VARIABLE RELUCTANCE PERMANENT MAGNET LINEAR MOTOR COMPUTER AIDED DESIGN

SZABÓ Loránd - Ioan-Adrian VIOREL
Technical University of Cluj
P.O. Box 358, 3400 Cluj, Romania
Fax: +40-64-192-035, E-mail: Lorand.Szabo@mae.utcluj.ro

Abstract: *The variable reluctance permanent magnet linear motor design presents some specific aspects because of the complex toothed structure and of the requirement to take into account the iron core saturation and permanent magnet operating point change. Some special problems do arise due to the permanent magnet presence and the peril of its demagnetization in case the temperature increases above the allowed limit. The design algorithm and the computer program elaborated by the authors mainly solve the problems, offering an utile tool to the engineer who would like to design such a motor. In this case the computer is completely under the direct control of the user, together with all needed data files on convenient.*

Key words: *variable reluctance permanent magnet linear motor, circuit-field motor model, computer aided motor design, electromagnetic and thermal analysis*

1. Introduction

Linear precise positioning systems are required in a variety of applications as robotics, NC machine-tools, computer aided manufacturing systems, etc.

The interest in these systems has been given proof of a steady increase in requirements for positioning accuracy, while, at the same time placing demands on the maximum speed and on the constancy of speed. The variable reluctance permanent magnet linear motor is one of the best choices for this category of systems. It offers many advantages such as high speed, accurate positioning, high servo stiffness, smooth travel at all speed and fast settling times [1].

The variable reluctance permanent magnet linear motor (shown in Fig. 1) has, basically, a movable armature, *1*, placed over a fixed

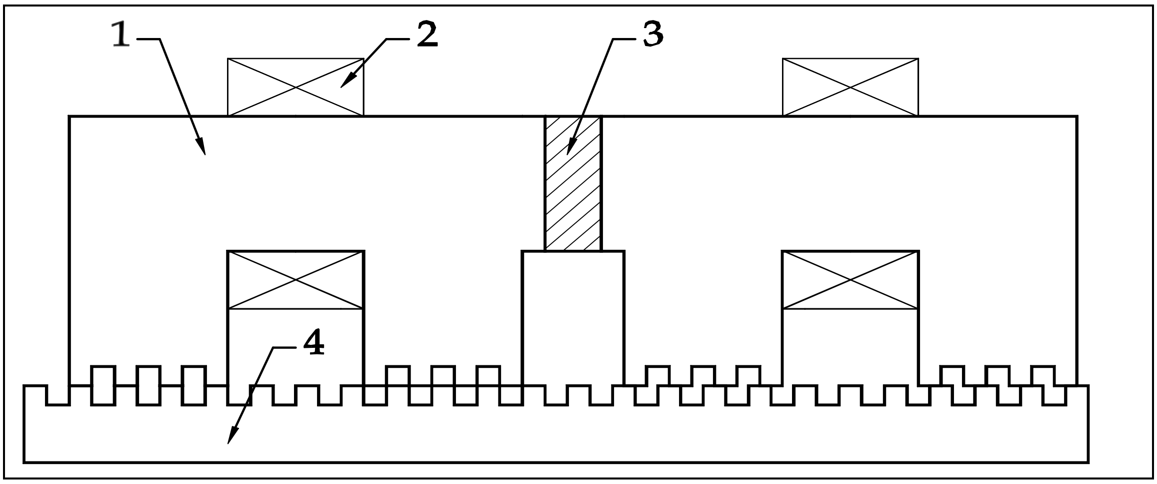

Fig. 1. The variable reluctance permanent magnet linear motor

platen, *4*. The platen is an equidistantly toothed bar of any length. The mover consists of two electromagnets having control coils, *2*, separated by a permanent magnet, *3*, which is the excitation source. Each electromagnet has two poles with the same number of teeth. The tooth pitch is identical on both armatures. The variable reluctance permanent magnet motor operates under the combined principles of permanent magnet excitation, variable air-gap reluctance and step by step supplying of the control coils.

Electrical machine design has more than hundred years background. The variable reluctance permanent magnet motor design is quite different thing than the classical electric motor design. The complex toothed configuration, the magnetic saturation of the iron cores and the permanent magnet operating point change due to air-gap variable reluctance and control MMF arise a lot of problems to the designer. Therefore establishing an accurate designing methodology and developing computer programs based on this is a step towards the direction of cutting down drastically the number of experiments.

In this paper a design algorithm and the software based on it will be presented. The powerful and useful capabilities of these programs are the ability to create the motor design almost totally. The practicing designer sets a few inputs and leaves the rest of design for the computer. The user can influence the design procedure as little or as much as he wants it.

The developed programs allow the designer to take fully into account iron-core saturation and permanent magnet working point variation. It enables the designer to optimize some components of the motor in order to attain the best efficiency possible with a good performance per cost ratio. Finally, the computer design program displays all the computed motor dimensions and each of the estimated motor performances.

