IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 11, Issue 1 Ver. III (Jan. – Feb. 2016), PP 29-35
www.iosrjournals.org

Design and Modeling of LSRM Driven Infusion Pump

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***Abstract**: Infusion Pump is a precision electromechanical device used to administer a required amount of highly potent medicines to the patient over a period of time. The Linear Switched Reluctance Motor based design of this pump improves the resolution and the power utilization of the motor without increasing the cost or compromising any other aspect of the device.*

I. Introduction

The Linear Switched Reluctance Motor is widely used in many industries nowadays. This is due to the advancements made in the power semiconductor devices and associated technology. These motors have a robust build and the added advantage of lack of transmission systems in the form of belts and gears for the attainment of linear movement. The objective of this paper is to model the Linear Switched Reluctance Motor for the specific application and also to control the actuator movement for the motorization of the syringe pump. A control algorithm optimized for closed-loop control of the motor is obtained with a PI Controller and Hysteresis Current Controller is used to obtain proper functioning of the device. The present day biomedical engineers employ stepper motors for this purpose. Theses stepper motors in conjunction with some transmission systems to obtain the linear movement is used for this purpose. The motorization of these biomedical systems is generally provided by a rotating stepping motor associated to a gear unit. The shaft of the stepper motor connects the syringe, is bulky, expensive and requires frequent maintenance. The reliability is considerably more compared to the previous models of infusion pumps. The basic architecture of the proposed system is shown in figure 1.Here the LSRM is used to push the syringe piston to administer the medicine to the patient. The movement of the LSRM is controlled to deliver the right amount of dosage over the required amount of time. In effect, we are controlling the speed of the LSRM in order to regulate the amount of medicine administered to the patient. A better force profile, improved performance characteristics and a robust build of the linear switched reluctance motor makes it a perfect candidate to replace the stepper motors in the infusion pumps.

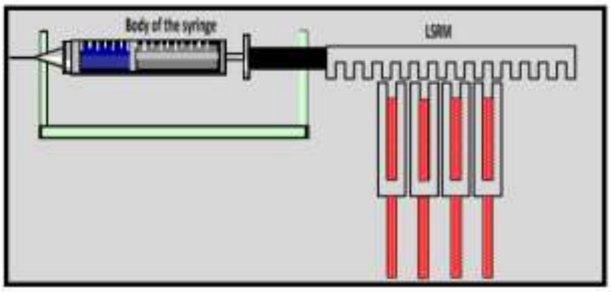

Figure 1: Basic architectureof LSRM driven Infusion Pump.

II. Design Of LSRM

The actuator proposed is a linear switched reluctance motor composed by a toothed sliding part on rail.The stator modules are regularly distributed. The stator windings are laminated copper and concentrated around the cylinder heads of the stator.These coils are excited by DC currents. The non-magnetic separations between the different modules impose a regular shift. If teeth of an active module are aligned with teeth of the translator or the moving part of the LSRM,, the other stator modules must be unaligned in order to create a translation force.We can move from a step command to another only when the actuator responded satisfactorily to the previous command and so there is no possibility of losing synchronism. The position sensor thus has to perform two functions

-Detect the equilibrium positions to generate the next step command to follow the excitation sequence without missing excited phases.

-Continuous detection of the position of the translator to implement closed loop control. This will enable the correction of the position using controllers solves the problems of overshoot and oscillations.

A standard design procedure for a linear switched reluctance machine (LSRM) is discussed next. The proposed design procedure utilizes the rotating switched reluctance machine (RSRM) design by converting the specifications of the linear machine into an equivalent rotating machine. The machine design is carried out in the rotary domain, which then is transformed back in to the linear domain. Such a procedure brings to bear the knowledge base and familiarity of the rotary machine designers to design a linear machine effectively. The design of LSRM is achieved by first translating its specifications into equivalent rotary SRM specifications. Then the rotary SRM is designed from which the LSRM dimensions and design variables are recovered by inverse translation.

Design Procedure

The LSRM is to be designed for a machine stator lengthL_t, with a maximum linear velocity of v_m and an acceleration time t_a required to reach the maximum velocity. The maximum mass of translator is restricted to M_t. Figure 2 shows the required velocity profile of the LSRM. If the deceleration time $t_d = t_a$, the maximum acceleration is given by,

$$a_a = \frac{V_m}{t_a} \quad (1)$$

and the maximum deceleration $a_d = -a_a$. The instantaneous acceleration force F_a is given by,

$$F_a = M_t a_a \quad (2)$$

and the instantaneous deceleration force

$$F_d = -F_a. \quad (3)$$

Assuming a zero instantaneous friction force, $F_f = 0$, the maximum power capacity of LSRM is given by,

