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THRUST DERATING DUE TO STABILITY REQUIREMENTS OF THE ZIGZAG LINEAR SYNCHRONOUS MOTOR-PAIR INTEGRATING LIFT AND THRUST FOR MAGLEV VEHICLES

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ABSTRACT

The Zigzag Linear Synchronous Motor Pair, ZLSMP, is composed of two magnets one of which is shown in Fig.1. These are attached to the maglev vehicle-boggie as shown in Fig.2, and are reacting against the zigzag-shaped rail shown in Fig.3. The coils of each magnet are connected as shown in Fig.4, with dc coils fed from a chopper power amplifier controlling field current to provide lift at constant gap, Z. The feedback loops involved in field control are shown in Fig.5. The ac are, on the other hand, fed from a two-phase inverter providing armature currents such that the fieldis distorted among the four sub-poles of each magnet, and hence propulsion is obtained.

It was found necessary to make a twin pair of magnets, for the elemenation of harmonic currents in the field circuits. This also improves the thrust force pulsation. Maximum thrust force was found when the armature mmf rms value equals to that of field mmf. This maximum thrust force relative to supported weight was found to be $\pi Z/p$, where p is fhe pole-pitch shown in

The work described in the proposed paper looks upon he stability requirements of ZLSMP and proves that the above maximum thrust value corresponds to unlift system. To make it controllable, this maximum thrusting force must be severely derated to gain

KEYWORDS

Zigzag; linear; synchronous; motor; machi suspension.

INTRODUCTION

The Zigzag Linear Synchronous Motor Pair, one of which is shown in Fig.1. These are a as shown in Fig.2, and are reacting against t As the rail moves relative to magnets in the emf's will appear at sub-pole coil terminals for constructive emf resultant, ac coils are c coils are connected in series and are fed from the field current to provide lift at constant g in the field control are shown in Fig.5. Th inverter providing armature currents such th four sub-poles of each magnet and hence prop

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This paper reviews the theory of ZLSMP and ments. It then proves that the above maximu uncontrollable lift system. To make it controlla must be derated for stability.

NOTATIONS

The symbols used in this paper are listed below

A sub-pole surface area

A_i overlap area of sub-pole i in motor-A

α derated maximum thrust relative to weight

B_i flux density over sub-pole i in motor-A

E_i open circui induced voltage at phase i coil

F_h horizontal force of both motor pairs

F_v vertical lift force of both motor pairs

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West [1] found it necessary to make a twin pair of magnets for the elimination of harmonic currents in the field circuit. This also cancels the thrust force pulsation, leaving only a steady component which he found to have a maximum when the sub-polar armature mmf rms value equals to that of field. This maximum thrust relative to the supported weight was found to be $\pi Z/p$, where p is the pole-pitch shown in Fig.3.

This paper reviews the theory of ZLSMP and then looks at its stability requirements. It then proves that the above maximum thrust value corresponds to an uncontrollable lift system. To make it controllable, this maximum thrusting force must be derated for stability.

NOTATIONS

The symbols used in this paper are listed below:

A sub-pole surface area

A_i overlap area of sub-pole i in motor-A

α derated maximum thrust relative to weight

B_i flux density over sub-pole i in motor-A

E_i open circuit induced voltage across phase i coil terminals in motor-A

F_h horizontal thrust force of both motor pairs

F_v vertical lift force of both motor pairs

ϕ_{ii} flux due to m_i which leaves sub-pole i of motor-A

ϕ_{ij} flux due to m_i which leaves sub-pole i to sub-pole j of motor-A

ϕ_k flux due to all sub-polar mmfs that leaves sub-pole k in motor-A

I_D current flowing in the field dc coils

i_i current flowing in phase-i ac coils

M_D net dc mmf excitation of field winding per pole in motor-A

$\overline{M}_D$ optimum M_D value for maximum thrust

m peak value of ac mmf excitation of any phase per sub-pole

$\overline{m}$ optimum m value for maximum thrust

m_i ac mmf excitation of phase-i armature winding per sub-pole

m_j resultant mmf excitation around sub-pole j of motor-A

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

r perturbation level of m_1 relative to operational level of M_D

T time period to complete one cycle

t time, starting zero when rail completely links sub-poles 1 and 3 of motor-A

θ phase angle of ac excitation of motor-A

$\overline{\theta}$ optimum phase angle at maximum thrust conditions

θ_m optimum phase angle at derated maximum thrust conditions

u speed of rail relative to magnet

W weight of supported boggie

ω angular frequency of ac supply

Z energized air gap

ASSUMPTIONS

For simplicity, the following assumptions we

1. All sub-poles have the same surface are

2. AC coils around sub-poles are identical

3. Slot-width in the main poles, fringing, le
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14. The induced voltages in all ac coils arour

15. AC coils are fed with sinusoidal ac currer

MAGNETIC SUB-POLAR EXCITATIC

Each of the sub-poles in Fig.4 could be consid

• dc due to the field current I_D flowing in t
a dc excitation magnitude of:

$$M_D = N_D$$

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. Slot-width in the main poles, fringing, leakage, steel loss, copper loss, windage, friction and other drag forces are all negligible.
4. Air gap, Z, is homogeneous over the sub-poles.
5. Flux lines in the energized airgaps are parallel.
6. The energized air-gap faces equal areas both at the rail-surface above it and at the magnet pole-surface below it throughout the motion.
7. 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.
8. Speed of motor relative to the track, u, is constant.
9. Track structure is rigid.
10. Reference axes are taken to be the gravity line, motion line and the axis perpendicular to both.
11. The motor does not rotate about any of the above axes.
12. The motor force is considered in two directions only, namely, along the gravity line and along the direction of motion. Although some force component in the third direction is exerted, it will be ignored.
13. Flux linkage for any ac coil varies sinusoidally between a minimum of zero when its sub-pole is fully uncoupled to the rail and a maximum when its sub-pole is fully coupled to the rail.
14. The induced voltages in all ac coils around sub-poles vary sinusoidally.
15. AC coils are fed with sinusoidal ac currents phase-locked to rail.

MAGNETIC SUB-POLAR EXCITATIONS FOR MOTOR-A

Each of the sub-poles in Fig.4 could be considered excited with two components:

- dc due to the field current I_D flowing in the dc coil of N_D turns, thus giving a dc excitation magnitude of:

$$M_D = N_D\, I_D, \tag{1}$$

and:

- ac due to the armature phase currents i_A or i_B flowing in the ac coils of N turns each, thus giving an ac excitation magnitude of:

$$m_A(t) = N\,i_A(t) = m\,cos(\omega\,t + \theta), \tag{2}$$

or:

$$m_B(t) = N\,i_B(t) = m\,sin(\omega\,t + \theta); \tag{3}$$

where: $\omega = 2\,\pi/T$, with T = $2p/u$; hence: $w = \pi\,u/p$.

Using Fig.4 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 of motor-A, with positive sense when forcing flux to leave the sub-pole, then:

$$m_1(t) = -M_D - m_A(t) = -m_3(t), \tag{4}$$

and:

$$m_2(t) = -M_D + m_A(t) = -m_4(t). \tag{5}$$

ENERGIZED SUB-POLAR AREAS FOR MOTOR-A

With A_1, A_2, A_3 and A_4 defined as above, then these areas are assumed sinusoids between a maximum of A and a minimum of zero. The equations describing these approximations are given by:

$$A_1(t) = A_3(t) = (A/2)\,[1 + cos(\omega\,t)], \tag{6}$$

and:

$$A_2(t) = A_4(t) = (A/2)\,[1 - cos(\omega\,t)]. \tag{7}$$

MAGNETIC SUB-POLAR FLUXES FOR MOTOR-A

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}, ϕ_{41}, ϕ_{42}, ϕ_{43}, ϕ_{44}, ϕ_1, ϕ_2, ϕ_3 and ϕ_4 be as defined earlier. 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, using Fig.6 and applying superposition, the fluxes $\phi_1(t)$, $\phi_2(t)$, $\phi_3(t)$ and $\phi_4(t)$ leaving sub-poles 1, 2, 3 and 4 of motor-A respectively due to all mmfs of m_1, m_2, m_3 and m_4 are found to be:

$$\phi_1(t) = \phi_{11} - \phi_{21} - \phi_{31} - \phi_{41} = \mu_0\,A_1\,m_1/Z, \tag{8}$$

$$\phi_2(t) = \mu_0\,A_2\,m_2/Z, \tag{9}$$

$$\phi_3(t) = -\phi_1(t), \tag{10}$$

and:

$$\phi_4(t) = -\phi_2(t). \tag{11}$$

This gives the sub-polar flux densities as.

$$B_1(t) = \mu$$

$$B_2(t) = \mu$$

$$B_3(t) = -$$

and:

$$B_4(t) = -$$

MAGNETIC LIFT FORCE FOR ZI

Motor-A will exert a lift force, F_{v_A}, in or mizing the energized air-gap, Z. This lift is given by:

$$F_{v_A}(t) = \sum_{i=}$$

Using eqs.(6) and (7) for A_1, A_2, A_3 and B_2, B_3 and B_4 respectively; and simplifyi and m_B; then F_{v_A} may be found as:

$$F_{v_A}(t) = \mu_0\,A\,[M_D^2 + m_A^2 -$$

Motor-B will exert a lift force, F_{v_B}, which

$$= \mu_0\,A\,[M_D^2 + m_B^2$$

Hence, the total lift force, F_v, of ZLSMP

$$F_v(t) = F_{v_A}(t) + F_{v_B}(t) = \mu_0\,A\,[2$$

which is seen to be steady to support via field control. The pulsating compon implicit in both expressions of F_{v_A} and connections of both motor pairs. Hence, for stable field excitation, $M_D(\theta, m)$, at as:

$$W = \mu_0\,A\,[2\,M_D^2 + m^2$$

OPEN CIRCUIT VOLTAGES FOR

The open circuit induced voltage, E_A, at Fig.4 to be:

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and:

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MAGNETIC LIFT FORCE FOR ZLSMP

Motor-A will exert a lift force, F_{v_A}, in order to minimize its reluctance by minimizing the energized air-gap, Z. This lift force is composed of several parts and is given by:

$$F_{v_A}(t) = \sum_{i=1}^{4} \frac{A_i B_i^2}{2\,\mu_0}.$$

Using eqs.(6) and (7) for A_1, A_2, A3 and A_4; eqs.(12), (13), (14) and (15) for B_1, B_2, B_3 and B_4 respectively; and simplifying with the aid of eqs.(2) and (3) for m_A and m_B; then F_{v_A} may be found as:

$$F_{v_A}(t) = \mu_0 A\,[M_D^2 + m_A^2 + 2\,M_D\,m_A\,cos(\omega t)]/Z^2. \tag{16}$$

Motor-B will exert a lift force, F_{v_B}, which can be similarly found to be:

$$F_{v_B}(t) = \mu_0 A\,[M_D^2 + m_B^2 + 2\,M_D\,m_B\,sin(\omega t)]/Z^2. \tag{17}$$

Hence, the total lift force, F_v, of ZLSMP is given as:

$$F_v(t) = F_{v_A}(t) + F_{v_B}(t) = \mu_0 A\,[2\,M_D^2 + m^2 + 2\,M_D\,m\,cos(\theta)]/Z^2, \tag{18}$$

which is seen to be steady to support the boggie weight, W, at constant gap via field control. The pulsating component at twice the synchronous frequency implicit in both expressions of F_{v_A} and F_{v_B} has been cancelled due to the clever connections of both motor pairs. Hence, the above equation gives the condition for stable field excitation, $M_D(\theta, m)$, at any ac excitation parameters of 6 and m as:

$$\mathrm{W} = \mu_0 A\,[2\,M_D^2 + m^2 + 2\,M_D\,m\,cos(\theta)]/Z^2. \tag{19}$$

