ANALYSIS OF PERFORMANCE OF SINGLE-PHASE RELUCTANCE LINEAR MOTOR

A Thesis

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Abstract

The design and principle of operation, as well as the electromechanical phenomena of a single-phase linear reluctance motor are discussed. The motor with transverse magnetic flux consists of a primary part, which is moving and a secondary part which is stationary and does not have any windings. The motor can operate under AC or DC supply. When supplied from an AC source it must be equipped with a capacitor connected in series with the coil. In this case the motor operates on the basis of resonance in an RLC primary circuit. When supplied from a DC source it must be equipped with a controlled switch connected to the primary circuit. In this case it operates as a linear switched reluctance motor. A comparison of the motor performance operating under AC and DC supply is presented.

The objectives of the project were to design the motor and to determine its performance under AC and DC supply. Design calculations were focused on determining the resistance, the inductance and the mass of the primary part. The calculations of primary winding inductance and magnetic flux density distribution were performed using finite element method. In order to determine the motor performance the simulation of motor operation under AC and DC supply was carried out using MATLAB/SIMULINK software package. For this purpose the mathematical models of the motor were defined and block diagrams were built.

The simulation results presented in this thesis show a better performance of the motor when supplied from DC source. The maximum efficiency that could be obtained is 55%. A study of the influence of the switching angle on the motors electromechanical characteristics shows that the motor performs better when switched ON earlier before the motor develops the positive driving force.
Chapter 1: Introduction

1.1 Overview of Thesis Object

Linear electric motors are electromechanical devices that develop motion in a straight line, without the use of a mechanism to convert rotary motion to linear motion. Linear motors have nearly the same long history as rotary motors. The first linear electric motor was devised in 1883. But large air gaps and low efficiencies prevented linear electric motors from being widely used. Unlike rotary electric motors, the linear motor has a start and an end to its travel.

Linear switched reluctance machines (LSRMs) are an attractive alternative to linear induction or synchronous machines due to lack of windings on either the stator or rotor structure. Some of the benefits of these motors are:

- Lack of windings on either the stator or rotor structure.
- Absence of mechanical gears.
- Ideal for manufacturing and maintenance as the winding are concentrated rather than distributed.
- Inexpensive secondary material.
- Absence of significant heat sources during secondary operation and only one part of the secondary that is opposite to the primary is present in the magnetic field [1].

These motors are increasingly chosen for material-handling applications because they are quieter, more reliable, and less expensive than rotary electric motors.

Some of the applications of LSRM are:

- Material handling systems, which require low speed operations.
- Transporting materials inside a totally contained system.
• Food processing plants, to move the items from one place to another during processing stage.

A proposal for linear reluctance oscillating motor was described by E.A. Mendrela et.al [2]. A similar type of motor is analyzed in this thesis, but with a continuous linear motion. In general the motor can be supplied from an AC or a DC source, exposing quite different performance in these two cases. In this thesis, motor characteristics under AC and DC supply are discussed and compared.

1.2 Contribution of Thesis

The objectives of this project are:

• To determine the performance of the linear reluctance motor under AC and DC supply conditions.
• To analyze the motor operation under variable load and variable switching angle conditions when supplied from DC source.

The tasks to be accomplished in this project are:

• Literature study about the linear reluctance motors.
• Design calculations of a motor in order to determine:
  • the dimensions of primary and secondary part,
  • inductance of the coil using finite element method,
  • the coil resistance and mass of the primary.
• Formulation of mathematical models of the motor under AC and DC supply.
• Analysis of the dynamics of the motor under AC and DC supply using MATLAB/SIMULINK software package.
• Study of motor performance at steady-state operation condition under AC and DC supply.
1.3 Outline of Thesis

- Chapter 1 gives a general and brief introduction about switched reluctance motors; its history, advantages and applications. Then the objective and tasks of this thesis are given.
- Chapter 2 describes the principle of operations of the LRM motor on the basis of one chosen structure. Equations that describe the electromagnetic energy conversions and different types of switched reluctance motors and their features are discussed.
- Chapter 3 focuses on the construction and principle of operation of a single-phase linear reluctance motor which is an object of further study. Different types of supply to a reluctance motor are discussed.
- Chapter 4 contains design calculations of a motor such as the number of primary winding turns, coil inductance, mass of the primary and winding resistance for a particular structure of primary and secondary magnetic cores.
- Chapter 5 presents the formulation of mathematical models (assumptions, equations), block diagrams developed in MATLAB/SIMULINK for AC and DC supply, performance of the motor in form of characteristics obtained from simulation. Comparison of the motor performance under AC and DC supply is made.
- Chapter 6 summarizes the project and provides the results and key conclusions.
Chapter 2: Currently Used Switched Reluctance Motors

2.1 Construction and Principle of Operation

A reluctance motor is an electric motor in which torque is produced by the tendency of its movable part to move to a position where the inductance of the excited winding is maximized [3]. A switched reluctance motor (SRM) is simple in construction compared to induction or synchronous machines. As any other motor the structure of the switched reluctance motor consists of a stator and a rotor (Fig. 2.1). The stator is composed of steel laminations shaped to form poles. The rotator is mounted axially in the centre of the stator housing. Unlike a conventional synchronous motor, both the rotor and stator of an SRM have salient poles as shown in Fig. 2.1.

In this version the stator has eight equally spaced projecting poles (or teeth), each wound with an exciting coil. Opposite poles are connected to form one phase. The rotor, which may be solid or laminated, has six projecting poles of the same width as the stator poles. The laminated rotor has no windings or magnets. The stator coils are energized sequentially with a single pulse of current at high speed. When the stator coils are energized, the nearest pair of rotor poles is pulled into alignment with the appropriate stator poles by reluctance torque. A torque is produced when one phase is energized and
the magnetic circuit tends to adopt a configuration of minimum reluctance (Fig. 2.2), i.e. the rotor poles align with the excited stator poles in order to maximize the phase inductance. The motor rotates in the anticlockwise direction when the stator phases are energized in the sequence 1, 2, 3, 4 as shown in Fig. 2.1 and in the clockwise direction when energized in the sequence 1’, 4’, 3’, 2’.

![Switch reluctance flux path](image)

**Fig. 2.2 Switch reluctance flux path [4].**

The principle parts of a switched reluctance drive are the motor, power electronic converter and the controller (Fig. 2.3). Continuous torque can be produced by synchronizing each phase’s excitation with the rotor position. Like the brushless DC motor, SRM cannot run directly from a DC bus or an AC line, but must always be electronically commutated.

The amount of current flowing through the SRM winding is controlled by switching ON and OFF the power electronic devices, such as MOSFETs or IGBTs, which can connect each SRM phase to the DC bus. These power electronic inverters play an important role in SRM control because they largely dictate how the motor can be controlled. The performance of a reluctance motor strongly depends on the applied control. Each phase is supplied with DC voltage by its power-electronic converter unit. Fig. 2.4 shows a simple electronic converter for a four-phase switched reluctance drive. Each unit consists of two transistors and two diodes.
Transistors T1 and T2 are turned ON to circulate the current in phase ‘A’ of the SRM. To maintain this current flow at a desired value, either one of the transistor is turned OFF thus making the current freewheel through the opposite diodes. To decrease the current flow further both transistors are turned OFF. Now the energy stored in the motor winding recharges the DC source through the two diodes, bringing rapidly the current below the reference value.

2.2 Forces in a Linear Reluctance Motor

The energy conversion process that takes place in any electromechanical converter is shown schematically in Fig. 2.5.

In electric motors an electric energy is converted into mechanical energy. In the linear synchronous motor the electric energy $W_v$ is delivered to the system through the primary and secondary winding terminals called electrical ports. This energy is converted to the energy of magnetic field $W_f$, which is partly stored in the magnetic circuit and
partly converted into mechanical energy \( W_m \). During the process of energy conversion the power losses dissipate in the system.

![Diagram of electromechanical energy conversion with power losses included.](image)

In the rotor and stator windings a part of electrical energy is converted into heat due to ohmic power losses in the winding resistances. In the rotor and stator cores, part of field energy is lost. In the mechanical part of the system, a part of mechanical energy is lost as heat in bearings and due to the friction between the rotating rotor and the air (windage losses). In a motor the field energy stored in the magnetic circuit is converted into mechanical energy.