2. The Design Procedure

The proposed design procedure is based on several relationships obtained from a simplified analytical motor model [2] and on some experience resulted values for important motor dimension ratios. The last part of the design methodology is build up around the coupled circuit-field motor model introduced by the authors in several previous papers [3, 4].

In the first stage of the variable reluctance permanent magnet motor design procedure the required design inputs must be prescribed depending on the needs of the application in which the motor will be used. The basic design inputs are the following:

i) the maximal tangential (traction) force developed by the motor ($f_{t_{\max}}$ 1),

ii) the resolution of the positioning (the step length), function of the selected control strategy (x_i 2),

iii) the length (l_r 3) and the width (w_r 4) of the running track.

In the second stage, which is the main part of the design procedure, all the motor dimensions must be established. At the beginning the sizes of the toothed air-gap structure must be computed. The tooth pitch, τ 5, is given by the imposed positioning accuracy:

$$\tau = 4x_i \qquad (1)$$

The air-gap length, g 6, must be as small as possible, being limited only by the mechanical constrains and the cost of manufacturing. The selection of the best tooth geometry is very important, too.

The next step consists in choosing the active ferromagnetic materials used for the motor construction. Extremely important is the permanent magnet selection, the most expensive and sensitive assembly of the motor. The imposed temperature rise in the mover and the motor cost to performance ratio must be taken into account. Rare-earth magnets are needed to meet the high thrust per unit volume necessities of the motor.

The mover armature is made of 0,35mm thick silicon steel lamination, having high saturation level and low specific losses. The platen is fabricated of soft iron. The flux density in the mover's poles, B_p 7, is limited only by the saturation of the teeth.

The magnet working point (B_{pm}, H_{pm}) on the straight demagnetization characteristic throughout the second quadrant must ensure the desired flux density levels in the mover and platen cores. The permanent magnet dimensions can be determined by computing its minimal active surface and thickness:

$$S_{pm_{\min}} = k_p \frac{f_{t_{\min}}}{B_p B_{pm}} \tag{2}$$

$$l_{pm} = k_x \frac{B_p B_r}{H_c \left(B_r - B_{pm}\right)} \tag{3}$$

where B_r 1 and H_c 1 are the remanent flux density and the coercive force of the selected magnet. The two designing constants, k_p 1 and k_x 1, have to be determined conditionally on the selected air-gap length and tooth width to tooth pitch ratio from the two diagrams shown in Figs. 2 and 3.

The number of the pole teeth can be calculated by:

$$Z = \frac{l_p}{\tau} \tag{4}$$

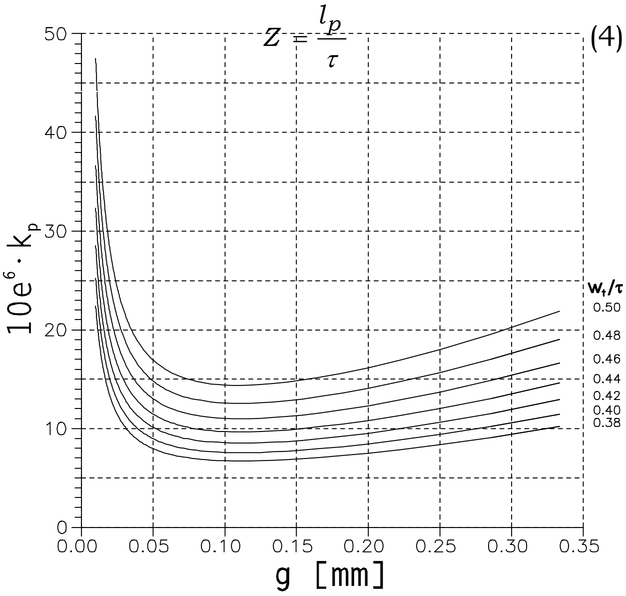

Fig. 2. Diagram for selecting the design constant k_p

where lp is the estimated pole length. The most appropriate integer number will be chosen.

Having the number of teeth selected, the final value of the pole length can be computed:

$$l_p = Zw_t + \left(Z - 1\right)w_s \tag{5}$$

where w_t 1 is the tooth width and w_s 1 the slot width.

The control coil design is made as a function of its MMF in order to ensure the necessary command magnetic flux throughout the poles. This guides the magnetic flux generated by the permanent magnet in such a way as to maximize, respectively minimize the total magnetic flux in the two poles of one electromagnet.

The last step of the design procedure is the electromagnetic and thermal checking of the designed motor. Using a computer program, based on the above mentioned mathematical motor model, the maximal tangential force and the highest flux densities in different motor portions can be calculated for the greatest expected command current.

Finally, the motor thermal analysis is performed in order to determine the temperature distribution over the whole motor cross-section.

