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# Small Linear Induction Motor

Design and Construction

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<p>The study was carried out to design a 3-phase Small Linear Induction Motor that can travel at the speed of 1 meter per second when supplied 9 Volts.</p> <p>In order to complete the goal of the study, first, physical dimensions and electrical properties were calculated by using MathCAD software and through mathematical equations, providing initial or required motor specifications. The obtained physical dimensions were then used to draw motor drawings using AutoCAD program, which was also used to laser cut the MS sheets according to drawings. All MS sheets were welded together and Primary part of motor was then winded whereas, Secondary part was filled by Aluminium. Bearings were fixed to the Primary part to withstand normal forces and maintain gap in between Primary and Secondary.</p> <p>The goal of study was successfully achieved as the motor was designed and build. As this was a lengthy process, unfortunately, there was not enough time to test the motor.</p>	
Keywords	Linear Induction Motor, Design, Build, LIM.

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## List of Abbreviations

Abbreviation	Meaning	Page
LEM	Linear Electromagnetic Machines	2
LOM	Linear Oscilatory Machines	2
LIM	Linear Induction Motor	5
DLIM	Double side Linear Induction Motor	6
SLIM	Single side Linear Induction Motor	6

## **1 Introduction**

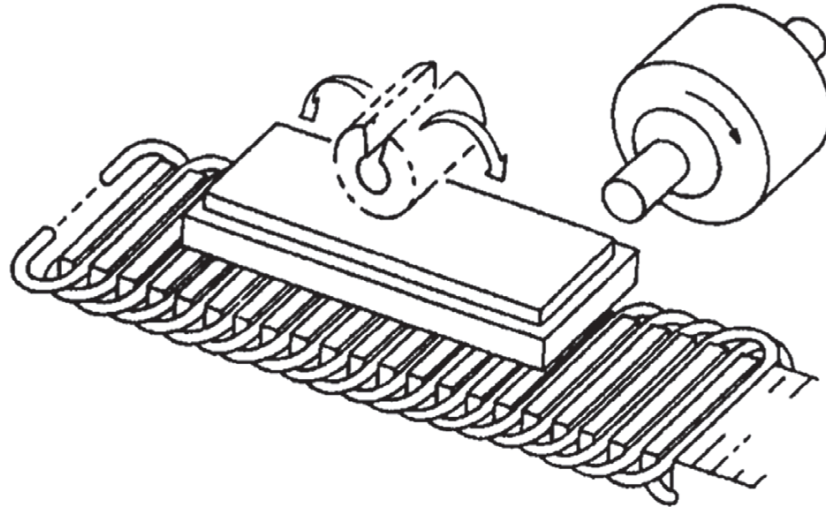
Every mechanism that is used to slide objects, e.g. automatic doors, is powered by conventional rotating motor and sway by chains, strings or belts. There are linear motors already in use in many automotive structures, but these are very expensive and heavy.

The purpose of this study is to replace the old conventional system by building a prototype of a small linear motor that can replace rotating motor and make the sliding mechanism more efficient and less expensive.

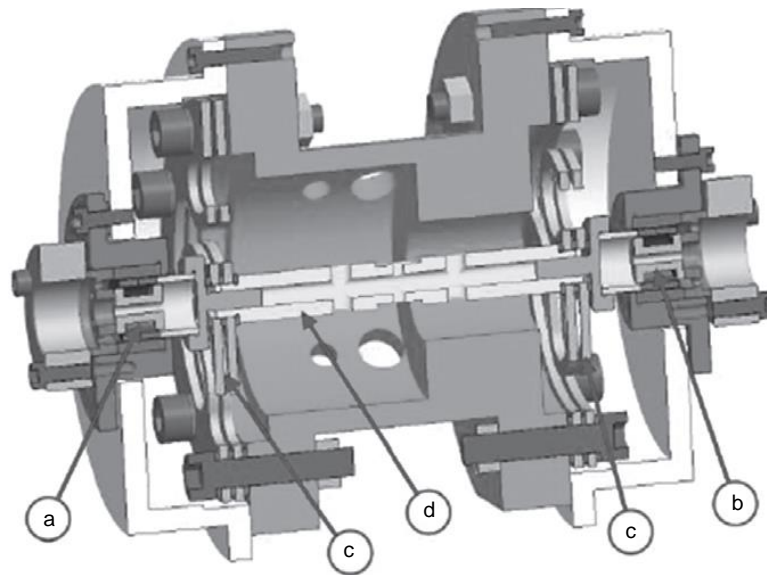
KONE Oy is a pioneer in manufacture, maintenance, and modernization of elevators, escalators, moving walkways and building doors. [1]. KONE Oy is providing full support to achieve the goal of this study and hence all the material concerning this study is property of KONE Oy.

## 2 Theoretical Background

Linear electromagnetic machines (LEMs) develop electromagnetic forces based on Faraday's and Ampere's laws and produce directly linear motion. Linear motion may be either progressive (Figure 1) or oscillatory (Figure 2) [2].



**Figure 1:** Linear electric machines with progressive motion (LEMs) (Copied from I. Boldea, Linear Electric Machines, Drives, and MAGLEVs Handbook, CRC Press, Boca Raton, London, New York, 2013.)



**Figure 2:** Linear electric machines with oscillatory resonant motion (LOMs): motor plus generator (a. linear motor, b. linear generator, c. resonant springs (features), d. coupling shaft). (Copied from I. Boldea, Linear Electric Machines, Drives, and MAGLEVs Handbook, CRC Press, Boca Raton, London, New York, 2013.)

Linear progressive motion, even when experiencing back and forth, but non-periodic, operation modes, leads to LEMs whose topology differ (in general) from that of linear oscillatory machines (LOMs). The linear oscillatory motion takes place in general at resonance—when mechanical Eigen frequency equals the electrical frequency—to secure high efficiency in the presence of a strong spring like force (mechanical or even magnetic) [2].

In general, the progressive motion LEMs are three-phase ac devices that operate in brushless configurations, while LOMs are typically single-phase ac devices. The progressive motion LEMs operate at variable voltage and frequency to vary speed at high efficiency for wide speed control ranges. On the contrary, LOMs operate in general at resonant (fixed) frequency and variable voltage [2].

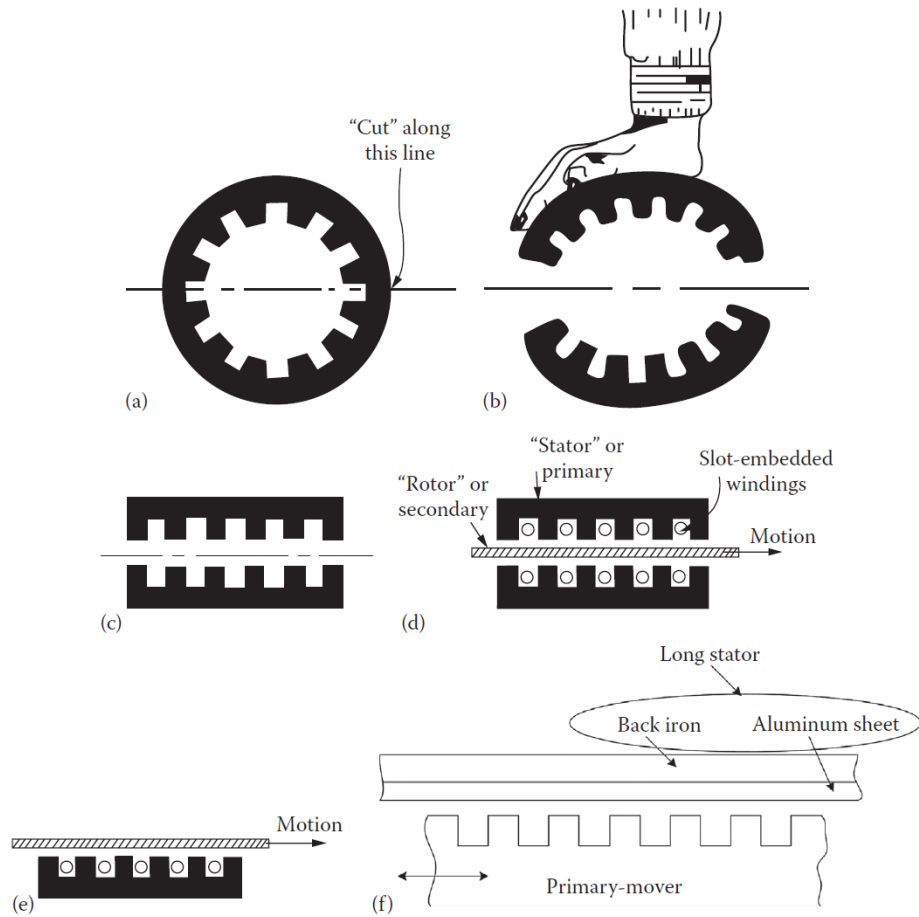
Linear progressive motion machines may be classified by principle into,

- Linear induction machines (with sinusoidal current control)
- Linear synchronous (brushless ac) machines (with sinusoidal current control)
- Linear brushless dc machines (with trapezoidal (block) current control)
- Linear dc brush machines

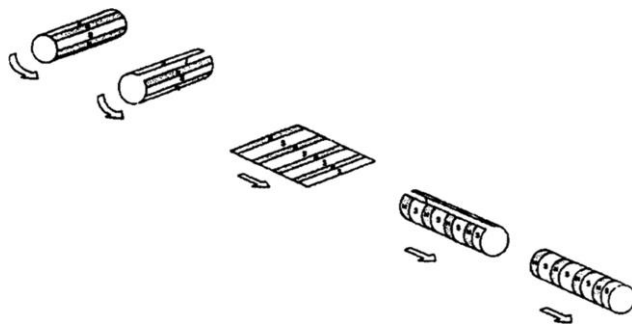
## 2.1 Linear Induction Machines

Linear induction machines resemble the principle and the topologies of rotary induction machines by the “cutting” and unrolling principle to obtain flat linear induction machines (Figure 3) [2].

When the flat Linear induction machine is rerolled around the motion axis, the tubular linear induction machine is obtained (Figure 4). Three-phase ac windings are placed in the slots of the primary. They are obtained by the same “cut” and “unrolling” routine from those of rotary induction machines [2].



**Figure 3:** Double- and single-sided LIMs: (a) round primary, (b) unrolling of primary (after cutting), (c) flat double-sided LIM primary with slots, (d) double-sided LIM primary plus Aluminum (copper) sheet secondary, (e) single-sided LIM (primary) plus Al (copper) sheet, and (f) with back iron in the secondary. (Copied from I. Boldea, *Linear Electric Machines, Drives, and MAGLEVs Handbook*, CRC Press, Boca Raton, London, New York, 2013.)

