the main poles is negligible.
4. Fringing and leakage are negligible.
5. Steel and copper losses are negligible.
6. Air gap,z,is homogeneous over the sub-poles.
7. The energized air-gap faces equal areas both at rail surface above it and at magnet pole surface below it throughout motion.This is justified in view of assumption 3 above.The rail of TRLHSM,for instance, overlaps with its poles as shown in Fig.3.Here,the total area above or below energization throughout motion is the sum of the rectangle area and the parallelogram area.This sum is seen to be constant and equals the sub-polar area,A.
8. The energized area per pole is composed of two portions.Each portion belongs to one of the two adjacent sub-poles within the main pole and is assumed to vary sinusoidally between zero and A.
9. Speed of motor relative to track,u,is constant.
10. Track structure is rigid.
11. The motor does no rotation.

12. The motor force is composed of *two* components only, namely,along gravity line and along direction of motion.Although some force component in the third direction is exerted,it will be ignored.

13. Field mmf excitations are constants.

14. Flux linkage for any ac coil varies sinusoidally between a minimum of zero when its sub-pole is fully uncoupled to rail and a maximum when its sub-pole is fully coupled to rail.

15. AC roils are fed with sinusoidal ac current phase-locked to rail.

16. Windage,friction and other drag forces are ignored.

THEORITICAL ANALYSIS OF TRLHSM PERFORMANCE

Coil Connections for TRLHSM

When the rail of TRLHSM moves in the direction indicated in Fig. 2b.flux linkages of ac coils will assume linear segments and can be approximated to sinusoidal variation as shown in Fig. 4a.Note that λ_1 & λ_2 vary in-phase with each another and that λ_3 & λ_4 also vary in-phase with each another but in quadrature lag with λ_1 & λ_2 variations.The period of these variations is given by:

$$T = \frac{4p}{u} \tag{1}$$

with angular frequency,ω,given by:

$$\omega = \frac{\pi u}{2p} \tag{2}$$

Hence,to obtain maximum variation in flux linkage per phase,the ac coils are connected as shown in Fig, 5a.Note that phase A leads B by a quarter of a cycle.and that the dc coils are connected so as to build constructive flux components.

Magnetic Sub - polar Excitations for TRLHSM

Each of the sub-poles in Fig. 5a could be considered excited with two components dc of:

$$M_D = N_D I_D \tag{3}$$

and ac of:

$$m_A(t) = N i_A(t) = m\cos(\omega t + \theta) \tag{4}$$

or :

$$m_B(t) = N i_B(t) = m\sin(\omega t + \theta)$$

Using Fig. 5a and denoting m_1,m_2,m_3 and m_4 to sub-poles 1,2,3 and 4 respectively,with positive pole,then:

$$m_1(t) = -M_D - m_A(t)$$

$$m_2(t) = -M_D + m_A(t)$$

$$m_3(t) = M_D + m_B(t)$$

$$m_4(t) = M_D - m_B(t)$$

Energized Sub - polar Areas for TRLHSM

With A_1,A_2,A_3 and A_4 defined as above,then th Fig. 4a during the rail motion indicated in Fig. 2 areas is constant and equals A.

For simplicity,these trapizoidal variations are ass and a minimum of zero as shown by the dotted these approximations are:

$$A_1(t) = (A/2)[1 + \cos(\omega t -$$

$$A_2(t) = (A/2)[1 - \cos(\omega t -$$

$$A_3(t) = (A/2)[1 + \cos(\omega t -$$

$$A_4(t) = (A/2)[1 - \cos(\omega t -$$

This approximation will give a maximum deviati 15%.However,the sum of areas constituting portic

Magnetic Sub - polar Fluxes for TRLHSM

Let ϕ_{11},ϕ_{12},ϕ_{13},ϕ_{14},ϕ_{21}, ϕ_{22},ϕ_{23},ϕ_{24},ϕ_{31},ϕ_{32},ϕ_{33}, ϕ_{34}, above.Hence, each of m_1,m_2,m_3 and m_4 mmfs is similar to that shown in Fig. 6.Hence:

$$\phi_{11}(t) = \frac{\mu_0 A_1 m_1 (A_2 + A_3 \cdot$$

$$\phi_{12}(t) = \frac{\mu_0 A_1 m_1 A_2}{2Az}$$

$$\phi_{13}(t) = \frac{\mu_0 A_1 m_1 A_3}{2Az}$$

$$\phi_{14}(t) = \frac{\mu_0 A_1 m_1 A_4}{2Az}$$

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dally between a minimum of zero when its naximum when its sub-pole is fully coupled

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ERFORMANCE

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(1)

(2)

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M

idered excited with two components dc of

$(\omega t+0)$ (3)

$(wt+0)$ (4)

Using Fig. 5a and denoting m_1,m_2,m_3 and m_4 to be the resultant mmf excitations around sub-poles 1,2,3 and 4 respectively,with positive eense when forcing flux to leave the sub-pole,then:

$$m_1(t) = -M_D - m_A(t) \tag{5}$$

$$m_2(t) = -M_D + m_A(t) \tag{6}$$

$$m_3(t) = M_D + m_B(t) \tag{7}$$

$$m_4(t) = M_D - m_B(t) \tag{8}$$

Energized Sub – polar Areas for TRLHSM

With A_1,A_2,A_3 and A_4 defined as above,then these areas vary trapizoidally as shown in Fig. 4a during the rail motion indicated in Fig. 2b.Note that the sum of any two adjacent areas is constant and equals A.

For simplicity,these trapizoidal variations are assumed sinusoids between a maximum of A and a minimum of zero as shown by the dotted tines in Pig. 2b.The equations describing these approximations are:

$$A_1(t) = (A/2)[1 + \cos(\omega t + \pi/4)] \tag{9}$$

$$A_2(t) = (A/2)[1 - \cos(\omega t + \pi/4)] \tag{10}$$

$$A_3(t) = (A/2)[1 + \cos(\omega t - \pi/4)] \tag{11}$$

$$A_4(t) = (A/2)[1 - \cos(\omega t - \pi/4)] \tag{12}$$

This approximation will give a maximum deviation error at trapizoidal corners of about 15%.However,the sum of areas constituting portions of adjacent sub-poles is still constant.

