DESIGN OF A SINGLE SIDED LINEAR INDUCTION MOTOR

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ABSTRACT:- This paper studies the design of SLIM, which can be used to power capsules in a pneumatic capsule pipeline (PCP) system. The design equations of the SLIM and the equivalent circuit model are studied and discussed in detail and then compared to a similar tubular linear induction motor (TLIM). The SLIM equations and design procedures are developed and its performance is predicted using equivalent circuit models. End effects and edge effects are neglected in this study. The SLIM design algorithm is made completely user-interactive where the user has the convenience of choosing various design parameters like the primary voltage and frequency, number of poles, number of phases and many more. Optimum design parameters are obtained by the iterative procedure of the design algorithm.

1. INTRODUCTION

The history of linear induction motors extends as far back as the 19th century. Although these machines have been practically forgotten for the last 30 or 40 years, there appears to be a genuine revival of interest in them. The fascinating history of these “unrolled” motors and their theory of operation are discussed in this report. The idea of the linear induction motor is probably contemporary with the invention of the rotating field machine by Tesla, Dolivo-Doborovolsky, and Ferrari some time after 1885. However, some authors give other dates for the discovery. The idea of a linear electric motor is almost as old as that of of a rotary electric motor. The first linear motor was a reluctance machine built by Charles Wheatstone in 1845, to be closely followed by a similar machine by Henry Fox Talbert. Nicola Tesla invented the induction motor in 1888. The first patent in linear induction motors was obtained by the mayor of Pittsburg in 1895. The first electromagnetic gun was undoubtedly Birkeland’s cannon of 1918, again a reluctance device, but possibly the first tubular motor using a row of simple coils energized in sequence with DC. In 1946, Westinghouse built a full-scale aircraft launcher, the “Electropult”, which was an induction motor with a moving primary.

The objective of this paper was to design a SLIM of specified parameters using a user-interactive computer program, and compare it to a similar tubular linear induction motor (TLIM). The study included developing SLIM equations and design procedures and predicting its performance using equivalent circuit models. Furthermore, a user interactive design algorithm was developed and a computer program was written in MATLAB software for the design of a SLIM as per required specifications. Optimum design parameters are obtained by the iterative procedure of the design algorithm. The values thus obtained were tabulated and then compared with those of a similar TLIM design of similar specifications.

2. SLIM THEORY AND EQUATIONS

The principle of operation of a LIM is the same as that of a rotary induction motor. A linear Induction motor is basically obtained by opening the rotating squirrel cage induction motor and laying it flat. This flat structure produces a linear force instead of producing rotary torque from a cylindrical machine. LIMs can be designed to produce thrust up to several thousands of Newtons. The winding design and supply frequency determine the speed of a LIM. The basic principle of LIM operation is similar to that of a conventional rotating squirrel-cage induction motor. Stator and rotor are the two main parts of the conventional three phase rotary induction motor. The stator consists of a balanced polyphase winding which is uniformly placed in the stator slots along its periphery. The stator produces a sinusoidally distributed magnetic field in the air-gap rotating at the uniform speed $2\omega/p$, with ω representing the network pulsation (related to the frequency f by $\omega = 2\pi f$) and p the number of poles. The relative motion between the rotor conductors and the magnetic field induces a voltage in the rotor. This induced voltage will cause a current to flow in the rotor and will generate a magnetic field. The interaction of these two magnetic fields will produce a torque that drags the rotor in the direction of the field. This principle would not be modified if the squirrel cage were replaced by a continuous sheet of conducting material.

3. SLIM CONCEPT

From the induction motor principle explained above, we obtain a linear motor if we imagine cutting and unrolling the motor, as shown in Fig. 3-1, causing the motor to have a linear motion

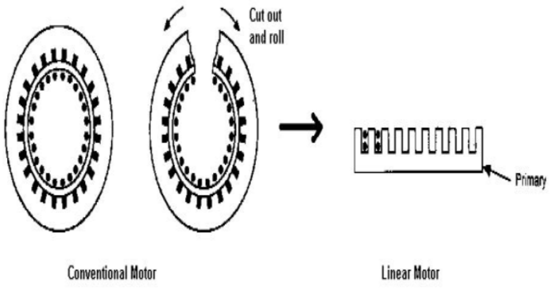

Fig 3-1 Imaginary process of unrolling a conventional motor to obtain a LIM Instead of rotating flux, the primary windings now create flux in a linear fashion.

The primary field interacts with the secondary conductors and hence exerts a force on the secondary. Generally, the secondary is made longer than the primary to make maximum use of the primary magnetic field As stated earlier, there should be relative motion between the conductor and the magnetic lines of flux, in order for a voltage to be induced in the conductor. That's why induction motors, normally operate at a speed *Vr* that is slightly less than the synchronous velocity *Vs*. Slip is the difference between the stator magnetic field speed and the rotor speed. Slip is the relative motion neededin the induction motor to induce a voltage in the

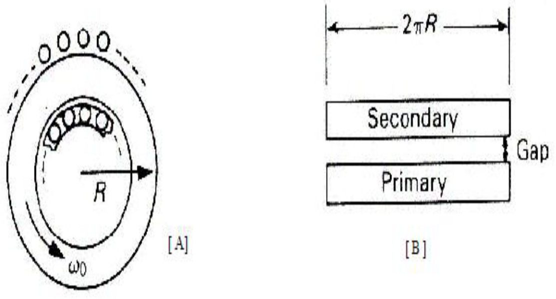

Fig 3-2 Radius of a rotary induction motor and length of a SLIM

The parameter τ is the distance between two neighboring poles on the circumference of the stator, called pole pitch,

$$\tau = \frac{2\pi R}{P} \qquad 3.3$$

The stator circumference of the rotary induction motor, *2πR*, in (3.3) is equal to the length of the SLIM stator core, *Ls* as shown in figure 3-2.Therefore, the pole pitch of a SLIM is

$$\tau = \frac{2\pi R}{P}\frac{Ls}{P} \qquad 3.4$$

If the velocity of the rotor is *Vr*, then t he slip of a SLIM can be defined as

$$S = \frac{Vs-Vr}{Vs} \qquad 3.5$$

The air-gap shown in Fig. 3-2[b] is the clearance between the rotor wall and the SLIM stator in a PCP-SLIM system.