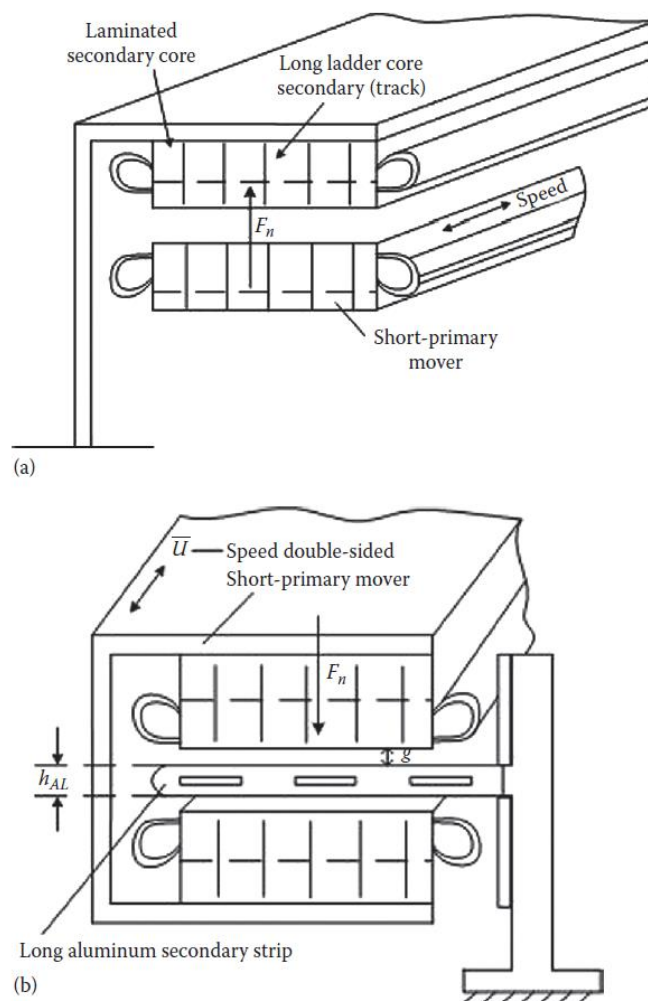


**Figure 4:** Flat and tubular Linear Induction Machines. (Copied from I. Boldea, *Linear Electric Machines, Drives, and MAGLEVs Handbook*, CRC Press, Boca Raton, London, New York, 2013.)



## 2.2 Linear Induction Motor

Linear induction motors, LIMs, are counterparts of rotary induction motors. They may be obtained by “cutting” and unrolling the rotary induction machines to yield flat, single-sided topologies (Figure 5a), where the cage secondary may be used as such or replaced by an aluminium sheet placed between two primaries to make the double-sided LIM (Figure 5b). The passive long secondary (track) is fixed for short-primary-mover configurations (Figure 5) and secures a reasonable low cost track/km, together with the static power converters and their control [2].



**Figure 5.** LIM flat topologies with short-primary mover: (a) single-sided with cage-core secondary (track), (b) double-sided with aluminum-strip secondary (track), and (c) single-sided with aluminum sheet on iron secondary. (Copied from I. Boldea, Linear Electric Machines, Drives, and MAGLEVs Handbook, CRC Press, Boca Raton, London, New York, 2013.)

There are a few basic topologies for low-speed LIMs [2]:

- Flat DLIMs with Al sheet secondary
- Flat SLIMs with Al-on-iron secondary
- Flat SLIMs with ladder secondary
- Tubular SLIMs with cage secondary.

### 2.3 Design Equations for Flat SLIM with Ladder Secondary

Presented here, are the design equations for Flat SLIM with Ladder Secondary which are used to calculate electrical characteristics, e.g. resistance, inductance, permeance and the like. And mechanical dimension e.g. length, pitch, area, and so on. The way these equations are derived is beyond the scope of this study. All the following equations are reproduced from books by Bolda [2; 3] and symbol meanings are presented in Appendix 1.

Primary Resistance per Phase,

$$R_1 = \frac{2\rho_{Copper} \cdot (l_{Stack} + l_{ec}) \cdot j_{cor} \cdot w_1^2}{w_1 \cdot I_{1r}} \quad (1)$$

Primary Leakage Inductance,

$$L_{1l} = \frac{2\mu_0}{p \cdot q_1} \cdot [(\lambda_{s1} + \lambda_{diff1}) \cdot l_{stack} + (\lambda_{ec1} \cdot l_{ec})] \cdot w_1 \quad (2)$$

Primary Slot Specific Permeance (NonDimensional),

$$\lambda_{s1} = h_{s1} \cdot \frac{(1+3\beta)}{12 \cdot b_{s1}} + \frac{h_{sp}}{b_{sp}} \quad (3)$$

Secondary Slot Specific Permeance (NonDimensional),

$$\lambda_{s2} = h_{s2} \cdot \frac{(1+3\beta)}{12 \cdot b_{s2}} + \frac{h_{ss}}{b_{ss}} \quad (4)$$

Primary Airgap Leakage Specific Permeance,

$$\lambda_{diff1} = \frac{5 \cdot K_c \cdot \frac{g}{b_{sp}}}{5 + 4 \left( K_c \cdot \frac{g}{b_{sp}} \right)} \quad (5)$$

Secondary Airgap Leakage Specific Permeance,

$$\lambda_{diff2} = \frac{5 \cdot K_c \cdot \frac{g}{b_{ss}}}{5 + 4 \left( K_c \cdot \frac{g}{b_{ss}} \right)} \quad (6)$$

Primary End-Coil Leakage Specific Permeance,

$$\lambda_{ec1} = 0.3[(3 \cdot \beta) - 1] \cdot q_1 \quad (7)$$

The Magnetization Inductance,

$$L_m = h_{s2} \cdot \frac{6 \cdot \mu_0 \cdot (K_{w1} \cdot w_1) \cdot \tau \cdot l_{stack}}{\pi^2 \cdot K_c \cdot g \cdot [p \cdot (1 + K_{ss})]} \quad (8)$$

Secondary Resistance (Referred To Primary),

$$R_2' = 12\rho_{Aluminum} \cdot \frac{(K_{w1} \cdot w_1)}{N_{s2}} \cdot \left( \frac{l_{stack}}{A_{s2}} + \frac{2 \cdot l_{lad}}{A_{lad}} \right) \quad (9)$$

Secondary Leakage Inductance,

$$L_{2l}' \approx 24 \cdot \mu_0 \cdot [l_{stack} \cdot (\lambda_{s2} + \lambda_{diff2})] \cdot \frac{(K_{w1} \cdot w_1)^2}{N_{s2}} \cdot (1 + K_{ladder}) \quad (10)$$

Area Of Ladder,

$$A_{lad} = \frac{A_{s2}}{2 \sin\left(\frac{\alpha_{es}}{2}\right)} \quad (11)$$

Electric Phase Angle,

$$\alpha_{ec} \approx \frac{2 \cdot \pi \cdot p}{N_{s2}} \quad (12)$$

Width of Ladder (Distance between steps in ladder),

$$l_{lad} \approx \frac{2 \cdot p \cdot \tau}{N_{s2}} \quad (13)$$

Secondary Slot Area,

$$A_{s2} = h_{s2} \cdot b_{s2} \quad (14)$$

Air gap Flux Density,

$$B_{g1} = \mu_0 \cdot K_e = \frac{\mu_0 \cdot j_{1m}}{\frac{\pi}{\tau} \cdot g \cdot K_c \cdot (1 + K_s) \sqrt{1 + (s^2 \cdot G e^2)}} = \frac{\mu_0 \cdot \theta_{1m}}{g \cdot K_c \cdot (1 + K_s) \sqrt{1 + (s^2 \cdot G e^2)}} \quad (15)$$

Primary mmf/pole,

$$\theta_{1m} = \frac{3 \cdot \sqrt{2} \cdot (K_{w1} \omega_1)^2 \cdot I_1}{\pi \cdot p} \quad (16)$$

Effective Goodness factor of Iron,

$$G_{ei} = \frac{\omega_1 \cdot L_m}{R_2' \cdot K_{l2}} \approx \frac{\mu_0 \cdot \omega_1 \cdot \tau^2 \cdot \sigma_{Al} \cdot h_{s2} \cdot \left(1 - \frac{b_{s2}}{\tau_{s2}}\right)}{\pi^2 \cdot g \cdot K_c \cdot (1 + K_s) \cdot K_r \cdot K_{l2}} \quad (17)$$

Carter coefficient for Rotor (Secondary),

$$K_r = 1 + \frac{L_{lad}}{A_{lad}} \cdot \frac{A_{s2}}{l_{stack}} \quad (18)$$

$$K_{l2} = \sqrt{1 + \left(\frac{\omega_2 \cdot L_{2l}'}{R_2'}\right)^2} \quad (19)$$

Magnetic Flux Density,

$$B_{gk} = \frac{\mu_0 \cdot \theta_{1m}}{g \cdot K_c \cdot (1 + K_s) \cdot \sqrt{1 + 1^2}} \quad (20)$$

Primary Winding Factor,

$$K_{w1} = \frac{\sin\left(\frac{\pi}{6}\right)}{q \cdot \sin\left(\frac{\pi}{6 \cdot q}\right)} \cdot \sin\left(\frac{\pi}{2} \cdot \frac{y}{\tau}\right) \quad (21)$$

Current per Turn per Phase, Peak Amperturn per Phase,

$$w_1 I_1 = \frac{\theta_{1m} \cdot \pi \cdot p}{3 \cdot \sqrt{2} \cdot K_{w1}} \quad (22)$$

Primary Active Area,

$$A_p = 2 \cdot p \cdot \tau \cdot l_{stack} = 2 \cdot p \cdot \tau^2 \left( \frac{l_{stack}}{\tau} \right) = \frac{F_{xn}}{f_{xn}} \quad (23)$$

Primary Slot Pitch,

$$\tau_s = \frac{\tau}{6} \quad (24)$$

Angular Frequency,

$$\omega_1 = \omega_{2r} = 2 \cdot \pi \cdot f_{2r} \quad (25)$$

Secondary Slot Useful Height,

$$h_{s2} = \frac{G_{ei} \cdot \pi^2 \cdot g \cdot K_c \cdot (1 + K_s) \cdot K_r \cdot K_{l2}}{\mu_0 \cdot \omega_1 \cdot \tau^2 \cdot \sigma_{Al} \cdot \left(1 - \frac{b_{s2}}{\tau_{s2}}\right)} \quad (26)$$

Primary Length,

$$l_{primary} = [(2 \cdot p) + 1] \cdot \tau \quad (27)$$

Active Primary Slot Area,

$$A_{ps} = \frac{(w_1 I_1)}{p \cdot q \cdot j_{cor} \cdot K_{fill}} \quad (28)$$

Active Primary Slot Height,

$$h_{s1} = \frac{A_{ps}}{b_{s1}} \quad (29)$$

Peak Normal Force,

$$F_{nk} \approx \frac{(B_{gik})^2}{2 \cdot \mu_0} \cdot 2 \cdot p \cdot \tau \cdot l_{stack} \quad (30)$$

Forward Force,

$$F_x \approx \frac{3 \cdot I_1^2 \cdot R_2' \cdot sG_e}{2 \cdot \tau \cdot f_1 [1 + (sG_e)^{-2}]} \quad (31)$$

Rated Thrust:

$$F_{xm} = \frac{3 \cdot \pi}{2 \cdot \tau} \cdot (w_1 \cdot I_1)^2 \cdot \frac{L_m}{K_{l2}} \quad (32)$$