Magnetic Sub – polar Fluxes for TRLHSM

Let $\phi_{11},\phi_{12},\phi_{13},\phi_{14},\phi_{21},\ \phi_{22},\phi_{23},\phi_{24},\phi_{31},\phi_{32},\phi_{33},\ \phi_{34},\phi_{41},\phi_{42},\phi_{43},\phi_{44},\phi_1,\phi_2,\ \phi_3$&$\phi_4$ be as defined above.Hence, each of m_1,m_2,m_3 and m_4 mmfs is driving an associated magnetic circuit similar to that shown in Fig. 6.Hence:

$$\phi_{11}(t) = \frac{\mu_0 A_1 m_1 (A_2 + A_3 + A_4)}{2Az}$$

$$\phi_{12}(t) = \frac{\mu_0 A_1 m_1 A_2}{2Az}$$

$$\phi_{13}(t) = \frac{\mu_0 A_1 m_1 A_3}{2A^2}$$

$$\phi_{14}(t) = \frac{\mu_0 A_1 m_1 A_4}{2Az}$$

Similarly:

$$\phi_{22}(t) = \frac{\mu_0 A_2 m_2 (A_1 + A_3 + A_4)}{2 A z}$$

$$\phi_{21}(t) = \frac{\mu_0 A_2 m_2 A_1}{2 A z}$$

$$\phi_{23}(t) = \frac{\mu_0 A_2 m_2 A_3}{2 A z}$$

$$\phi_{24}(t) = \frac{\mu_0 A_2 m_2 A_4}{2 A z}$$

Likewise:

$$\phi_{33}(t) = \frac{\mu_0 A_3 m_3 (A_1 + A_2 + A_4)}{2 A z}$$

$$\phi_{31}(t) = \frac{\mu_0 A_3 m_3 A_1}{2 A z}$$

$$\phi_{32}(t) = \frac{\mu_0 A_3 m_3 A_2}{2 A z}$$

$$\phi_{34}(t) = \frac{\mu_0 A_3 m_3 A_4}{2 A z}$$

Finally:

$$\phi_{44}(t) = \frac{\mu_0 A_4 m_4 (A_1 + A_2 + A_3)}{2 A z}$$

$$\phi_{41}(t) = \frac{\mu_0 A_4 m_4 A_1}{2 A z}$$

$$\phi_{42}(t) = \frac{\mu_0 A_4 m_4 A_2}{2 A z}$$

$$\phi_{43}(t) = \frac{\mu_0 A_4 m_4 A_3}{2 A z}$$

Hence,applying superposition theorm to find the fluxes $\phi_1(t)$,$\phi_2(t)$,$\phi_3(t)$&$\phi_4(t)$ leaving sub-poles 1,2,3 and 4 respectively due to all mmfs of m_1,m_2,m_3 and m_4;then:

$$\phi_1(t) = \phi_{11} - \phi_{21} - \phi_{31} - \phi_{41}$$

Using the above equations for ϕ_{11},ϕ_{21},ϕ_{31}& ϕ_{41} respectively and rearranging,then:

$$\phi_1(t) = \frac{\mu_0 A_1 [A_2 (m_1 - m_2) + A_3 (m_1 - m_3) + A_4 (m_1 - m_4)]}{2 A z}$$

Using eqs. 5,6,7&8 for m_1,m_2,m_3&m_4 and rearranging then:

$$\phi_1(t) = \frac{-\mu_0 A_1 [2 M_D (A_3 + A_4) + m_A (2 A_2 + A_3 + A_4) + m_B (A_3 - A_4)]}{2 A z}$$

Using eqs. 10,11&12 for A_2,A_3&A_4 and simplifying,then:

$$\phi_1(t) = \frac{-\mu_0 A_1 [2 M_D + m_A [2 - \cos(\omega t + \pi/4)] + m_B \cos(\omega t - \pi/4)]}{2 z}$$

Using eqs. 3&4 for $m_A(t)$ and $m_B(t)$ respectivel

$$\phi_1(t) = \frac{-\mu_0 A_1 [2 M_D + 2 m_A + n}{2 z}$$

Similarly:ϕ_2,ϕ_3&ϕ_4 can be found to be:

$$\phi_2(t) = \frac{-\mu_0 A_2 [2 M_D - 2 m_A + n}{2 z}$$

$$\phi_3(t) = \frac{\mu_0 A_3 [2 M_D + 2 m_B - m}{2 z}$$

$$\phi_4(t) = \frac{\mu_0 A_4 [2 M_D - 2 m_B - m}{2 z}$$

Magnetic Sub - polar Flux Densities for TRLH

From the above equations,the sub-polar flux d

$$B_1(t) = \frac{\phi_1(t)}{A_1(t)} = \frac{-\mu_0 [2 M_D + 2 m_A}{}$$

$$B_2(t) = \frac{\phi_2(t)}{A_2(t)} = \frac{-\mu_0 [2 M_D - 2 m_A}{}$$

$$B_3(t) = \frac{\phi_3(t)}{A_3(t)} = \frac{\mu_0 [2 M_D + 2 m_B}{}$$

$$B_4(t) = \frac{\phi_4(t)}{A_4(t)} = \frac{\mu_0 [2 M_D - 2 m_B}{}$$

Magnetic Lift Force for TRLHSM

The TRLHSM will exert a lift force,F_v,in orde the energized air-gap,z.This lift force is compo polar areas A_i above which air is energized,and densities B_i.Hence,F_v is given by:

$$F_v(t) = \sum_{i=1}^{4} \frac{A_i B_i^2}{2 \mu_0}$$

Using eqs. 9,10,11&12 for A_1, A_2,A_3& A_4; eqs. 17 with the aid of eqs. 3&4 for m_A&m_B;then F_v n

$$F_v(t) = \frac{\mu_0 A [8 M_D^2 + 3 m^2 + 8 M_D m \cos}{8}$$

ng eqs. 3&4 for $m_A(t)$ and $m_B(t)$ respectively,and simplifying;then:

$$\phi_1(t) = \frac{-\mu_0 A_1 [2 M_D + 2 m_A + m \sin(2\omega t + \theta - \pi/4)]}{2z} \tag{13}$$

ilarly;ϕ_2,ϕ_3&ϕ_4 can be found to be:

$$\phi_2(t) = \frac{-\mu_0 A_2 [2 M_D - 2 m_A + m \sin(2\omega t + \theta - \pi/4)]}{2z} \tag{14}$$

$$\phi_3(t) = \frac{\mu_0 A_3 [2 M_D + 2 m_B - m \sin(2\omega t + \theta - \pi/4)]}{2z} \tag{15}$$

$$\phi_4(t) = \frac{\mu_0 A_4 [2 M_D - 2 m_B - m \sin(2\omega t + \theta - \pi/4)]}{2z} \tag{16}$$