$$P = F_a \times v_m \quad (4)$$

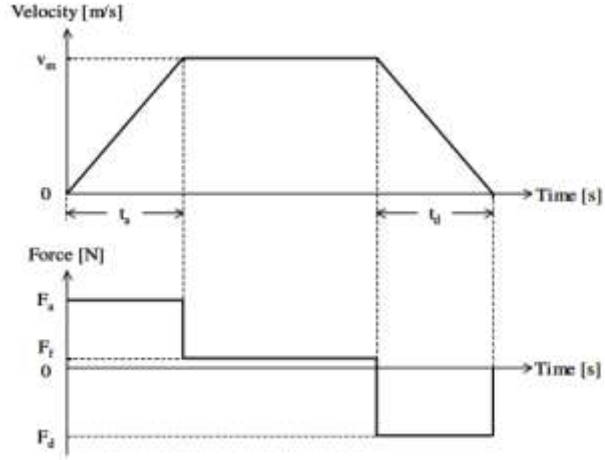

Figure 2 Velocity and Required Force Profiles of LSRM

Design of Rotary SRM

An LSRM prototype is designed for a length of 30cm, with a maximum linear velocity of 30cm/hr and acceleration time of 1 second. The maximum mass of translator assembly is restricted to 10 kg.

Acceleration is given by,

$$a_a = \frac{V_m}{t_a} = 8.33 \times 10\, m/s^2$$

Force for initial acceleration is set as

$$F_a = 100\, N$$

The deceleration, a_d= -8.33m/s^2 and deceleration force F_d= –100 N

Power capacity of LSRM is

$$P = F_a \times V_m = 9W$$

The RSRM is assumed to have a stator pole angle, β_s= 30° = 0.524 rads and rotor pole angle of β_r= 36°= 0.628 rads.

The power output equation of an RSRM in terms of key physical variables, is described by

$$P = k_e k_d k_1\, k_2\, B_g A_{sp} D^2 L N_r \quad (5)$$

where P is the power output, k_e is the efficiency, k is the duty cycle determined by the current conduction angle for each rising inductance profile, k_1= 1/4, k is a variable dependent on the operating point and is determined by using aligned saturated inductance and unaligned inductance, B_g is the flux density in the air gap at the aligned

position, A_{sp} is the specific electric loading which is defined as ampere conductor per meter of stator inner periphery, L is the stack length of the magnetic core, and N_r is the speed.
After fine tuning the parameters using Finite Element analysis, the constants are set as follows:
k_e= 0.4, k_d= 1, k_2= 0.7, B_g=1215mWb, A_{sp}= 0.23886 and k= 0.655
Converting the rotational angular velocity to linear velocity,

$$P = k_e k_d k_1 k_2 B_g A_{sp} D^2 kD \left(\frac{v_m}{D/2}\frac{60}{2\pi}\right) \quad (6) \qquad P = k_e k_d k_1 k_2 B_g A_{sp} D^2 v_m \frac{60}{2\pi} \quad (7)$$

Bore diameter,

$$D = \sqrt{\frac{P\pi}{60\ k_e k_d k_1 k_2 B_g A_{sp} v_m}} = 97.72 \text{ mm} \quad (8)$$

Setting the stack length of RSRM as a multiple or submultiple of the bore diameter,
L= kD = 64.06 mm (9)
The air gap of the LSRM is usually much larger than that of the RSRM. In the aligned portion, the B-H characteristic of the magnetic material is fairly linear and the reluctance of the steel core is very small when compared to the reluctance of the air gap in the aligned position. The machine flux linkage can be calculated as

$$\emptyset = B_g A_g \ (10)$$

where A_g is the area of cross section of the air gap and during alignment is approximately

$$A_g = \left(\frac{D}{2} - g\right)\left(\frac{\beta_r + \beta_s}{2}\right) L (11)$$

where g is the length of the air gap. Magnetic field intensity in the air gap is calculated as,

$$H_g = \frac{B_g}{\mu_0} = 892461.3 \frac{A}{m} \quad (12)$$

Assuming the existence of a large air gap, the ampere-turns required to produce the air gap magnetic field intensity is given by,

$$T_{ph} I_p = H_g 2g (13)$$

where T_{ph} is the number of winding turns per phase and I_p is the peak phase winding current. Assuming a peak phase winding current I_p= 0.5 A, allowable in the machine, the number of turns per phase of the RSRM can be calculated as,

$$T_{ph} = \frac{H_g 2g}{I_p} = 210\ turns/phase$$

If J is the maximum allowable current density in the winding and m is the number of phases, the cross-section area of a conductor is calculated as,

$$a_c = \frac{I_p}{J\sqrt{m}} (14)$$

For a maximum current density of
J = 6A/mm^2, $a_c = 0.818\ mm^2$.
Neglecting the leakage of flux linkages, the area of the stator pole, the flux density in the stator pole, the area of the stator yoke, and the height of the stator pole can be calculated, respectively, as,