3.1.1. The concept of current sheet:- As mentioned earlier, the stator of an induction machine consists of several coils, each having many turns of wires – the windings – embedded in slots in laminated iron. The current carried by the windings can be replaced by a fictitious and infinitely thin layer of current distributed over the surface of the stator facing the air gap. This current is called the "current sheet." The current sheet produces the same sinusoidal magnetomotive force (mmf) in the air gap as that produced by the conductors. The current sheet strength, i.e, the amount of current per unit stator length (*Ls*) in a current sheet of a SLIM, can be calculated as in Nasar and Boldea [1] as follows:

$$Jm = \frac{2\surd MkwNcI1}{Ls} \qquad 3.6$$

In (3.6), *Jm* is the current sheet strength (amp/meter); *m* is the number of phases of the motor; *kw* is the winding factor, defined below; *Nc* is the number of turns per slot; *I1* is the RMS value of the input current; *Ls* is the length of one section of the stator of the LIM, which is equivalent to the circumference of a rotary motor, namely, *Ls = 2πR= p*τ. The winding factor, *kw*, is defined as the product of pitch factor *kp* and the distribution factor *kd*.

$$k_w = k_p k_d \qquad 3.7$$

where *kp* is the pitch factor of the coil, which is given by

$$k_p = \sin(\frac{\Theta P}{2}) \qquad 3.8$$

where *θp* is the coil span in electrical degrees. In (3.7), *kd* is the breadth or distribution factor given by

$$k_d = \left(\frac{\sin\left(\frac{q1\alpha}{2}\right)}{q1\sin\left(\frac{\alpha}{2}\right)}\right) \qquad 3.9$$

where α is the slot angle in electrical degrees given as

$$\alpha = \left(\frac{\pi}{mq1}\right) \qquad 3.10$$

One pole pitch is equal to 180 electrical degrees. So, in a full pitch coil where the coil span is equal to one pole pitch, the pitch factor becomes one. Therefore, the winding factor for the fundamental harmonic of a full pitch coil can be obtained by substituting (3.10) in (3.9) resulting in (3.11)

3.1.2. Power Rating and Rated Input Phase Current:

The electrical power input to the stator windings is converted into useful mechanical power by the principle of electrical induction, as explained before, and the expressions relating to the power balance are derived as follows. The power input to the stator windings is given by

$$\cos iP = mV\,I\,\varphi\ , \qquad (3.12)$$

where m is the number of electrical phases, $V1$ and $I1$ are the RMS input phase voltage and current, respectively, and φ is the power factor, which is the phase angle between $V1$ and $I1$. Included in this input power is a component for the copper losses in the stator windings, and a component for the iron losses in the stator core and teeth. The remaining input power is transferred to the rotor through the magnetic field of the air-gap. Neglecting the rotor conductor losses and friction and windage losses, the power transferred to the rotor can be equated to the mechanical power developed by the rotor. The total mechanical power developed by the rotor of the SLIM is given by [9]

$$Po = FsVr,$$

where Fs is the electromagnetic thrust generated on the rotor by the stator, and, as stated before, Vc is the speed of of the rotor. The SLIM efficiency η is calculated from

$$\eta = \frac{Po}{Pi} = \frac{FsVr}{mV1I1cos\phi}$$

From (3.14), we initially assume a suitable operating value for ηcosφ, and then the rated input phase current can be estimated from.

$$I1 = \frac{FsVr}{mV1\eta\cos\phi}$$

3.2.2. Normal Forces: In a double-sided linear induction machine (DLIM) configuration, the reaction plate is centrally located between the two primary stators. The normal force between one stator and the reaction plate is ideally equal and opposite to that of the second stator and hence the resultant normal force is zero. Therefore, a net normal force will only occur if the reaction plate (secondary) is placed asymmetrically between the two stators. This force tends to center the reaction plate. In a SLIM configuration, there is a rather large net normal force between the primary and secondary because of the fundamental asymmetrical topology. At synchronous speed, the force is attractive and its magnitude is reduced as the speed is reduced. At certain speeds the force will become repulsive, especially at high-frequency operation.

3.2.3. Lateral Forces: As shown in Fig 3.4, lateral forces act in the y- direction, perpendicular to the movement of the rotor. Lateral forces make the system unstable. These occur due to the asymmetric positioning of the stator in a LIM. Generally, small displacements will only result in very small lateral forces. These forces are a matter of concern in high frequency operation (>>60Hz) where they increase in magnitude. A set of guided mechanical wheel tracks is sufficient to eliminate a small lateral force.

4. CONCLUSION

In this paper, a detailed study of the design of the SLIM was performed and compared with that of a comparable TLIM design. The main objective of this paper was to formulate the design equations of the SLIM and then develop a user-interactive computer program for its design. The equivalent circuit model of the SLIM was studied in order to obtain the performance equations for thrust and efficiency. The SLIM design algorithm is made completely user-interactive where the user has the convenience of choosing various design parameters like the primary voltage and frequency, number of poles, number of phases and many more. It can be concluded that the air-gap plays a very important role in the performance of the SLIM. The air-gap needs to be as small as possible to have a better thrust and efficiency. Another crucial design parameter is the thickness of rotor outer layer which is aluminum.

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