In an electromagnet the current is generated by the magnetic field. To determine the magnetic field energy stored in the motor let the electromagnetic structure shown in Fig. 2.6 be considered. It consists of primary part, which does not move and the secondary part that can move and does not have the winding.

Assuming that the secondary part does not move, the instantaneous voltage across the terminals of a single-phase SRM winding is related to the flux linked in the winding by Faraday’s law,

\[
v = iR + \frac{d\lambda}{dt}
\]

(2.1)

where,
\( v \) - is the terminal voltage,

\( i \) - is the phase current,

\( R \) - is the motor resistance,

\( \lambda \) - is the flux linked by the winding.

**Fig. 2.6 Illustration to derivation of formula for field energy of a SRM.**

The flux linkage in a SRM varies as a function of rotor position, \( \theta \) and the motor current \( i \). Thus the equation can be represented as:

\[
\frac{dv}{dt} = iR + \frac{d\lambda}{di} \frac{di}{dt} + \frac{d\lambda}{d\theta} \frac{d\theta}{dt}
\]  

(2.2)

Where \( \frac{d\lambda}{di} \) is defined as winding inductance \( L(\theta, i) \), which is a function of rotor position and current. Multiplying each side of equation by the electrical current, \( i \), gives an expression for the instantaneous power in an SRM:

\[
vi = i^2R + i \frac{d\lambda}{di} \frac{di}{dt} = i^2R + i \frac{d\lambda}{di} \frac{di}{dt}
\]  

(2.3)

The left hand side of the equation represents the electrical power \( P_e \), delivered to the SRM. The first term on the right hand side represents the ohmic losses and the second
term represents the electric power at coil terminal, which is a sum of mechanical output and any power stored in SRM.

\[ P_e = L \frac{di}{dt} \]  \hspace{1cm} (2.4)

The relation between power and energy is,

\[ \frac{dW_e}{dt} = P_e \]  \hspace{1cm} (2.5)

Where \( W_e \) is a part of the total energy delivered to the winding, which is a sum of energy stored in the coil \( W_f \) and energy converted into mechanical work \( W_m \). It can be written as:

\[ W_e = W_f + W_m \]  \hspace{1cm} (2.6)

The magnetic field energy \( W_f \) can be given by the equation,

\[ W_f = \int id\lambda \]  \hspace{1cm} (2.7)

The graphical interpretation of the field energy is shown in the Fig. 2.7.

The \( \lambda - i \) characteristic curve shown in Fig. 2.7 will become more flat and straight as the air gap displacement \( \Delta \theta \) between stator and rotor poles of the system increases. This is because, to maintain the same magnetic flux, greater current should flow in the winding and consequently greater energy is stored in the magnetic circuit.

Since the volume of magnetic core remains unchanged, the field energy in the air gap increases. Fig. 2.8 shows the \( \lambda - i \) characteristics for various air-gaps in the machine.

The energy stored in the magnetic field with the air gap \( g \), can be expressed in terms of magnetic flux density \( B_g \) as follows,

\[ W_f = \int \frac{B_g}{\mu_0} dB_g \cdot V_g = \frac{B_g}{2\mu_0} \cdot V_g \]  \hspace{1cm} (2.8)
From the above equation we see that the field energy is inversely proportional to the permeability and directly proportional to the volume $V_g$.

The area below the curve in Fig. 2.9 is defined as magnetic field co-energy $W'_f$. The equation can be written as:

$$W'_f = \int_{0}^{i} \lambda \cdot di$$

(2.9)

It does not have any physical significance but it helps in determining the magnetic torque acting on the rotor. Co-energy and energy of the system are shown in the Fig. 2.9.
If $\lambda - i$ characteristic is nonlinear then $W'_f > W_f$, but if $\lambda - i$ characteristic is linear (straight line) then $W'_f = W_f$.

![Fig. 2.9 Field energy $W_f$ and field Co-energy $W'_f$.](image)

Let the system shown in Fig. 2.6 be considered again. If the secondary part has moved slowly the current, $i = v/R$ remains the same at both positions in the steady state because the coil resistance does not change and the voltage is set to be constant.

![Fig. 2.10 Illustration to the magnetic force derivation.](image)

The operating point has moved upward from point $a \rightarrow b$ (Fig. 2.10). During the motion the increment of electric energy that has been sent to the system is:

$$dW_e = \int e \cdot i \cdot dt = \int i \cdot d\lambda = area(abcd) \quad (2.10)$$

The field energy that has changed by this increment is:
\[ dW_f = area(0bc - 0ad) \]  
(2.11)

The mechanical energy,
\[
dW_m = dW_e - dW_f \\
= area(abcd) + area(0ad) - area(0bc) \\
= area(0ab)
\]  
(2.12)

is equal to the mechanical work done during the motion of the secondary part and is represented by the shaded area in Fig. 2.10. This shaded area can also be seen as the increase in the co-energy:
\[ dW_m = dW'_f \]  
(2.13)

Since:
\[ dW_m = f_m dx \]  
(2.14)

the force \( f_m \) that is causing differential displacement is:
\[
f_m = \left. \frac{\partial W'_f(i, x)}{\partial x} \right|_{\lambda=\text{const}}
\]  
(2.15)

In a linear system the coil inductance \( L \) linearly varies with the primary position for a given current. Thus for the idealized system:
\[ \lambda = L(x, i) i \]  
(2.16)

Since the field co-energy is given by the Eqn. 2.9, after inserting the value of \( \lambda \) from Eqn. 2.16 into Eqn. 2.9 we obtain:
\[
W'_f = \int_0^i L(x, i) i \cdot di = \frac{1}{2} L(x) i^2
\]  
(2.17)

The magnetic force acting on the secondary part is then obtained from Eqns. 2.15 and Eqn. 2.17:
\[
f_m = \left. \frac{\partial}{\partial x} \left( \frac{1}{2} L(x) i^2 \right) \right|_{\lambda=\text{const}} = \frac{1}{2} i^2 \left. \frac{dL(x)}{dx} \right|
\]  
(2.18)
For a linear system the field energy is equal to the co-energy, thus:

$$W_f = W'_f = \frac{1}{2} L(x) \cdot i^2$$  \hspace{1cm} (2.19)

If the primary part of the reluctance motor is an electromagnet (Fig. 2.11) we can use Eqn. 2.18 to determine the linear force $f_x$ acting on the secondary part. The data that is required is the current $i$ flowing in the primary winding and the inductance $L(x)$ expressed as the function of the $x$ coordinate.

There is another force, attractive force $f_y$, which can be expressed in terms of magnetic flux density in the air-gap $B_g$. If we assume that the magnetic field intensity in the core $H_c$ is negligible (due to high permeability $\mu_c$ of the core), then, for the electromechanical system in Fig. 2.6, the relation between the current, number of turns and field intensity is given by:

$$Ni = H_g 2g = \frac{B_c}{\mu_0} 2g$$  \hspace{1cm} (2.20)

thus,

$$i = \frac{B_c}{N\mu_0} 2g$$  \hspace{1cm} (2.21)

![Fig. 2.11 Force component $f_x$ produced in the linear reluctance motor.](image)

The coil inductance $L$ depends on the reluctance of the magnetic circuit which is given by:
\[ L = \frac{N^2 \mu A_n}{g} \]  

(2.22)

From Eqns. 2.17, 2.19 and 2.21 we obtain:

\[ W_f' = \frac{B_g^2}{2\mu_0} \cdot A_g \cdot 2g \]  

(2.23)

The above expression can also be obtained from the field energy. For the linear magnetic circuit \( W_f' = W_f \) and negligible the magnetic energy stored in the core:

\[ W_f' = \frac{B_g^2}{2\mu_0} \cdot V_g = \frac{B_g^2}{2\mu_0} \cdot A_g \cdot 2g \]  

(2.24)

where, \( A_g \) is the active area of the air-gap.

From Eqns. 2.15 and 2.24 the normal force acting on the secondary part is:

\[ f_y = \frac{\partial}{\partial g} \left( \frac{B_g^2}{2\mu_0} \cdot A_g \cdot 2g \right) = \frac{B_g^2}{2\mu_0} \cdot 2A_g \]  

(2.25)

It means that the magnetic force is proportional to the magnetic flux density in square.

