VOLTAGE FED MAGNETIC BEARING MODEL

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1 INTRODUCTION

Magnetic bearings are used in electrical applications for the purposes of pulling, lifting and holding. Irrespective of the application, all types of bearing operate on similar physical principle and their construction details differ. In the design consideration it is necessary to get reasonable output for magnetic modeling and losses when modeling magnetic bearing. In this report electro-mechanical energy conversion from voltage forced system modeling is presented.

2 BEARING - ENERGY CONVERSION

The electro-mechanical energy conversion consists of an electrical system, the coupling field and a mechanical system (**Figure 1**).

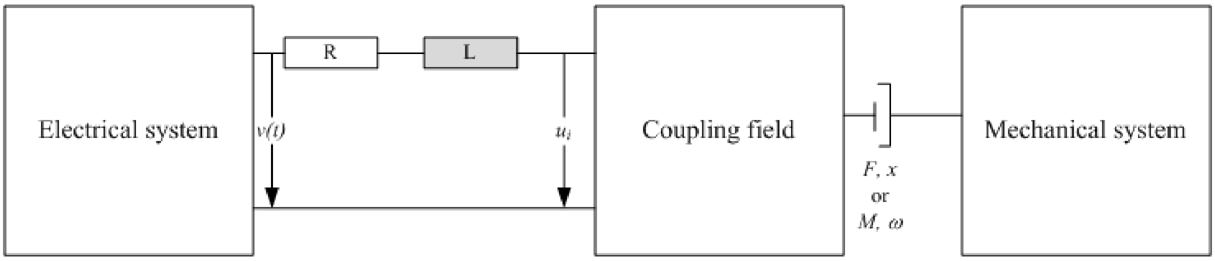

Figure 1: General representation of electromechanical conversion system

The conversion work is based on energy balance equation

$$W_{elec} = W_{mech} + W_{field}$$

and

$$v(t) \cdot dt = i^2(t) \cdot R \cdot dt + i \cdot d\Psi \qquad (1)$$

W_{elec} is the electrical energy input, W_{mech} is the mechanical energy output. It is the mechanical work, done when the armature is in motion. W_{field} is the stored field energy.

When the armature of the bearing is not moved the entire electrical energy input is stored in the magnetic field. It is understood from the Ψ, i - diagram (**Figure 2)** below.

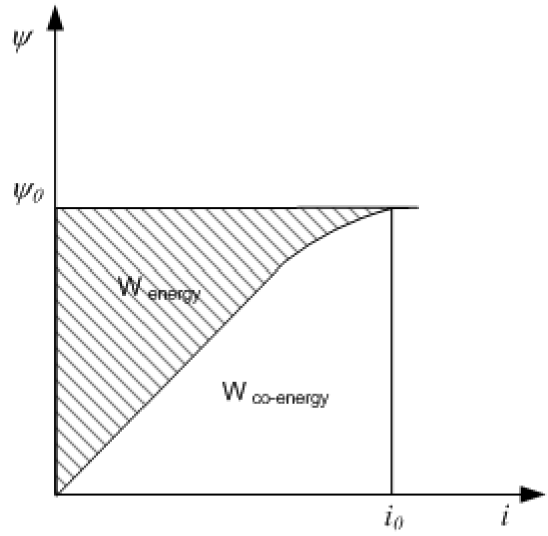

Figure 2: Energy and co-energy

The unshaded area in **Figure 2** is called co-energy that is useful in calculating magnetic forces and has no physical significance. In general for a linear magnetic circuit

$$W_{field} = W_{coenergy} = \frac{1}{2} \cdot \Psi \cdot i = \frac{1}{2} \cdot L \cdot i^2 \quad . \tag{2}$$