OPEN CIRCUIT VOLTAGES FOR ZLSMP

The open circuit induced voltage, E_A, at phase-A coil teminals can be seen from Fig.4 to be:

$$E_A(t) = N\,\frac{d}{dt}\,[\phi_2 - \phi_1 + \phi_3 - \phi_4]_{m=0}.$$

This is found to be:

$$E_A(t) = -2N\mu_0 M_D A w sin(\omega t)/Z. \quad (20)$$

Similarly, E_B can be found to be:

$$E_B(t) = 2N\mu_0 M_D A\omega cos(\omega t)/Z. \quad (21)$$

MAGNETIC THRUST FORCE FOR ZLSMP

The ZLSMP thrust force, F_h, can be obtained using the energy principle. Assuming ideal conversion, then, the mechanical power is equated to the electrical power and hence:

$$F_h u = E_A i_A + E_B i_B.$$

This is found to be:

$$F_h(t) = 2\mu_0 \pi A M_D m sin(\theta)/p/Z. \quad (22)$$

Hence; the thrust force, F_h, is composed of only one steady component. The ac second harmonic wmponent of motor-A cancelled that of motor-B due to the clever connection of both motors.

Eq.(22) shows that the ZLSMP will propel when the current phase angle is within $(0,\pi)$ and brake within $(\pi, 2\pi)$. This is due to the mechanical and electrical system lags. The ZLSMP can be used either for motoring with electric power converted to kinetic power or for braking with kinetic power converted to electric. At two θ values, namely: 0 and π, the ZLSMP is exerting virtually zero force.

MAXIMUM THRUST OF ZLSMP

The maximum of $F_h(\theta, m)$ for a given θ occurs at $\overline{m}(\theta)$. This could be found using eqs.(19) and (22) to give:

$$\overline{M}_D(\theta) = \overline{m}(\theta)/\sqrt{2}; \quad (23)$$

where:

$$\overline{m}(\theta) = Z\sqrt{\frac{W}{\mu_0 A[2+\sqrt{2}cos(\theta)]}}. \quad (24)$$

On the other hand, the maximum of $F_h(\theta)$ occures at $\overline{\theta}$. This could be found using eqs.(19) and (22) to be:

$$\overline{\theta} = \pm 135°. \quad (25)$$

This gives the following maximum thrust:

$$F_{h_{max}} = \pi W Z/p.$$

Substituting either $\overline{\theta}$ values in eqs.(23) and (24

$$\overline{m} = Z\sqrt{\frac{2W}{\mu_0 A}}$$

and:

$$\overline{M}_D = Z\sqrt{\frac{W}{\mu_0}}$$

STABILITY OF ZLSMP LIFT SYSTEM

The ZLSMP lift system shown in Fig.5 is contr
These signals are:

1. the gap, Z, that can be measured using th motor poles,
2. the gap speed, $\dot{Z}$, that can be measure certain frequency band, and:
3. the pole flux linkage, λ, that can be meas magnet poles.

Since the equations of the ZLSMP lift syste treme instability; linearization techniques are a whereby Linear Control Theory is utilized to feed-back signals. The controller is shown in circuit that adds up all three signals after appr system comp with the pre-determined char:

The ZLSMP lift-system being considered for l of its variables perturbing about a non-zero op nitude of perturbation must be much smaller t of these two conditions is violated, the linearize to the actual system. This will consequently e

The most crit variable in this respect wa typically given as:

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$$r = m/M_D$$

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$Z/p.$

Substituting either $\overline{\theta}$ values in eqs.(23) and (24) for $\overline{m}$ & $\overline{M}_D$ gives:

$$\overline{m} = Z\sqrt{\frac{2W}{\mu_0 A}}, \tag{26}$$

and:

$$\overline{M}_D = Z\sqrt{\frac{W}{\mu_0 A}}. \tag{27}$$

STABILITY OF ZLSMP LIFT SYSTEM

The ZLSMP lift system shown in Fig.5 is controlled using three feed-back signals. These signals are:

1. the gap, Z, that can be measured using the capacitance between the rail and motor poles,

2. the gap speed, $Z^{\cdot}$, that can be measured using differentiation of Z over a certain frequency band, and:

3. the pole flux linkage, λ, that can be measured using a search coil around the magnet poles.