2.3 Types of Switched Reluctance Motors and Their Features

Switched reluctance motors may be classified on the basis of the motion, direction of the flux path and electronic converters. Based on the nature of motion they are classified as:

- Rotatory switched reluctance motor (RSRM)
- Linear switched reluctance motor (LSRM)

The magnetic circuit of a 4-phase reluctance rotary machine is shown in Fig. 2.12. The magnetic core of the stator has salient poles with solenoidal coils. The magnetic core of the rotor also has salient poles and no winding of any kind. The magnetic circuit of the LSRM is shown in Fig. 2.13. It has an active stator, a passive translator that is analogous to the rotor in a RSRM. A LSRM may have windings either
on the stator (primary) or translator (secondary). The LSRM configuration corresponds to a 6/4 (number of stator poles/number of rotor poles) RSRM configuration.

![Fig. 2.12 Rotary switched reluctance motor [5].](image)

Based on the direction of the flux path with respect to the axial length of the machine the SRMs are further differentiated as:

- Longitudinal flux configuration
- Transverse flux configuration

If the magnetic field path is perpendicular to the shaft, which is seen along the radius of the cylindrical stator and rotor, the SRM is classified as radial field or transverse configuration. Fig. 2.14 shows the structure of a transverse flux configuration. When the flux path in the back of core of both the static and moving parts are longitudinal, the machine is called an axial field SRM or longitudinal flux SRM. Fig.

![Fig. 2.13 Linear switched reluctance motor (LSRM) [6].](image)
Fig. 2.14 Transverse flux configuration of LSRM [7].

Fig. 2.15 Longitudinal flux configuration of LSRM [7].

SRMs cannot run directly from a DC bus or an AC line, but must always be electronically commutated. A large number of topologies for SRM converters have been proposed [8]. Fig. 2.16 shows a power converter for a four-phase switched reluctance drive. There is one converter unit per phase. Each phase is supplied with DC voltage by its power - electronic converter unit, as dictated by the control unit a driving force is produced, which tends to move the secondary poles in line with the energized primary poles. When both transistors are turned ON current will build–up.

Fig. 2.16 Four-phase switched reluctance driver.
Chapter 3: Construction and Principle of Operation of Single-Phase Linear Reluctance Motor

3.1 Construction of the Motor

A linear reluctance motor is the counterpart of the rotating reluctance motor. There are different versions of linear reluctance motors [7]. One among them is the motors with transverse flux. In this chapter two types of transverse flux motors are considered:

- U shape primary core motor
- E shape primary core motor

3.1.1 Single Phase Reluctance Motor with U-Shaped Primary Core

The motor structure is shown schematically in Fig. 3.1. The motor consists of primary part that possesses the winding and secondary part. The winding of the primary is supplied by the voltage $v$, which causes the current $i$ to flow. The current produces the magnetic flux $\phi$ that is closed through the path that is perpendicular to the direction of motion (axis $x$).

![Fig. 3.1 Single-phase linear reluctance motor with U-shaped primary core.](image)

Due to the magnetic field, the primary part is affected by two forces: linear force $f_x$ and attraction force $f_y$. The linear force, which is the driving force, is expressed by the formula:
\[ f_x = \frac{1}{2} l^2 \frac{dL(x)}{dx} \quad (3.1) \]

where, \( L(x) \) is the coil inductance which is expressed as the function of \( x \) co-ordinate.

The higher the value of \( \frac{dL(x)}{dx} \), the stronger the driving force. One of the aims of design calculations is to obtain the highest value of inductance gradient.

The inductance of the primary coil is expressed by the function that depends on the shape of primary and secondary core. For the construction shown in Fig. 3.1 it may be approximated by the function

\[ L = L_m \left[ 1 + \cos\left(\frac{\pi}{l} x\right) \right] + L_{\text{min}} \quad (3.2) \]

shown graphically in Fig. 3.2. In Eqn. 3.2 \( L_m = \frac{L_{\text{max}} - L_{\text{min}}}{2} \).

The force that is proportional to \( \frac{dL(x)}{dx} \) is changing not only in value but also in its direction, which is seen in the derivative of inductance:

\[ \frac{dL(x)}{dx} = -L_m \sin\left(\frac{\pi}{l} x\right) \times \frac{\pi}{l} \quad (3.3) \]

When the position of the center of the coil is at \( -x_1 \), (Fig. 3.2) the force is positive and at position \( +x_1 \), it is negative. The primary placed between the elements of secondary part is not affected by the \( x \) directed force. The same is when the primary is placed in the middle of secondary element.

The primary is always affected (when coil is excited) by the attractive force, expressed by the equation:

\[ f_y = \frac{B^2}{2\mu_0} \cdot A_g \quad (3.4) \]
where, $B$ is the magnetic flux density in the air-gap and $A_r$, is the active area between the two motor parts. This force will also change during the primary part movement along $x$ co-ordinate, due to the variation in $B$.

![Fig. 3.2 Inductance and derivative of inductance changing.](image)

One of the disadvantages of the single-phase motor is the lack of starting force at positions when the primary is aligned with secondary or is placed between its elements. Another disadvantage is that at certain positions, it develops negative force (at $+x_1$, Fig. 3.2). To overcome these deficiencies one of the part must be asymmetrical or a permanent magnet PM has to be applied [9] as shown in Fig. 3.3. When the coil is de-energized the primary coil always takes the position at the edge of the secondary element because the PM takes the position in the middle of the secondary element. The primary when energized will develop a strong starting force at this position, which is always in positive direction. The permanent magnet will experience the force which changes its direction but the average value remains zero when moving.
3.1.2 Single Phase Reluctance Motor with E-Shaped Primary Core

The principle of operation of this version of the motor is similar to the previous one. The only difference is in the structure (Fig. 3.4). In this structure the primary coil contributes greatly to the magnetic flux than in the U-shaped core version. Of course, to take the advantage of this, the primary should be designed in such a way that the value of $\frac{dL(x)}{dx}$ is maximized.

The performance of the motor is strongly dependent on the supply. In the next section the operation of the motor under DC and AC supply are discussed.

3.2 Operation of Reluctance Motor under Different Supply Conditions

The linear reluctance motor studied in this thesis can operate under AC and DC supply. In each case the motor operates on a different principle and due to this, different performance is expected. In this section the operation and parameters of AC and DC supply source, are discussed.
3.2.1 AC Supply

The reluctance motor when supplied from AC source operates on the principle of resonance in RLC circuit of primary part. The circuit diagram of the motor is shown in Fig. 3.5. The primary coil moves with respect to the secondary in the $x$ direction. During this motion the inductance of the coil $L$ changes since it depends on the position of the primary part with respect to the secondary part.

Suppose, the middle of the primary coil is placed at the distance $-x_1$ (see Fig. 3.5) then the inductance of the coil is equal to $L(-x_1)$ as shown in Fig. 3.6.

![Fig. 3.5 LRM supplied from an AC source.](image)

![Fig. 3.6 Inductance and the derivative of inductance wave forms.](image)
Since the force acting on the primary part is \( f_m = 0.5i^2 \frac{dL}{dx} \) and the derivative \( \left( \frac{dL(x)}{dx} \right) \bigg|_{x=x_1} \) is positive it will be pulled to the middle \((x = 0)\) of the secondary element.

Due to the inertia of the primary part, it moves further to the second edge of secondary element. During its movement it will experience the negative force beyond ‘0’ point but this braking force is less than the driving force, which the primary experiences before ‘0’ point [2]. The resultant effect is that the primary part is leaving the present secondary part and approaching the next secondary part where again it is driven towards the positive direction of \(x\)-axis. The resultant effect of an interaction of primary and secondary part is the motion of the motor in \(x\)-direction.

To increase the force that drives the primary part the capacitor \(C\) is connected in series with the coil. If its capacitance is chosen to give the resonance in RLC circuit, for example at position \(-x_1\) (Fig. 3.7) then the heavy coil current floes and the coil is pulled towards ‘0’ point with a very strong force.

The resultant effect is that primary part gets the “kick” at the place when resonance occurs moving more effectively along the \(x\)-direction. In order to determine the capacitance at particular primary position the resonant condition formula is used.

\[
C = \frac{1}{(2\pi \cdot f)^2 L(x_1)} \tag{3.5}
\]

**Fig. 3.7** Inductance and resonance current as a function of displacement \(x\).
3.2.2 DC Supply

The primary part when supplied from AC source is being driven by the magnetic force practically only during the time when it is moving from \(-x_i\) to the point ‘0’ (Fig. 3.5). During the rest of the cycle, the coil current contributes only to the power dissipation in the coil resistance, but not to the driving. Moreover, when the primary part moves from the center of the secondary element towards its edge (in \(+x\) direction), the magnetic force tries to stop the primary, which diminishes the average driving force over one cycle.