2.1 Force

Since the work done is $F \cdot dx$, x is the displacement, the magnetic force is partial derivative of magnetic co-energy:

$$F = \frac{\partial W_{coenergy}}{\partial x} \tag{3}$$

The above expressions are explained more in detail in electro-mechanical literature [1]. These have broad significance and are valid for all physical systems having coupled magnetic field. For the linear system by substituting the values in the equation yields force

$$F = \frac{1}{2} \cdot \frac{L}{x} \cdot i^2 \quad . \tag{4}$$

Force can also be represented with flux density in the air gap:

$$F = \frac{B_\delta^2}{2 \cdot \mu_0} \cdot A \tag{5}$$

2.2 Dynamic equations

The complete analysis of the electro-mechanical system under dynamic condition involves differential equation solution of electric circuit equations and equation of motions. Since the coil involves RL circuit in series like equation (1), the solution of the first linear order differential equation for DC transient is

$$i = \frac{V}{R}\left(1 - e^{-(R/L)\cdot t}\right) \quad . \tag{6}$$

For RL transient, the time constant $\tau = L/R$ is the time at which the exponent of e is unity. Graphically it is not shown here. Thus sum of voltage across the resistance and inductance satisfies the Kirchhoff's law throughout the transient operation.

$$V = v_R + v_L = V(1 - e^{-(R/L)\cdot t}) + Ve^{-(R/L)\cdot t} \tag{7}$$

The magnetic force is opposed by the inertial force, damping force and the spring force. The force balance equation is

$$F_{mag} = m \cdot \ddot{x} + b \cdot \dot{x} + c \cdot x \quad . \tag{8}$$

c is the spring constant proportional to the displacement, b is the damping coefficient proportional to the velocity and m is the mass of the system. This second order mechanical system is shown in the **Figure 3**.

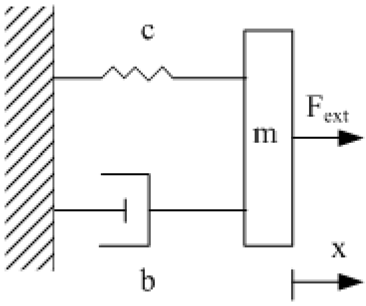

Figure 3: Mechanical system, Spring-Mass-Damper

When the coil is excited from sinusoidal voltage, then the flux in the air gap is given as $\Phi = \hat{\Phi} \cdot \cos(\omega t)$. When there is a permanent magnet in the magnetic circuit (**Figure 4**), the time varying flux density in the air gap is of the form $\Phi = \Phi_0 + \hat{\Phi} \cdot (\cos \omega t)$. The term Φ_0 is the DC field created by the permanent magnet. When damping is neglected, the differential equation of force balance equation is given as

$$m \cdot \ddot{x} + c \cdot x = \frac{\hat{\Phi}^2}{4\mu_0 \cdot A} \cdot \left(1 + \cos(2\omega t)\right) \quad . \tag{9}$$

The equation is the forcing function and consists of constant and double frequency components on the right hand side. The steady state solution for displacement of this equation is

$$x = \frac{\hat{\Phi}^2}{4\mu_0 \cdot c \cdot A}\left[1 + \frac{c \cdot \cos(2\omega t)}{c - 4 \cdot \omega^2 \cdot m}\right] \quad . \tag{10}$$

In this work such type of model is solved using finite element program FLUX2D software.

3 MAGNETIC DESIGN AND COIL DESIGN

The elementary structure of axial bearings is shown in the **Figure 4**. Two models are under consideration, magnetic circuit with and without permanent magnet (PM).

