Mansoura Engineering Journal

Volume 14 | Issue 2 Article 6

5-25-2021

Analysis of Linear Synchronous Motor Fed with Current Source Inverter at High Speeds and Low Speeds.

S. El-Drieny
Electrical Power Engineering Department, Faculty of Engineering, Mansoura University, Mansoura, Egypt.

M. El-Shamoty
Electrical Power Engineering Department, Faculty of Engineering, Mansoura University, Mansoura, Egypt.

A. Amin
Electrical Power Engineering Department, Faculty of Engineering, Mansoura University, Mansoura, Egypt.

Recommended Citation

El-Drieny, S.; El-Shamoty, M.; and Amin, A. (2021) "Analysis of Linear Synchronous Motor Fed with Current Source Inverter at High Speeds and Low Speeds.," *Mansoura Engineering Journal*: Vol. 14 : Iss. 2 , Article 6.
Available at: https://doi.org/10.21608/bfemu.2021.172232

ANALYSIS OF LINEAR SYNCHRONOUS MOTOR FED WITH CURRENT SOURCE INVERTER AT HIGH SPEEDS AND LOW SPEEDS

تحليل أداء المحرك التزامني الخطي المتصل بمنبوع تيار ثلاثي
المراحل ذي تردد متغير عند سرعات عالية ومنخفضة

S. A. EL-DRIEHY   M. M. I. EL-SHAMOTY   A. R. A. AMIN

Department of Electrical Engineering , Faculty of Engineering .
El-Mansoura University , El-Mansoura , Egypt

الخلاصة - يتركز البحث في دراسه نظرية لحساب القدرة الخارجة لمحرك تزامني خطي وعلاقتها بزوايا تيار الحمل عندما يتغذى من ينبوع تيار ثلاثي المراحل ذو تردد متغير . لقد تم حساب القدرة عند سرعات عالية ومنخفضة ، في حالة السرعة المنخفضة فقد فرض أن شكل موجة التيار الناشئ في ملفات عضو الاستنتاج هي مستطيلة الشكل تماما وفي هذه الحالة تحسب القدرة الخارجة بحاصل ضرب معاملي التحميل الكهربي والمغناطيسي في ثابت . أما في حالة السرعة العالية فقد فرض دائرة مكافئة مكونة من مكثفات التوحيد (الخاصة بالينبوع) متصلة بالتوازى مع ملفات عضو الاستنتاج (الخاصه بالمحرك المتزامن) وفرض أيضا أن موجة التيار الناشئ في ملفات عضو الاستنتاج هي شبه مربعة الشكل . ولقد تم حساب القدرة الخارجة بناء على هذه الدائرة المكافئة .

ABSTRACT :

A theoritical analysis of linear synchronous motor LSM fed by a current source inverter is presented. The analysis is carried out at the two ends of speed range using entirely two different models. The low speed model assumes a perfect rectangular current waveform which is established in the armature windings. So, the thrust is calculated from the product of specific electric loading and specific magnetic loading. The high speed model assumes that the commutating capacitors are permanently connected in parallel with the LSM and the resulting parallel commutation is fed by a quasi-square current waveform. The equivalent circuit which des-cribes the LSM during commutation is presented and the output power is calculated.

1. INTRODUCTION :

The behaviour of LSM fed with current source inverter at high speeds and low speeds, can be predicted. This prediction is

obtained by entirely different models. A large air-gap of such type of linear machine is left over the range of intermediate speeds when operation of inverter is complex [1].
The low speed model assumes commutation to be instantaneous .i.e. , a perfect rectangular current waveform is established in the armature windings. The r.m.s. of this waveform is only 21.6% greater than that of the equival- ent sinusoid hence the losses are increased by no more than this figure. The attractive force in this model is calculated.
At high speed model, as the edges of the current waveform become a large part of the cycle, the harmonic content is reduced. This inherent limitation in harmonic current is one of the major advantages of the current fed inverter. The biggest disadvantage in this model is the nature of commutation mechanism. This is due to blocking of the current in one phase and re-estabilishing it in another. So, the energy associated with the inductive part of the load must be absorbed by one commutating capacitor and supplied by another. The amount of energy to be handled, which determine the bulk and cost of the capaciotors. is very large in the linear synchronous motor. This is due to the inductive part of the load can be entire synchronous reactance of the LSM. As well as the capacitor being large in size, it must also be large in value in order to limit the rise in voltage when the energy is absorbed. This inturn leads to slow the commutation process which severly modifies the behaviour of the model. So, the equivalent circuit which describes the LSM during commutation is represented in this paper assuming commutating capacitors which are permanently connected in parallel with the LSM. The equivalent circuit and vector diagram are shown in figures (1) and (2). This circuit exhibits resonant behaviour at a certain frequency and is not valid until the frequency is far in excess of the resonant frequency [2.5]

