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Numerical modelling of linear generators

Abstract. This paper deals with linear generator design. Different topologies of linear generators are presented. Numerical methods are used in the design of electric machines. A 3D model of a flat one-sided synchronous linear electric generator was made and analysed with Ansys Workbench software. Within the numerical analysis, calculation of magnetic flux density was made.

Streszczenie. W artykule przedstawiono projekt generatora liniowego. Przedstawione zostały różne topologie generatorów liniowych. Wykorzystano metody numeryczne w projektowaniu maszyn elektrycznych. Zbudowany został model 3D synchronicznego generatora liniowego i model ten poddano realizacji numerycznej oprogramowaniem ANSYS. W realizacji numerycznej obliczono indukcję magnetyczną. **Numeryczne modelowanie generatora liniowego**

Keywords: numerical modelling, linear generator, linear motor topologies
Słowa kluczowe: modelowanie numeryczne, generator liniowy

Introduction

Linear electric machines are devices that directly produce or exploit linear movement. They have become commercially better known between years 1970 and 1980, when there were huge efforts to build a MAGLEV train for carrying passengers, which would be driven by linear synchronous motors. Linear machines are used in many other applications, as they have many good properties, such as high accelerations and decelerations, high thrust forces, high precision and reproducibility of the position [1].

Eric R. Laithwaite wrote that a linear electric machine is easiest to imagine as a rotary machine, of which stator and rotor are cut and unrolled in the plane [2]. Stator and rotor in a rotary electric machine become primary and secondary in a linear machine. Primary is the part of the machine which is supplied with electric current. Secondary is the part of the machine, with permanent magnet excitation system, a squirrel cage or magnetic saliency.

All types of linear machines can have different topologies. In general there are two different geometry types; tubular and flat geometry type. Both geometries may have a long or short secondary or primary. Flat linear motors can be one-sided or double-sided [3].

Some most common applications where linear motors are used are sliding doors, swing doors, elevators, pneumatic hammers, electromagnetic pumps, electromagnetic flow meters, automation and robotics [4].

Lineat motor topologies

The linear electric machine is represented as a rotary machine, which has been cut and unrolled in a plane. The rotor becomes the secondary; above it the unrolled stator represents the primary. Such a structure would have a distinctly high detent force between the secondary and the primary. This force can be reduced by adding an additional primary or secondary on the other side, this type of linear electric machine is called double-sided linear motor. With this type of machine the detent force depends only on the inequality of both air gaps [4].

Tubular linear electric machine can be represented as a one-sided flat linear electric machine twisted around an axis which is parallel to its movement. The primary of a real tubular linear electric machine with permanent magnets is composed of a large number of windings which are inserted in the magnetic core of the primary. The secondary consists of permanent magnets of cylindrical shape [4, 5].

A major drawback of a tubular linear electric machine is covering large distances. Its structure is completely cylindrical, primary is traveling up and down the secondary and among both of them is the air gap. Due to such a construction the only option for support is on the ends of the machine. This means that there is a maximum length of the secondary, at which the magnets on the secondary do not touch the primary due to bending.

Figure 1 is showing a simple 3D presentation of a one-sided flat linear electric machine on the left (a) and a tubular linear electric machine with a cross-section on the right (b).

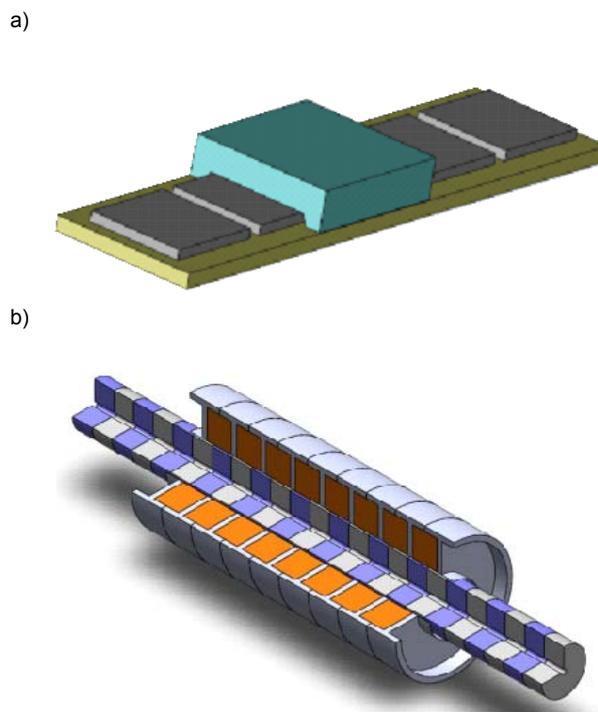


Fig. 1. A simple 3D model of a one-sided flat linear motor (a) and a tubular linear motor (b)