Primary Required Frequency,

$$f_{1r} = f_2 + \frac{u_r}{2 \cdot \tau} \quad (33)$$

Available Voltage (RMS) per phase,

$$V_{10} = 0.95 \cdot \frac{V_{line}}{\sqrt{3}} \quad (34)$$

Primary Slot Opening,

$$b_{sp} = \frac{b_{s1}}{g} \quad (35)$$

Secondary slot opening,

$$b_{ss} = 2 \cdot g \quad (36)$$

Secondary Slot Pitch,

$$\tau_{s2} = \tau_{s1} \cdot \lambda_{ec1} \quad (37)$$



Relative Slip,

$$S = \frac{f_2}{f_1}$$

(38)

Primary Voltage,

$$V_{1r} = I_{1r} \cdot \left[ R_1 + j \cdot \omega_{1r} \cdot L_{1l} + \frac{j \cdot \omega_1 \cdot L_m \left( \frac{R_2'}{s} + j \cdot \omega_1 \cdot L_{2l}' \right)}{\frac{R_2'}{s} + [j \cdot \omega_1 \cdot (L_m + L_{2l}')] } \right]$$

(39)

Current for Rated Thrust,

$$I_{1n} = \frac{(w_1 I_1)}{w_1}$$

(40)

Input Power,

$$P_{1n} = 3 \cdot V_{1n} \cdot I_{1n} \cdot \cos(\phi_{1n})$$

(41)

Power Factor,

$$PF = \cos(\phi_{1n})$$

(42)

where,

$$\phi_{1n} = \arg(Z_e)$$

(43)

End effect Impedance, (See Figure 6)

$$Z_e = R_1 + j \cdot \omega_{1r} \cdot L_{1l} + \frac{j \cdot \omega_1 \cdot L_m \left( \frac{R_2'}{s} + j \cdot \omega_1 \cdot L_{2l}' \right)}{\frac{R_2'}{s} + [j \cdot \omega_1 \cdot (L_m + L_{2l}')]}$$
(44)

Electromagnetic Power,

$$P_{elm} = 3 \cdot I_{ln}^2 \cdot R_2' \cdot \left( \frac{1-S}{S} \right)$$
(45)

Synchronous Speed,

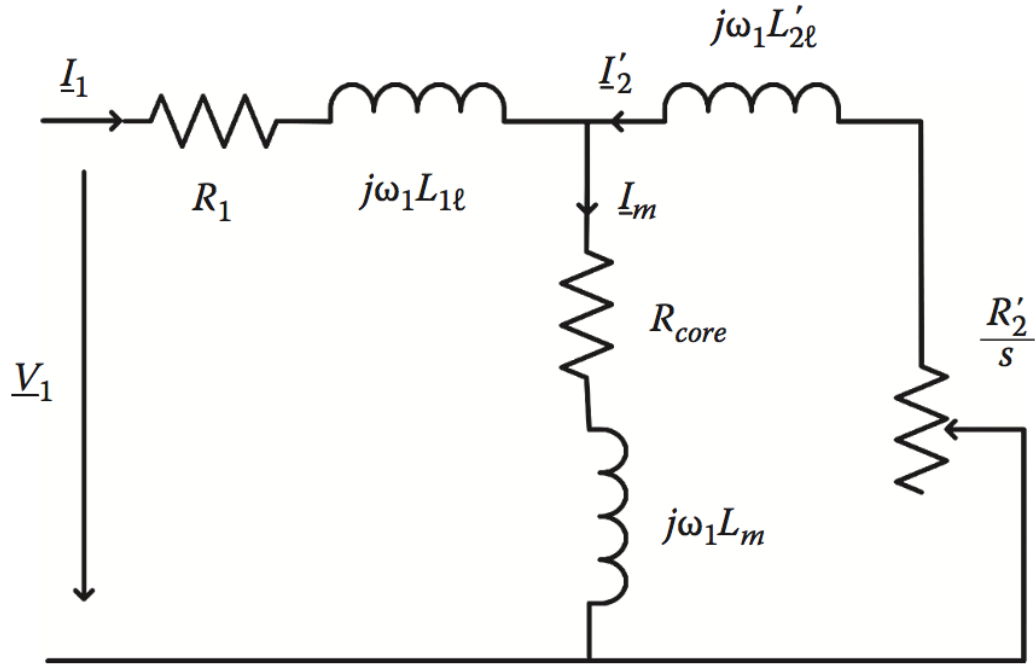
$$u_s = 2 \cdot \tau \cdot f_1$$
(46)

Motor Thrust,

$$F_x = \frac{P_{elm}}{u_s}$$
(47)

Efficiency,

$$\eta_n = \frac{F_x \cdot u_r}{P_{ln}}$$
(48)



**Figure 6:** Electrical equivalent circuit for motor. (Modified from I. Boldea, Linear Electric Machines, Drives, and MAGLEVs Handbook, CRC Press, Boca Raton, London, New York, 2013.)

There were some more equation that are used for this study and can be find in Appendix 3.

### 3 Methods and Materials

#### 3.1 Introduction to MathCAD

Mathcad is computer software primarily intended for the verification, validation, documentation and re-use of engineering calculations [4].

Mathcad is oriented around a worksheet, in which equations and expressions are created and manipulated in the same graphical format in which they are presented (WYSIWYG) - as opposed to authoring in plain text, an approach later adopted by other systems such as Mathematica and Maple [4].

### 3.2 Required Specification

The initial specifications that the motor should possess are stated in the Table 1.

Table 1: Initial parameters

Parameter	Symbol	Value	Unit
Voltage	$V_{line}$	9	V
Rated Thrust	$F_{xn}$	10	N
No. of phases	$m_0$	3	
Rated Speed	$u_n$	1	m / s
Travel length	$l_{travel}$	1	m

### 3.3 Motor Dimensions

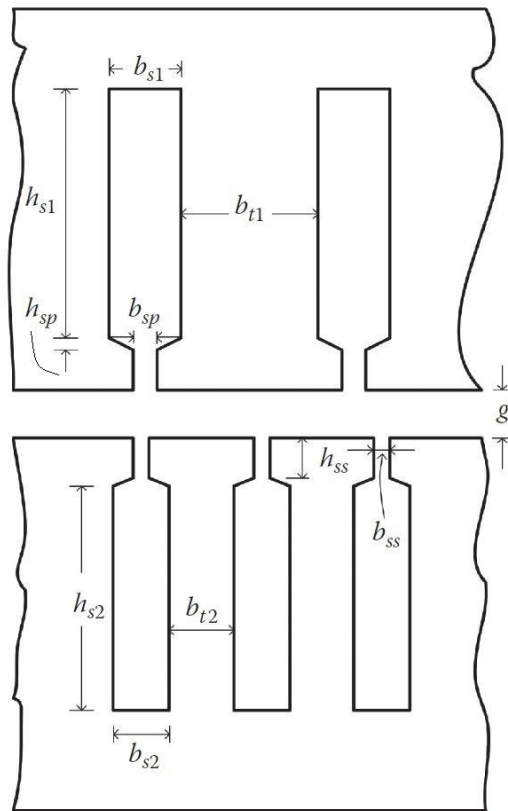
With initial parameters (Table 1), design equations (Section 2.3) and Mathcad software, the dimensions are calculated for both primary and secondary part and presented in Table 2. Appendix 3 contains all the the necessary calculation made by the help of MathCAD software in order to obtain motor's parameters.

Parameter	Symbol	Value	Unit
Primary slot height	$h_{s1}$	0.2	mm
Primary tooth height	$h_{sp}$	1	mm
Primary slot width	$b_{s1}$	2.523	mm
Primary slot opening	$b_{sp}$	1	mm
Primary tooth width	$b_{t1}$	2.064	mm
Airgap	$g$	0.2	mm
Secondary slot height	$h_{s2}$	18	mm

Secondary slot width	$b_{s2}$	2.271	mm
Secondary slot opening	$b_{ss}$	1	mm
Secondary tooth height	$h_{ss}$	1	mm
Secondary tooth width	$b_{t2}$	1.858	mm
Primary length	$l_{primary}$	16.5	cm
Stack width	$l_{Stack}$	6.881	mm

To obtain a better view, Slot geometry of both Primary and Secondary block is shown in Figure 7 along with parameter symbols.

Table 2: Motor Dimensions.



**Figure 7:** Slot geometries. (Modified from I. Boldea, Linear Electric Machines, Drives, and MAGLEVs Handbook, CRC Press, Boca Raton, London, New York, 2013.)

### 3.4 Introduction to AutoCAD

AutoCAD is a commercial computer-aided design (CAD) and drafting software application. Developed and marketed by Autodesk [5].

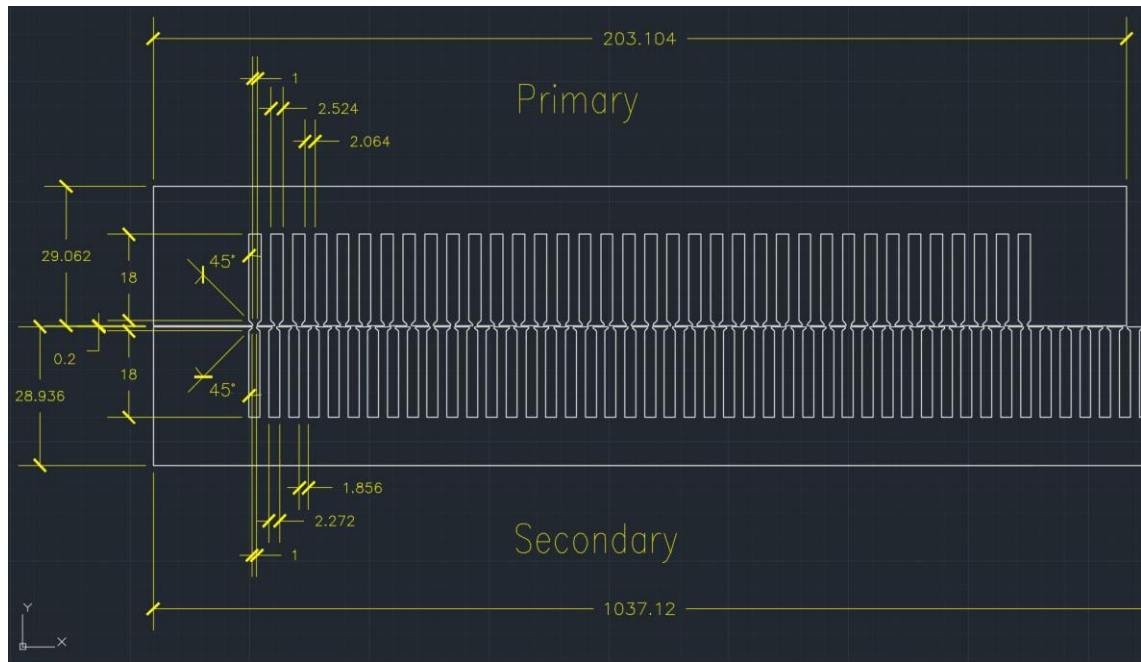
Computer-aided design (CAD) is the use of computer systems to aid in the creation, modification, analysis, or optimization of a design [6].

CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing. CAD output is often in the form of electronic files for print, machining, or other manufacturing operations [6].