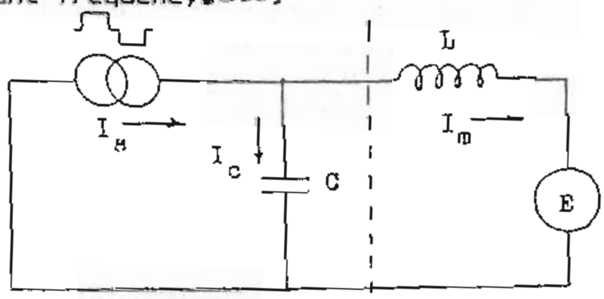

Fig.(1): Equivalent circuit of inverter/LSM combination at high frequencies.

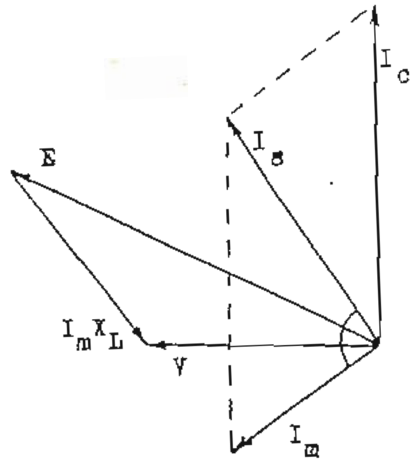

Fig.(2): Phasor diagram showing that a large angle can be developed between I_s, I_m and loading angles σ & δ.

2. DESCRIPTION OF THE SYSTEM :

A current fed inverter consists of a fully controlled 3-phase bridge through which a constant current source is forced with the assistance of a large choke in the d.c. link. The principle components are outlined in Fig.(3) which shows the inverter fed from a controlled rectifier. The basic fundamental of a commutation between two inverter thyristors is a forcing of current through the windings of the machine and this cannot be achieved instantaneously since such type of linear synchronous machine is distinguished by great values of inductance. The damper winding of synchronous machine reduces the mutual inductance between two phases and consequently makes the commutation much easier. In case of LSM such type of damper windings are undesirable as they would lead to degradation of motor performance through end effects. So, the LSM is distinguished by the great values of inductance. The forcing current through the windings of the machine establishes extra stored energy in the windings inductance of it which will be consequently transferred to the commutating capacitors over part of a resonant cycle. The capacitor must be large enough to absorb the stored energy without too much rise in voltage for the thyristors to handle. This rise may be estimated from the equation ;

$$L \cdot I^2 = C \cdot V^2$$

hence ,

$$V = \sqrt{L\ I^2/C}$$

Where, C is the value of one of the bridge commutating capacitors , I is the current to be commutated and L is the winding inductance per phase. The time taken for commutation to complete itself is a little more than one quarter of a cycle of resonance between L and C , i.e. , commutation time is :

$$\tau = (\pi/2) \cdot \sqrt{L.C}$$

For the values used in this type of LSM (l = 0.05 H . C = 120 µf) the τ is over 4.64 ms. This becomes an appreciable part of the complete cycle at low frequencies.

3. LOW SPEED ANALYSIS :

Since the current distribution in the armature winding is fixed relative to the stator block for each $\pi/3$ part of inverter cycle the calculation of the thrust is essentially a static force problem.

Suppose the current distribution of Fig.(4) is established :

$J = 0$	for	$0 < x < p/6$
$J = \hat{J}$	for	$p/6 < x < 5p/6$
$J = 0$	for	$5p/6 < x < 7p/6$
$J = -\hat{J}$	for	$7p/6 < x < 11p/6$
$J = 0$	for	$11p/6 < x < 2p/6$

If the rotor is positioned such that zero magnetizing flux occurs α radians from x=0 then the magnetizing flux density can be expressed as :

$$B = \hat{B} \cdot \sin(\pi x/p + \alpha) \qquad (1)$$

If the stator block width is W then the output thrust per pole (F/pole) is given by :