$$A_s = \frac{DL\beta_s}{2} \quad (15)$$

$$B_s = \frac{\emptyset}{A_s} \quad (16)$$

$$A_y = C_{sy} L = \frac{A_s B_s}{B_y} \quad (17)$$

$$h_s = \frac{D_0}{2} - \frac{D}{2} - C_{sy} (18)$$

Stator yoke thickness, C_{sy} is given by

$$C_{sy} = \frac{D\ \beta_s}{2} = 25.60\text{mm} \quad (19)$$

Assuming D_0= 190 mm height of stator pole, $h_s = 27.815$ mm.
where C_{sy} is the thickness of the yoke and D_0 is the outer diameter of the stator lamination. The rotor pole area is given by,

$$A_r = \left(\frac{D}{2} - g\right) L\beta_r \quad (20)$$

If the rotor yoke has a radius equal to the width of the rotor pole, the rotor yoke width and the height of the rotor pole are sequentially calculated as,

$$C_{ry} = \left(\frac{D}{2}\right)\beta_r = 30.68 \text{ mm} \quad (21)$$

$$h_r = \frac{D}{2} - g - C_{ry} = 20.45\ 0\text{mm} \quad (22)$$

This completes the analytical relationships required for the RSRM design.

Conversion from RSRM Dimensions to LSRM Dimensions:

The bore circumference of the RSRM forms the length of one sector of the LSRM. The total number of sectors of the LSRM is given by,

$N_{sc} = \frac{L_t}{\pi D} = 22$ (23)

For the number of poles N_s in the stator of the RSRM, the number of stator poles is obtained by,

$n = N_s N_{sc} = 132$(24)

Width of stator pole and width of stator slot are given by,

$W_{sp} = \frac{D\beta_s}{2} = 30.68\ mm$ (25)

$W_{ss} = \frac{\pi D - 6W_{sp}}{6} = 20.49\ mm$(26)

Translator pole width and translator slot width are,

$W_{tp} = \mathrm{C_{ry}} = 30.68\ \mathrm{mm}$(27)

$W_{ts} = \frac{\pi D - 4W_{tp}}{4} = 46.07\ mm$ (28)

Total length of the translator is given by,

$L_{tr} = 6W_{tP} + 5W_{ts} = 414.43\ mm$(29)

The core stack width of the LSRM is obtained from stator stack length of RSRM as,

$L_w = L = KD = 64.06\ mm$ (30)

Diameter of the conductor is given by,

$d_c = \sqrt{\frac{4a_c}{\pi}} = 1.02\ mm$ (31)

Assuming width of wedges, w= 3 and packing factor, f_f= 0.8, number of vertical layers of winding and number of horizontal layers of winding are obtained as,

$N_v = f_f \frac{(h_s - w)}{d_c} = 20$ (32)

$N_h = \frac{T_{ph}}{2\ N_v} = 7$ (33)

Stator winding area is given by,

$\frac{2\ a_c N_v N_h}{f_f} = 286.3\ mm^2$ (34)

Fill factor is calculated as,

$f_f = \frac{stator winding area}{stator slot window area} = 0.499$ (35)

III. Proposed System Simulation In SRM Model

The simulation model for the Linear Switched Reluctance Motor based infusion pump is as shown below. The simulation is carried out in the Switched Reluctance Motor Model available in the MATLAB/SIMULINK. A Linear Switched Reluctance Motor is basically a Switched Reluctance motor cut radially and spread out on a surface. The working of the two variations of the reluctance motor is exactly the same. Hence we use the SRM Model which is available in the MATLAB to obtain the simulation for the LSRM model.

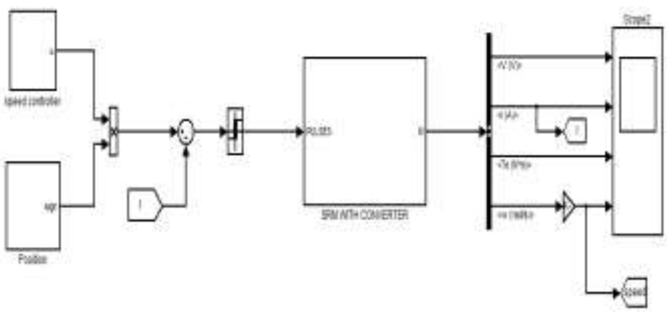

Figure3. Closed loop control of LSRM

The position controller block is as shown in fig.4.12. The angular velocity is converted into radians using an integrator. The modulus operator output is taken to the relational operator. The modulus operator output value will always be less than 90 degrees. The firing is required between 40-75 degrees for the optimum operation of the motor. The speed controller block is as shown in fig.4. The output of the two blocks is taken to a multiplexer. The output of the multiplexer will serve as the current reference. The current output from the previous instant and the current reference is used to get the error in current value. This is given to the hysteresis controller. The output of whose is used to generate the PWM signals required for the switching operation.