To improve the motor performance the only solution is to supply the coil when it is affected by the force in positive direction \(\frac{dL(x)}{dx}\) is positive - see Fig. 3.6), that is, when the primary moves from the edge (position \(-x_i\)) to the center of the coil (point ‘0’). This of course, requires the application of a controlled switch, which would switch the coil ON and OFF at its particular position with respect to the secondary [10]. It means, the motor must be equipped with a switching circuit instead of a capacitor (Fig. 3.8).

The operation of the motor in such a condition is similar to that of a linear switched reluctance motor. When the motor is supplied from a DC source a controlled switch \(S\) is connected to the coil instead of a capacitor (Fig. 3.8).

Fig. 3.8 A diagram of the motor supplied from a DC source.
A simple circuit diagram for the linear reluctance motor under DC supply is shown in Fig. 3.9. As a switch, power MOSFET would provide a reliable and long-lived method of switching the motor current. When the MOSFET turns ON, the full voltage appears across the motor and the inductance of the coil windings causes the current to flow through the coil. When the MOSFET turns OFF, the energy stored in the inductance of the motor windings forces the diode into conduction. During this time the current is ramping down. Fig. 3.10 shows the two modes of operation under DC supply condition. After a period of time, the MOSFET turns ON again and the cycle repeats. The diode and the resistor, which are connected in parallel to the coil, allow the magnetic energy stored in the coil to be released after switching OFF.

Fig. 3.9 Circuit diagram for linear reluctance motor under DC supply.

Fig. 3.10 Switch control of a DC motor. (a)MOSFET conduction cycle (b) diode “flyback” conduction cycle on the right.
Chapter 4: Design Calculations of Linear Reluctance Motor

The aim of the design calculations is to determine the main dimensions of the primary part and secondary part of LRM and to find out the winding parameters: inductance $L$ and resistance $R$ for the required (assumed) force, speed, mechanical power, supply voltage and frequency. For the purpose of this thesis it was assumed that the primary and secondary core dimensions are of elements available in the lab. The available supply source is 110v voltage and 60Hz frequency. The dimensions of the motor are shown in Fig. 4.1.

![Diagram of motor dimensions](image)

The unknown parameters that will be determined from the design calculations in the following section are:

$N$ – number of coil turns,

$R$ – winding resistance,
4.1 Number of Primary Winding Turns

In general the winding will be supplied from AC and DC source. In case of AC supply the number of turns decides the voltage for a given permissible flux density in the core. According to Faraday’s law the induced voltage $e$ depends on the rate of change of flux $\phi$, according to the equation

$$e = N \times \frac{\partial \phi}{\partial t}$$  \hspace{1cm} (4.1)

where $\phi = \phi_m \sin \omega t$.

The rms value of this voltage is

$$E = \sqrt{2} \pi N \times f \times \phi_m \approx 4.4 f \cdot N \cdot \phi_m$$  \hspace{1cm} (4.2)

where $\phi_m = A_c \cdot B_c$,

$A_c$ - is the area of the core cross section,

$B_c$ - is the permissible magnetic flux density, which, for the laminated steel is equal to 1.8 T.

Assuming: $V \approx E$, Eqn. 4.2 can be rewritten to calculate the number of turns

$$N = \frac{V}{4.4 f \cdot B_c \cdot A_c}$$  \hspace{1cm} (4.3)

where, $V$ is the supply voltage. Fig. 4.1 shows the dimensions of the motor.

According to the dimensions of the motor shown in Fig. 4.1

$$A_c = a \times n = 0.0278 \times 0.01117 = 3.105 \times 10^{-4} \text{m}$$

From Eqn. 4.3 the number of turns is
\[
N = \frac{110}{4.4 \times 60 \times 1.8 \times 3.105 \times 10^{-4}} = 745.5
\]

The number taken to further calculations is \( N = 746 \) turns

### 4.2 Winding Resistance

The resistance of the coil depends on the type of the material and shape of the material. It is proportional to the length of the wire \( l_w \), its resistivity \( \rho \) and inversely proportional to cross section area \( A_w \).

\[
l_w = N \cdot l_c \quad (4.4)
\]

\[
R_c = \rho \frac{l_w}{A_w} \cdot N \quad (4.5)
\]

The average length of the coil \( l_c \) can be determined from the following equation (see Fig. 4.2)

\[
l_c = 2 \times n + 2 \times d + 4 \times \frac{l}{2} \times \frac{\pi}{2} \quad (4.6)
\]

\[
l_c = 2 \times 2.8 + 2 \times 1.06 + 4 \times \frac{1.5}{2} \times \frac{\pi}{2} = 0.1243 \text{ m}
\]

Area of the wire is determined from the following equation:

\[
A_w = \frac{A_{cu}}{N} \quad (4.7)
\]

Area of the copper coil \( A_{cu} \) can be found from the total area \( A_c \) occupied by the coil.

\[
A_{cu} = A_c \cdot K_{cu} \quad (4.8)
\]

where coefficient \( K_{cu} = 0.5 \) [9].

For the dimensions shown in Fig. 4.1,

\[
A_c = b \times e = 0.0379 \times 0.015 = 5.685 \times 10^{-4} \text{ m}^2
\]

\[
A_{cu} = 5.685 \times 10^{-4} \times 0.5 = 2.84 \times 10^{-4} \text{ m}^2
\]
Thus the diameter of the wire used to wind round the iron core can be calculated as:

\[ d_w = 2 \times \sqrt{\frac{3.806 \times 10^{-7}}{\pi}} = 6.963 \times 10^{-4} \, m \]

Substituting the values of \( l_w \) and \( A_w \) we get the resistance of the coil, which, for copper resistivity \( \rho = 16 \times 10^{-9} \, \Omega \cdot m \) is,

\[ R_c = \frac{16.8 \times 10^{-9} \times 12.43 \times 10^{-2} \times 746}{3.806 \times 10^{-7}} = 4.092 \, \Omega \]

Fig. 4.2 Average length of the winding coil.

The resistivity is temperature dependent. The resistance increases as the temperature increases according to the equation:

\[ R^* = R_{r_1} \frac{T_2 - \beta_{cu}}{T_1 - \beta_{cu}} \quad (4.9) \]

where,

- \( R_{r_1} \) - resistance at ambient temperature,
- \( T_1 \) - ambient temperature,
\( T_2 \) - temperature during the operation,

\( \beta_{cu} = 38 \) - coefficient for copper winding.

### 4.3 Determination of the Winding Inductance

Performance of LRM depends predominantly on the inductance of the primary winding. Hence, determination of this inductance with a good accuracy is very important. The winding inductance \( L \) will be determined from the magnetic flux linkage \( \lambda \) according to the equation

\[
L = \frac{\lambda}{i} \quad (4.10)
\]

For a simplified model of the motor, when the saturation of the iron core and the leakage flux are not considered (Fig. 4.3), the coil inductance is,

\[
L = \Lambda_m \cdot N^2 \quad (4.11)
\]

where,

- \( N \) – number of coil turns,
- \( \Lambda_m \) - permeance for the main flux \( \phi \) equal to,

\[
\Lambda_m = \mu_0 \mu_r \frac{A}{l_g} = \frac{a \cdot l}{2g} = \frac{\mu_0 \cdot a \cdot \mu_r}{2g} \quad (4.12)
\]

After substituting Eqn. 4.12 in Eqn. 4.11 the inductance is

\[
L = \mu_0 \cdot l \cdot N^2 \cdot \Gamma \quad (4.13)
\]

where, \( \Gamma = \frac{a}{2g} \cdot \mu_r \).

In case of primary being placed between two secondary elements, the leakage flux cannot be ignored and the very simple Eqn. 4.13 cannot be used. In this case the finite element method (FEM) is the best suitable method to determine the inductance.
This method had been understood, at least in principle, for more than 50 years. The fundamental procedure in the application of the FEM is in the subdivision of the domain of study into simple domains of finite dimensions. Over each of these domains, called finite elements, the unknown function is approximated by a polynomial, the degree of which can vary from one application to another, but which is usually small [11]. These elements, triangles or quadrilaterals, must create a partition of the domain of study.

