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Design and Development of a Variable Reluctance Power Block for Electrical Linear Actuators

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ABSTRACT

Power Electrically powered linear Actuators found application in various domains like automation, robotics and IoT based devices. Conventionally to provide the motive power for such Actuators designers either use permanent magnet, brushless DC motors or DC brushed motors. Recent vacillations in geopolitics and economics have affected the supply chain immensely. The inherent dependence of BLDC and DC motors on permanent magnets and the monopoly of China has made the local manufacturing industries explore novel alternatives for magnet-less motors. To tackle this supply chain problem permanent magnet free variable reluctance motors have been identified as a viable option. This paper describes the design and development process of 150-Watt geared VRM for 5000 N - 3mm/sec linear Actuators a 6/4 topology VRM with a worm wheel gearbox was designed for intermittent duty cycle actuator. The actuator was tested, and the results were found satisfactory.

Keywords: Variable Reluctance Motor, Asymmetric half bridge, Worm and worm wheel gearbox, BLDC motors

I. INTRODUCTION

In modern industries electrically powered linear actuators are rapidly replacing hydraulic and pneumatic actuators due their higher reliability, efficiency, and power density [1]. Linear actuators find application in a wide spectrum of industries, namely in aerospace for control of aerodynamic surfaces, automation, medical devices like recliners, ventilators [2], robotics etc. With the advent of IoT, far too many applications like automated doors, beds, furniture etc. rely on linear actuators as the primary motion control solution. More than 90% of the actuators available in the market are either powered by brushed DC motors or permanent magnet brush less (BLDC) motors. Where brushed DC motors provide a low-cost solution, their overall efficiency is of the order of 65 to 70 % and specific power density is on the lower side. PM-BLDC motors however come with a higher efficiency and specific power density. Moreover, BLDC motors have a higher starting torque w.r.t DC motors [3]. As per [4] more than 85 % of the linear actuator market is directly or indirectly dependent on China. This is primarily due to the two factors, namely humongous economies of scale and control over the permanent magnet supply chain. Recent turmoil due to COVID-19 pandemic has demonstrated the grave effects of disruption of China dependent supply chains on the world market. Since electric motors are an indispensable part of many electrically powered actuators other than linear actuators, a cost-effective permanent magnet free motor alternative is a need of the hour. Such a motor shall be independent of Chinese imports and can lead the way for indigenization.

Variable Reluctance Motors is one such viable alternative as it is permanent magnet free, highly efficient and has a good temperature independent characteristic. SRM) is a doubly salient electric machine that relies on reluctance to rotate rather than electromagnetic torque. The rotor of a SRM can be made solid as it doesn't carry any currents, thus making the motor very robust [5]. The SRM can be controlled using sensor as well as sensor-less drives and can have very high speeds which amounts to a high-power density. The material of construction for these motors is readily available non-grain-oriented steel, thus making it easy to manufacture. Moreover, since the design is devoid of permanent magnets, the overall cost of these motors is 35 % less than its competition.

This paper investigates the feasibility of reluctance motors in electrically powered linear actuators, which undoubtedly have become the backbone of modern industries. Subsequent sections of this paper describe the design procedure, fabrication methods and experimental findings of a SRM powered 1000 N-20 mm/s actuator.

II. METHODS AND MATERIAL

Figure 1: Height Adjustable Table (HAT) used as a benchmark product for linear actuator testing

An electrically powered linear actuator designed to be used in a height adjustable table (HAT) was chosen for this work. A HAT comprises two linear actuators, one in each leg of the table. For this specific application the actuator motors are controlled in such a manner that both the actuators work in a synchronous manner when powered. Figure 1 describes the height adjustable table which can be used by users of different body height and structures. The table specifications are described in Table 1.

Table 1

Static Holding Load	1000 N
Dynamic Load Capacity	400 N
Maximum Lifting Speed	20 mm/s
Total Weight	24 kg
Input Power	220 V˜50 Hz AC

Every single actuator carries 20 kg dynamic load at a maximum speed of 20 mm/s which amounts to total dynamic loading of 400 N.