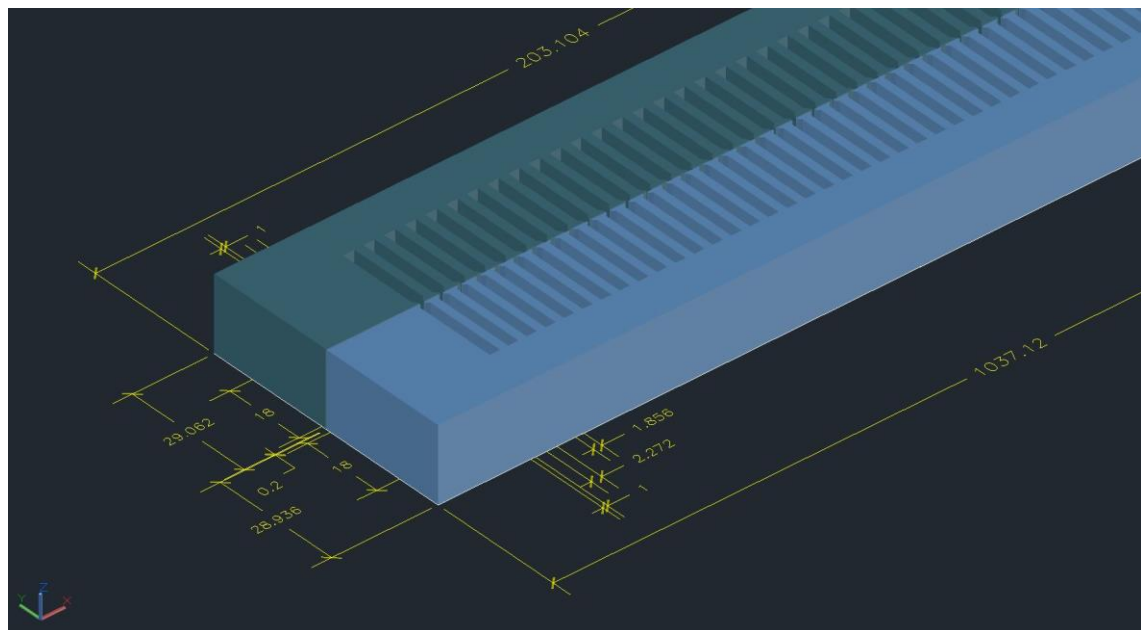
CAD is an important industrial art extensively used in many applications, including automotive, shipbuilding, and aerospace industries, industrial and architectural design, prosthetics, and many more [6].

### 3.5 Motor Drawings

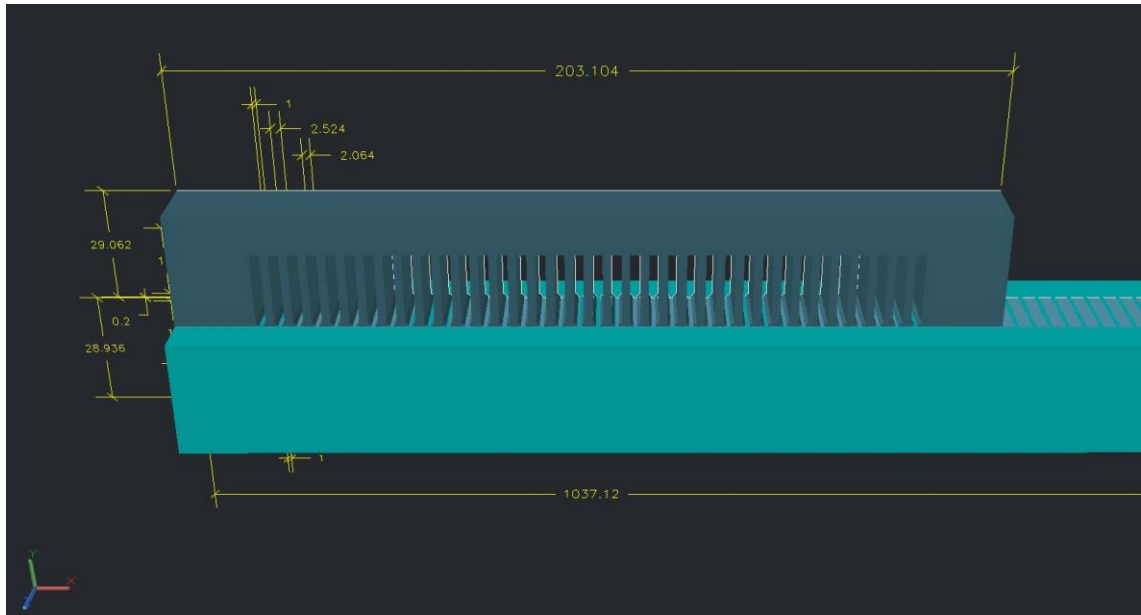
Using dimensions, obtained from section 3.3, and AutoCAD software, drawings were produced. Dimensions are slightly rounded off as compare to calculated values. End lengths of both Primary and Secondary block are increased to facilitate bearings. While 6 mm is added to the height to make structure durable. Figure 8 shows motor dimensions while Figure 9 represents 3D view of Primary and Secondary. An illustration of motor with Secondary block filled with Aluminium is shown in Figure 10.



**Figure 8:** Motor Dimension for Primary and Secondary.



**Figure 9:** 3-dimension view of motor. Green is Primary whereas Blue is Secondary.



**Figure 10:** Complete motor including Primary (Green), Secondary (Light Green) and filled Aluminium (Blue) in Secondary.

### 3.6 Manufacturing

The manufacturing of a whole motor is a lengthy process comprising different phases which are described as under.

#### 3.6.1 Metal Sheets

To manufacture the motor, first requires the metal sheet. The metal sheet selected was Mild Steel sheet (or MS sheet) sold first to ABB Oy by Severstal and then purchased from ABB Oy for this study. Figure 11 shows the metal sheet.





**Figure 11:** Mild Steel sheet that is used to make motor core.

### 3.6.2 Sheet Cutting

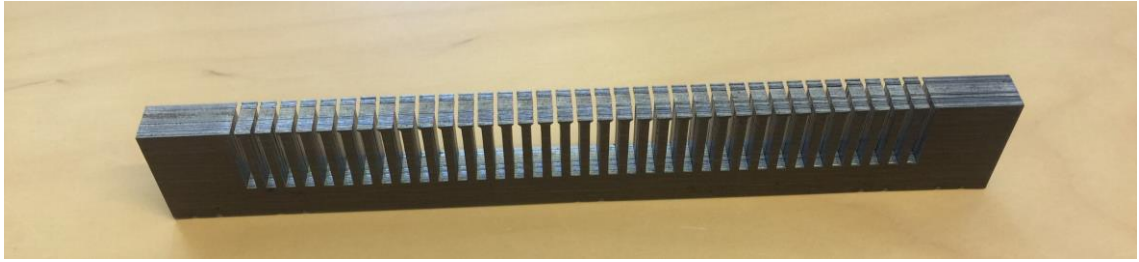
Motor's drawings and MS sheets were provided to Veslatec Oy who performed laser cutting. Veslatec Oy was asked to provide 60 pieces of primary and 60 pieces of secondary. Both primary and secondary sheets are shown in Figure 12.



**Figure 12:** Single cut sheet of Primary at the top while Secondary at bottom.

### 3.6.3 Welding

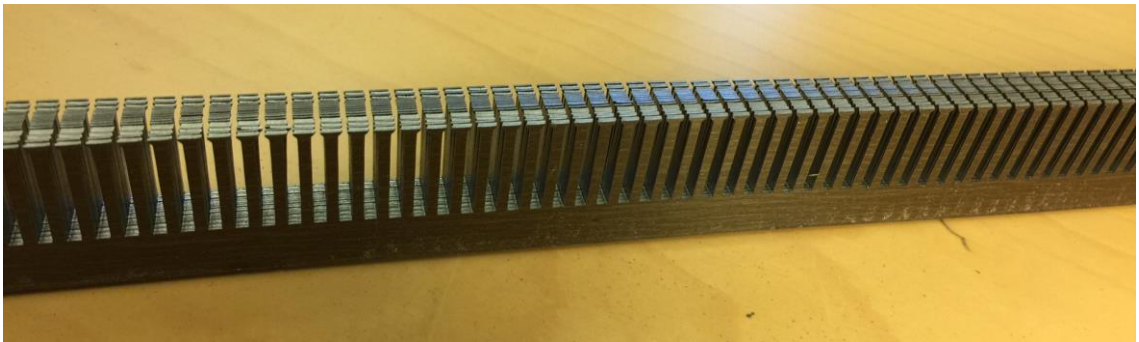
Out of 60 pieces of primary and secondary, 20 pieces of each were handed over to Weldo Oy to weld all primary sheets together as one Primary block and secondary sheets as a Secondary block. Figure 13 and Figure 14 shows both blocks. Figure 15 is a close up of Secondary block



**Figure 13:** Primary block of motor.



**Figure14:** Secondary block of motor.



**Figure15:** Close up of Secondary block.

The normal force pull between Primary and Secondary block is a lot and to maintain a steady gap in between, two bearings are installed on each side of primary and shown in Figure 16.



**Figure 16:** Primary block with bearing installed on both ends.

#### 3.6.4 Aluminium Filling

The slots of secondary block of the motor have to be filled with Aluminium and the conventional way to fill the slots is to cast aluminium in the slots. This works fine only for

conventional rotary induction motors. As both ends of the Secondary block are not connected together in a circular manner, the difference in thermal properties of Aluminium and MS might cause secondary block to bend towards open slot side and inflicts movement restriction on the primary block.

As casting Aluminium was not suitable for linear structure, a new method was devised. In that scheme two Aluminium sheet of 2mm thickness were cut exactly same length and height of Secondary and they also have same slot geometry except that the slots were not open. One of this Aluminium sheet is shown in Figure 17 below.



**Figure 17:** Side Aluminium sheet for Secondary block.

These slotted Aluminium sheets were placed along the sides of Secondary block one at each side. Then small pieces of Aluminium sheet (Figure 18) were inserted manually in the all the slots. Figure 19 show completely filled Secondary block while a close up of it can be seen in Figure 18.



**Figure 18:** Small cut pieces of Aluminium (Top) and close up of Aluminium filled Secondary block (Bottom).



**Figure 19:** Aluminium filled Secondary block.

After that all slots were filled with Tin paste (Figure 20) which was used to make Aluminium joint together at further baking stage. In the last step two more Aluminium sheets (Figure 20) of 8mm thickness and same height and length of Secondary block were placed on slotted aluminium sheets.



**Figure 20:** Tin paste (Top), Filled Aluminium sheet (Centre) and Side Aluminium (Bottom).

This complete structure was then kept inside an oven (Figure 21) at 200° C for a 30 minutes.

