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Design of Single Phase Linear Induction Motor with Toroidal Winding

Rahul A. Lekurwale, Ajay Krishna Bandari
Assistant Professor, Dept. of Electrical Engineering, Maharastra
rahullekurwale18@gmail.com, ajay.nani7@gmail.com

Abstract: In this paper, design, performance and experimental results for single phase linear induction motor (LIM)with toroidal winding having a special type of reaction plate is presented. The main idea behind the proposed reaction plate is to provide better performance and efficiency with toroidal winding inspace-constrained applications where a LIM with much higherprimary length in comparison with the primary width is required. Also, as the motor is designed to operate at any speedthe output power, and thus efficiency, would be good. However, an improvement in performance,and thus efficiency, may be achieved when the special reaction plate is used. This paper mainly focuses on thedesign optimization, prototyping, and performance evaluation of single phase LIM with toroidal winding.

Keywords: LIM (Linear Induction Motor),Reaction Plate, Toroidal Winding, Space Constraints.

I. INTRODUCTION

Linear Induction motor is a conventional development of conventional three phase induction machines. Instead of rotary motion in a three-phase conventional induction motor rectilinear motion is obtained in a linear induction motor. "Whenever a relative motion occurs between the field and short-circuited conductors, currents are induced in them which results in electro-magnetic forces and under the influence of these forces, according to Lenz's law the conductors try to move in such a way as to eliminate the induced currents" In this case the field movement is linear and so is the conductor movement.

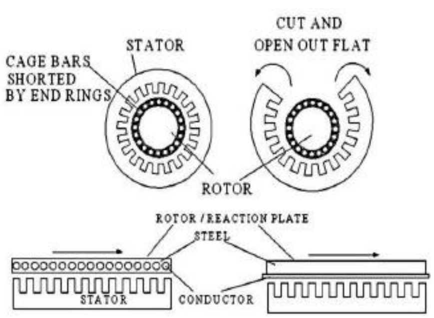

Fig. 1. Formation of Mover Core

The structure diagram of a single-sided linear induction motor (SLIM) is shown in Fig1 The SLIM primary can be simply regarded as a rotary cut-open stator and then rolled flat. The secondary, similar with the rotary induction motor (RIM) rotor, often consists of a sheet conductor, such as copper or aluminum, with a solid backiron acting as the return path for the magnetic flux. The thrust corresponding to the RIM torque can be produced by the reaction between the air-gap flux density and the eddy current in the secondary sheet.

The stator produces a sinusoidal 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. Slip is the relative motion needed in the induction motor to induce a voltage in the rotor[1]-[3]. The SLIM has the following merits comparing with the rotary induction motor (RIM)greater ability to exert thrust on the secondary without mechanical contacts, higher acceleration or deceleration, less wear of the wheels, smaller turn circle radius, and more flexible road line. Because of its cut-open magnetic circuit, the linear induction motor (LIM) possesses the inherent characteristics such as longitudinal end effect, transversal edge-effect and normal force. It uses a rotary electrical motor as source of motion to convert the rotary motion into a linear motion. Often, it is necessary to use a complex mechanical system of gears, axles and screws jacks. When used directly, these transmission systems for movement have great losses. Among the reasons is the increased an abrasive wear due to the friction of the mechanical parts, even when using low viscosity fluids for the lubrication. This results into higher operational and maintenance costs Therefore, for transport applications, the use of an electrical machine that produces directly the linear motion would result in lowers operational and maintenance costs as well as higher reliability and efficiency. Linear induction motors (LIMs) usually use distributed windings either single layer or double layer. The main advantage of a distributed winding is that the flux produced by the primary windings has a good sinusoidal wave, as well as reducing the high-order harmonics in the voltage wave and providing a nearly perfect sinusoidal current wave. However, this type of winding suffers from some drawbacks such as overlapping coils and bulky coil end connection.[1]

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In space-constrained applications where a secondary sheet LIM with large pole pitch in comparison with the primary width is required, toroidal winding is the most appropriate choice. Toroidal winding enjoys many advantages such as short end connection length, high slot fill factor, and switchable number of poles. On the other hand, toroidal winding suffers from some disadvantages. This type of winding presents greater complexity than a distributed winding, as the coils are wound by hand. Moreover, the major drawback of a toroidal winding is that only one side of the coil plays an active role and hence, the coil introduces a large inactive part. In this paper design of single phase linear induction motor with toroidal winding is discussed. Focusis on the design of the core, toroidal winding and reaction plate.