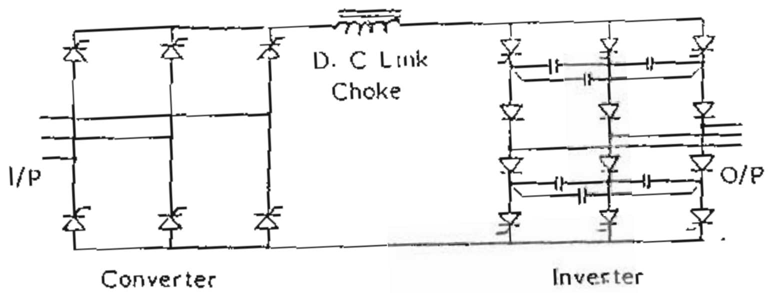

Fig. (3): Principle Component of the Current Fed Inverter.

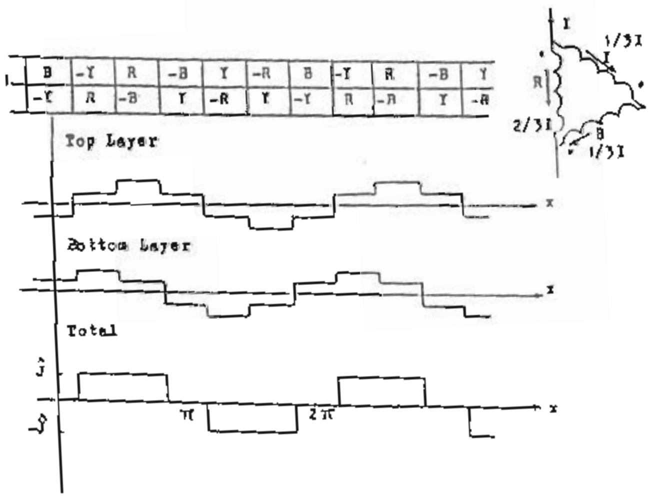

Fig. (4): Current Distribution in 2/3 Corded Pitch Armature Fed By Six Pulse Current Waveform.

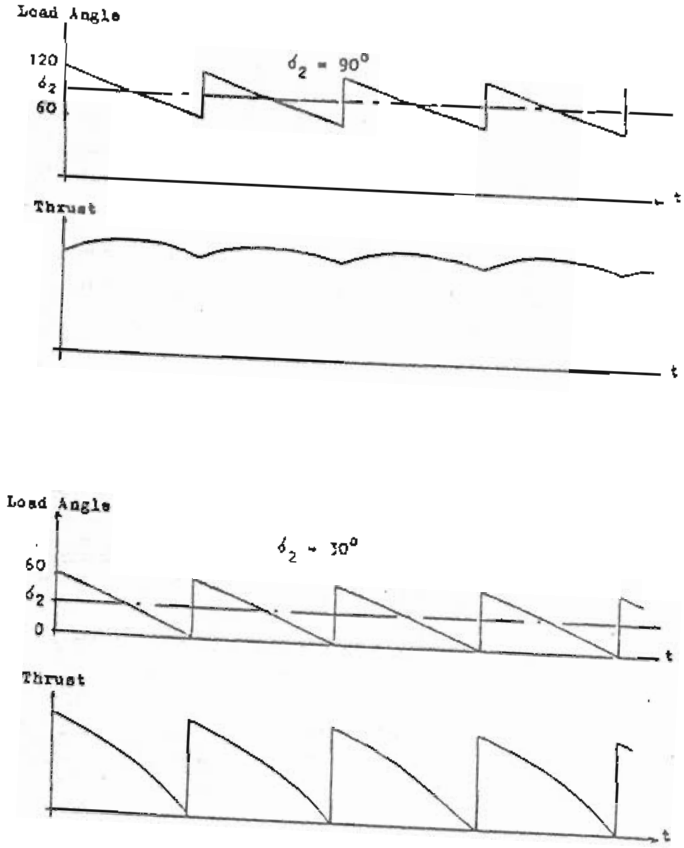

Fig. (5): Pulsation in Thrust and Load Angle at Low Speeds.