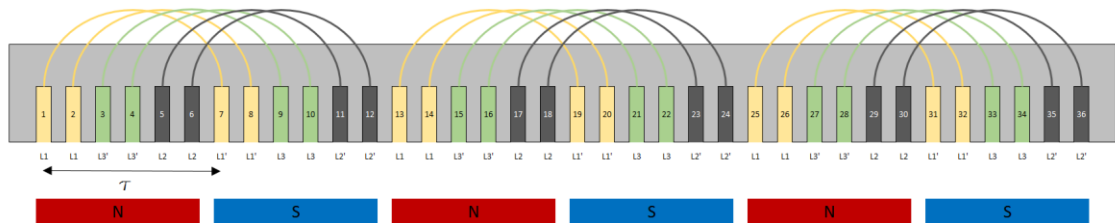


**Figure 21:** Metropolia AMK's oven used for soldering Aluminium together.



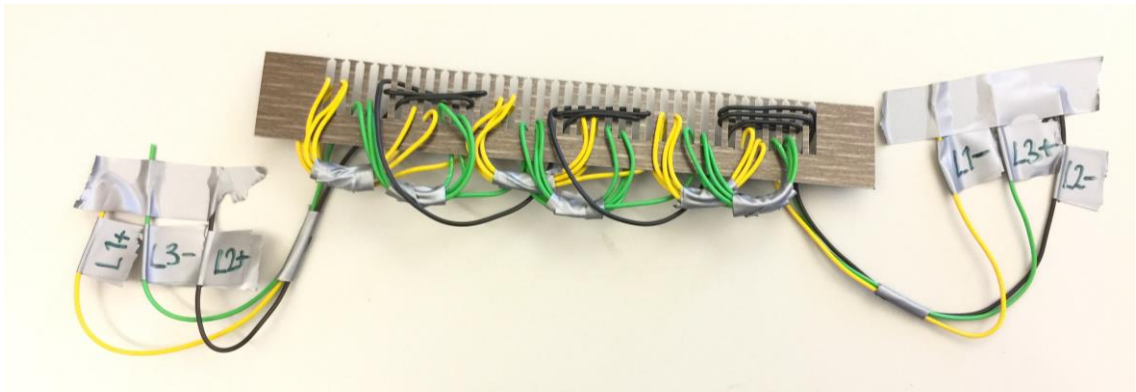
### 3.6.5 Primary Winding

The Primary block need to be wound in order to produce traveling magneto motive forces and the type of winding chose was Single-Layer  $2p$  (even) pole winding with  $q = 2$ .



**Figure 22:** Graphical illustration of winding.

The winding illustration is represented in Figure 22 and to make it understand more visibly a single Primary sheet is wound by three different colours of wires each represent different phase (Figure 23). Only single turn is made so that it is easy to recognize and follow wire through slots.

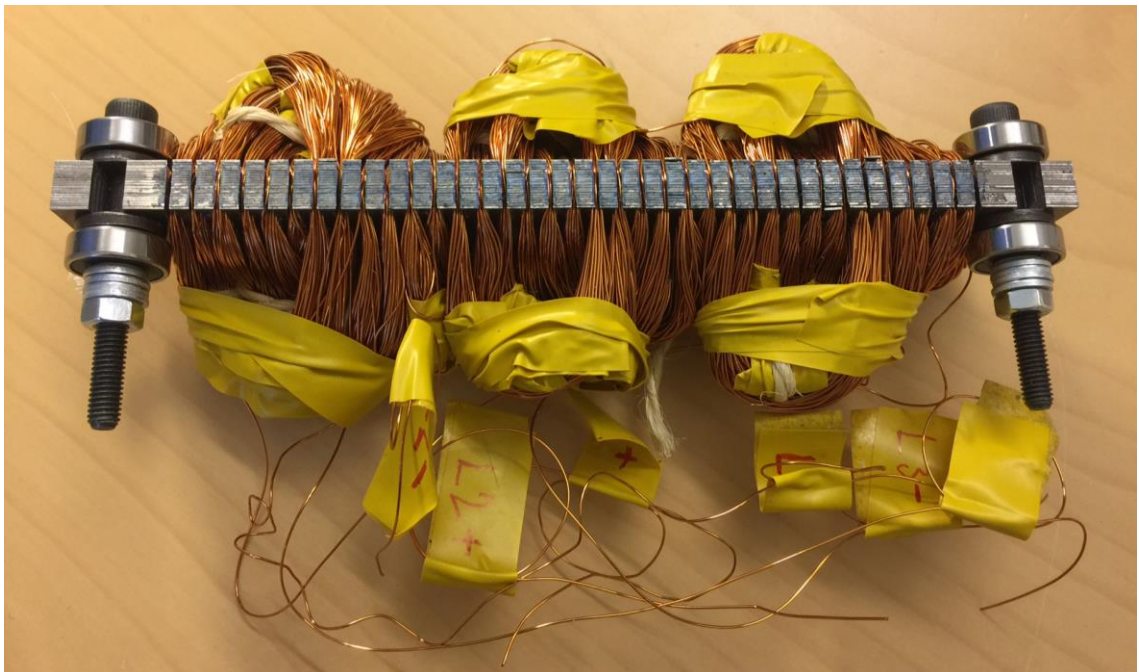


**Figure 23:** Winding on a single Primary sheet.

The wire selected for winding was 0.5mm diameter copper wire and shown in Figure 24. Slot area was small enough to accommodate only 90 turns instead of 100. Completely wound Primary block is shown in Figure 25.



**Figure 24:** Copper wire used to wind Primary Block.



**Figure 25:** Wounded Primary block.

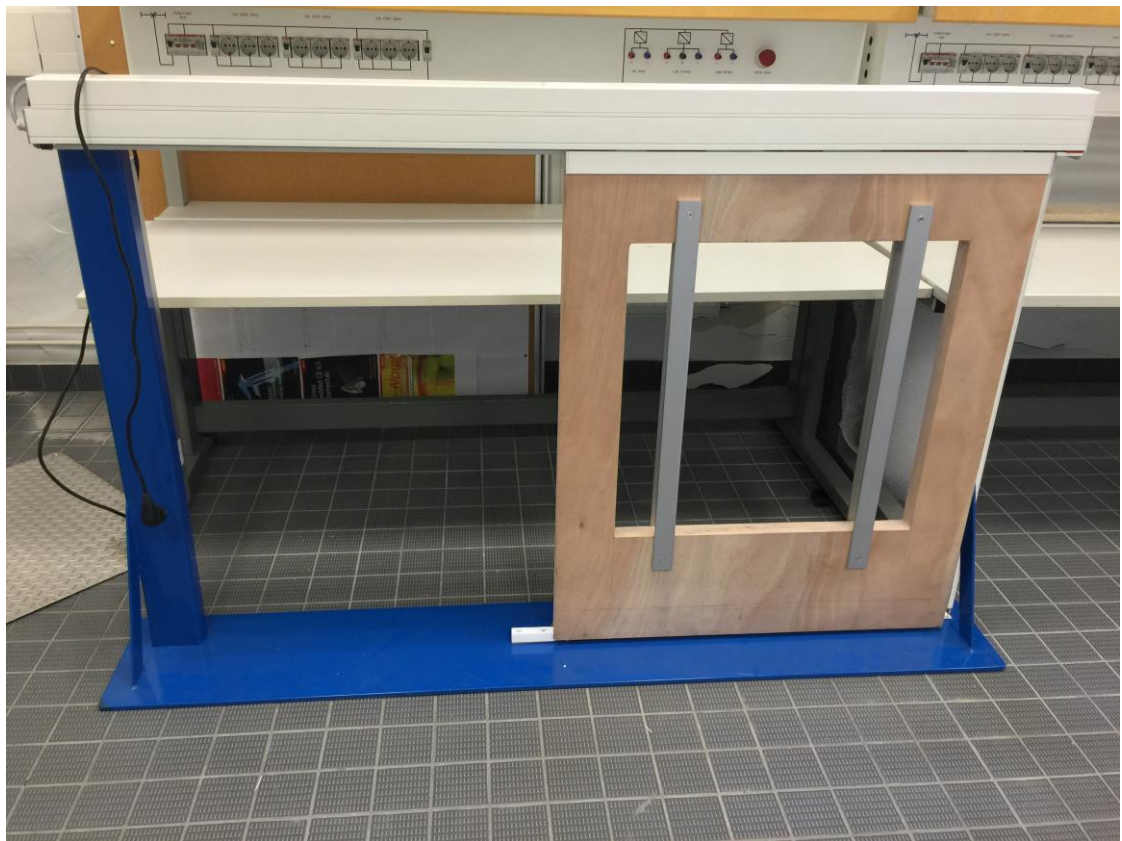
#### 4 Discussion

The overall goal of the study was achieved and a small size Linear Induction Motor was successfully build. As it was the first prototype further improvement can lead to a better version. This kind of motor can be used to operate automatic doors as the travel length

is reasonable in term of manufacturing cost. Down side of this prototype was manufacturing cost which was due to the Aluminum filling part and this can be overcome by choosing different process for Aluminum filling in Secondary block.

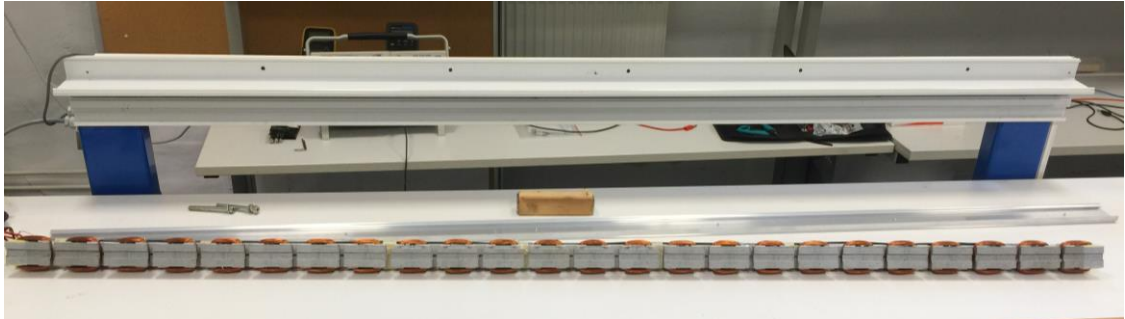
As linear motors of induction type are not available in small size, plenty of research has to be done to come up with a better version of motor. Due to the lack of time not much could be done to improve the building process and design of motor, especially Aluminum filling in Secondary.

Before the start of this study KONE provided a model of one of their automatic door (Figure 20) that is operated by a Linear Motor. The intention was to study how their current automatic door system works and how it can be enhanced further in term of technology and cost.



**Figure 20:** A model of automatic sliding door provided by KONE Oy.

The provided door contains Linear Synchronous Motor that has a Primary block of equal length of the whole frame. This makes it costlier as Primary block has to copper wound end to end with 3-phase winding.