Since the equations of the ZLSMP lift system are nonlinear with inherted extreme instability; linearization techniques are applied to obtain a linearized model, whereby Linear Control Theory is utilized to design a controller using the above feed-back signals. The controller is shown in Fig.5 and is composed simply of a circuit that adds up all three signals after appropriate scaling so that the resulting system complies with the pre-determined characteristics.

The ZLSMP lift-system being considered for linearization is trusted to have each of its variables perturbing about a non-zero operational level. Moreover, the magnitude of perturbation must be much smaller than the operational level. If either of these two conditions is violated, the linearized model is no longer representative to the actual system. This will consequently endanger stability.

The most critical variable in this respect was found to be the sub-polar mmf, typically given as:

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

This suggests that the perturbation in $m_1(t)$ is equal to $m_A(t)$ plus the perturbation of M_D. Using eq.(2), the ratio r of the perturbation of $m_1(t)$ to the operating level of M_D is found as:

$$r = m/M_D;$$

which at maximum thrusting force indicated in eq.(23) evaluates to:

$$r = \sqrt{2}.$$

This violates both conditions trusted to the lift system. To correct for that, $\overline{m}$ must be derated to match reasonable level for r. Hence, substituting in eq.(22):

$$F_h = 2\,\mu_0\,\pi\,A\,r\,M_D^2\,sin(\theta)/p/Z.$$

But M_D relates to W using eq.(19) as:

$$M_D^2 = \frac{W\,Z^2}{\mu_0\,A\,[2 + r^2 + 2\,r\,cos(\theta)]}.$$

Hence:

$$F_h(\theta) = \frac{2\,\pi\,r W\,Z\,sin(\theta)}{p[2 + r^2 + 2r\,cos(\theta)]}.$$

This is maximum at θ_m given by:

$$\theta_m = cos^{-1}(\frac{-2\,r}{2 + r^2}).$$

The resulting thrust force is:

$$F_{h_{max}}(r) = \frac{2\,\pi\,r\,W\,Z}{p\sqrt{4 + r^4}}.$$

Hence, derated maximum thrust relative to weight is:

$$\alpha = \frac{2\,r}{\sqrt{4 + r^4}}\,(\pi\,Z/p).$$

For the linearized lift model to represent *the* actual ZLSMP lift system, the value of r must be fairly small. Hence:

$$\alpha \cong r\,(\pi\,Z/p).$$

This shows that the maximum thrust relative to weight is derated by factor r from its value at passive support due to active lift of ZLSMP weight. Tollerable perturbation level depends on the severity of nonlinearity of ZLSMP relationships, and could reach as low as 10 % of the operational level. This results in a 10 % derating a from its d u e when ZLSMP is passively supported.

CONCLUSION

This paper shows that the representablity of the linearized model used to design a controller for stable active suspension of ZLSMP system, [illegible] derating the maximum thrust of the ZLSMP that can be achieved when passively supported, say by wheels. Suspending ZLSMP actively using the controller shown in Fig.5 has the price of derating the maximum thrust from its value when supported otherwise. The derating factor equals the acceptable level of perturbation relative to the operational level of sub-polar mmf excitation. This can be as bad as 10 %.

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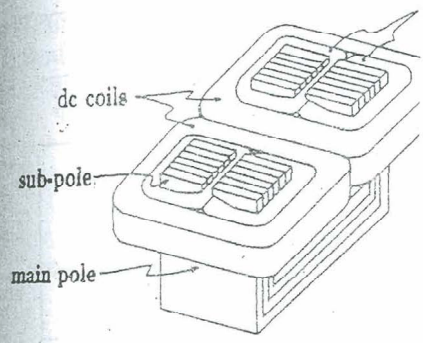
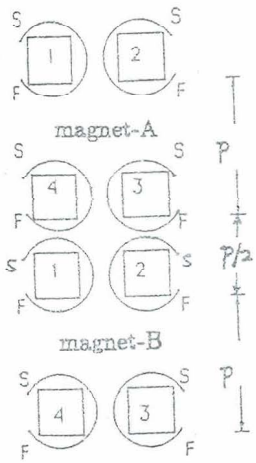