It is very important to check the permanent

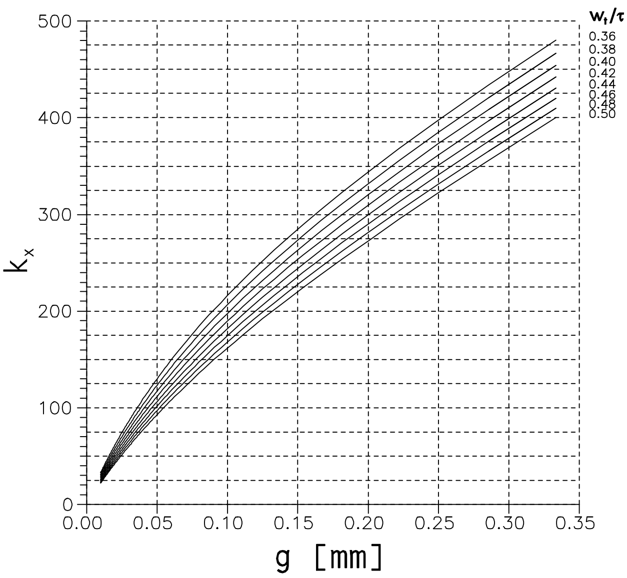

Fig. 3. Diagram for selecting the design constant k_x

magnet and the coil insulation teperature.
In general form the thermal equilibrium at a given time of an ideal homogeneous body is described by:

$$p\mathrm{d}t = Gc_h \mathrm{d}\theta + \alpha S\theta \mathrm{d}t \qquad (6)$$

where p 1 [W] is the total loss in the body, G 1 [Kg] and c_h 1 [Ws/Kg°C] are the mass, respectively the specific heat capacity of the body and α 1 [W/m²°C] is the heat transfer coefficient.
Solving the differential equation the temperature rise (the difference between the internal and external temperatures) in the body can be obtained. As it appears in the above equation the temperature in each point of the motor depends not only on the losses in that point, but also on the heat generated in the surrounding area, as well as on the heat flow path throughout the motor.
In a simplified form the variable reluctance permanent magnet motor can be considered as an assembly of four basic bodies: the two command coils, the mover, respectively the stator core.
The temperature rise in the four parts of the motor can be computed by solving the differential equation system, that describes the heat equilibrium in the motor.
The computer program for the thermal analysis was integrated in a global program based on the coupled circuit-field mathematical model of the motor.
Using this model the dynamic simulation of the motor is possible [5].
The software developed by the authors is flexible and easy to use. Only seconds are required for the user to determine the effects made by changing any one of the parameters that fully influence the motor behavior.

3. Results and Conclusions

The above mentioned design procedure and program have been used to design several types of variable reluctance permanent magnet motors.
Results of the design of a variable

$$\begin{array}{ll} f_{t_{\max}} = 50\mathrm{N} & x_i = 0.5\mathrm{mm} \\ l_r = 200\mathrm{mm} & w_r = 85\mathrm{mm} \end{array} \qquad (7)$$

reluctance permanent magnet motor of so-called sandwich magnet type will be presented. In this case the motor acts with one permanent magnet piece, disposed between the two mover electromagnets.
In the first step the required design inputs

$$\begin{array}{c} l_{pm} = 2\mathrm{mm} \\ h_{pm} = 9\mathrm{mm} \\ w_{pm} = 83\mathrm{mm} \\ S_{pm} = h_{pm} w_{pm} = 747\mathrm{mm}^2 \end{array} \qquad (8)$$

were prescribed:
In the second stage all the motor dimensions were established.
In order to reduce the motor cost an optimization of the magnetic circuit has been done. The optimized sizes of the permanent magnet are:
Studying several values for the width to length ratio of the control coil (k_{coil} 1) its optimal value was found out as to be 3. For this value the mover volume was minimal (82.96cm³).
Five teeth per pole were selected. Having the teeth number the precise pole length was computed, (5),

$$l_p = 5 \cdot 0.84 + 4 \cdot 1.16 = 8.84\mathrm{mm} \qquad (9)$$

The cross-section of the designed motor with the main dimensions are shown in Fig 4. with all of the dimensions in millimeters.