Finite element analysis of the chosen linear motor geometry

For the finite element analysis with the program package ANSYS Workbench a flat linear synchronous generator, with 12 grooves and 10 permanent magnets has been

selected. This generator has a three-phase double layered concentrated winding, which is shown on figure 2 [7].

Figure 2 is showing the winding of the discussed linear generator. Phase 1 is marked with red colour and phases 2 and 3 are marked with blue and green colour. The minus sign in front of a number indicates the current flowing in the negative direction of the z-axis. Permanent magnets and steel of the secondary are also shown in the picture. Light blue and pink colour marked permanent magnets have opposite directions of their polarization.

With help of two different coordinate systems, which are attributed to the conductors, direction of the electric current

in the positive or negative direction of the z-axis is determined. The moment in time when the value of electric current in the first phase is maximum and in other two phases the electric current is half the maximum and with opposite direction is being observed.

Electric current in phase 1 is 15 A and in phase 2 and 3 the electric current is -7,5 A. Each conductor has 24 coil turns and a conductive surface of 33 mm². With this data current densities in the conductors were determined. Current flow density in all three phases is calculated in Eq. (1) and Eq. (2).

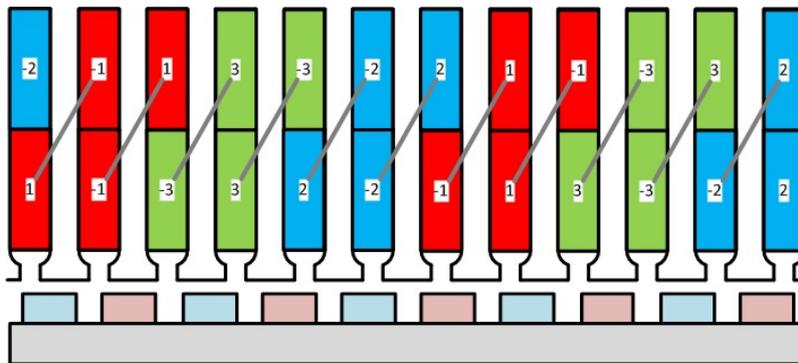


Fig. 2. Winding of the discussed linear generator

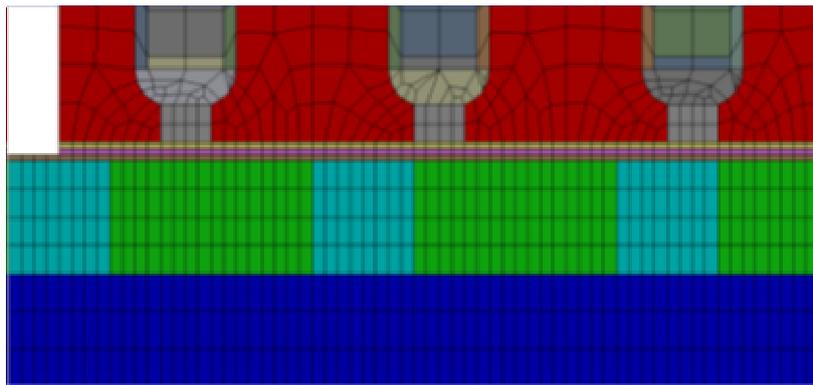


Fig. 3. Mesh of the air gap, magnets and steel secondary

$$(1) \quad J_1 = \frac{I_1 N}{S} = \frac{15\sqrt{2} \cdot 24}{33} = 15,4278 \left(\frac{\text{A}}{\text{mm}^2} \right)$$

J_1 is the current flow density in phase 1, I_1 is the value of electric current in phase 1, N is the number of coil turns and S is the conductive surface of a conductor.

$$(2) \quad J_{2,3} = \frac{I_{2,3} N}{S} = \frac{7,5\sqrt{2} \cdot 24}{33} = 7,7139 \left(\frac{\text{A}}{\text{mm}^2} \right)$$

$J_{2,3}$ is the current flow density in phases 2 and 3, $I_{2,3}$ is the value of electric current in phases 2 and 3, N is the number of coil turns and S is the conductive surface of a conductor. For the mentioned linear generator following materials have been defined: iron (laminated sheet for primary and secondary of M330-50A quality), copper (for the double-layered concentrated winding), permanent magnet material (Nd-Fe-B) and air [7].