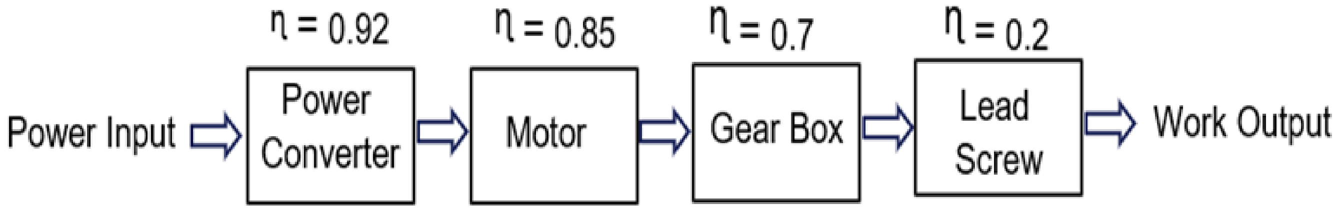


Figure 2 : Schematic flow diagram of linear actuator comprising of sub-components

Figure 2 shows the various sub-components of an electric linear actuator describing flow of power from subsequent components. The target subcomponent efficiencies are typical for low-cost linear actuator components. The following subsections describe the design procedure employed for subcomponent design.

III. POWER CONVERTER DESIGN

For the actuator design of 1000 N – 20 mm/sec specification, power requirement is calculated as follows:

$$\text{Power} = \text{Force x Velocity} \quad (1)$$

$$= 1000 \text{ x } \frac{20}{1000} \text{ Nm/s}$$

$$= 20 \text{ Watt}$$

$$P_{in} \text{ x } (\eta_{Drive} \text{ x } \eta_{Motor} \text{ x } \eta_{Gearbox} \text{ x } \eta_{Lead\ Screw}) = P_{out} \quad (2)$$

$$P_{out} = \frac{20}{0.91 \times 0.85 \times 0.78 \times 0.2}$$

$$P_{in} = 110.49 \text{ Watt}$$

Hence, a switched mode power supply as shown in Figure 2 was selected as the main power converter.

3.1 LEAD SCREW DESIGN

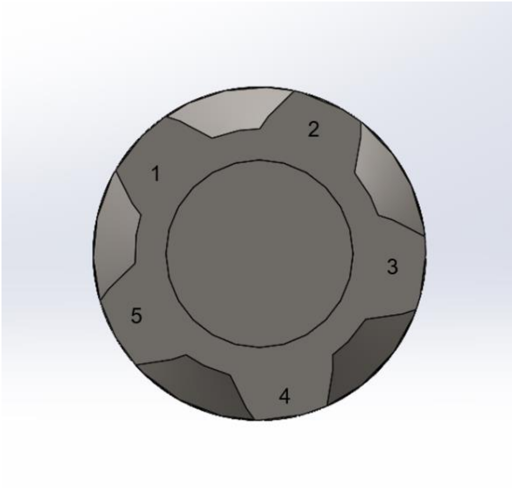


Figure 1: 5 start lead screw

Design calculation used for a 20 mm lead; 4 mm pitch 5-start lead screw are shown in equations (3)-(5)

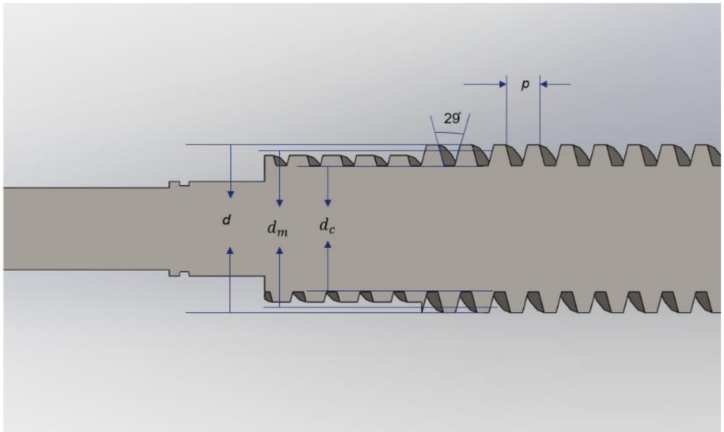


Figure 2: Lead screw of 5 start, 4 mm pitch and 20 mm lead

Acme threads Lead Screw

Thread angle (θ) = 30°

Lead Screw is 5 start therefore,

Lead (l) = 5 x p = 5 x 4 = 20 mm (3)