$$F/\text{pole} = W \int_0^p B \cdot J \cdot dx$$

$$= W.\hat{B}.\hat{J}. \int_{p/6}^{5p/6} \sin(\pi x/p + \alpha).dx$$

$$= \frac{2}{\pi} .\hat{B} .\hat{J} .W .p .\sin\frac{\pi}{3} .\cos\alpha$$

$$= \frac{2}{\pi} .\hat{B} .\hat{J} .W .p .\sin\frac{\pi}{3} .\sin\sigma \qquad (2)$$

where,

$$\sigma = \frac{\pi}{2} - \alpha$$

The total output thrust of the machine is therefore :

$$F = \frac{2}{\pi} . \hat{B} . \hat{J} . W . L . \sin\frac{\pi}{3} . \sin\sigma \qquad (3)$$

$$= \hat{F}_o . \sin\sigma \qquad (4)$$

where,

$\hat{F}_o$:= is the peak thrust

$$= \frac{2}{\pi} . \hat{B} . \hat{J} . W . L . \sin\frac{\pi}{3} \qquad (5)$$

Between one commutation and the next the current load angle (σ) varies by $\pi/3$ as the rotor moves continuously relative to the current distribution which is moving by $\pi/3$ steps. Figure (5) shows the variation of current load angle σ and the thrust F_a. The system maintains an average load angle , σ_a . and just before a commutation $\sigma = \sigma_a - \pi/6$ and just after a commutation $\sigma = \sigma_a + \pi/6$ the output thrust F_a is pulsating and results in a mean level, F_a is given by:

$$F_a = \frac{3}{\pi} \int_{\sigma-\pi/6}^{\sigma+\pi/6} \hat{F}_o . \sin\sigma .d\sigma$$

$$= 0.955 . \hat{F}_o . \sin\sigma \qquad (6)$$

4. HIGH SPEED ANALYSIS :

The equivalent simplified circuit of Fig.(6) will be analysed with the assumption that the current source is sinusoidal. Since the frequency range of interest is in the capacitance dominated region the higher harmonics are not likely to contribute much torque even through the open circuit e.m.f. has a few harmonics since the harmonic currents will be bypassed by the capacitor. The mesh equation for Fig.(6) is :

$$j\omega L\ i_m + \frac{1}{j\omega C}(i_m - i_b) - e = 0 \tag{7}$$

therefore,

$$i_m = (i_b + j\omega C_e)/(1 - \omega^2 LC) \tag{8}$$

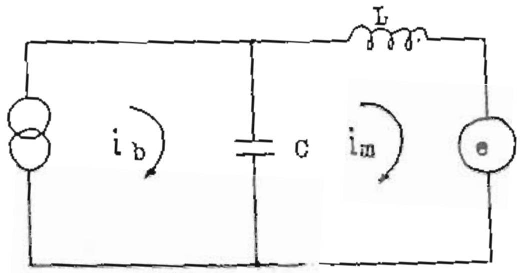

Fig.(6) : Equivalent commutation circuit

Letting :

$$i_b = I_b.(1 + j0) \tag{9}$$

$$e = E\ .(\sin\sigma + j.\cos\sigma) \tag{10}$$

Substituting by the instantaneous values of i_b and e in the equation of i_m , it is found that :

$$i_m = (I_b - \omega CE.\cos\sigma)/(1 - \omega^2.LC) + j.(\omega CE.\cos\sigma)/(1 - \omega^2.LC) \tag{11}$$

The output power P is calculated as :

$$P = Re\ (i_m \ . \ e^*) \qquad (12)$$

$$= Re\ [((I_b - \omega CE.\cos\sigma)/(1 - \omega^2.LC) + j.(\omega CE.\sin\sigma)/(1 - \omega^2.LC)) \ . \ E \ . (\sin\sigma - j.\cos\sigma)] \qquad (13)$$

$$= (E \ . \ I_b)/(1 - \omega^2.LC). \ \sin\sigma \qquad (14)$$

The circuit becomes valid at frequencies considerably higher than the resonant frqency , hence the denominator is always negative and invreases in magnitude with frequency. The values of σ required to produce positive power are therefore in the range π to 2π.

5. THEORITICAL RESULTS :

The following is a summary of the motor important operating properties of the reference designed motor at rated load :

Thrust	= 1 kN ,	Efficiency	= 80%
Voltage/phase	= 200 V ,	Frequency	= 50 Hz
Rated current	= 32 A ,	cos ϕ	= 1.0
Prephery speed	= 18 m/sec ,	Air-gap	= 20 mm
Stator length L	= 1220 mm ,	Pole pitch p	= 180 mm
Centre width W	= 100 mm ,	Coil pitch	= 120 mm
X_d	= 15.2 Ohm ,	X_q	= 13.8 Ohm

Type of armature winding = Double layer

A set of prediction is made for 30 A link current on the following data and the thrust characteristics against the speed is shown in Fig.(7).