Finite element analysis, in general, provides more accurate results than the magnetic equivalent circuit approach because it considers a large number of flux paths compared to the magnetic equivalent circuit method. Therefore, it is very often used to verify the accuracy of the analytical method and the design procedure.

To determine the magnetic field distribution in the LRM, the following assumptions are made:

- The magnetic field distribution is constant along the longitudinal direction of the LRM (z direction see Fig. 4.3).
• The magnetic field outside the LRM periphery is negligible and has zero magnetic vectors potential.

• Hysteresis effect is neglected under the assumption that the magnetic materials of the primary and secondary are isotropic and the magnetization curve is single valued.

• The end effects are neglected.

Calculation of magnetic field distribution and coil inductance was done using the program called P_rys developed by Dr. A. Demenko [12]. This program is based on FEM applied to 2-D structure.

In this program the 2-D space is covered by the net of triangles that represent the finite elements (Fig. 4.4). Due to symmetry only one half of the motor is considered with the infinitely long in $x$ direction\(^1\) (see assumptions). The data of the primary and secondary are introduced to the program in the tool bar above and on the left side (Fig. 4.4).

The symbols used refer to the dimensions shown in Fig. 4.5. The program also allows changing the network elements shown in Fig. 4.6.

After inserting the data the program calculates the parameters $\Gamma$ (see Eqn. 4.12), which allows calculating inductance $L$ of the coil. The data inserted into the program are shown in Table 4.1.

It was assumed that the inductance of the primary winding is changing with the position of the coil according to the equation:

$$L = L_m \left[ 1 + \cos\left(\frac{\pi l}{l_{max}} x \right) \right] + L_{min} \quad (4.14)$$

\(^1\) The axis directions $x, y, z$ considered in Fig.4.3 are different from the axis directions considered in the P_rys software.
Fig. 4.4 Network view of the finite element software P_rys.

Fig. 4.5 Structural view of model.
Fig. 4.6 Description of network parameters for Type-0 model.

Table 4.1 Parameters inserted in the program that corresponds to the real motor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ho$</td>
<td>3.8 cm</td>
</tr>
<tr>
<td>$hoy$</td>
<td>1.5 cm</td>
</tr>
<tr>
<td>$hu$</td>
<td>3.7 cm</td>
</tr>
<tr>
<td>$wu$</td>
<td>1.5 cm</td>
</tr>
<tr>
<td>$del$</td>
<td>0.1 cm</td>
</tr>
<tr>
<td>$hs$</td>
<td>6.0 cm</td>
</tr>
<tr>
<td>$gx = gy_2 = gy_1$</td>
<td>1.1 cm</td>
</tr>
<tr>
<td>$\frac{hoy}{ho}$</td>
<td>$\frac{1.5}{3.79} = 0.39$</td>
</tr>
<tr>
<td>$\frac{hu}{ho}$</td>
<td>$\frac{3.7}{3.7} \approx 0.99$</td>
</tr>
<tr>
<td>$\frac{wu}{hoy}$</td>
<td>$\frac{1.5}{1.5} = 1.00$</td>
</tr>
<tr>
<td>$\frac{del}{ho}$</td>
<td>$\frac{0.1}{3.79} = 0.026$</td>
</tr>
</tbody>
</table>
It means that inductance in the presence of the secondary \( L_{\text{max}} \) and in the absence of the secondary \( L_{\text{min}} \) should be determined. According to this, calculations were done and the results are as follows:

\[
\begin{align*}
\Gamma_{\text{max}} & = 7.0886 \\
\Gamma_{\text{min}} & = 1.167
\end{align*}
\]

Since the parameters:

\[
l = 2.84 \times 10^{-2} \ m
\]

\[
N = 746 \ \text{turns}
\]

The inductance values are:

\[
L_{\text{max}} = 7.0886 \times 746^2 \times 4 \pi \times 10^{-7} \times 2.84 \times 10^{-2} = 0.137 \ \text{H}
\]

\[
L_{\text{min}} = 1.167 \times 746^2 \times 4 \pi \times 10^{-7} \times 2.84 \times 10^{-2} = 0.02258 \ \text{H}
\]

The flux density distribution calculated for the two cases mentioned above are shown in Fig. 4.7 and Fig. 4.8 in the form of magnetic field lines. The function that describes the winding inductance has finally the form:

\[
L = L_m \left[1 + \cos \left(\frac{\pi}{l} x\right) \right] + L_{\text{min}} = 0.05785 \left[1 + \cos \left(\frac{\pi}{0.028} x\right) \right] + 0.02258
\]

Where, \( L_m = \frac{L_{\text{max}} - L_{\text{min}}}{2} = \frac{0.137 - 0.02258}{2} = 0.05785 \ \text{H} \)

- **Fig. 4.7** Flux lines passing through the electromagnet and the iron bar.
4.4 Mass of the Primary

Mass depends on the density and the volume of a substance. Density \( d \) relates mass \( M \) of a substance to its volume \( V \) through the formula:

\[
M = d \times V
\]

If the geometry of block is simple, then the volume can be calculated from the linear dimensions. Here the volume of the primary core and the copper windings are calculated separately. The total mass is the sum of these individual masses. Since the volume of the particular element is filled with air, the volume of pure iron \( V_{Fe} \) and pure copper \( V_{Cu} \) is less than the volume of core \( V_c \) and coil \( V_{coil} \). Thus the estimated values of coefficients are \( K_{Fe} \leq 1 \) and \( K_{Cu} = 0.5 \) [9].

The volumes of the primary core and winding are:

\[
V_{Fe} = K_{Fe} \cdot V_c \\
V_{Cu} = K_{Cu} \cdot V_{coil}
\]

The volume of iron core \( V_c = 2(a \times n \times f) + b \times d \times n = 27.06 \times 10^{-6} \text{ m}^3 \)

The volume of the copper wire \( V_{coil} = [h \times b \times n - b \times d \times n] = 56.662 \times 10^{-6} \text{ m}^3 \)
Hence

$$V_{Fe} = 1 \times 27.06 \times 10^{-6} = 27.06 \times 10^{-6} \, m^3$$

$$V_{Cu} = 0.5 \times 56.662 \times 10^{-6} = 28.331 \times 28.33 \times 10^{-6} \, m^3$$

Since,

Density of iron $d_{Fe} = 0.011 \, kg/cm^3$

Density of copper $d_{Cu} = 0.08930 \, kg/cm^3$

The mass of primary core $M_c = 27.06 \times 11.34 = 0.305 \, kg$

Mass of the copper wire $M_{Cu} = 28.331 \times 8.930 = 0.252 \, kg$

Total mass $M_t = M_c + M_{Cu} = 0.557 \, kg$

(a) (b)

Fig. 4.9 Dimensions of the primary core with the coil windings.
Chapter 5: Computer Simulation Analysis of the Motor

5.1 Motor Performance under AC Supply

5.1.1 Mathematical Model of the Motor

This chapter deals with the analysis of the motor’s behavior when supplied from an AC source. It operates on the basis of resonance in an RLC circuit. It consists of a coil which is connected in series with a capacitor and energized from an AC voltage source (Fig. 5.1).

![Diagram of the motor supplied from AC source.](image)

The equilibrium equation for the electromagnetic system when supplied with AC source can be written as follows:

For electrical port:

$$ v_s = Ri + \frac{1}{C} \int i \cdot dt + i \frac{dL(x)}{dt} + L(x) \frac{d}{dx} \frac{di}{dt} \tag{5.1} $$

where,

- $v_s$ - AC voltage applied,
- $R$ - coil resistance,
- $i$ - coil current,
- $L(x)$ - coil inductance, which depends on the position of the primary,
- $C$ – capacitor.
For mechanical port:

\[ f_m = M \frac{d^2 x}{dt^2} + D \frac{dx}{dt} + f_L \]  

(5.2)

The magnetic force \( f_m \) is expressed by the following formula:

\[ f_m = 0.5i^2 \frac{dL(x)}{dx} \]  

(5.3)

where,

\( f_m \) - the magnetic force acting on the secondary,

\( M \) – mass of the primary,

\( D \) – the damping coefficient which represents the secondary friction,

\( f_L \) - load force.