Fig.1 Magnet



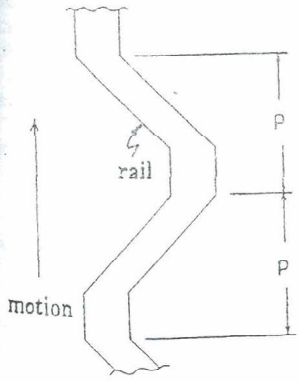


Fig.3 Rail

ft system. To correct for that,
-. Hence, substituting in eq.(22)

$\iota(\theta)/p/Z$.

$\overline{2r\cos(\theta)]}$.

$\frac{sin(\theta)}{2r\cos(\theta)]}$.

$\frac{2r}{-r^2}$).

$\frac{\cdot W Z}{1+r^4}$.

weight is:

Z/p).

actual ZLSMP lift system, the valu

$/p$).

tive to weight is derated by factor
tive lift of ZLSMP weight. Tollerable
f nonlinearity of ZLSMP relationships
rational level. This results in a 10 %
passively supported.

of the linearized model used to desig
ZLSMP system, requires derating th
be achieved when passively supported
ely using the controller shown in Fig.
thrust from its value when supported
acceptable level of perturbation relative
excitation. This can be as bad as 10 %.

ar Homopolar Synchronous Mot
er University.

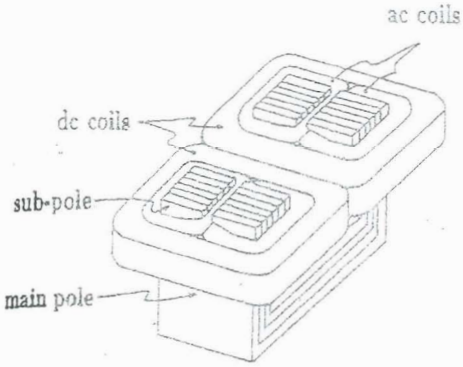


Fig.1 Magnet

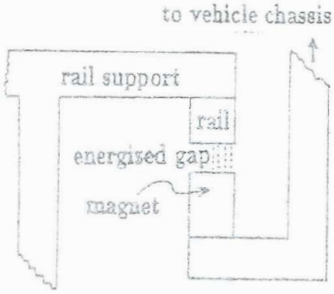
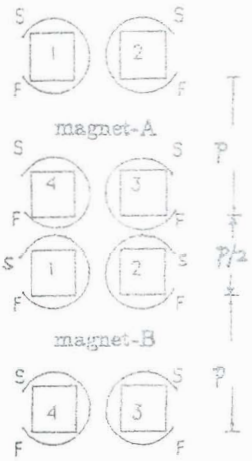


