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Parameters Effects on Force in Tubular Linear Induction Motors with Blocked Rotor

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Abstract: This paper is concerned with the study of several parameters effects on longitudinal force applied on the rotor in the generator driven air-core tubular linear induction motors with blocked rotor. With developing the motor modeling by involving temperature equations in the previous computer code, we first study variations of the coils and rings temperatures and the effect of the temperature on the rotor force. In the next section, the effect of the rotor length on the rotor force is studied and it is shown that there is an almost linear relation between the rotor length and the rotor force. Finally we have given the optimum time step for solving the state equations of the motor and calculating the force. By this time step the code will have reasonable speed and accuracy. These studies can be useful for the force motors and for finding a view for dynamic state analysis of the acceleration motors.

Keywords: - Air Core Tubular Linear Induction Motor, Coilgun, Linear Induction Launcher

1 Introduction

Tubular Linear Induction Motors (TLIMs) may have unique applications as electromagnetic launchers with very high speed and acceleration abilities, and controllability [1]. As all motors, a TLIM consists of two main parts: stationary (stator) and moving (armature here) members. The motor supplying is by stator which consists of several coaxial coils. Number of the coils is determined with respect to number of phases, poles, and sections. Usually it is necessary to design the coils in such a way that they could be changeable individually [2].

When analyzing the motor by current filament method, the rotor which is usually a conductive and thin circular layer is divided to several current sections called as rings. We have assumed one layer and 42 or 84 rings for rotor in most of the simulations. Links of the stator coils and rings of the rotor are assumed as circular and parallel links with uniform current densities, called as current filaments. By this method, coils and rings self inductances as well as mutual inductances between coils and rings in any given respective position are calculated. Then by applying a circuit analysis, the currents of all coils and rings are calculated. Having the value of coils and rings currents and calculating the gradient of mutual inductance between coils and rings, we can calculate the force applied on the rotor [3].

In a former paper [3], we modeled the motor with blocked rotor but without temperature effect. Although as the motor starts and the currents flow in the coils and rings, the temperatures of the coils and rings rise up. In this paper, we have studied the effect of the temperature as well as the rotor length on the rotor force. Also we have got optimized time step for achieving calculations with sufficient fastness and accuracy.

2 Temperature and Resistance Equations

The value of coils and rings resistance matrix would change due to current flowing in the stator and the rotor, and heating of them. After calculating the initial value of the resistances, it is necessary to put resistance equation in the solving time loop of the state equations and to calculate momentarily the resistance matrix. A computer code was written regarding this matter.

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One can calculate the resistance value at temperature T_2 with respect to the resistance value at temperature T_1 as

$$R_{T_2} = R_{T_1}[1+\alpha_{T_1}(T_2-T_1)+\beta_{T_1}(T_2-T_1)^2] \quad (1)$$

where T_2 is calculated based on T_1 by

$$mC_v \frac{\partial T}{\partial t} - RI^2 = 0 \quad (2)$$

and m is the mass of the coil or ring, and

$$C_v(T) = C_4 \exp(C_5 T) \quad (3)$$

So we will have

$$T_2 = T_1 + \Delta t.\frac{RI^2}{mC_v} \quad (4)$$

The coefficients α_T, β_T, C_4, and C_5 for the copper and aluminum used in the code are given in table 1 [5]:

Table 1: Coefficients of α_T, β_T, C_4 and C_5 [5]

	Copper	*aluminum*
C_4	0.819	0.333
C_5	3.971×10^{-4}	3.917×10^{-4}
α_T	0.00393	0.00403
β_T	16.92×10^{-8}	23.00×10^{-8}

Some data used in the computer code are given in the table 2.

Table 2: some data used in the computer code

Initial temperature of coils and rings (environment temperature), $T_\circ$	25°C
Copper volume mass, ρ_{cu}	8900 kg/m^3
aluminum volume mass, ρ_{al}	2700 kg/m^3

Mass of a coil or a ring is given as

$$m = \rho v = \rho l s \quad (5)$$

where *v*, *l*, and s are respectively the volume, the length, and the cross section area of the coil or the ring. A coil length equals the links average length multiplied with the links number, and the rings length equals the sleeve average perimeter. The cross section area of a coil used in the above equation is the cross section area of the wire used in the coil.

3 Solution Algorithm

3.1 Initial Conditions

At the beginning of the analysis,
- Currents of coils and rings are zero.
- Voltages of rings are zero.
- Temperatures of coils and rings are all 298 °K, equal to 25 °C.