**Figure 21:** Primary block of automatic sliding door.

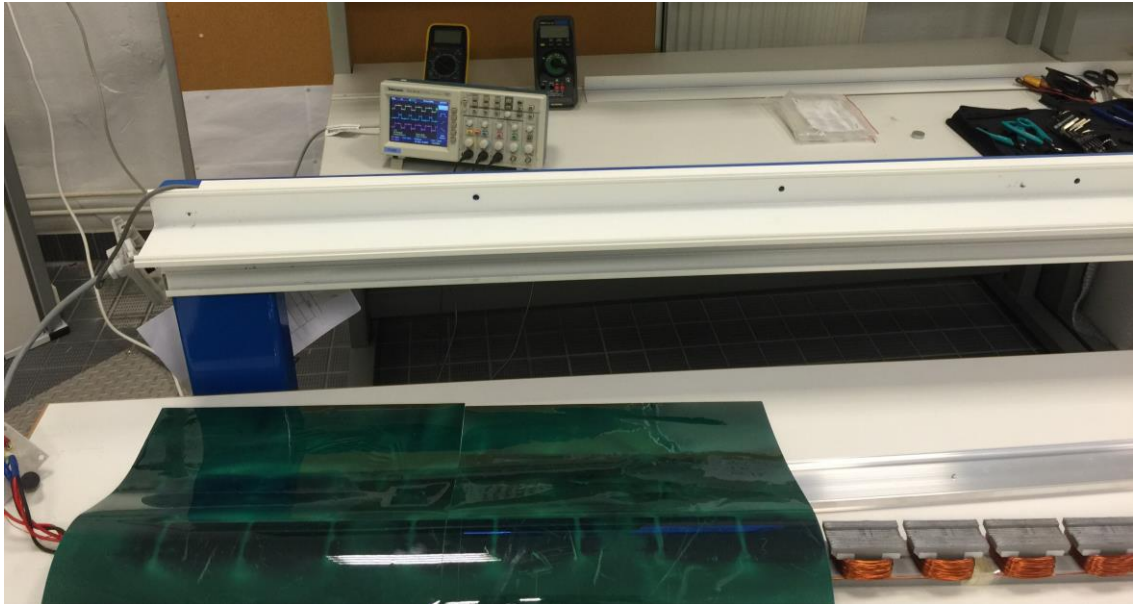
The Secondary block was embedded inside the door itself and contained Permanent Magnets that keeps the door hanging while there is no power and the same magnets create linear movement upon powering up Primary block due to the traveling magnetic field. Air gap is maintained by the bearing wheels.



**Figure 22:** Permanent magnets (in Red and White colour) embedded inside.



Traveling magnetic field was observed by the help of magnetic paper and at the same time waveform of input voltages was investigated by the help of oscilloscope (Figure 23).



**Figure 23:** Magnetic field on Primary block and input waveform of Primary block.

According to my opinion, small Linear Induction Motor is quite suitable for KONE's Automatic doors as further improvement can make it less expensive than current Linear Synchronous Motor.

Aluminum filling part in this study was quite tricky and there was no exact way to figure it out except hit and trail method. The method of laser cutting the whole Aluminum sheet cost a lot but below are some points that are learned to improve this section of study.

1. The teeth width could be reduced to the same as slot width. That is mean that slot width is equal till slot opening and this can reduce some manufacturing time, and may be some cost too, for both Aluminum and Iron core.
2. Despite laser cutting, a bent in Aluminum sheet was observed. This can be overcome by making small pieces of Side Aluminum sheet first and then weld these after all of them are fitted across Secondary block.

3. Instead of Laser cutting the Aluminum sheet, an Aluminum wire of same thickness as the Secondary slots width can be tried. Or rings of Aluminum sheet of same thickness as the Secondary slots width and same breath as Secondary slot height can also be attempted and after that all the rings are short circuited with one long Aluminum sheet.

## **5 Conclusions**

The sole goal of this study was to design and build a small Linear Induction Motor. As the travel length could be any length, the length of actual motor, i.e. Primary part, was about 17cm which is considerable small enough for this kind of motor. The motor of this size has quite an importance in any sliding mechanism such as automatic sliding door which was the prime focus for the application.

This subject can be further proceeded by improving Secondary block. Aluminum filling and reducing tooth size are two important points that can make a noticeable improvement. There are few techniques that are realized quite late during the study to fill Aluminum efficiently and are discussed above. If a motor of different specification is needed then only changing the initial parameters can provide the dimensions and new version can easily be build. KONE Oy has sufficient technical resources to further improve and carry on research on this study to make a commercial versions of the motor for different application fields.

## References

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## List of Symbols

Symbol	Parameter
$q$	Number of Slot per Pole per Phase.
$p$	Number of poles.
$2p$	Number of pole pairs.
$q_1$	Same as q.
$G_e$	Equivalent goodness factor.
$G_{e0}$	Optimum goodness factor
$F_{xn}$	Rated thrust.
$l_{travel}$	Maximum travel length.
$u_n$	Rated speed.
$g$	Mechanical airgap.
$F_n$	Normal force.
$B_{g1n}$	Airgap flux density.
$N_{s1}$	Number of slots in Primary.
$N_{s2}$	Number of slots in Secondary per Primary length.
$\tau_{s1}$	Primary slot pitch.
$\tau_{s2}$	Secondary slot pitch.
$f_{xn}$	Shear secondary stress.
$R_1$	Primary resistance per phase.
$\rho_{Copper}$	Resistivity of copper
$l_{Stack}$	Stack width
$l_{ec}$	End-coil length per side

$j_{cor}$	Current density in copper winding.
$w_1$	Number of turns per phase in Primary.
$I_{1r}$	Current in Primary winding.
$L_{1l}$	Primary leakage inductance.
$\mu_0$	Permeability of Vacuum or Air.
$\lambda_{s1}$	Slot specific (Nondimensional) permeance in Primary.
$\lambda_{diff1}$	Airgap leakage specific permeance in Primary.
$\lambda_{ec1}$	Primary end-coil leakage.
$h_{s1}$	Active Primary slot height.
$\beta$	Damping coefficient.
$h_{sp}$	Primary tooth height.
$b_{s1}$	Primary slot width.
$b_{sp}$	Primary slot opening.
$\lambda_{s2}$	Slot specific (Nondimensional) permeance in Secondary
$h_{s2}$	Secondary slot useful height.
$h_{ss}$	Secondary tooth height.
$b_{s2}$	Secondary slot width.
$b_{ss}$	Secondary slot opening.
$\lambda_{diff1}$	Airgap leakage specific permeance in Secondary
$K_c$	Carter coefficient for dual slotting.
$L_m$	Magnetization inductance.
$K_{w1}$	Primary winding factor

$\tau$	Pole pitch
$K_{ss}$	Total (Primary and Secondary) core magnetic saturation coefficient.
$R_2'$	Secondary resistance.
$\rho_{Aluminum}$	Resistivity of Aluminum.
$l_{lad}$	Length of ladder. Width of ladder
$A_{s2}$	Area of Secondary slot.
$A_{lad}$	Area of ladder.
$L_{2l}'$	Secondary leakage inductance.
$K_{ladder}$	Ladder coefficient.
$\alpha_{es}$	Electric Phase Angle.
$B_{g1}$	Airgap flux density at rated (or peak) thrust
$K_e$	End effect factor.
$j_{1m}$	Stator or Secondary mmf.
$K_s$	Magnetic saturation factor.
$s$	Relative Slip.
$\theta_{1m}$	Rated Primary mmf per pole.
$\omega_1$	Primary frequency in radians.
$I_1$	RMS value of primary phase current / RPS current per phase.
$G_{ei}$	Goodness factor of iron.
$K_{l2}$	Secondary leakage inductance coefficient.
$\sigma_{Al}$	Density of Aluminium.
$K_r$	Carter coefficient for Rotor.

$L_{lad}$	Length of ladder.
$\omega_2$	Secondary frequency in radians.
$B_{gk}$	Airgap flux density when $(s \cdot Ge) = 1$
$y$	Coil span.
$w_1 I$	Current per turn per phase. Peak Amperturns per Phase
$A_p$	Active area of Primary.
$\tau_s$	Same as Ts1
$l_{primary}$	Primary length.
$A_{ps}$	Active primary slot area.
$K_{fill}$	Slot filling factor.
$F_{nk}$	Peak normal force.
$f_{1r}$	Primary required frequency
$f_2$	Secondary frequency. Secondary slip frequency.
$u_r$	Required speed.
$V_{10}$	Available RMS voltage per phase.
$V_{line}$	Line or Supply voltage.
$S$	Slip
$f_1$	Frequency of Primary.
$V_{1r}$	Primary Voltage.
$I_{1n}$	RMS phase current for rated thrust.
$P_{1n}$	Input power.
$V_{1n}$	Phase voltage.

[illegible]



### List of Constants and Coefficients.

[illegible]

## MathCAD model of Small Linear Induction Motor.

## Slow SLIM

Version 8, March 2, 2016  
Specifications for the example of the book

$$\begin{aligned}
 B_{glk} &:= 0.7 \cdot T = 0.7 \text{ T} \\
 g_0 &:= 0.0002 \cdot m \\
 \mu_0 &:= 4 \cdot \pi \cdot 10^{-7} \cdot \frac{T}{A} = (1.257 \cdot 10^{-6}) \frac{kg \cdot m}{A^2 \cdot s^2} \\
 p &:= 3 \quad \text{Number of pole pairs} \\
 s_0 &:= 1 \\
 G_e &:= 1 \\
 m_0 &:= 3 = 3 \\
 F_{xn} &:= 10 \cdot N \\
 f_{xn} &:= 0.88 \cdot 10^4 \cdot \frac{N}{m^2} = (8.8 \cdot 10^3) \text{ Pa} \\
 l_{stackPERt} &:= 0.25 \\
 f_{2r} &:= 4 \cdot \frac{1}{s} \\
 V_{line} &:= 9 \cdot V \\
 u_n &:= 1 \cdot \frac{m}{s} \\
 N_{s2} &:= 40 \quad \text{Ns2 is number of secondary slots per primary length} \\
 \sigma_{Al} &:= 3.2 \cdot 10^7 \cdot \frac{1}{\Omega \cdot m} = (3.2 \cdot 10^7) \frac{A^2 \cdot s^3}{kg \cdot m^3} \\
 \rho_{Co} &:= 2.3 \cdot 10^{-8} \cdot \Omega \cdot m = (2.3 \cdot 10^{-8}) \frac{kg \cdot m^3}{A^2 \cdot s^3} \\
 j_{cor} &:= 4 \cdot 10^6 \cdot \frac{A}{m^2} = (4 \cdot 10^6) \frac{A}{m^2} \\
 \beta &:= \left( \frac{.9}{.3 \cdot 2} + 1 \right) \cdot \frac{1}{3} = 0.833 \\
 K_{ladder} &:= 0.1 = 0.1 \\
 K_{fill} &:= 0.6 \\
 u_r &:= u_n = 1 \frac{m}{s} \\
 f_{2r} &:= 4 \frac{1}{s} \\
 K_s &:= 0.4 \\
 K_c &:= 1.25 \quad \text{Carter coefficient} \\
 K_l &:= 1.5 \\
 K_r &:= 1.5 \\
 K_{l2} &:= 1.2 \quad \text{Initial value.}
 \end{aligned}$$

Somehow  $K_l=1.5$  (5.31)

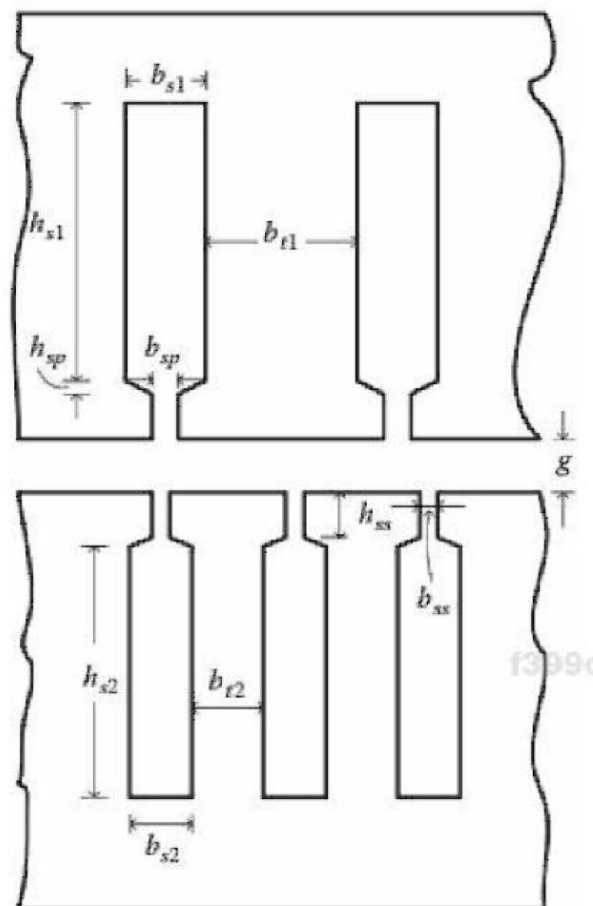
Somehow  $K_{l2}=1.2$ ,  $K_r=1.5$  (5.12):

$k_{ss}$  (42.7) is the total (primary and secondary) core magnetic saturation coefficient ( $k_{ss} = 0.3...0.6$  in general).  $k_i$ ,  $i=1...3$ .  $k_i = k_i(k_{ti})$  (4.27).