Nominal Diameter (d) = 16mm

Major Diameter (d_m) = (d – 0.5p) = 14 mm (4)

d_c= d – p = 16 – (4) = 12mm

Helix Angle (α)

$Tan\ \alpha = \frac{1}{\pi d_m}$; α= 0.0227 rad (5)

Efficiency η = 0.3

3.2 GEAR BOX DESIGN

For torque conversion a worm-worm wheel gear box configuration as shown in figure xxx was selected. This was primarily done due to the inter-locking feature and high gear ratio. A worm gear box provides a passive breaking feature which is highly desired in actuators under normal loading. High gear ratio achieved in a single worm-worm wheel render the design very compact.

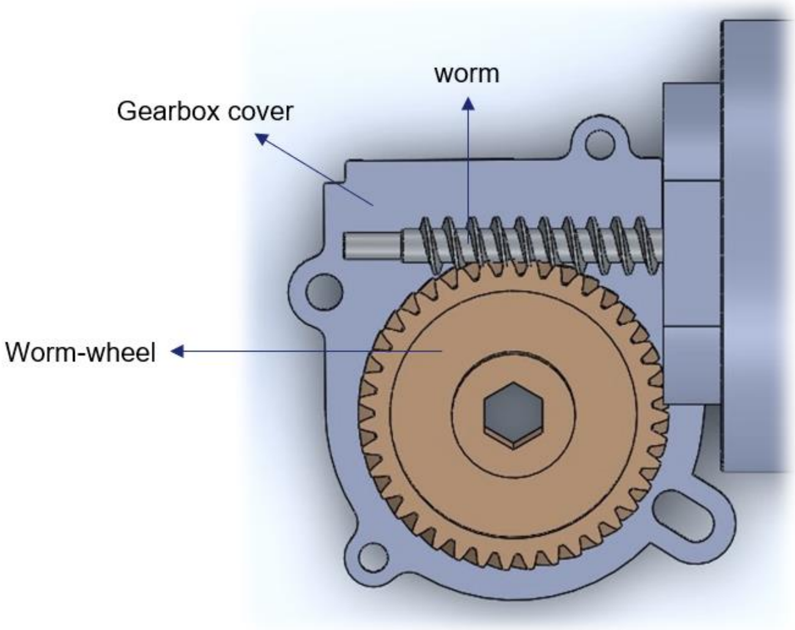


Figure 3: Worm - worm wheel gearbox design used in HAT actuator

A pair of worm gears is specified and designated by four quantities in the following manner: z1/z2/q/m
where,
z_1= number of starts on the worm
z_2= number of teeth on the worm wheel
q = diametral quotient
m = module (mm)
$d_1$and d_2 are pitch circle diameters of the worm and the worm wheel respectively.
d_2=41.05mm
z_2= 39
Module,

d_2= m x z_2 (6)

m = 1.05

Axial Pitch P_x= π m (7)

= 3.3 mm

Lead I = π m z_1 = 3.3 mm (8)