3.2 Algorithm

- The input three phase voltages are calculated and the voltage vector of the three phase and the rings is constituted.
- The resistance vector of the phases and rings is calculated at the initial conditions or at the previous step.
- The current vector of the phases and rings is calculated by Runge- Kutta method.
- The C_v vector of the coils and rings is calculated. Of course C_v of series coils, i.e. coils 1, 4, coils 2, 5, and coils 3, 6 are the same because their currents are the same. But the other elements of the vector are different from each other, and all are calculated in each step by (3).
- Temperature rising vector of the coils and rings is calculated as

$$\Delta T = \Delta t.\frac{RI^2}{mC_v} \quad (6)$$

  Here also the temperature rise of series coils are the same.
- Temperature vector of the coils and rings is calculated. Temperature rising vector of the coils and rings is calculated as

$$\overset{j+1}{T} = \overset{j}{T} + \Delta \overset{j}{T} \quad (7)$$

  where $\overset{j}{T}$ denotes to the temperature vector at j_{th} time step, and $\overset{j+1}{T}$ denotes the temperature vector at $j+1_{th}$ time step.
- The resistance vector of the coils and rings is given as

$$\overset{j+1}{R} = \overset{j}{R}(1+\alpha\Delta\overset{j}{T}+\beta(\Delta\overset{j}{T})^2) \quad (8)$$

where α is a vector consisting of two sub vector of α_{cu} and α_{al}. The elements of sub vector of α_{cu} as well as α_{al} are equal and constant. Also β is a vector

Table 3: Simulated Motor Characteristics[3]

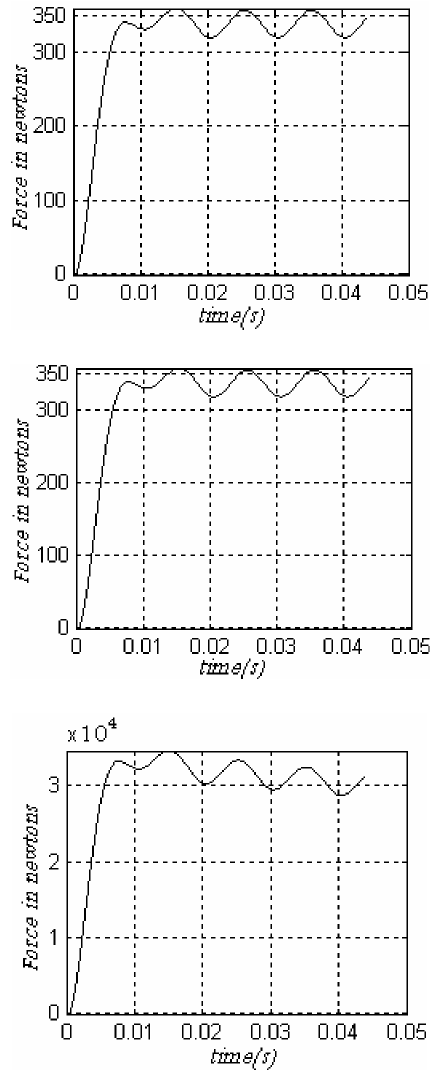
Stator(coils)	
Outer radius of coils	45.5 mm
Radial thickness of coils	14.9 mm
longitudinal length of coils	71.1 mm
Layer number of coils	8
Links number in each layer	40
Clearance between coils	3.9 mm
Copper wire diameter	1.7 mm
Coating thickness of wire	0.05 mm
Number of coils	6
Rotor(rings)	
outer radius	29.5 mm
Radial thickness	2 mm
Material	Aluminum
Length	45 cm
supply	
voltage	220 V
frequency	50 Hz

consisting of two sub vector of β_{cu} and β_{al} with equal and constant elements.

- The current vector of coils and the current vector of rings are derived from the current vector of the phases and rings.
- Instantaneous force applied on the rotor is given by

$$f = I_d^{'} .dM.I_p \qquad (9)$$

where I_d is the coils current vector, I_p is the rings current vector, and dM is the mutual inductance gradient matrix of the coils and rings with dimension of $(N_d + N_p) \times (N_d + N_p)$. dM in this code is a constant and time invariable value, but if rotor moves, dM also must be laid in time link of solution and would be calculated in each iteration.



(a)

(b)

(c)

Fig. 1: Heat Effect on the Force, a) simulation with 220 V and without heat effect, b) heat effect with 220 V, c) heat effect with 2200V

4 Results

4.1 Heat Effect on the Force

Considering heat effect, a computer code was written and run for calculating the instantaneous force applied on the rotor of the motor with table 3 characteristics without a distance between the beginning of the stator and rotor which result is represented in Fig. 1.b. Beside, result of the previous code without heat effect is given for comparison in Fig 1.a. As it is seen, it is not a significant difference between the instantaneous forces of two codes. It is because the resistances of coils are high, so the currents flowed in them and the currents induced in the rotor are light, so the temperatures and resistances rising are very light. In this case, currents values do not decrease seriously with time and the force remains constant.