agnetic Sub - polar Flux Densities for TRLHSM

om the above equations,the sub-polar flux densities are found as:

$$B_1(t) = \frac{\phi_1(t)}{A_1(t)} = \frac{-\mu_0 [2 M_D + 2 m_A + m \sin(2\omega t + \theta - \pi/4)]}{2z} \tag{17}$$

$$B_2(t) = \frac{\phi_2(t)}{A_2(t)} = \frac{-\mu_0 [2 M_D - 2 m_A + m \sin(2\omega t + \theta - \pi/4)]}{2z} \tag{18}$$

$$B_3(t) = \frac{\phi_3(t)}{A_3(t)} = \frac{\mu_0 [2 M_D + 2 m_B - m \sin(2\omega t + \theta - \pi/4)]}{2z} \tag{19}$$

$$B_4(t) = \frac{\phi_4(t)}{A_4(t)} = \frac{\mu_0 [2 M_D - 2 m_B - m \sin(2\omega t + \theta - \pi/4)]}{2z} \tag{20}$$

agnetic Lift Force for TRLHSM

The TRLHSM will exert a lift force,F_v,in order to minimize its reluctance by minimizing the energized air-gap,z.This lift force is composed of several parts,according to the sub-polar areas A_i above which air is energized,and according to the energizing magnetic flux densities B_i.Hence,F_v is given by:

$$F_v(t) = \sum_{i=1}^{4} \frac{A_i B_i^2}{2\mu_0}$$

Using eqs. 9,10,11&12 for A_1,A_2,A_3& A_4; eqs. 17,18,19&20 for B_1,B_2,B_3&B_4;and simplifying with the aid of eqs. 3&4 for m_A&m_B;then F_v may be found as:

$$F_v(t) = \frac{\mu_0 A [8 M_D^2 + 3 m^2 + 8 M_D m \cos(\theta - \pi/4) + m^2 \sin(4\omega t + 2\theta)]}{8 z^2}$$

Hence the lift force,F_v,of TRLHSM is composed of two components:one steady which is supposed to support the boggie weight,W,via field control; and the other pulsating at four times the synchronous frequency.

Writing the mechanical equation of motion for the TRLHSM suspension boggie shown in Fig. 1b,then:

$$F_v - W = W\,\alpha_{vp}$$

Hence,the above two equations give:

1. the condition for stable field excitation, $M_D(\theta,m)$,at any ac excitation parameters of θ&m as:

$$\frac{\mu_0\,A\,[8\,M_D^2 + 3\,m^2 + 8\,M_D\,m\,cos(\theta - \pi/4)]}{8\,z^2} = W \tag{21}$$

2. the resulting lift acceleration pulsation,α_{vp}, at any ac excitation parameters of θ&m as:

$$\alpha_{vp}(\theta,m,t) = \frac{\mu_0\,A\,m^2\,sin(4\omega\,t + 2\,\theta)}{8\,z^2\,W} \tag{22}$$

Open Circuit Voltages for TRLHSM

The open cicuit induced voltage,E_A,at phase A coil teminals can be seen from Fig. 5a to be:

$$E_A(t) = N\,\frac{d}{dt}\,[\phi_2 - \phi_1]_{m=0}$$

Using eqs. 9,10,13&14 for A_1,A_2,ϕ_1&ϕ_2 and simplifing,then:

$$E_A(t) = \frac{-\mu_0\,\omega\,A\,M_D\,N\,sin(\omega\,t + \pi/4)}{z} \tag{23}$$

Similarly,the open cicuit induced voltage,E_B,at phase B coil terminals can be found to be:

$$E_B(t) = \frac{-\mu_0\,\omega\,A\,M_D\,N\,sin(\omega\,t - \pi/4)}{z} \tag{24}$$

Magnetic Thrust Force for TRLHSM

The TRLHSM thrust force,F_h,can be obtained using the energy principle.Assuming ideal conversion,then:

$$F_h\,u = E_A\,i_A + E_B\,i_B$$

Using eqs. 2,3,4,23&24 for ω,i_A,i_B,E_A&E_B;this simplifies to:

$$F_h(t) = \frac{\mu_0\,\pi\,A\,M_D\,m\,sin(\theta - \pi/4)}{2\,p\,z} \tag{25}$$

Hence;the thrust force,F_h,is composed onl
the ZZLHSM developed by West[3].In his
one steady and the other pulsating at twic

Eq. 25 shows that the TRLHSM will prope
and brake within $(\frac{-3\pi}{4}, \frac{\pi}{4})$.This is due to t
TRLHSM can be used either for motorin
for braking with kinetic power converted
TRLHSM is virtually exerting zero force.

Maximum Steady Thrusting Acceleration f

The steady thrusting acceleration,α_{hs}, relat
for the steady thrusting force,F_{hs},by dividin

$$\alpha_{hs}(\theta,m) = \frac{\mu_0\,\pi\,A\,M_D(\theta,$$

where $M_D(\theta,m)$ is an implicit function of θ&

The maximum of $\alpha_{hs}(\theta,m)$ for a given θ occ
21&26 to give:

$$\overline{M}_D(\theta) = M_D(\theta,\overline{m}(\theta))$$

$$\overline{m}(\theta) = 2z\,\sqrt{\frac{}{\mu_0\,A\,[3+\sqrt}}$$

$$\alpha_{hs}(\theta) = \alpha_{hs}(\theta,\overline{m}(\theta)) = \frac{}{p\,[\sqrt}$$

On the other hand,the maximum of $\alpha_{hs}(\theta)$ oc
to be:

$$\bar{\theta} = \frac{\pi}{4} \pm (\pi - cos^{-1}$$

This would split into two values:

$$\bar{\theta}_+ = \frac{5\pi}{4} - cos^{-1}\sqrt{\frac{2}{3}} = 3.3$$

where $\bar{\theta}_+ \in (\frac{\pi}{4}, \frac{5\pi}{4})$,the motoring range discusse
thrusting acceleration:

$$\alpha_{hs}(\bar{\theta}_+) = \frac{\pi\,z}{\sqrt{2}\,p}$$

and:

$$\bar{\theta}_- = \frac{5\pi}{4} + cos^{-1}\sqrt{\frac{2}{3}} = 4.542r$$

osed of two components:one steady which is
field control; and the other pulsating at four

or the TRLHSM suspension boggie shown in

v_p

$M_D(\theta,m)$,at any ac excitation parameters of

$$\frac{m\cos(\theta-\pi/4)]}{} = W \tag{21}$$

v_{op}, at any ac excitation parameters of θ&m

$$\frac{\sin(4\omega t+2\theta)}{8z^2W} \tag{22}$$

A coil teminals can be seen from Fig. 5a to

$\phi_1]_{m=0}$

implifing,then:

$$\frac{\sin(\omega t+\pi/4)}{} \tag{23}$$

at phase B coil terminals can be found to be:

$$\frac{\sin(\omega t-\pi/4)}{} \tag{24}$$

ed using the energy principle.Assuming ideal

$e_B i_B$

is simplifies to:

$$\frac{(\sim -_{11}/^{\circ}1)}{z} \tag{25}$$

0

Hence;the thrust force,F_h,is composed only of one steady component:an advantage over the ZZLHSM developed by West[3].In his machine,West has bad two force components one steady and the other pulsating at twice the synchronous frequency.