Lead Angle γ,

$$\text{Tan } \gamma = \frac{l}{\pi\, d_1} \quad (9)$$

γ = 7.44°

Helix Angle φ ,

$$\gamma + \varphi = \frac{\pi}{2} \quad (10)$$

φ= 82.56°

3.3 SRM DESIGN

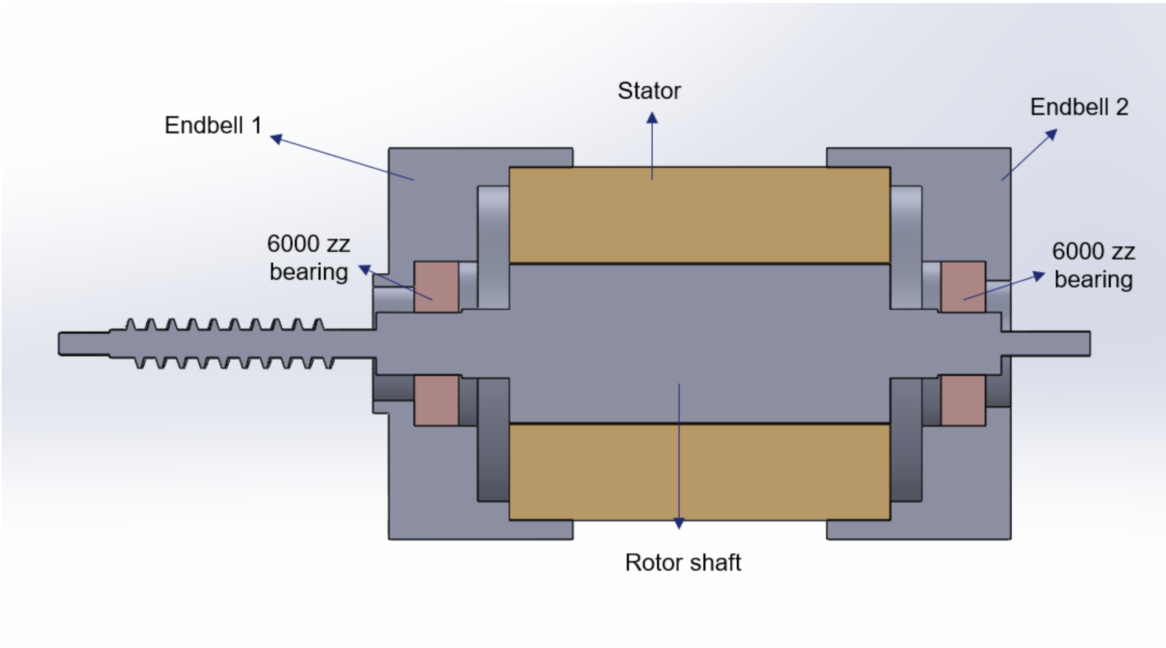


Figure 4: SRM motor assembly depicting worm machined on the motor shaft

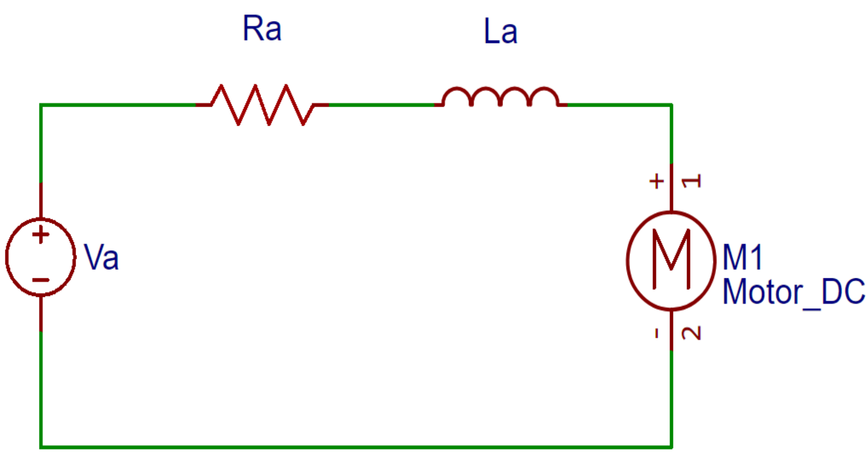


Figure 5: Simplified equivalent circuit of a switched reluctance motor

1. v = Voltage
2. Ψ = Flux Linkage
3. t = Time
4. i = current
5. R = winding Resistance
6. ω = rotor speed rad/s