Final temperature variations of the coils and rings at degrees centigrade with the supply voltage of 220 V, 50 Hz in nearly two cycles of the supply (0.044 s) are given in table 4.

We notice that:

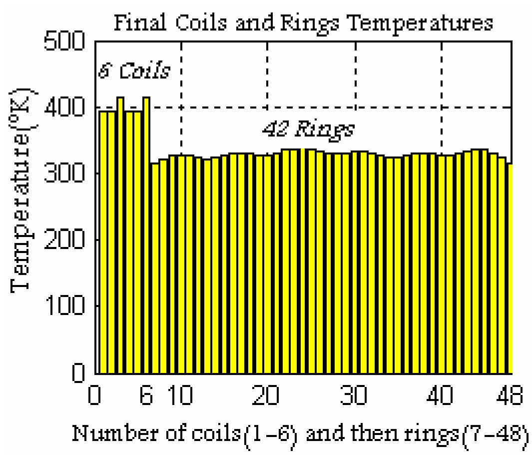


Fig. 3: final temperatures of the coils and rings

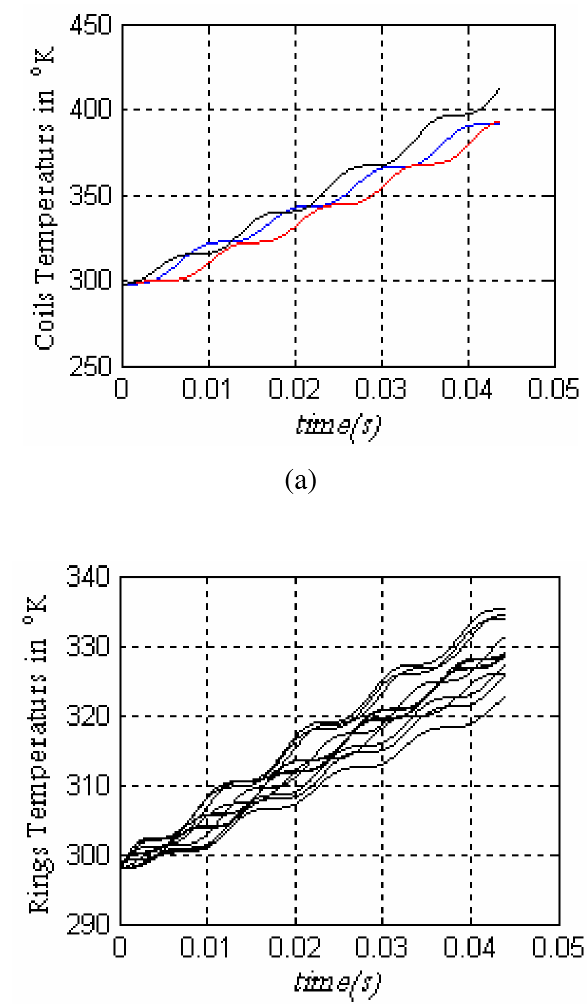
First, the temperatures rising are very light, so in this time duration of 0.44 s - which would be equal to the rotor exiting time entirely from the stator if the rotor is free - we can apply a voltage with higher peak.

Second, the temperatures rising in the coils are higher than in the rings that are because of great number of coils links leading to high coils resistances. In Industrial high speed tubular linear induction motors, they choose few links for coils, so the rings appoint the temperature limit for the motor application.

For study of the temperature effect, the supply voltage was increased sententiously to 2200 V while other conditions were unchanged. The results are shown in Fig. 1.c. The average force in the first cycle is 33.2 kN. The force is oscillating and its mean value is decreasing with time. In time duration of 0.04 s, mean value of the force decreases to nearly 31 kN, i.e. decreases nearly 7 percent.

The mean value of the force in steady state with supply voltage of 220 V is 335 N while by decoupling the voltage, i.e. 2200 V, this force increases to 31 kN. So we can deduce that the force is nearly proportional to the square of supply voltage.

Final temperature variations of the coils and rings at degrees centigrade with the supply voltage of 2200 V in nearly two cycle of the supply (0.044 s) are given in table 4. Although the coils temperatures have almost passed the allowable limit but rings temperatures have a high distance to the allowable limit which is melting temperature. Curves of the coils and rings instantaneous temperature variations are given in the Fig. 2a and b. The number of rings for deriving the Fig. 2b is assumed only 12 for clarity of the figure. Bar illustration of the final temperatures of the coils and rings are given in the Fig. 3. Curves of stator's three phase currents with respect to time are shown in the Fig. 4.