To solve the above equations numerically using PC-MATLAB/SIMULINK software package they are transformed and written in Laplace domain in the following form:

for the mechanical system,

\[ sM \frac{fu}{D} + Lu \frac{Ld}{Ld} = \]  

(5.4)

for the electrical circuit,

\[ \omega V_{sm} \cos(\omega t) - [R + 2L_{dd} \cdot u] si - \left[ \frac{1}{C} + L_{dd} \cdot u^2 \right] \frac{dx}{dt} \]  

(5.5)

where, \( L_d = \frac{dL(x)}{dx} \), \( L_{dd} = \frac{d^2 L(x)}{dx^2} \), \( u = \frac{dx}{dt} \)

5.1.2 Performance of the Motor

5.1.2.1 Block Diagram of the Motor in SIMULINK

To analyze the performance of the linear reluctance motor it is assumed that all
the variables of the electromagnetic system under study are linear. Eqn. 5.1, 5.2 describes fully the operation of the system. The simulation block diagram that implements these basic equations is shown in Fig. 5.2. It consists of two parts, viz. the electric circuit and the mechanical system. Fig. 5.3 shows the subsystem for inductance calculation.

![Fig. 5.2 SIMULINK block diagram of the LRM with an AC supply.](image)

![Fig. 5.3 Simulation subsystem that describes the inductance calculation.](image)
The parameters of the LRM model that are used in the simulation system are as follows:

Coil resistance \( R = 4.096 \, \Omega \),

Mass of the primary \( M_1 = 0.557 \, \text{kg} \),

Inductance as a function of \( x \)
\[
L = 0.05785 \left[ 1 + \cos \left( \frac{\pi}{0.028} x \right) \right] + 0.02258,
\]

Damping coefficient \( D = 0.02 \, N \cdot s/m \),

Length of the secondary (equal to length of the primary) \( l = 0.028 \, \text{m} \).

5.1.2.2 Simulation of Motor Starting

The operation of the motor under AC supply depends on the position at which the resonance occurs in the circuit. The position at which the resonance occurs can be controlled by varying the capacitance according to the Eqn. 3.3. Here the simulations were carried out when the primary is placed at distance of \( x = -0.024 \, \text{m} \) from the center of the secondary. The value of capacitor \( C = 0.0295 \, \mu F \) which corresponds to \( x = -0.025 \, \text{m} \) is where resonance occurs.

Simulation results are shown in Fig. 5.4 and Fig. 5.5. In particular:

- Displacement waveform in Fig. 5.4(a).
- Speed wave form in Fig. 5.4(b).
- Current and voltage wave form in Fig. 5.4(c).
- Magnetic force and \( dL(x)/dx \) wave form in Fig. 5.4(d).
- Input power in Fig. 5.5(a).
- Mechanical power output in Fig. 5.5(b).

The mechanical power \( P_m \) transferred from the electrical circuit to the mechanical system was calculated from the following equation:

\[
P_m = u \cdot f_m \quad (5.6)
\]
The input power $P_{in}$ of the electrical circuit can be determined from the following equation:

$$P_{in} = v_s \cdot i$$  \hspace{1cm} (5.7)

The motor was loaded with the Constance force $F_c = 2 \, N$. The supply voltage $v_s = 110 \, V$. The steady state is reached for the motor after 0.15 seconds when the primary speed is $u = 2.11 \, m/s$ (Fig. 5.4(b)). The value of capacitor is taken as $C = 0.0295 \, \mu F$.

Fig. 5.4(d) shows that the force which drives the bar to the center of the coil is more than the force which pulls the secondary back when it moves towards the edge of the coil.

Fig. 5.5(a) shows the input power $P_{in}$, a small portion of the input power, $P_{in}$, is delivered to the mechanical system $P_m$. During certain periods of the cycle the input power becomes negative, which implies that it is returned to the power source. The maximum efficiency that could be reached is 6 %. This was calculated from the formula:

$$Eff = \frac{P_m}{P_{in}} \cdot 100\%$$  \hspace{1cm} (5.8)

Fig. 5.4 Simulated time characteristics of the motor at starting (a) displacement [x], (b) speed [u], (c) current [i] and velocity [v], (d) Force [F_m] and derivative of inductance [L_s].  \hspace{1cm} (Fig Con’d.)
Fig. 5.5 Simulated time characteristics of the motor at starting (a)-(b) power in the motor’s electric circuit \([P_i]\), (c)-(d) power in the motor’s mechanical system \([P_m]\).
The results of simulation are enclosed in table 5.1.

Table 5.1 Average input power, output power and efficiency.

<table>
<thead>
<tr>
<th>$P_{in}$ (W)</th>
<th>$P_{m}$ (W)</th>
<th>Eff %</th>
</tr>
</thead>
<tbody>
<tr>
<td>132.2</td>
<td>7.8</td>
<td>5.9</td>
</tr>
</tbody>
</table>

The behavior of the motor under AC supply is rather difficult to analyze. It depends on the place where the primary is initially placed. At certain positions it develops negative force. The place where the resonance occurs depends on the value of capacitor which is fixed for the simulation, hence for that simulation care should be taken so that the primary is placed approximately at the place where the resonance occurs. Otherwise the behavior of the motor may be unpredictably.

To avoid this kind of a situation, one of the parts of the primary must be asymmetrical or permanent magnet PM has to be applied as shown in Fig. 3.3. When the coil is de-energized the primary always takes the position at the edge of the secondary element because the PM takes the position in the middle of the secondary element.

When the motor was supplied from AC source maximum efficiency that could be reached is 6 %. The reason for this is that, the primary is being driven by the magnetic force practically only during the time when the resonance occurs. During the rest of the cycle, though the coil current is much smaller, it contributes to the power dissipation in the coil resistance, rather than driving the bar [10]. When the primary moves from the center of the coil towards its edge, the magnetic force brakes the bar, which diminishes the average driving force over one cycle.

To improve the motor performance further the only solution is to supply the coil when it strictly contributes to driving the bar. This requires the application of a controlled switch which would switch the coil ON and OFF with respect to the position.
of the bar. A motor equipped with such a switch and supplied from DC source is further
studies in next section.

5.2 Motor Performance under DC Supply

5.2.1 Mathematical Model of the Motor

This section deals with the analysis of the motor’s behavior when supplied from
DC source. Here the principle of operation is different when compared to motor under
AC supply. Under DC supply the motor must be equipped with a switching circuit
instead of a capacitor (Fig. 5.6).

The equilibrium equation for the whole electromagnetic system when supplied from a
DC source can be written as follows:

\[
\frac{dv_s}{dx} = R + \frac{dL(x)}{dt} i + L(x) \frac{di}{dx} \frac{dx}{dt}
\]

Where,

\[ v_s \] - DC voltage applied,

\[ R \] - coil resistance,

\[ i \] - coil current,

\[ L \] - coil inductance which depends on the position of the primary.

![Fig. 5.6 The diagram of the motor supplied from a DC source.](image)
For DC supply as the capacitor is replaced by a switch the term \( \frac{1}{C} \int i \cdot dt = 0 \).

Under DC supply there are two modes of operation. First when the switch is open, and second when the switch is closed.

The equilibrium equations for the two modes of operation are as follows (Fig. 5.7):

\[
L \frac{di}{dt} + i \frac{dL}{dx} \frac{dx}{dt} + i \cdot R = v_s \quad \text{(When the switch is closed (Fig. 5.7(a)))} 
\]

\[
L \frac{di}{dt} + i \frac{dL}{dx} \frac{dx}{dt} + i \cdot (R + R_D) = 0 \quad \text{(When the switch is open (Fig. 5.7(b)))} 
\]

Where, \( R_D \) - is the diode resistance.

The above equations were derived on the assumption that the voltage drop across the diode and MOSFET were negligible.

To solve the above equations numerically using PC-MATLAB/SIMULINK software package they are transformed and written in Laplace domain in the following form:

\[
\frac{v(s) - i(s) \cdot R - \frac{dL}{dx} \frac{dx}{dt} \cdot i(s)}{sL(x)} = i(s) 
\]

\[
\frac{v(s) - i(s) \cdot R - L_d \cdot i(s) \cdot u}{sL} = i(s) 
\]
where, $L_d = \frac{dL}{dx}$

For the mechanical port, the second-order differential equation can be expressed by the following formula:

$$f_m = M \frac{d^2x}{dt^2} + D \frac{dx}{dt} + f_L = M \frac{du}{dt} + Du + f_L$$ \hspace{1cm} (5.14)

where,

$$f_m = 0.5i^2 \cdot \frac{dL(x)}{dx}$$ - the magnetic force acting upon the bar,

$M$ - mass of the primary,

$D$ - the damping coefficient which represents the secondary friction,

$u$ - velocity of the coil.