If we consider a phase winding excited by a voltage source:

$$v = Ri + \frac{d\Psi}{dt} \qquad (11)$$

Now,

$$\Psi = Li \qquad (12)$$

$$v = Ri + \frac{d(Li)}{dt} \qquad (13)$$

$$v = Ri + L\frac{di}{dt} + i\frac{dL}{dt} \qquad (14)$$

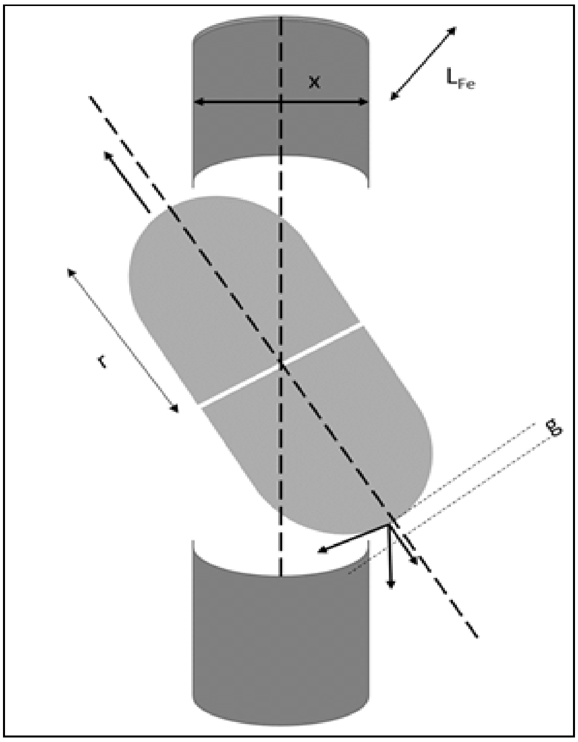
Now L = f(t, θ)

$$v = Ri + L\frac{di}{dt} + i\frac{dL}{d\theta}\frac{d\theta}{dt} \qquad (15)$$

$$v = Ri + L\frac{di}{dt} + \omega i\frac{dL}{d\theta} \qquad (16)$$

The instantaneous electric power input to the machine is given by

$$i(v = Ri + L\frac{di}{dt} + \omega i\frac{dL}{d\theta})$$



Torque $= \frac{1}{2}i^2\frac{dL}{d\theta}$

Stored magnetic energy

$= \frac{d}{dt}\left(\frac{1}{2}Li^2\right)$

Thermal Loss $= Ri^2$

Figure 6: Single stator-rotor phase configuration of a SRM

The instantaneous electric power input to the machine is given by

$$i(v = Ri + L\frac{di}{dt} + \omega i\frac{dL}{d\theta}) \quad (17)$$

$$vi = Ri^2 + iL\frac{di}{dt} + \omega i^2\frac{dL}{d\theta} \quad (18)$$

$$vi = Ri^2 + iL\frac{di}{dt} + \frac{1}{2}\omega i^2\frac{dL}{d\theta} + \frac{1}{2}\omega i^2\frac{dL}{d\theta} \quad (19)$$

$$\frac{1}{2}\omega i^2\frac{dL}{d\theta} = \frac{1}{2}i^2\frac{dL}{d\theta}\frac{d\theta}{dt} \quad (20)$$

Hence, we combine the 2nd and 3rd terms of equation

$$vi = Ri^2 + \frac{d}{dt}\left(\frac{1}{2}Li^2\right) + \frac{1}{2}\omega i^2\frac{dL}{d\theta} \quad (21)$$