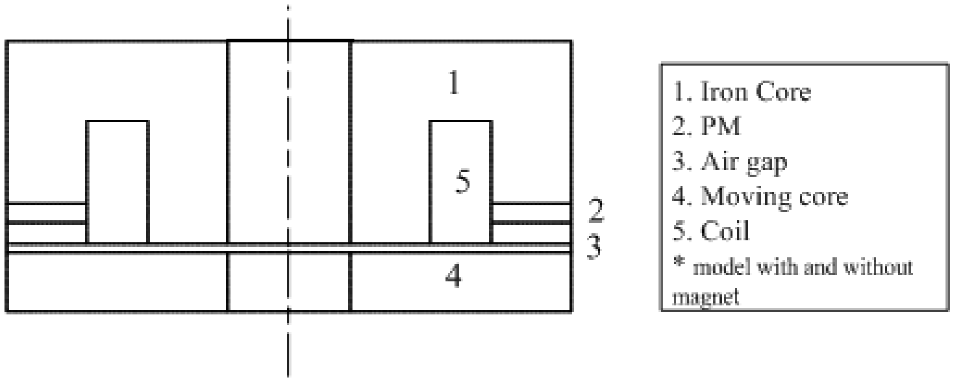

Figure 4: Cross section of an axial bearing consider with & without PM

The model consists of ferromagnetic core which carries flux Φ and winding that produces a flux when excited (MMF). The permanent magnet is used to produce bias flux. The advantage is less power consumed in the magnetic bearing. The linear relationship between flux Φ produced and MMF ($w \cdot i$) applied is

$$\Phi = \frac{w \cdot i}{\Re} \quad . \tag{11}$$

$\Re = \frac{1}{\mu_0 \mu_r} \cdot \frac{l}{A}$ is the magnetic resistance, w is the number of turns, i is the current and A is the area of the magnetic circuit. The magnitude of force in the air gap is obtained by substituting the above relation to the equation (5). The coil conductor is usually round, or a rectangular section with rounded corners is used. The resistance of one conductor is

$$R = \frac{\rho \cdot l_{wire}}{A_{wire}} \quad . \tag{12}$$

A_{wire} is the area of the conductor, ρ is the resistivity of copper and l_{wire} is the length of the conductor. More details on coil design are given in [2].

3.1 Magnetic Calculation result

For the model shown in **Figure 4** - without permanent magnet - a DC transient FEM calculation has been carried out for a voltage of 19.5 V and with a stroke of 2 mm. The simulation is carried out in FLUX2D. The calculated flux lines are shown in **Figure 5**.

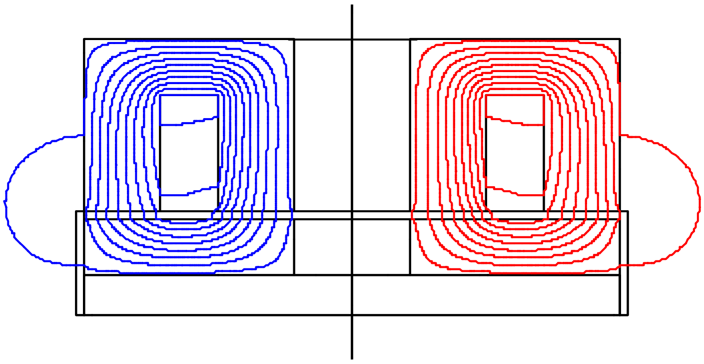

Figure 5: Flux lines for $F = 1729$ N, $\Theta = 2320$ A, $J = 5.2$ A/mm^2

The coil current for typical movement of armature to its closed position for the applied voltage is shown in the **Figure 6**.