Eqn. 5.14 written in Laplace domain has the form:

$$u = \frac{f_m - f_L - Du}{sM}$$ \hspace{1cm} (5.15)

### 5.2.2 Performance of the Motor

#### 5.2.2.1 Block Diagram in SIMULINK

To analyze the performance of the linear SRM we assume that all the variables of the electromagnetic system under study are linear. Eqn. 5.12, 5.14 describes fully the operation of the system. The simulation block diagram that implements these basic equations is shown in Fig. 5.8. It consists of two parts viz. the electric circuit and the mechanical system. There are two subsystems: one that concerns the switch control shown in Fig. 5.9 (Appendix – B) and the second one in Fig. 5.10 for inductance calculation.
Fig. 5.8 SIMULINK block diagram of the SRM (DC supply).

Fig. 5.9 Simulation subsystem that describes the switch control.

Fig. 5.10 Simulation subsystem that describes the inductance calculation.
The parameters of the SRM model that are used in the simulation system are as follows:

- **Coil resistance** \( R = 4.096 \Omega \),
- **Mass of the primary** \( M_1 = 0.557 \text{ kg} \),
- **Inductance as a function of } x \) \( L = 0.05785 \left[1 + \cos \left( \frac{\pi}{0.028} x \right) \right] + 0.02258 \text{ H} \),
- **Damping coefficient** \( D = 0.02 \text{ N s/m} \),
- **Length of the secondary (equal to length of the coil)** \( l = 0.028 \text{ m} \),
- **Resistance in diode circuit** \( R_D = 1500 \Omega \).

**5.2.2.2 Simulations of Motor Starting**

When the motor was switched ON, the primary was positioned at a distance of -0.014 m from the center of the secondary (Fig. 5.6). It starts to move immediately after the switch is closed. Simulation results are shown in Fig. 5.11. In particular:

- Displacement waveform in Fig. 5.11(a).
- Speed waveform in Fig. 5.11(b).
- Current and voltage waveform in Fig. 5.11(c).
- Magnetic force and \( \frac{dL(x)}{dx} \) waveform in Fig. 5.11(d).
- Input power in Fig. 5.12(a).
- Mechanical power output in Fig. 5.12(b).

The mechanical power \( P_m \) transferred from the electrical circuit to the mechanical system was calculated from the following equation:

\[
P_m = u \cdot f_m \tag{5.16}
\]

The input power \( P_{in} \) of the electrical circuit was determined from the following equation:

\[
P_{in} = v_s \cdot i \tag{5.17}
\]
The motor was loaded with the Constance force $F_e = 2\, N$. The switching ON and OFF positions were set for $x = 155^\circ$ and $x = 335^\circ$ respectively. The supply voltage was $v_s = 110\, V$.

The steady state is reached for the motor after 2 seconds when the primary speed is 12 m/s (Fig 5.11(b)). Certainly this speed depends on supply voltage and the load force, which is studied in section 5.2.2.4.

Fig 5.11(d) shows that the motor is switched ON when the position of primary gives the positive force, that is when the derivatives $dL(x)/dx$ is positive. The current Fig 5.11(c) is not initially build up to its final value after switching ON due to high value of inductance in relation to coil resistance $R$. It drops to zero almost immediately after switching OFF due to high value of resistance in the diode current $R_D$.

In general, the switching ON position has essential impact on the operation of the motor and its performance. This impact is studied in the next section.

![Fig. 5.11 Simulated time characteristics of the motor at starting](image)

**Fig. 5.11** Simulated time characteristics of the motor at starting (a) displacement $[x]$, (b) speed $[u]$, (c) current $[i]$ and velocity $[v]$, (d) Force $[F_e]$ and derivative of inductance $[L_d]$. (Fig Con’d.)
Fig. 5.12 Simulated time characteristics of the motor at starting (a)-(b) power in the motor’s electric circuit \[ P_{in} \], (c)-(d) power in the motor’s mechanical system \[ P_{m} \].
5.2.2.3 Influence of Switching Angle on Motor Characteristics

The motor behavior under DC supply depends strongly on the position of the switch ON and OFF sensors. At a certain distance from the center the driving force drops practically to zero. Thus to avoid unnecessary power loss, the coil should be switched OFF before this point. After switching off, the coil current drops to zero with the time constant, that depends on circuit resistance and inductance. As force depends on the inductance, positive torque (i.e. driving force) can be produced only if the primary is between the unaligned position and the next aligned position in the forward direction. In other words, driving force can be produced only in the direction of rising inductance. To obtain negative (braking) force, it has to be switched ON during the decreasing part of the corresponding primary inductance region.

A simulation of motor operation at various switching positions was carried out at load force \( F_L = 2 \text{ N} \). The results are enclosed in Table 5.2 for various turn ON positions, while keeping the turn OFF position constant and equal to \( 335^\circ \).

In Table 5.2 the switch ON angle \( \beta \) is expressed in degrees. The linear position at which the circuit should be turned ON is converted into degree by the following relation:

\[
\beta = \frac{2\pi}{\tau} \cdot x \tag{5.18}
\]

where \( x \) is the position of the primary placed with respect to secondary and \( \tau = 360^\circ \).

Fig. 5.13 shows the particular turn ON position considered for simulation in terms of phase angle \( \beta \) and distance \( x \) respectively. The maximum efficiency that could be reached when \( x = -0.014 \text{ m} \) and the circuit is switched ON at the optimum time is 55.25%. This was calculated from the formula:

\[
Eff = \frac{P_m}{P_{in}} \cdot 100\% \tag{5.19}
\]
Table 5.2 Average input, output power and efficiency at various switching angles.

<table>
<thead>
<tr>
<th>Switching angle</th>
<th>Case</th>
<th>Power output W</th>
<th>Power Input W</th>
<th>Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°</td>
<td></td>
<td>77.75</td>
<td>153.5</td>
<td>50.651</td>
</tr>
<tr>
<td>47°</td>
<td></td>
<td>69.4</td>
<td>125.6</td>
<td>55.25</td>
</tr>
<tr>
<td>70°</td>
<td></td>
<td>57.1</td>
<td>107.2</td>
<td>53.26</td>
</tr>
<tr>
<td>93°</td>
<td></td>
<td>51.84</td>
<td>96.02</td>
<td>53.0</td>
</tr>
<tr>
<td>110°</td>
<td></td>
<td>41.00</td>
<td>79.2</td>
<td>51.76</td>
</tr>
<tr>
<td>134°</td>
<td></td>
<td>31.22</td>
<td>61.72</td>
<td>50.05</td>
</tr>
<tr>
<td>148°</td>
<td></td>
<td>28.07</td>
<td>61.86</td>
<td>45.37</td>
</tr>
<tr>
<td>180°</td>
<td></td>
<td>20.07</td>
<td>55.86</td>
<td>36.37</td>
</tr>
<tr>
<td>210°</td>
<td></td>
<td>16.07</td>
<td>49.86</td>
<td>32.07</td>
</tr>
</tbody>
</table>
It is observed that maximum efficiency is obtained when the circuit is turned ON at the point ‘a’ (Fig. 5.14) (when the primary leaves the center of the secondary) and turned OFF at the point ‘b’ (before the primary reaches the center of the next secondary). Here, during the time from point ‘a’ to ‘c’ the inductance is decreasing and hence the force is negative (dragging force). From point ‘c’ to ‘b’ the inductance is increasing and force is positive (driving force). It is observed that though there is dragging force acting on the primary the driving force is high, so the average force is large. This average force is more than the average force that is acting on the primary, when the circuit is switched on only when the inductance is raising (Fig. 5.15).
Fig. 5.15 Dragging force and the driving force waveform at maximum efficiency.

Fig. 5.16 shows the influence of the switching angle on motor characteristics. As seen from the graph, maximum efficiency of 55% is reached when the turn ON angle of the motor is at 47°. Here the turn OFF is kept constant at an angle of 335° as shown in Fig. 5.13.

Fig. 5.16 Influence of switching angle ‘ON’ on mechanical power and efficiency.