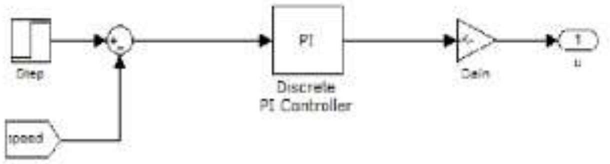

Figure.4: Speed controller block

The converter is provided for each phase. Two switches and two freewheeling diodes are provided in each phase. Each of the two switches in a phase operates simultaneously. After their de-energizing the energy in the winding of the phase is expended through the freewheeling diodes. This block is shown in figure 7 and the consequent energizing for the corresponding windings is shown in figure6

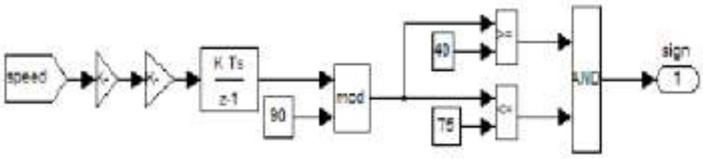

Figure.5: Position sensor block

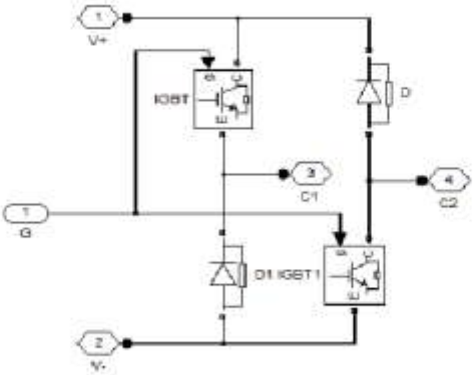

Figure.6: Converter topology for A Phase

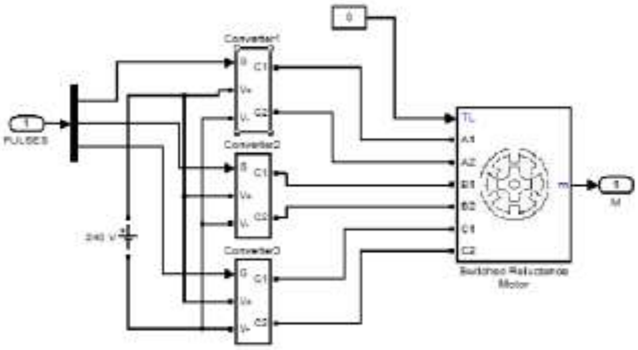

Figure.7: SRM with Converter

The MATLAB Simulation output is as shown in figure.8

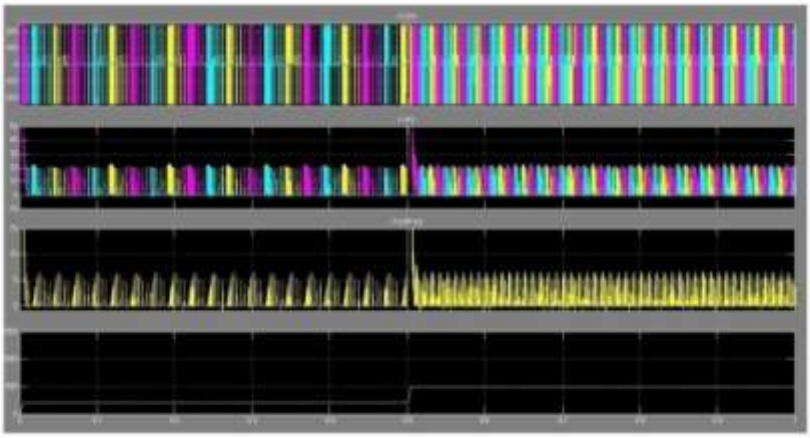

Figure. 8 Simulation Result

IV. Conclusion

In this proposed system, an Infusion Pump using a Linear Switched Reluctance Motor is implemented. The use of the switched reluctance motor eliminated the presence of the additional frictional encountered while using a stepper motor. This is done by removing the need for a transmission system to obtain the linear movement. The occurrence of oscillations in the movement of the Linear Switched Reluctance Motor is also greatly reduced by ensuring a smooth and continuous motion of the translator of the motion.

Authors Profile

Mr.Praveen Kumar .C is workingpresently as Assistant Professor in the Electrical and Electronics Engineering Dept. of NSS College of Engineering Palakkad. His research areas include Plasma Physics, Electric Propulsion, Mechatronics, BiomedicalDevices and Electromagnetism.

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