(a)

(b)

Fig. 2: coils and rings instantaneous temperature variations, a) Coils, b) Rings

Table 4: temperature variation of coils and rings

	number	Temperature rising(°C)	
		220 V	2200 V
coils	1	0.80	99
	2	0.80	100
	3	0.95	120
	4	0.80	99
	5	0.80	100
	6	0.95	120
Rings	1	0.26	29
	2	0.29	32
	3	0.33	35
	4	0.32	35
	5	0.40	42
	6	0.39	41
	7	0.35	38
	8	0.31	34
	9	0.32	35
	10	0.33	35
	11	0.38	40
	12	0.30	33

The Fig. 5 represents the results of a written code running for rotors from very small lengths of 1 cm to lengths corresponding to a rotor length of 67.5 cm equal to 1.5 stator length. It is seen that the force increases as the rings number as well as the rotor length increases, but this linear force increasing is only to the ring number of 37 (corresponding to 88 percent of the stator length) and then goes to Satiated zone to rings number of 42 (corresponding to the whole stator length). One can almost connive the force applied on the rings out of the stator. Noting the given curve, it is known that decreasing rings number of 7 (corresponding to one coil length) does not linearly decreases the force to zero. So the code was run for the less lengths of the rotor (Table 5) and the whole curve of force-rotor length is represented in the Fig. 5. We have indicated less length rotors with more respective rings number to increase the calculations accuracy.

Table 5: Force applied on the rotor with very small lengths

Rings number	*Rotor length(cm)*	*Mean force(N)*
4	1.07	-0.39
4	2.14	-0.23
4	4.28	3.85
5	5.35	9.25
6	6.42	18.76

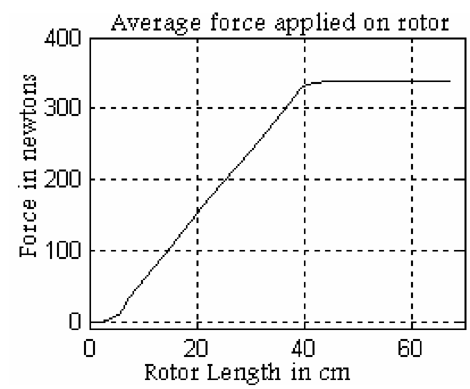


Fig. 5: final temperatures of the coils and rings

Beside, the values of the force applied on the rotor with very small rotor lengths are given negative (Table 5). For rotor lengths less than half a coil length, we can deduce that when the rotor enters the stator, a braking force applies on the rotor.

4.3 Optimum Time Step

The big the calculations time step, the further calculations error, and the less time step, the further calculations time. So it is necessary to find an optimized time step with certified both accuracy and speed of calculations. The written code was run for ring number of 42 and different time steps, and the steady state mean value forces applied on the rotor were calculated (Table 6).

As it is observed from the table 6:

- A time step of 400 µs and further leads to infinite solutions (instability). 400 µs equals to 0.02 cycle with supply frequency of 50 Hz, i.e. 50 sample in each cycle.
- A time step of 300 µs and less leads to the solution of the code.
- A time step of 10 µs requires only a run time 1.5 time the time step of 300 µs while with an error less than 0.1 percent is 15 time more accurate than it. Time steps less than 10 µs require a further and further run times. So one can choose the time step of 10 µs as the optimum time step.

5 Conclusions

We have studied some parameters effects on force of a generator driven air-core tubular linear induction motor with blocked rotor.

Supply voltage of 220 V for this motor dose not lead to considerable temperature increasing in the stator and rotor, so in such level of voltages and currents we can ignore heat effect. Also temperature increasing in the stator is higher than the rotor while the rotor abound the temperature in the fast tubular linear induction motors.

Appling supply voltage of 2200 V to the motor, temperature increasing in the stator and rotor gets considerable amounts, and first stator passes temperature limits.

Heat effect in high level of voltages causes average force applied on the rotor decreases gradually by time.

Supply voltage level has a quadratic effect on the rotor force.

Table 6: run time and mean force for different time steps

Time step(µs)	*Run time(s)*	*Mean force(N)*	*Relative error percent of force*
>300	instability	-	-
300	75	343	1.57
100	75	340.56	0.85
50	76	339.2	0.44
10	113	338	0.09
5	208	337.88	0.05
1	3957	337.7	base

The rotor length of 0.1 to 0.9 stator length has a linear relation to the mean force if rotor is entirely inside the stator. Sections of the rotor facing with the ends of the stator do not affect considerably the force. Beside, a negative force is applied on the section of the rotor faced to the initial end of the stator.

Increasing solution time step decreases the run time, but decreases calculations accuracy as well. Beside, increasing time step than a given value leads to the solution instability. A time step of 1×10^{-5} s was given as optimum time step with a balanced solution accuracy and speed.

One can study the effect of the stator and rotor constructive parameters and the supply parameters on the force applied on the rotor at stationary state of the motor. These studies can be useful for the force motors as well as finding a view for dynamic state analysis of the acceleration motors.

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