It is also observed, that the motor has less efficiency when the switch is turned OFF beyond the point where the primary crosses the center of the secondary. When the supply is given constantly without turning it OFF the motor starts to oscillate. This is because the driving force acting on the bar will be equal to the dragging force. So, as the
primary moves towards the edge of the secondary it will be pulled back by the dragging force towards the center of the secondary.

5.2.2.4 Motor Performance for Variable Load Conditions

In practice, motors operate with changing load conditions. The influence of load variation on some of the parameters like the velocity, current, $P_m$ and the efficiency of the motor are studied.

The results shown in Table 5.3 are obtained when the circuit is turned ON at the point when the inductance starts to increase and turned OFF before it starts to decrease.

**Table 5.3 Influence of load on motor performance.**

<table>
<thead>
<tr>
<th>$F_L$ N</th>
<th>I A</th>
<th>$u$ m/s</th>
<th>$P_{in}$ W</th>
<th>$P_m$ W</th>
<th>Eff %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 1.09</td>
<td>12.42</td>
<td>57.96</td>
<td>26.03</td>
<td>44.91</td>
<td></td>
</tr>
<tr>
<td>5 1.28</td>
<td>10.03</td>
<td>66.05</td>
<td>31.23</td>
<td>47.28</td>
<td></td>
</tr>
<tr>
<td>10 1.72</td>
<td>7.40</td>
<td>90.76</td>
<td>38.55</td>
<td>42.47</td>
<td></td>
</tr>
<tr>
<td>20 2.31</td>
<td>5.02</td>
<td>114.80</td>
<td>46.64</td>
<td>40.62</td>
<td></td>
</tr>
<tr>
<td>40 3.19</td>
<td>3.35</td>
<td>151.00</td>
<td>57.34</td>
<td>37.97</td>
<td></td>
</tr>
<tr>
<td>60 3.87</td>
<td>2.65</td>
<td>183.70</td>
<td>65.66</td>
<td>35.74</td>
<td></td>
</tr>
<tr>
<td>80 4.29</td>
<td>2.28</td>
<td>193.20</td>
<td>67.09</td>
<td>34.72</td>
<td></td>
</tr>
<tr>
<td>100 4.79</td>
<td>2.05</td>
<td>213.50</td>
<td>70.81</td>
<td>33.16</td>
<td></td>
</tr>
<tr>
<td>120 5.50</td>
<td>1.90</td>
<td>252.40</td>
<td>76.78</td>
<td>30.41</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5.17(a) shows the velocity and current variation for different load conditions. The velocity steadily decreases with an increase in load. This characteristic reminds of the speed-load characteristic of a series DC motor. Fig. 5.17(b) shows the characteristics of mechanical power $P_m$, and the efficiency with change in load. It can be seen that,
initially as the load increases the efficiency increases and when load is further increased the efficiency started to decrease.

(a)

![Graph showing variation of current and velocity with load.](image)

(b)

![Graph showing variation of $P_m$ and efficiency with load.](image)

Fig. 5.17 (a) Variation of current and velocity with load, (b) Variation of $P_m$ and efficiency with load.
Fig 5.18 shows how the motor speed varies at starting before steady state is reached, when the motor is loaded with different force. At heavy load the speed is changing at steady-state due to the winding commutation.

This is practically not visible at light load and high speeds due to inertia of the moving motor part. It was observed that the motor starts to oscillate when the load is increased beyond 120 N. The motor can be loaded more when operating under DC supply compared to AC supply.

![Graph showing velocity variation for two different load conditions](image)

Fig. 5.18 Variation of velocity for two different load conditions.
Chapter 6: Conclusions

The performance of single-phase reluctance motor with transverse flux was analyzed in this thesis. The motor can operate under AC or DC supply. In case of AC supply the resonance in RLC circuit is utilized to drive the motor. To study the motor operation the mathematical model has been proposed which became the basis for block diagram and simulations were performed using the MATLAB/SIMULINK software package. The results obtained from the simulation in variable load conditions shows, that the motor under AC supply develops a maximum efficiency of 6%. Such low efficiency is caused by the fact that the primary is only driven during the short period of resonance. During the rest of the cycle, the current, though much smaller than at the resonance, contributes exclusively to the power losses in the coil resistance.

A significant improvement in motor performance was obtained under DC supply. In this case the motor is supplied from DC source via inverter and operates as switched reluctance motor. The primary winding, unlike AC supply is powered only during the time when the driving force is positive.

A study of motor performance under DC supply has been carried out using MATLAB/SIMULINK. For this purpose a mathematical model of the inverter-motor set was proposed and the block diagram was built for simulation under variable supply and load conditions. The conclusions from this study are as follows:

- A study on the influence of load on motor performance shows the increase of efficiency up to 55% when the load decreases down to 2 N. The motor can be loaded up to 120 N, still operating properly, while under AC supply it could be loaded only up to 5 N.
- Simulation of the motor operation at variable switching angle shows its influence on motor performance, in particular on its efficiency. The motor
performs at maximum efficiency when the primary winding is switched ON at angle \( \beta_{ON} = 47^\circ \) and turned OFF at \( \beta_{OFF} = 335^\circ \). It means the winding should be switched ON before the motor starts to develop the positive driving force, which is at \( \beta_{ON} = 180^\circ \). This comes from the fact that due to the relatively high winding inductance the winding current reaches the maximum value at point where the motor reveals the best driving conditions (the \( dL/dx \) has its highest value).

- To develop the starting force the motor must be equipped with permanent magnet or its geometrical structure must exhibit magnetic asymmetry irrespective of the type of supply.

Further study on the switched reluctance motor with single-phase winding should focus on optimization of geometrical structure of the primary and secondary part using FEM. The aim is to reach the maximum efficiency and higher ratio of the driving force to the motor mass. It would be a very interesting study for such a motor when scaled down to MEMS technology.
References


Appendix – A: M-files

(a) M files for plotting the Pm and efficiency for various switching angles:
Switching angle = [30 47 70 93 110 134 148 180 210];
Power output = [77.75 69.4 57.1 51.84 41.00 31.22 28.07 20.07 16.07];
Efficiency = [50.651 55.25 53.26 51.76 50.05 45.37 36.37 32.07];
Plot (Switching angle, Power output, 'r*-',Switching angle, Efficiency,'g+-'),grid
xlabel('Switching angle [deg]');
ylabel('Pm [W], Efficiency [%]');

(b) M files for plotting the Pm and efficiency for various load:
Load = [2 5 10 20 40 60 80 100 120];
Power output = [26.03 31.23 38.55 46.64 57.34 65.66 67.09 70.81 76.78];
Efficiency = [44.91 47.28 42.47 40.62 37.97 35.74 34.72 33.16 30.41];
Plot (Load, Power output, 'r*-',Load, Efficiency,'g+-'),grid
xlabel('Load [N]');
ylabel('Pm [W], Efficiency [%]');

(c) M files for plotting the Current and velocity for various load:
Load = [2 5 10 20 40 60 80 100 120];
Current = [1.09 1.28 1.72 2.31 3.19 3.87 4.29 4.79 5.50];
velocity = [12.42 10.03 7.40 5.02 3.35 2.65 2.28 2.05 1.90];
Plot (Load, current, 'r*-',Load, velocity ,'g+-'),grid
xlabel('Load [N]');
ylabel('Current [A], velocity [m/sec]');
Appendix – B: Switch Control Subsystem

The block diagram for the generation of pulse that controls the switching circuit when the motor is supplied from DC source is shown below:

![Block Diagram](image)

**Fig. 1 Subsystem for pulse generation.**

Depending on the position at which the switch should be turned ON or turned OFF the corresponding value of inductance and the value of derivative of inductance are noted and used in the simple control logic. Edge triggering blocks are used to generate the pulse. These blocks are used for either raising edge triggering or falling edge triggering or both depending on the position of turn ON and turn OFF.

- **Pulse - 1** is used if the circuit should be turn ON at the point where the inductance starts to raise and turn off before it starts to decrease.

- **Pulse - 2** is used if the circuit should be turn ON when the inductance is decreasing and derivative of inductance is negative and raising and turn OFF before the value of inductance starts to decrease.
• Pulse - 3 is used if the circuit should be turned ON when the inductance is decreasing, the derivative of inductance is negative and decreasing and turn OFF before the value of inductance starts to decrease.
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