$k_s$  is the magnetic saturation factor and it accounts for secondary back iron and primary teeth and back-iron contribution to magnetization current (Chapters 3 and 4).

$k_{trAL}$  (4.30) or  $k_{ti}$  (4.31) are the transverse edge effect coefficients (for Al and iron).  $k_{ti}$ ,  $i=1...3$  for from 1 to 3 laminations in the bottom iron.

$k_{tr}>1$  is the edge effect coefficient and reduced by the contribution of solid back in thrust.



We have, however, three pole pairs (not two like here)

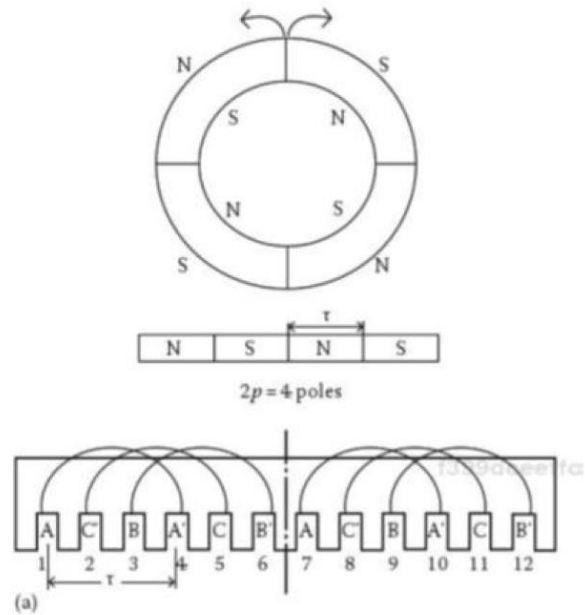


FIGURE 3.2 Single- and two-layer three-phase LIM windings: (a)  $2p=4$ ,  $q_1=1$  slot/pole/phase, single layer; (b)  $2p+1=5$ ,  $q_1=1$ , double layer.

$$\theta_{lm} := Bglk \cdot \frac{g0 \cdot Kc \cdot (1 + Ks) \cdot \sqrt{1 + s0^2} \cdot Ge^2}{\mu0} = 275.722 \text{ A}$$

$$Q := 3 \cdot 6 \cdot 2 = 36$$

$$q := \frac{Q}{m0 \cdot 2 \cdot p} = 2$$

Please, note that there the (b) figure is omitted from the adjacent copy of the FIGURE 3.2.

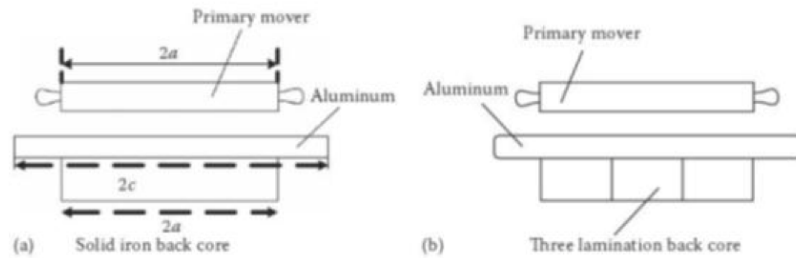


FIGURE 3.10 SLIM secondaries: (a) with solid back iron and (b) made of three "laminations."

$$Kdl := \frac{\sin\left(\frac{\pi}{6}\right)}{q \cdot \sin\left(\frac{\pi}{6 \cdot q}\right)} = 0.966$$

$$Kpl := \sin\left(\frac{5}{6} \cdot \frac{\pi}{2}\right) = 0.966$$

$$Kwl := Kdl \cdot Kpl = 0.933$$

$$wlll := \frac{\theta lm \cdot \pi \cdot p}{3 \cdot \sqrt{2} \cdot Kwl} = 656.476 \text{ } \mu\text{A}$$

w111

$$\tau := \sqrt{\frac{Fxn}{fxn} \cdot \frac{1}{2 \cdot p \cdot lstackPER\tau}} = 0.028 \text{ } \mu\text{s}$$

$$\tau sl := \frac{\tau}{6} = 0.005 \text{ } \mu\text{s}$$

$$\tau s2 := 0.9 \cdot \tau sl = 0.004 \text{ } \mu\text{s}$$

$$hys := \frac{\frac{Bglk \cdot \tau}{\pi}}{1.5 \cdot T} = 0.004 \text{ } \mu\text{s}$$

$$hgr := \frac{\frac{Bglk \cdot \tau}{\pi}}{1.6 \cdot T} = 0.004 \text{ } \mu\text{s}$$

$$g0 = (2 \cdot 10^{-4}) \text{ } \mu\text{s}$$

$$bs1 := 0.55 \cdot \tau sl = 0.003 \text{ } \mu\text{s}$$

$$bs2 := 0.9 \cdot bs1 = 0.002 \text{ } \mu\text{s}$$

$$KI2 = 1.2$$

$$hs2 := \frac{1 \cdot \pi^2 \cdot g0 \cdot Kc \cdot (1 + Ks) \cdot Kr \cdot KI2}{\mu0 \cdot 2 \cdot \pi \cdot f2r \cdot \tau^2 \cdot \sigma Al \cdot \left(1 - \frac{bs2}{\tau s2}\right)} = 0.018 \text{ m}$$

$$lprimary := (2 \cdot p + 0) \cdot \tau = 0.165 \text{ m}$$

The active primary slot area is:

$$Aps := \frac{wIII}{p \cdot q \cdot jcor \cdot Kfill} = (4.559 \cdot 10^{-5}) \text{ m}^2$$

$$Apsmm := Aps \cdot 1000^2 = 45.589 \text{ m}^2$$

This has wrong unit, not used!

$$hs1 := \frac{Aps}{bs1} = 0.018 \text{ m}$$

hs1, good?

$$\frac{hs1}{bs1} = 7.162$$

This is in the example of the book 5.67

$$lstack := \tau \cdot lstackPER\tau = 0.007 \text{ m}$$

$$2 \cdot p \cdot \tau = 0.165 \text{ m}$$

This is in the example of the book 0.483

The peak normal force, of attractive character, as the secondary slots are semiclosed:

$$FnK := \frac{BgIk^2}{2 \cdot \mu0} \cdot 2 \cdot p \cdot \tau \cdot lstack = 221.551 \text{ N}$$

$$F = [1/(2 \cdot \mu0)] \cdot B^2 \cdot A$$

$$\frac{FnK}{Fxn} = 22.155$$

$$Kss := Ks = 0.4$$

$$\tau = 0.028 \text{ m}$$

$$lm0 := \frac{6 \cdot \mu0 \cdot KwI^2 \cdot \tau \cdot lstack}{\pi^2 \cdot Kc \cdot g0 \cdot p \cdot (1 + Kss)} = (1.2 \cdot 10^{-7}) \text{ H}$$

$$wIII = 656.476 \text{ A}$$

$$KI2 = 1.2$$

$$Fxb := \frac{3 \cdot \pi}{2 \cdot \tau} \cdot \frac{wIII^2}{KI2} \cdot lm0 = 7.376 \text{ N}$$

Is a little smaller than Fxn = 10 N.

$$T = l \times \Psi = l \times (L \cdot I) = l \times (w1)^2 \cdot lm0 \cdot I$$

For one phase only:

$$\begin{aligned} F &= I \cdot l_{\text{stack}} \times B = I \cdot w_1 \cdot l_{\text{stack}} \times (L \cdot I) / (A \cdot w_1) \\ &= I \cdot w_1 \cdot l_{\text{stack}} \times I \cdot w_1 \cdot l_{m0} / (\tau \cdot l_{\text{stack}}) \\ &= (I \cdot w_1)^2 \cdot (l_{m0} / \tau) \end{aligned}$$

In the example of the book this is 589.7 N when seeked for 500 N.

$$F_{xn} = 10 \text{ N}$$

$$f1r := f2r + \frac{ur}{2 \cdot \tau} = 22.166 \frac{1}{s}$$

$$V10_{\text{American}} := 0.95 \cdot \frac{V1_{\text{line}}}{\sqrt{3}} = 4.936 \text{ V}$$

$$\rho Co = (2.3 \cdot 10^{-8}) \frac{\text{kg} \cdot \text{m}^3}{\text{A}^2 \cdot \text{s}^3}$$

$$V10 := V1_{\text{line}} = 9 \text{ V}$$

$$jcor = (4 \cdot 10^6) \frac{\text{A}}{\text{m}^2}$$

$$R10 := \frac{2 \cdot \rho Co \cdot (l_{\text{stack}} + 1.5 \cdot \tau) \cdot jcor}{w111} = (1.35 \cdot 10^{-5}) \Omega$$

$$w111 = 656.476 \text{ A}$$

$$R10b := R10 \cdot \frac{3.28}{3.475} = (1.274 \cdot 10^{-5}) \Omega$$

$$g01 := 1.5 \cdot g0 = (3 \cdot 10^{-4}) \text{ m}$$

$$bs2 = 0.002 \text{ m}$$

$$hs1 = 0.018 \text{ m}$$

$$bss := 2 \cdot g01 = (6 \cdot 10^{-4}) \text{ m}$$

$$bs1 = 0.003 \text{ m}$$

$$hss := g01 = (3 \cdot 10^{-4}) \text{ m}$$

$$hss000 := 2 \cdot g0 = (4 \cdot 10^{-4}) \text{ m}$$

$$hspold := 1 \cdot 10^{-3} \cdot \text{m}$$

$$bspold := 6.32 \cdot 10^{-3} \cdot \text{m}$$

$$hsp := 2 \cdot g01 = (6 \cdot 10^{-4}) \text{ m}$$

$$bsp := 2 \cdot g01 = (6 \cdot 10^{-4}) \text{ m}$$

$$\lambda s1 := \frac{hs1}{3 \cdot bs1} + \frac{hsp}{1 \cdot bsp} = 3.387$$

$$hs1 = 0.018 \text{ m}$$

$$bs1 = 0.003 \text{ m}$$

$$Kc = 1.25$$

$$Kl = 1.5$$

$$\lambda diff1 := \frac{5 \cdot Kc \cdot \frac{g01}{bsp}}{5 + 4 \cdot Kl \cdot \frac{g01}{bsp}} = 0.391$$

$$\tau = 0.028 \text{ m}$$

$$\lambda ec1 := 0.3 \cdot (3 \cdot \beta - 1) \cdot 2 = 0.9$$

$$\lambda ec\_version1 := 0.08625 = 0.086$$

$$1.25 \cdot \tau = 0.034 \text{ m}$$

$$\lambda ec := 1.25 \cdot \tau = 0.034 \text{ m}$$

$$L110 := \frac{2 \cdot \mu 0}{p \cdot q} \cdot ((\lambda s1 + \lambda diff1) \cdot lstack + \lambda ec1 \cdot \lambda ec) = (2.386 \cdot 10^{-8}) \text{ H}$$

#### Some rules::

Here hs1 is Aps/bs1

hsp = somehow ..

g0 =

g01 = 1.5 \* g0

$$\tau s1 = 0.005 \text{ m}$$

$$bs1 = 0.003 \text{ m}$$

$$bt1 := \tau s1 - bs1 = 0.002 \text{ m}$$

$$\tau s2 = 0.004 \text{ m}$$

$$bs2 = 0.002 \text{ m}$$

$$bt2 := \tau s2 - bs2 = 0.002 \text{ m}$$

$$\tau s2 = 0.004 \text{ m}$$

$$bs2 = 0.002 \text{ m}$$

#### Some rules:

Here bs1 is 0.55 \* ts1

bt1 =

bsp = somehow ...