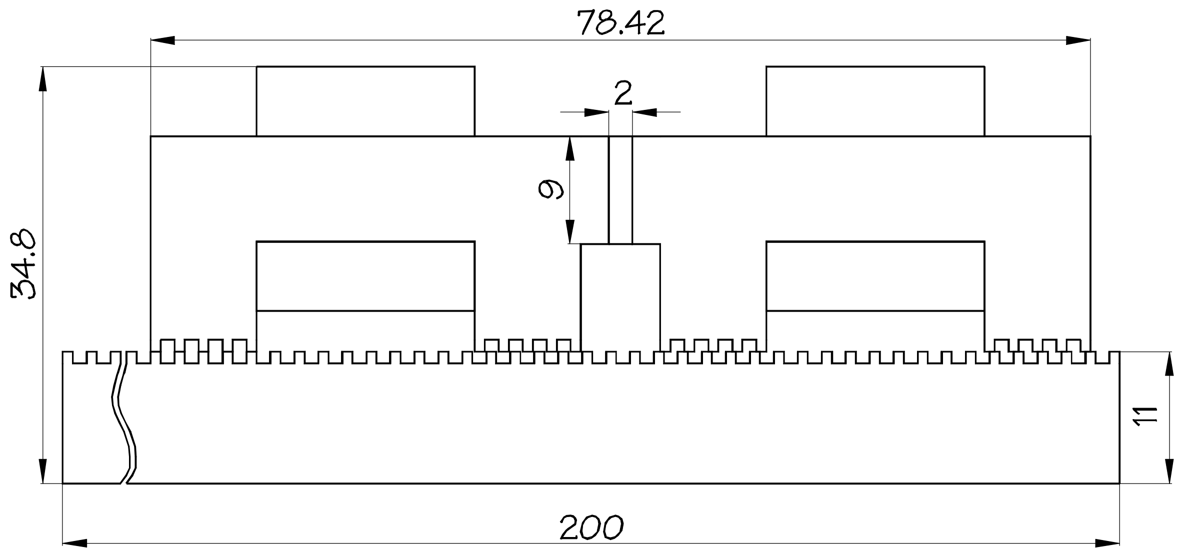

Fig. 4. The main dimensions of the designed motor

Finally the electromagnetic and thermal checking of the designed motor was performed.

Using a separate computer program the maximal tangential force and the highest flux densities in different motor portions were calculated. All these parameters were found as in accordance with the imposed data.

By solving the differential equation system, that describes the heat equilibrium of the motor, at each time step considered during the iterative process of the dynamic simulation, the heating curves represented in Fig. 5 were obtained.

As it can be seen the major temperature limits (the maximum temperature of the permanent magnet without the risk of damaging its magnetic properties and the greatest winding temperature, that is in relation with its electric insulation) were not reached.

As a consequence of the very low losses the motor can be cooled sufficiently by natural air convection.

The presented computer aided design methodology not only shortens the design process, but also gives more economic, efficient and higher quality alternatives.

It can be and was used with insignificant changes for the design of other similar motor types.

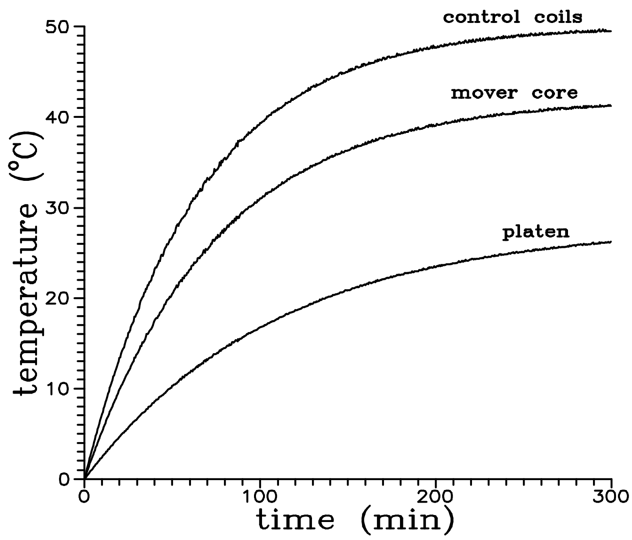

Fig. 5. The heating curves obtained by the thermal checking of motor

4. References

1. EBIHARA D.: *Design of a PM Type Linear Stepping Motor for Automatic Conveyer System*. In: Proceedings of the International Conference on Electrical Machines Design and Applications, London, 1985, p. 265-269.

2. VIOREL I.A.-KOVÁCS Z.-SZABÓ L.: *Sawyer type linear motor dynamic modelling*, In: Proceedings of the International Conference on Electrical Machines, Manchester, 1992, p. 697-701.

3. VIOREL I.A.-BIRÓ K.-SZABÓ L.: *Transformer Transient Behavior Simulation by a Coupled Circuit - Field Model*, In: Proceedings of the International Conference on Electrical Machines, Paris, 1994, p. 654-659.

4. VIOREL I.A.-SZABÓ L.: *Permanent-magnet variable-reluctance linear motor control*, In: Electromotion, vol. 1., nr. 1. (1994), p. 31-38.

5. SZABÓ L.-VIOREL I.A.-KOVÁCS Z.: *Computer Simulation of a Constant Velocity Contouring System Using x-y Surface Motor*, In: Proceedings of the PCIM Conference, Nürnberg, 1995, vol. Intelligent Motion, p. 375-384.