Eq. 25 shows that the TRLHSM will propel when the current phase angle is within $(\frac{\pi}{4},\frac{5\pi}{4})$ and brake within $(\frac{-3\pi}{4},\frac{\pi}{4})$.This is due to the mechanical and electrical system lags.The TRLHSM can be used either for motoring with electric power converted to kinetic or for braking with kinetic power converted to electric. At two θ values,namely:$\frac{\pi}{4}$&$\frac{5\pi}{4}$, the TRLHSM is virtually exerting zero force.

Maximum Steady Thrusting Acceleration for TRLHSM

The steady thrusting acceleration,α_{hs}, relative to gravity could be obtained from eq. 25 for the steady thrusting force,F_{hs},by dividing by the supported weight,W.Hence :

$$\alpha_{hs}(\theta,m)=\frac{\mu_0\pi A M_D(\theta,m)m\sin(\theta-\pi/4)}{2pWz} \tag{26}$$

where $M_D(\theta,m)$ is an implicit function of θ&m.

The maximum of $\alpha_{hs}(\theta,m)$ for a given θ occures at $\overline{m}(\theta)$.This could be found using eqs. 21&26 to give:

$$\overline{M}_D(\theta)=M_D(\theta,\overline{m}(\theta))=\sqrt{\frac{3}{8}}\,\overline{m}(\theta) \tag{27}$$

$$\overline{m}(\theta)=2z\sqrt{\frac{W}{\mu_0 A[3+\sqrt{6}\cos(\theta-\pi/4)]}} \tag{28}$$

$$\alpha_{hs}(\theta)=\alpha_{hs}(\theta,\overline{m}(\theta))=\frac{\pi z\sin(\theta-\pi/4)}{p[\sqrt{6}+2\cos(\theta-\pi/4)]} \tag{29}$$

On the other hand,the maximum of $\alpha_{hs}(\theta)$ occures at $\bar{\theta}$.This could be found using eq. 29 to be:

$$\bar{\theta}=\frac{\pi}{4}\pm(\pi-\cos^{-1}\sqrt{\frac{2}{3}}) \tag{30}$$

This would split into two values:

$$\bar{\theta}_+=\frac{5\pi}{4}-\cos^{-1}\sqrt{\frac{2}{3}}=3.312rad=190^{\circ}$$

where $\bar{\theta}_+\in(\frac{\pi}{4},\frac{5\pi}{4})$,the motoring range discussed earlier giving the following maximum thrusting acceleration:

$$\alpha_{hs}(\bar{\theta}_+)=\frac{\pi z}{\sqrt{2}p}$$

and:

$$\bar{\theta}_-=\frac{5\pi}{4}+\cos^{-1}\sqrt{\frac{2}{3}}=4.542rad=260^{\circ}$$

with $\overline{\theta}_- \in (\frac{-3\pi}{4}, \frac{\pi}{4})$, the generation range discussed earlier,giving the following maximum braking deceleration:

$$\alpha_{hs}(\overline{\theta}_-) = \frac{-\pi z}{\sqrt{2}p}$$

Hence,the maximum value of α_{hs} is given by:

$$\alpha_{hsx} = |\alpha_{hs}(\overline{\theta})| = \frac{\pi z}{\sqrt{2}p} \tag{31}$$

Substituting either $\overline{\theta}$ values in eqs. 28&27for $\overline{m}$&$\overline{M}_D$ gives:

$$\overline{m} = 2z\sqrt{\frac{W}{\mu_0 A}} \tag{32}$$

and:

$$\overline{M}_D = z\sqrt{\frac{3W}{2\mu_0 A}} \tag{33}$$

Lift Pulsating Acceleration for TRLHSM

Eq. 22 can provide a scale for the magnitude of lift acceleration pulsation,α_{vp},the worst of which is α_{vpz} occuring at $\overline{\theta}$&$\overline{m}$. Hence,using eqs. 30&32 for $\overline{\theta}$&$\overline{m}$,this gives:

$$\alpha_{vpz}(t) = \alpha_{vp}(\overline{\theta}, \overline{m}) = \frac{1}{2}sin(4\omega t + 2\overline{\theta}) \tag{34}$$

This means that the worst pulsation in lift acceleration is half that of gravity in magnitude and running at four times the synchronous frequency.

Thrust Pulsating Acceleration for TRLHSM

It was mentioned earlier that the thrust pulsating acceleration, α_{hp},is zero.Hence:

$$\alpha_{hp}(t) = 0 \tag{35}$$

REVIEW ANALYSIS OF ZZLHSM PERFORMANCE

Coil Connections for ZZLHSM

When the rail of ZZLHSM moves in the direction indicated in Fig. 2a,flux linkages of ac coils will assume linear segments and can be approximated to sinusoidal variation as shown in Fig. 4b. The period of these variations is given by:

$$T' = \frac{2}{}$$

with angular frequency,ω',given by:

$$\omega' = \frac{\pi}{}$$

Hence,to obtain maximum variation in flux as shown in Fig. 5b.