Fig.2 Boggie support



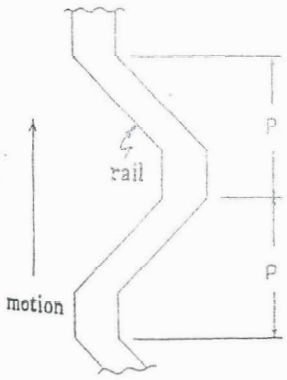


Fig.3 Rail

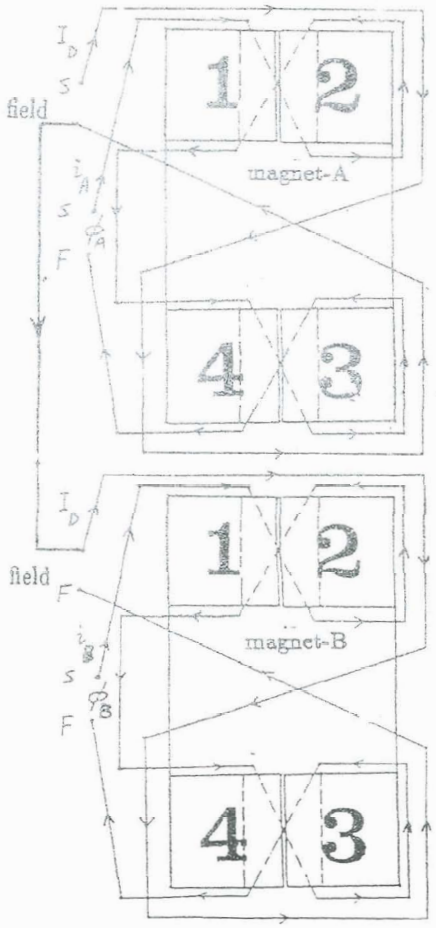


Fig.4 Coil connections

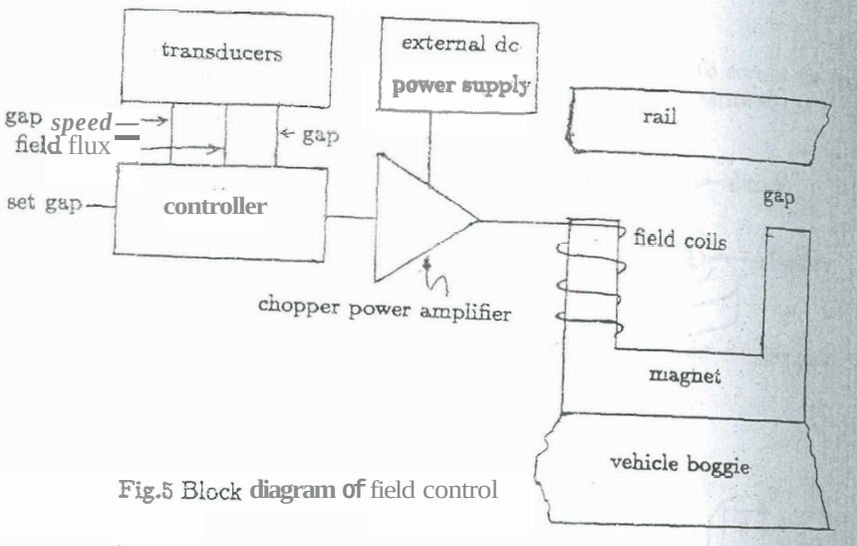


Fig.5 Block diagram of field control

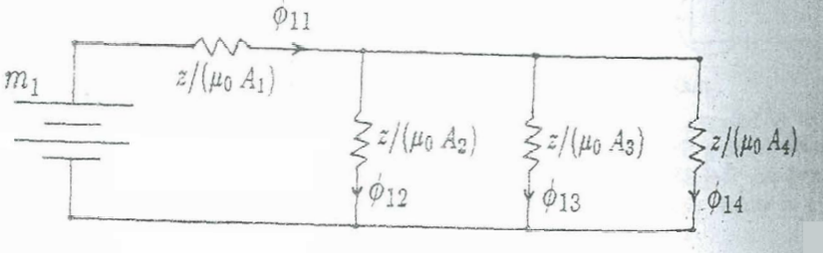


Fig.6 Magnetic circuit driven by m_1 around sub-pole 1

AEIC'9

ENGINEERING THIRD
NATIONAL CONFERENCE
BER 18-21, 1993

COMPUTATION OF EDDY-CURRENT

A. A
Dept. of El
Faculty
Menoui
Sheb:

ABSTRACT

The calculation of eddy-current factor in the design of po Manufacturers make every eff of loss calculation and loss proposed to compute eddy-curr The method is based on the distribution of a transformer. is accounted for by means currents. The validity and is demonstrated by applyin cases. The test cases include distribution transformer bu Egypt and a core-type transfo for air-cored reactors. The those obtained by a statis The method is simple and and reactors the designer so he can to

KEYWORDS

Power transformers, eddy-c electromagnetic field theor