$\tau = Ap / (2p \cdot lstack)$

$\tau s1 = \tau / 6 = 11.5 \text{ mm}$

$lstack = lstackPER \cdot \tau$

#### Some rules:

Here bs2 is 0.9 \* bs1

bt2 =

bss = 2 \* g01

$\tau s2 = 0.9 \cdot \tau s1$

#### Some roles:

With semiclosed slots in the secondary:

$\tau s2 = 0.9 \cdot \tau s1$

secondary slot width is bs2

slot opening = bss = 2 \* g01

hss

We may proceed to calculate

L2l' with Kladder = 0.1



$$hs2 = 0.018 \text{ m}$$

$$hss = \langle 3 \cdot 10^{-4} \rangle \text{ m}$$

$$bss = \langle 6 \cdot 10^{-4} \rangle \text{ m}$$

$$\lambda s2\_version1 := hs2 \cdot \frac{(1 + 3 \cdot \beta)}{12 \cdot bs2} + \frac{hss}{bs2} = 10.266$$

$$\lambda s2\_version2 := 1.2975 = 1.298$$

$$\lambda s2 := \frac{hs2}{3 \cdot bs2} + \frac{hss}{bs2} = 3.149$$

$$\lambda diff2 := 0.15 = 0.15$$

$$1000 \cdot hs2 = 18.047 \text{ m}$$

$$1 + 3 \cdot \beta = 3.5$$

$$hs2 = 0.018 \text{ m}$$

$$Ns2 = 40$$

$$Kladder = 0.1$$

$$bs2 = 0.002 \text{ m}$$

$$L2l0 := 24 \cdot \mu 0 \cdot lstack \cdot (\lambda s2 + \lambda diff2) \cdot \frac{KwI^2}{Ns2} \cdot (1 + Kladder) = \langle 1.639 \cdot 10^{-8} \rangle \text{ H}$$

$$As2 := hs2 \cdot bs2 = \langle 4.098 \cdot 10^{-5} \rangle \text{ m}^2$$

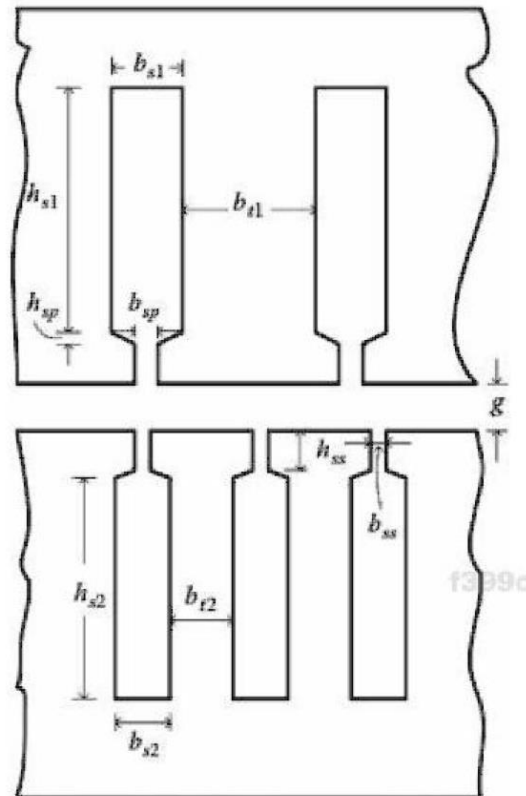
$$aes := \frac{2 \cdot \pi \cdot p}{Ns2} = 0.471$$

$$Alad := \frac{As2}{2 \cdot \sin\left(\frac{aes}{2}\right)} = \langle 8.777 \cdot 10^{-5} \rangle \text{ m}^2$$

$$llad := 2 \cdot p \cdot \frac{\tau}{Ns2} = 0.004 \text{ m}$$

$$\rho Al := \frac{1}{\sigma Al} = \langle 3.125 \cdot 10^{-8} \rangle \frac{\text{kg} \cdot \text{m}^3}{\text{A}^2 \cdot \text{s}^3}$$

$$2 \cdot \tau = 0.055 \text{ m}$$



$$lstack = 0.007 \text{ m}$$

$$R20 := 12 \cdot \rho A l \cdot \frac{Kw I^2}{Ns2} \cdot \left( \frac{lstack}{As2} + \frac{2 \cdot llad}{Alad} \right) = (2.138 \cdot 10^{-6}) \Omega$$

$$Slip := \frac{f2r}{f1r} = 0.18$$

$$f1r = 22.166 \frac{1}{s}$$

$$f2r = 4 \frac{1}{s}$$

$$Z0 := 1 \cdot \left( R10 + 1i \cdot 2 \cdot \pi \cdot f1r \cdot L10 + \frac{1i \cdot 2 \cdot \pi \cdot f1r \cdot lm0 \cdot \left( \frac{R20}{Slip} + 1i \cdot 2 \cdot \pi \cdot f1r \cdot L210 \right)}{\frac{R20}{Slip} + 1i \cdot 2 \cdot \pi \cdot f1r \cdot (lm0 + L210)} \right)$$

$$Z0 = (2.01 \cdot 10^{-3} + 9.45i \cdot 10^{-6}) \, \Omega$$

$$wI := \frac{V10}{wIII \cdot |Z0|} = 617.216$$

$$IIn := \frac{wIII}{wI} = 1.064 \, A$$

$$\phi := \arg \left( \operatorname{Re} \left( \frac{1}{Z0} \right) - 1i \cdot \operatorname{Im} \left( \frac{1}{Z0} \right) \right) = 0.439$$

$$\phi := \arg(Z0) = 0.439$$

$$\cos(\phi) = 0.905$$

$$\frac{180}{\pi} \cdot \phi = 25.179$$

$$R1 := R10 \cdot wI^2 = 5.143 \, \Omega$$

$$R2 := R20 \cdot wI^2 = 0.815 \, \Omega$$

$$Lm := lm0 \cdot wI^2 = 0.046 \, H$$

$$L1l := L1l0 \cdot wI^2 = 0.009 \, H$$

$$L2l := L2l0 \cdot wI^2 = 0.006 \, H$$

$$Xm := 2 \cdot \pi \cdot flr \cdot Lm = 6.364 \, \Omega$$

$$X1 := 2 \cdot \pi \cdot flr \cdot L1l = 1.266 \, \Omega$$

$$X2 := 2 \cdot \pi \cdot flr \cdot L2l = 0.87 \, \Omega$$

=====

$$Pin := 3 \cdot V10 \cdot IIn \cdot \cos(\phi) = 25.989 \, W$$

$$us := 2 \cdot \tau \cdot flr = 1.22 \, \frac{m}{s}$$

$$ur = 1 \, \frac{m}{s}$$

$$Pelm\_old := Fxnb \cdot us = 9 \, W$$

$$Pelm := 3 \cdot IIn^2 \cdot (R20 \cdot wI^2) \cdot \frac{1 - Slip}{Slip} = 12.554 \, W$$

$$Fx := \frac{Pelm}{us} = 10.289 \, N$$

$$\eta := \frac{Fx \cdot ur}{Pin} = 0.396$$

=====

$$I_{1n\phi} := I_{1n} \cdot e^{11 \cdot \phi} = (0.963 + 0.453i) \text{ A}$$

$$|I_{1n\phi}| = 1.064 \text{ A}$$

$$I_{2n\phi} := I_{1n\phi} \cdot \frac{1i \cdot X_m}{1i \cdot X_m + \frac{R_2}{Slip} + 1i \cdot X_l} = (0.429 + 0.631i) \text{ A}$$

$$|I_{2n\phi}| = 0.764 \text{ A}$$

$$P_{axis} := 3 \cdot (|I_{2n\phi}|)^2 \cdot R_2 \cdot \frac{1 - Slip}{Slip} = 6.47 \text{ W}$$

$$\eta_2 := \frac{P_{axis}}{P_{in}} = 0.249$$

$$l_{primary} = 0.165 \text{ m}$$

$$\tau = 0.028 \text{ m}$$

$$l_{stack} = 0.007 \text{ m}$$

$$bs1 = 0.003 \text{ m}$$

$$ts1 = 0.005 \text{ m}$$

$$hys = 0.004 \text{ m}$$

$$hs1 = 0.018 \text{ m}$$

$$hsp = (6 \cdot 10^{-4}) \text{ m}$$

$$bsp = (6 \cdot 10^{-4}) \text{ m}$$

$$bt1 = 0.002 \text{ m}$$

$$w1 = 617.216$$

$$\eta_2 = 0.249$$

$$V10 = 9 \text{ V}$$

$$I_{1n} = 1.064 \text{ A}$$

$$F_x = 10.289 \text{ N}$$

$$F_{xnb} = 7.376 \text{ N}$$

$$F_{nK} = 221.551 \text{ N}$$

$$Diam := 2 \cdot \sqrt{\frac{I_{1n}}{\pi \cdot j_{cor}}} = (5.819 \cdot 10^{-4}) \text{ m}$$

$$h_{Al} := \frac{Ns2 \cdot As2}{2 \cdot p \cdot \tau} = 0.01 \text{ m}$$

**Length of mover**

$$g0 = (2 \cdot 10^{-4}) \text{ m}$$

$$hss = (3 \cdot 10^{-4}) \text{ m}$$

$$bss = (6 \cdot 10^{-4}) \text{ m}$$

$$bt2 = 0.002 \text{ m}$$

$$hs2 = 0.018 \text{ m}$$

$$hys = 0.004 \text{ m}$$

$$bs2 = 0.002 \text{ m}$$

$$ts2 = 0.004 \text{ m}$$

**Primary round count/phase**

**Efficiency**

**Supply voltage**

**Nominal current**

**Horizontal force**

**Horizontal force**

**Normal force**

**Wire diameter**

**Back aluminium thickness**