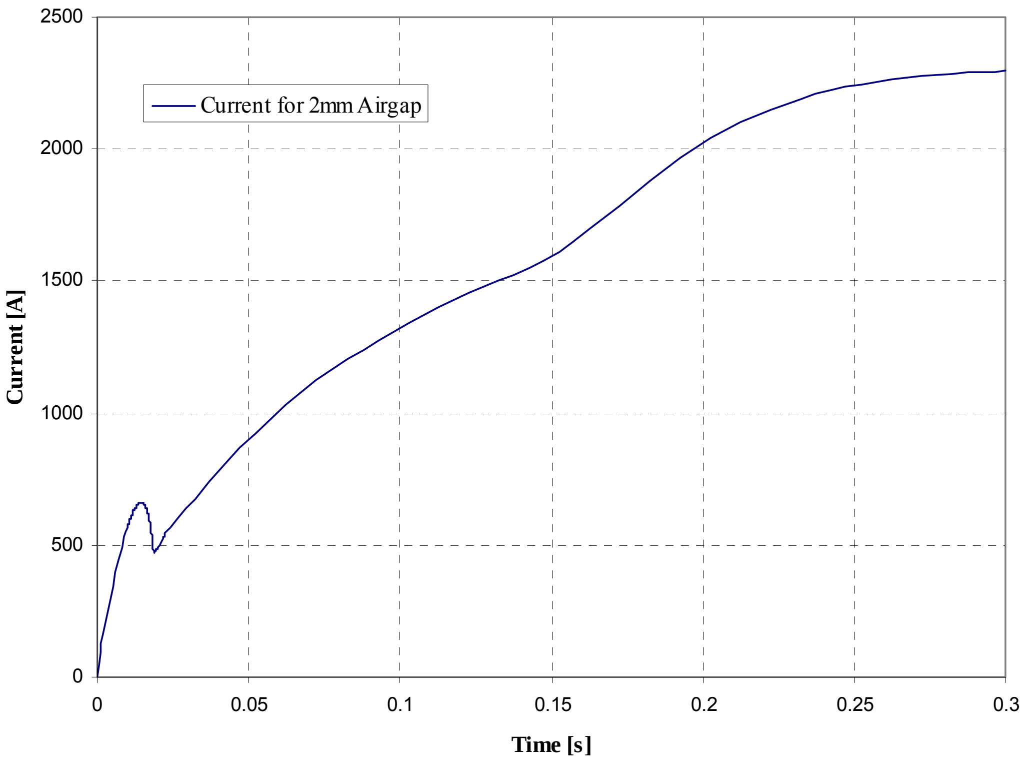

Figure 6: Transient response of current for 19.5 V

The simple model provides an approach for the dynamic behaviour of the bearing. When the voltage source is connected at time $t = 0$ s, the current starts increasing exponentially and the core starts moving. After some time inductance of the coil increases rapidly and the resistance is minimum when the core is in contact with non-movable iron part. The change in flux tends to decrease the current. When the core is at the closed position the current reaches its steady state U/R.

The same model is calculated with a permanent magnet in the bearing. The calculated flux lines are shown in the **Figure 7**.

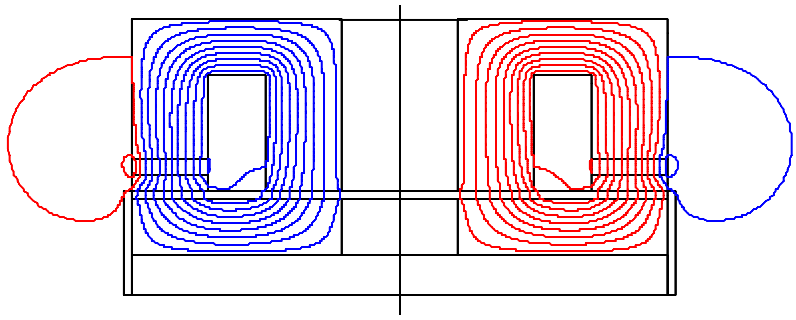

Figure 7: Flux lines for $F = 1726$ N, $B_r = 1.1$ T, $\Theta = 892$ A, $J = 2$ A/mm^2

With the permanent magnet in the bearing, less power is consumed. Transient operation for the model with permanent magnet is shown in **Figure 8**.