Material air was defined for the air gap and the surrounding air. Selection of other non-ferromagnetic materials for the actual simulation is not very important; on places of isolation air is also defined as the material [7].

Components of the linear generator are modelled from several smaller parts, this is more time consuming when modelling, but it facilitates the later meshing. In order to define boundary conditions more easily a layer of surrounding air is modelled around the 3D model. The thickness of the surrounding air should be thick enough, so that we don't influence the calculation of magnetic field by defining the boundary conditions. In our case, most of the magnetic field lines already conclude in ferromagnetic iron core of the generator, therefore the layer of the surrounding air can be thin [7].

On the outer surfaces of the surrounding air Dirichlet boundary conditions are defined. By this, the size of the magnetic vector potential on the outer surfaces is equal to zero. Direction of the electric current in the windings, electric current density and the polarization of permanent magnets are also defined [7].

Meshing is a critical step in all types of simulations. If the mesh is too dense this leads to very long calculation times. On the other side mesh with too few elements may lead to inaccurate results. ANSYS enables automatic meshing

depending on the type of application, but in this case a quality mesh is not obtained. Anyway users can choose among different mesh methods and element types to optimize the mesh for each specific case.

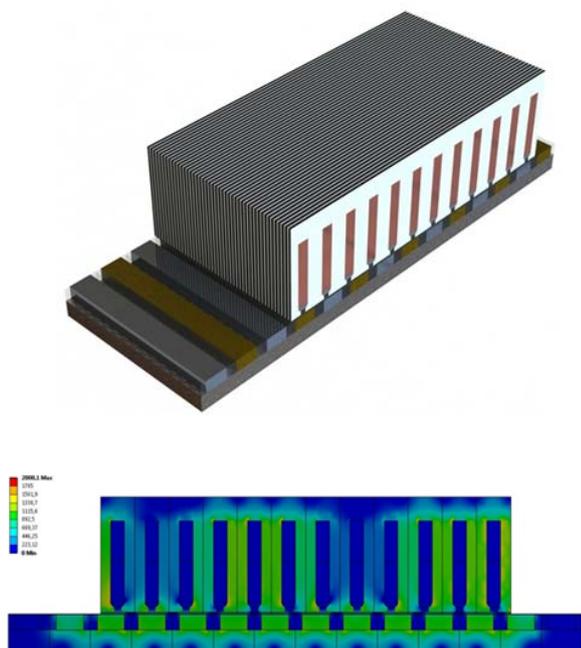


Fig. 4. 3D model and magnetic flux density distribution

A 3D SOLID236 element with 20 nodes was chosen for the discussed analysis. Mesh method was not automatic. Each part was meshed separately. Smaller parts, like air gap, were meshed first. The surrounding air was meshed last. With this type of meshing each next step in meshing adapts to the size of elements of previous elements. In this way of meshing a good quality mesh is achieved. Figure 4 shows a detail of mesh in the air gap, one section of magnets and steel secondary [8].

Conclusion

This article briefly presents linear electric generators, some applications and various topologies of these. A 3D model of a flat synchronous linear generator is presented. This model will be used in a finite element analysis, which is particularly reliable and efficient in the analysis of electromagnetic devices, with program package ANSYS Workbench.

Most important steps in the procedure of making a finite element analysis were discussed. This steps are modelling the geometry, choosing and applying proper material

properties, applying loads and boundary conditions. The most critical and time consuming step is meshing. A good mesh must be obtained in order to get an accurate solution. A too dense mesh can lead to very long calculation times. Experiences are most important in finding a compromise between mesh density, accuracy of the obtained results and computation time.

With all the preparation done, such a model can be used to calculate magnetic flux density, current density, detent force, cogging force and magnetic flux linkage of the linear generator. Magnetic flux linkage can be further used to calculate the induced voltages, which are a product of the derivative of the magnetic flux linkage and the intended speed of the discussed linear generator. Furthermore, power in each phase and the overall power can be calculated [7].

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