$$vi = Ri^2 + \frac{d}{dt}\left(\frac{1}{2}Li^2\right) + T\omega \quad (22)$$

From the above equations

$$K_t = \frac{1}{2}i\frac{dL}{d\theta} \quad (23)$$

$$K_e = i\frac{dL}{d\theta} \quad (24)$$

Now we know in this case that L = $\frac{\mu_0 N^2 x L_{Fe}}{g}$

Also, from the geometry of this problem,

$$dx = rd\theta \quad (25)$$

$$dL = \frac{\mu_0 N^2 L_{Fe}}{g}dx \quad (26)$$

$$dL = \frac{\mu_0 N^2 L_{Fe}}{g}rd\theta \quad (27)$$

$$\frac{dL}{d\theta} = \frac{\mu_0 N^2 L_{Fe} r}{g} \quad (28)$$

$$\text{Torque, } T = \frac{1}{2}i^2\frac{\mu_0 N^2 L_{Fe} r}{g} \quad (19)$$

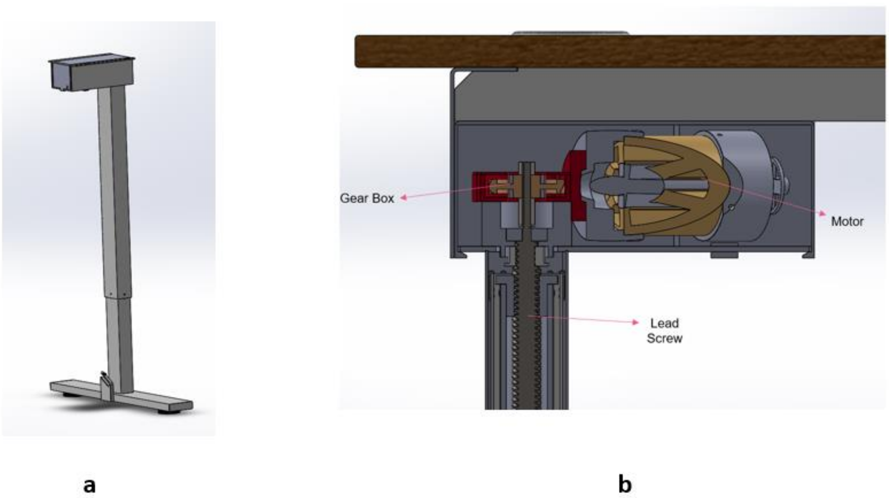
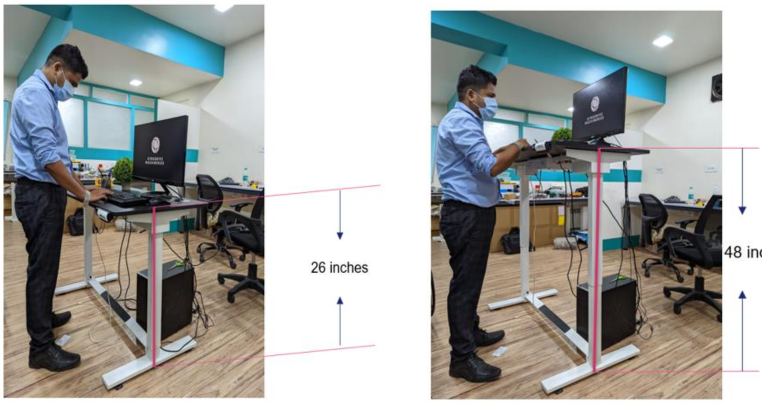


Figure 9: Cut section of actuator assembly

IV. RESULTS AND DISCUSSION

Figure 10 respectively shows the lowest and highest elevation achieved by the height adjustable table. The actuator motors were programmed to run at a fixed speed resulting in a lifting speed of 20 mm/s. It was observed that during starting and stopping a 60 dB jerk noise was produced. Hence, an acceleration and deceleration routine need to be added to have a smooth starting and stopping operation. The table was easily able to lift randomly distributed weight up to 40 kg in a dynamic condition.



a b

Figure 10: Height adjustable table testing showing various elevated positions

Table 2

Motor Temperature	60° - 65°
Lowest Height	26 inches
Highest height	48 inches
Duty Cycle	5 minutes
Noise Level	40 db. – 50 db.

Table 2 shows the various measured parameters while testing the height adjustable table.

V. CONCLUSION

Electrically powered linear actuators have become an indispensable part of modern automation. This work primarily focused on developing a reluctance motor powered linear actuator system as an alternative to conventional actuators using brushed DC motors. For validation and feasibility study a height adjustable table was selected to be the benchmark application. It was found that the SRM powered actuator provides an economically better, energy efficient alternative which is less prone to adverse effects of the international supply chain disruption.

VI. ACKNOWLEDGEMENT

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