Magnetic Sub – polar Excitations for ZZLH

With treatment similar to that of TRLHSM be given as:

$$m'_1(t) = -m'_3(t) = -$$

$$m'_2(t) = -m'_4(t) = -$$

where $m'_A(t)$ is given by:

$$m'_A(t) = N\,i'_A(t) = m$$

Energized Sub – polar Areas for ZZLHSM

The ZZLHSM sub-polar areas vary triangul indicated in Fig. 2a. These variations are as

$$A'_1(t) = A'_3(t) = (A/2)$$

$$A'_2(t) = A'_4(t) = (A/2)$$

This approximation will give a maximum d

Magnetic Sub – polar Fluxes for ZZLHSM

With similar treatment to that of TRLHSM

$$\phi'_1(t) = -\phi'_3(t) = \frac{-\mu_0}{}$$

$$\phi'_2(t) = -\phi'_4(t) = \frac{-\mu_0}{}$$

Magnetic Sub – polar Flux Densities for ZZ

These are given by:

$$B'_1(t) = -B'_3(t) = \frac{-\mu}{}$$

l earlier,giving the following maximum

(31)

$_D$ gives:

(32)

(33)

accderatioti pulsation,α_{vp},the worst of
)&32 for $\overline{n}$&$\overline{m}$,this gives:

$\cdot t + 2\bar{\theta})$ (34)

tion is half that of gravity in magnitude
icy.

acceleration, α_{hp},is zero.Hence:

(35)

NCE

n indicated in Fig. 2a,flux linkages of
pproximated to sinusoidal variation as
given by:

$$T' = \frac{2p}{u} \tag{36}$$

with angular frequency,ω',given by:

$$\omega' = \frac{\pi u}{p} \tag{37}$$

Hence,to obtain maximum variation in flux linkage per phase,the ac coils are connected as shown in Fig. 5b.

Magnetic Sub - polar Excitations for ZZLHSM

With treatment similar to that of TRLHSM,then the sub-poles excitations in Pig. 5b could be given as:

$$m'_1(t) = -m'_3(t) = -M'_D - m'_A(t) \tag{38}$$

$$m'_2(t) = -m'_4(t) = -M'_D + m'_A(t) \tag{39}$$

where $m'_A(t)$ is given by:

$$m'_A(t) = N\, i'_A(t) = m' \cos(\omega' t + \theta') \tag{40}$$

Energized Sub - polar Areas for ZZLHSM

The ZZLHSM sub-polar areas vary triangularly as shown in Fig. 4b during the rail motion indicated in Fig. 2a. These variations are assumed sinusoids with equations given by:

$$A'_1(t) = A'_3(t) = (A/2)[1 + \cos(\omega' t)] \tag{41}$$

$$A'_2(t) = A'_4(t) = (A/2)[1 - \cos(\omega' t)] \tag{42}$$

This approxiination will give a maximum deviation error near corners of about 21%.

Magnetic Sub - polar Fluxes for ZZLHSM

With similar treatment to that of TRLHSM, then these fluxes are given by:

$$\phi'_1(t) = -\phi'_3(t) = \frac{-\mu_0 A'_1 (M'_D + m'_A)}{z} \tag{43}$$

$$\phi'_2(t) = -\phi'_4(t) = \frac{-\mu_0 A'_2 (M'_D - in:,)}{z} \tag{44}$$

Magnetic Sub - polar Flux Densities for ZZLHSM

These are given by:

$$B'_1(t) = -B'_3(t) = \frac{-\mu_0 (M'_D + m'_A)}{z} \tag{45}$$

$$B'_2(t) = -B'_4(t) = \frac{-\mu_0 (M'_D - m'_A)}{z} \tag{46}$$

Magnetic Lift Force for ZZLHSM

This is found,in a similar way to that of TRLHSM,as:

$$F'_v(t) = \frac{\mu_0 A [2 {M'_D}^2 + {m'}^2 + 2 M'_D m' cos(\theta') + {m'}^2 cos(2\omega' t + 2\theta') + 2 M'_D m' cos(2\omega' t + \theta')]}{2 z^2}$$

Hence,the lift force, F'_v,of ZZLHSM is composed of a steady component restricting $M'_D(\theta', m')$, at any ac excitation parameters of θ'&m' to satisfy:

$$\frac{\mu_0 A [2 {M'_D}^2 + {m'}^2 + 2 M'_D m' cos(\theta')]}{2 z^2} = W \tag{47}$$

and a pulsation one given by:

$$\alpha'_{vp}(\theta', m', t) = \frac{\mu_0 A m' [2 M'_D cos(2\omega' t + \theta') + m' cos(2\omega' t + 2\theta')]}{2 z^2 W} \tag{48}$$

Open Circuit Voltage for ZZLHSM

This is found to be:

$$E'_A(t) = \frac{-2\mu_0 \omega' A M'_D N sin(\omega' t)}{z} \tag{49}$$

Magnetic Thrust Force for ZZLHSM

This is given as:

$$F'_h(t) = \frac{\mu_0 \pi A M'_D m' [sin(\theta') - sin(2\omega' t + \theta')]}{p z} \tag{50}$$

and is composed of two components:one steady and the other pulsating at twice the synchronous frequency.Note that when the rail completely links sub-poles 1&3 or 2&4,then $\omega' t$ = integral multiple of π giving F'_h zero.This is why ZZLHSM needs a starter.

Maximum Steady Thrusting Acceleration for ZZLHSM

This is given as:

$$\alpha'_{hs}(\theta', m') = \frac{\mu_0 \pi A M'_D(\theta', m') m' sin(\theta')}{p W z} \tag{51}$$

Hence,the ZZLHSM will propel when the current phase angle is within $(0, \pi)$ and will brake within $(-\pi, 0)$.

The maximum of $\alpha'_{hs}(\theta', m')$ for a given θ' occures at:

$$\overline{M}'_D(\theta') = M'_D(\theta', \overline{m}'($$

$$\overline{m}'(\theta') = \sqrt{\frac{\sqrt{}}{\mu_0 A [\sqrt}}$$

$$\alpha'_{hs}(\theta') = \alpha'_{hs}(\theta', \overline{m}'(\theta')) =$$

On the other hand,the maximum of $\alpha'_{hs}(\theta'$

$$\overline{\theta}' = \pm\frac{3\pi}{4}$$

This would split into two values:

$$\overline{\theta}'_+ = \frac{3\pi}{4} \in ($$

in the motoring range discussed above,giv tion:

$$\alpha'_{hs}(\overline{\theta}'_+) =$$

and:

$$\overline{\theta}'_- = \frac{-3\pi}{4} \in ($$

in the generating range discussed above,gi tion:

$$\alpha'_{hs}(\overline{\theta}'_-) =$$

Hence,the maximum value of α'_{hs} is given

$$\alpha'_{hsx} = |\alpha'_{hs}(\overline{\theta}'$$

with:

$$\overline{m}' = z \sqrt{}$$

and :

$$\overline{M}'_D = z \sqrt{\frac{}{\mu_}}$$

Lift Pulsating Acceleration for ZZLHSM

Eq. 48 can provide a scale for the magnitu which is α'_{vpx} occuring at $\overline{\theta}'$&$\overline{m}'$. Hence,usi

$$\alpha'_{vpx}(t) = \alpha'_{vp}(\overline{\theta}', \overline{m}')$$

$\frac{{}_D - m'_A)}{z}$ (46)