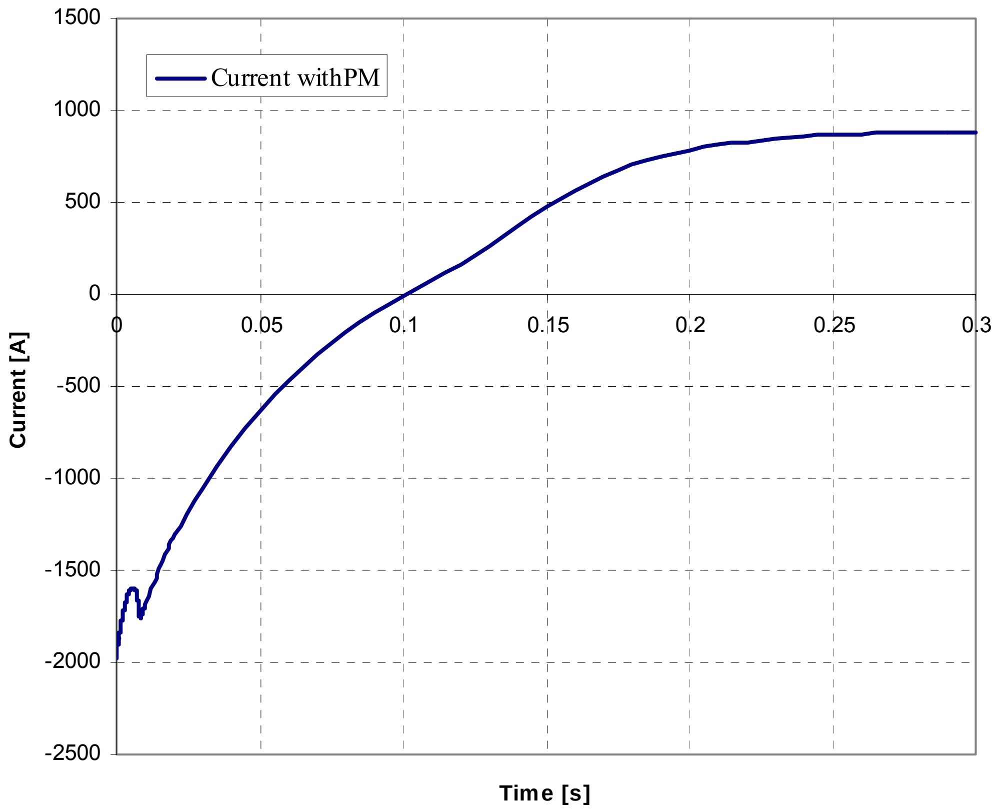

Figure 8: Transient response of current for 7.5 V

Here the same characteristics persist as in the case of model without magnet, but the current starts from negative value. This is because at the initial stage the moving core is stationary. It means that no force is applied and there is no work done. The presence of permanent magnet exerts force and the initial condition of zero movement in the core can be expected only with negative excitation in the coil current.

4 AXIAL BEARING CONTROLLER AND LOSSES INFLUENCE

A controller is needed for the model explained to have a stable system. A simple PD controller design is explained in [3] for a magnetic bearing system. The transfer function of standard model for the second order system used for controller design shown in the **Figure 4** is given by

$$G(s) = \frac{X(s)}{Y(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad . \tag{13}$$

ω_n is the natural frequency and ζ is the damping ratio. In practice there is possible delay due to the eddy current losses caused in the magnetic system. This loss is caused by the changing magnetic field inside the magnetic circuit. This delay due to electro-magnetic damping has to be incorporated in the system. This can improve the bearing design and the system behavior. This effect is not studied here. Nevertheless the influence of the delay is introduced in the model and is given in [3]. The analytical model of eddy current is studied in [4], where the mathematical analytical solution for flux is solved from which force can be calculated.

5 SUMMARY

In this report force calculation using FLUX2D software for a simple axial magnetic bearing is shown. The simple model provides an approach for the dynamic behaviour for the bearing model. A dynamic response for the model with and without permanent magnet is studied. It is based on the set of differential equations. Influence of the losses in the magnetic circuit is also explained. The method described in this report is the approach for the voltage fed magnetic bearing system.

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