(i) For low speed model

B = 0.074 Tesla

J = 39000 A/m

t_B = 6 ms

(ii) For high speed model

E = 73 V/phase

I = 22.1 A/phase

L = 0.05 H/phase

C = 350 μf/phase

The low speed predictions are made for three rotor angles settings. The high speed model is used for the rotor angle setting of 225°. This is the only one that produces a siginfic-

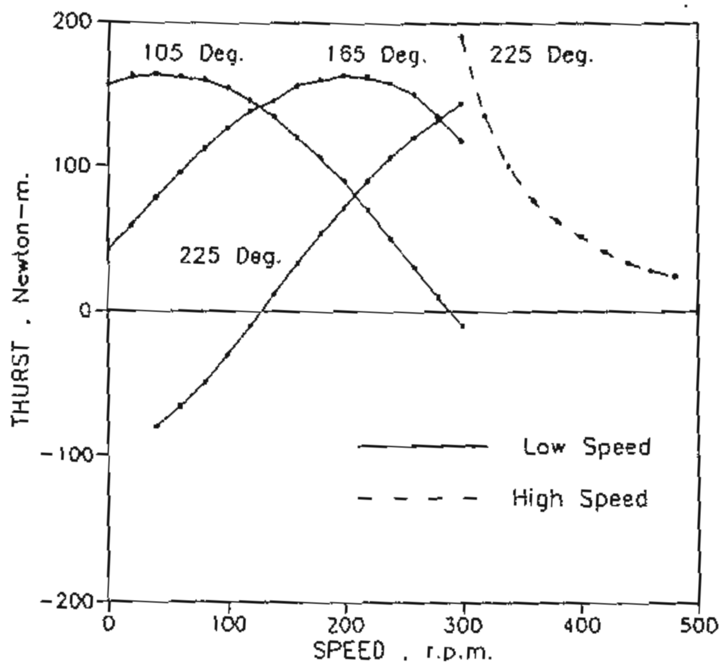

Fig. (7): Thrust Characteristics at 30 A Link Current.

ant amount of thrust beyond 300 r.p.m. (50 Hz). Below 350 r.p.m. the effect of resonant peak at 38 Hz is beginning to show.

6. CONCLUSION :

The two models of the system are derived and simulated on a digital computer to investigate its dynamical behaviour in some operating conditions. The equivalent circuit, which described the LSM during commutation at high speed model, exhibits resonant behaviour at a certain frequency and is not valied until the frequency is far in excess of the resonant frequency. The low speed model is used for three rotor angles settings while the high speed model is used for one rotor angle setting.

LIST OF SYMBOLS :

B := gap flux-density.
$\hat{B}$:= peak gap flux-density.
F := output thrust.
F_o := maximum static thrust.
F_a := average output thrust.
J := current loading.
$\hat{J}$:= peak current loading.
L := effective motor length.
p := pole pitch.
W := motor core width.
x := displacement of motor a long direction of motion.
α := rotor displacement angle.
σ := current load angle.
σ_a := average current load angle.

REFRENCES :

1. Slemon G.R. , Turton R.A. , et al ,"Analysis and Control of aLinear Synchronous Motor for High Speed Ground Transport" , Conference on Linear Electric Motor , Organised by Power Division of IEE , 21 - 23 October 1974 , pp. 143-148

2. Slemon G.R. , Dewan S.B. , et al , "Synchronous Motor Drive with Current Source Inverter" , IEEE Trans. , Vol. IA - 10 , No. 3 , May/June 1974.

3. Ong C.M. , Lipo T.A. , "Steady-state Analysis of Current Source Inverter Reluctance Motor Drive" , IEEE Trans. , PAS , Vol. 96 , No. 4 , July/August 1977

4. Faucher J. , Lajoie-Mazenc M., et al, "Experimental and Theoritical Investigation on an Autopiloted Current Fed 3-phase Vernier Reluctance Motor with Par- ticular Reference to the Commutation" , International Conference on Electrical Machine ICEM'78 , 11 - 13 September 1978 Brussels-Belgium.

5. Aimo B. , Buja G. , "Dynamic Analysis of Synchronous Motor Drive with Current Source Inverter" , ibid.