ISM,as:

$\frac{{}^2 cos(2\omega' t + 2\theta') + 2 M'_D m' cos(2\omega' t + \theta')]}{2 z^2}$

posed of a steady component restricting θ'&$\overline{m}'$ to satisfy:

$\frac{m' cos(\theta')]}{} = W$ (47)

$\frac{+ \theta') + m' cos(2\omega' t + 2\theta')]}{z^2 W}$ (48)

$\frac{' sin(\omega' t)}{}$ (49)

$\frac{- sin(2\omega' t + \theta')]}{}$ (50)

, and the other pulsating at twice the syn-
ompletely links sub-poles 1&3 or 2&4,then
is why ZZLHSM needs a starter.

ZZLHSM

$\frac{n') m' sin(\theta')}{z}$ (51)

nt phase angle is within $(0, \pi)$ and will brake

es at:

$$\overline{M}'_D(\theta') = M'_D(\theta', \overline{m}'(\theta')) = \frac{\overline{m}'(\theta')}{\sqrt{2}} \tag{52}$$

$$\overline{m}'(\theta') = \sqrt{\frac{\sqrt{2}\, W\, z^2}{\mu_0\, A\, [\sqrt{2} + cos(\theta')]}} \tag{53}$$

$$\alpha'_{hs}(\theta') = \alpha'_{hs}(\theta', \overline{m}'(\theta')) = \frac{\pi\, z\, sin(\theta')}{p\, [\sqrt{2} + cos(\theta')]} \tag{54}$$

On the other hand,the maximum of $\alpha'_{hs}(\theta')$ occure at $\overline{\theta}'$.This is given as:

$$\overline{\theta}' = \pm \frac{3\pi}{4} \tag{55}$$

This would split into two values:

$$\overline{\theta}'_+ = \frac{3\pi}{4} \in (0, \pi)$$

in the motoring range discussed above,giving the following maximum thrusting acceleration:

$$\alpha'_{hs}(\overline{\theta}'_+) = \frac{\pi\, z}{p}$$

and:

$$\overline{\theta}'_- = \frac{-3\pi}{4} \in (-\pi, 0)$$

in the generating range discussed above,giving the following maximum braking deceleration:

$$\alpha'_{hs}(\overline{\theta}'_-) = \frac{-\pi\, z}{p}$$

Hence,the maximum value of α'_{hs} is given by:

$$\alpha'_{hsx} = |\, \alpha'_{hs}(\overline{\theta}')\, | = \frac{\pi\, z}{p} \tag{56}$$

with:

$$\overline{m}' = z \sqrt{\frac{2\, W}{\mu_0\, A}} \tag{57}$$

and :

$$\overline{M}'_D = z \sqrt{\frac{W}{\mu_0\, A}} \tag{58}$$

Lift Pulsating Acceleration for ZZLHSM

Eq. 48 can provide a scale for the magnitude of lift acceleration pulsation,α'_{vp},the worst of which is α'_{vpx} occuring at $\overline{\theta}'$&$\overline{m}'$. Hence,using Eqs. 55&57 for $\overline{\theta}'$&$\overline{m}'$, then:

$$\alpha'_{vpx}(t) = \alpha'_{vp}(\overline{\theta}', \overline{m}') = -cos(2\omega' t) \tag{59}$$

This means that the worst pulsation in lift acceleration is equal to that of gravity in magnitude and running at twice the synchronous frequency.

Thrust Pulsating Acceleration for ZZLHSM

It could be seen from eqs. 50,55&56 that the worst magnitude of thrust acceleration pulsation, a'_{hp} is a'_{hpx}, occuring at $\overline{\theta}'$ &$\overline{m}'$, and is given by:

$$a'_{hpx}(t) = -\sqrt{2}\,sin(2\omega' t + \overline{\theta}') \tag{60}$$

This means that the worst pulsation in thrust acceleration is over 1.4 that of gravity in magnitude and running at twice the synchronous frequency.

CHARACTERISTICAL DIFFERENCES BETWEEN ZZLHSM AND TRLHSM

The ZZLHSM is a single phase linear machine that needs a starter. Its maximum thrusting acceleration is $\pi z/p$ and this occures at field excitation, M_D, of $z\sqrt{W/(\mu_0 A)}$; armature excitation, m, of $\sqrt{2}\,z\sqrt{W/(\mu_0 A)}$ with 135° phase. Pulsation in accelerations operates at twice the synchronous frequency with worst value relative to gravity of 1.0 in the lift direction and $\sqrt{2}$ in the thrust direction.

On the other hand, The TRLHSM is a two-phase self-starting linear machine. Its maximum thrusting acceleration is $\sqrt{0.5}\,\pi\,z/p$ and this occures at field excitation, M_D, of $\sqrt{1.5}\,z\sqrt{W/(\mu_0 A)}$; armature excitation, m, of $2\,z\sqrt{W/(\mu_0 A)}$ with 190° or 260° phase. Pulsation in accelerations operates at four times the synchronous frequency with worst value relative to gravity of 0.5 in the lift direction and 0.0 in the thrust direction.

CONCLUSION

For same speed, TRLHSM is advantageous over ZZLHSM in that it is self-starting, operating at half the switching frequency, having half the worst lift pulsation and no thrust pulsation at all.

On the other hand, ZZLHSM is advantageous over TRLHSM in that it is a single phase machine with $\sqrt{2}$ gain in thrust acceleration involving $\sqrt{0.5}$ less armature excitation and $\sqrt{2/3}$ less field excitation.

Both machines pulsate at same frequency, but this is a second harmonic in ZZLHSM and a fourth in TRLHSM.

ACKNOWLEDGMENT

The author would like to express his thanks to Dr. S. Abu-Shadi at the electrical engineering department of King Abdul-Aziz University in Saudi Arabia for his valuable assistance and comments.

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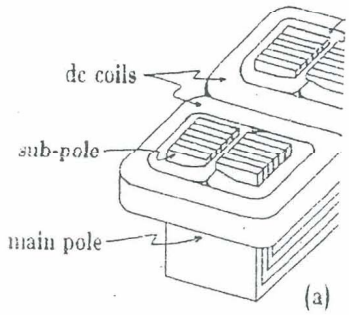

Fig. 1 (a) ZZLH

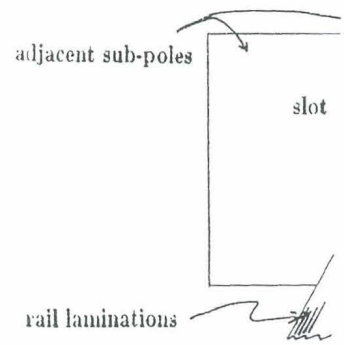

Fig. 3 Overlap

ion is equal to that of gravity in
ency.

magnitude of thrust acceleration

(60)

ation is over 1.4 that of gravity in
ency.

ZZLHSM AND TRLHSM

ls a starter.Its maximum thrusting
m, M_D, of $2\sqrt{W/(\mu_0 A)}$; armature
ation in accelerations operates at
lative to gravity of 1.0 in the lift

-starting linear machine.Its max-
cures at field excitation, M_D, of
with 190° or 260° phase.Pulsation
requency with worst value relative
st direction.

SM in that it is self-starting, oper-
worst lift pulsation and no thrust

LHSM in that it is a single phase
$\sqrt{0.5}$ less armature excitation and

second harmonic in ZZLHSM and

u-Shadi at the electrical engineer-
Arabia for his valuable assistance

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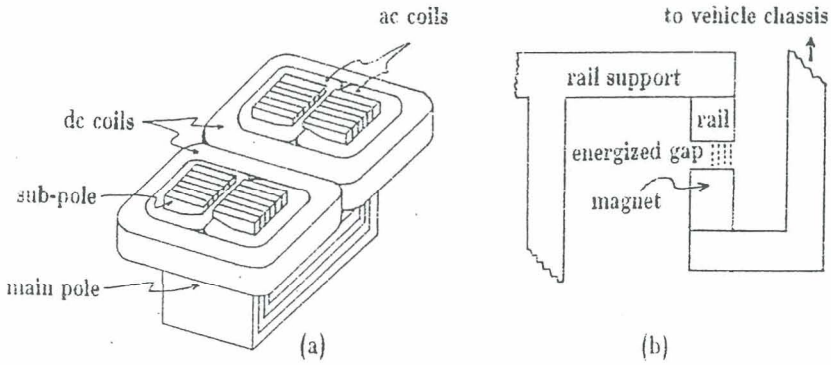
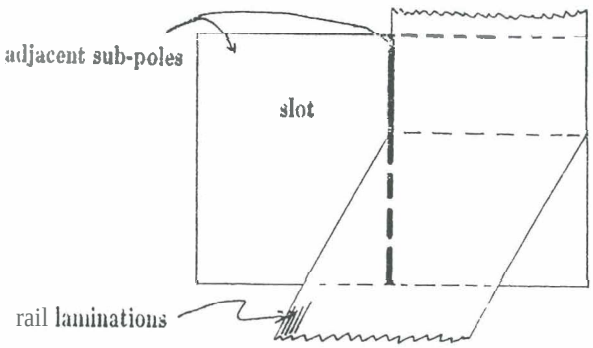


Fig. 1 (a) ZZLHSM magnet and (b) vehicle boggie



Pig. 3 Overlap area between rail and ZZLHSM sub-poles

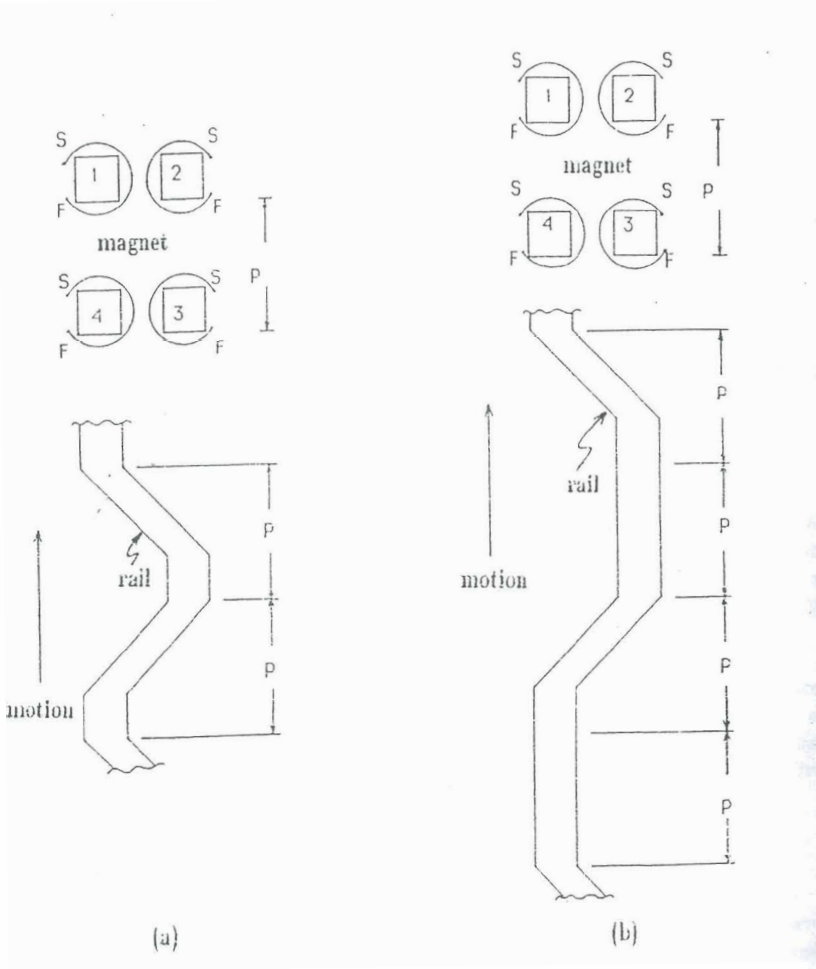


Fig. 7 Magnet and rail of (a) ZZLHSM and (b) TRLHSM

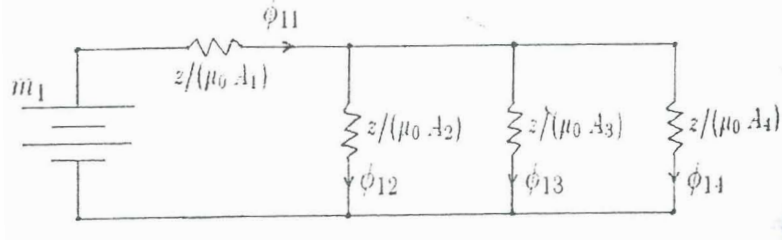


Fig. 6 The magnetic circuit driven by m_1 around sub-pole 1

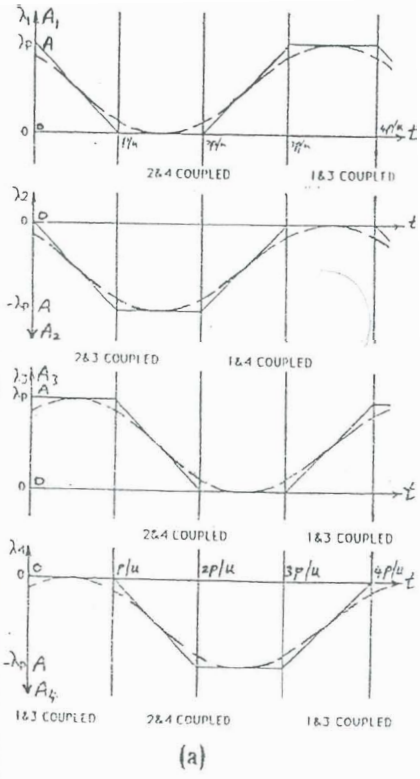


Fig. 4 Sub-polar flux-linkages and areas f

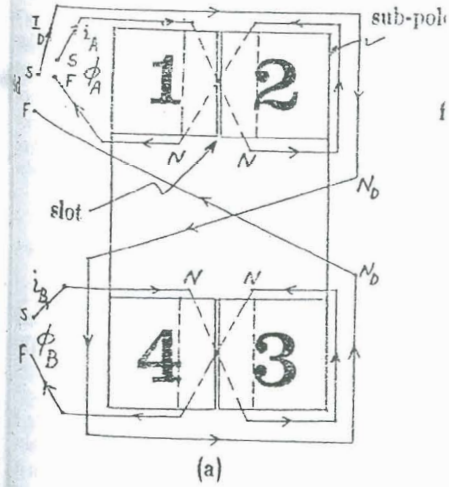
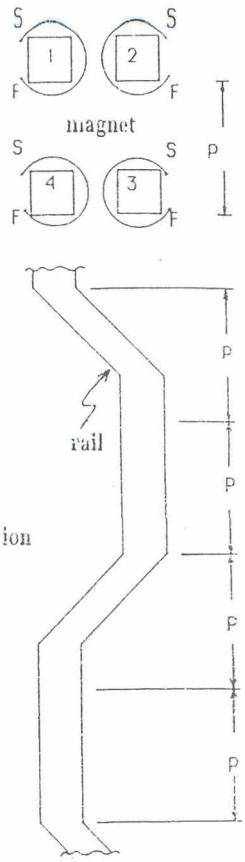
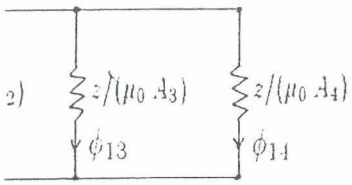


Fig. 5 Coil connections for (a)



(b)

M and (b) TRLHSM



y m_1 around sub-pole 1

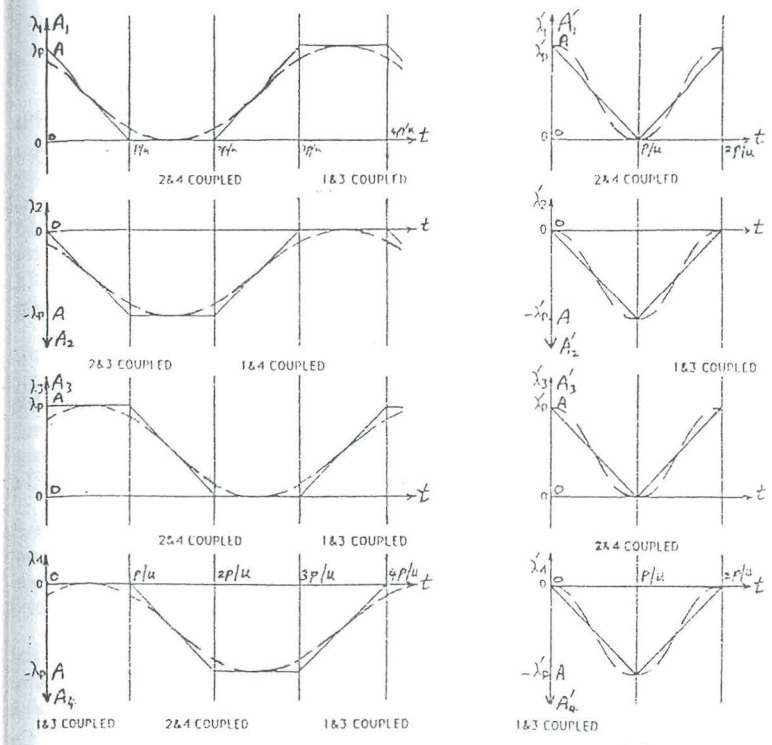


Fig. 4 Sub-polar flux-linkages and areas for (a) TRLHSM and (b) ZZLHSM

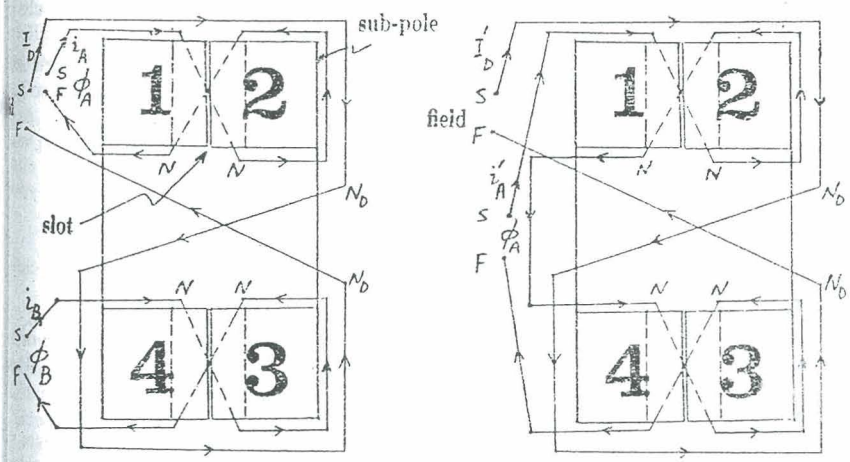


Fig. 5 Coil connections for (a) TRLHSM and (b) ZZLHSM