II. DESIGN OF CORE

Core of linear induction motor is formed such that flux produced in core of single sided core linear induction motor is diverted in two different direction by extending part of core in opposite direction to each other by extending the core into two part there exist the need of two different counteracting reaction plates or secondary. Flux which are diverted into two directions are cut by the two-counteracting reaction plate made up of specific material and acting as a squirrel cage rotor in case of conventional rotating induction motor. [1]

The design parameters of linear induction motor are calculated from output equation.

$Q=C_0D^2Ln_s$ (1)

Where,

Q is output of IM in KVA,

Dis diameter of conventional IM,

L is length of core of circular IM,

n_s is synchronous speed in RPS,

C_0 is output coefficient.

L is length of core in case of conventional induction motor considering this as thickness of proposed linear induction motor as unwrapping circular motor into linear one. Hence above equation can rewrite as follows[5].

$Q=C_0D^2Tn_s$ (2)

Where Output coefficient

$C_0=11\times Kw\times Bav\times ac\times 10^{-3}$ (3)

Where, Kw is winding factor, Bav is average flux density (specific magnetic loading), ac is specific electric loading.

Table I. Necessary Contents in the Design of LIM

Constant	Values
Specific Magnetic Loading [Bav] in wb/m2	0.35 to 0.55
Specific Electric Loading [ac] in A/m	5000 to 15,000

A. Winding Factor (Kw):

Winding factor (Kw), before knowing about the winding factor we should know about pitch factor (kp) and distribution factor (kd), as winding factor is the product of pitch factor and distribution factor [5].

The pitch factor and distribution factor are explained below one by one,

B. Pitch Factor:

In short pitched coil, the induce emf of two coil sides is vertically added to get, resultant emf of the the coil. In short pitched coil , the phase angle ,the phase angle between the emfs induced in two opposite coil sides is less than 180^o (electrical) but we know that,in full pitched coil , the phase angle between the emfs induced in two coil sides in exactly 180^o(electrical).

$Kp=\sin(\theta p/2)$ (4)

Where θp is the coil span in electrical degree.

C. Distribution Factor:

Distribution factor is defined as the ratio of the phasor sum of the emfs induce in all the coils distributed in a number of slots under one pole to the arithmetic sum of the emf induced [4].

Distribution factor is,

$Kd = \sin(q1\alpha 2)1\sin(\alpha\mathbf{2})$ (5)

Where α is the slot angle in electrical degree given as

$\alpha = \pi mg1$ (6)

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 (6) in (5) resulting in (7).

$Kw = \sin(\pi/2m)/\ q1\sin(\pi/2mg1)$ (7)

In (7) q1 is the number of slots-per-pole-per-phase in the stator iron core. Also in case of conventional rotating induction motor the speed of rotation of rotor in rps given as Ns=2f/p (rps)

For linear induction motor Synchronous velocity is given as

Vs = 2fτ (m/s) (8)

Pole pitch

τ = πD/P substituting this value in eq. (8) we get

Vs=2fπD/P

P=2fπD/Vs (9)

D is diameter of linear induction motor, to form a linear motor , first convert this into length to convert D into *l* equation for circumference as follows

Circumference=πD and length of proposed motor *l* =Circumference

D=*l*/π (m)

P=2f*l*/Vs (10)

hence get number of poles of linear induction motor.

D. Winding Parameter:

Winding parameter of the DSLIM can also calculated by following the conventional method for number of turns of conventional motor. [3]

Induced emf per phase

Eph= 4.44 f Φm Tph kw (11)

Where Φm =maximum flux, Tph= turns per phase, kw winding factor

Φm= BavτT (12)

Tph= Eph/4.44f Φm kw (13)

Slot per pole per phase =q

Slot =q×m×P

q= 2 or 3 and m = no. of phases

slot pitch Ysm=πD/no. of slots

Calculated mover conductor per slot Zsm

Zsm= total mover conductor/no. of mover slot

Total mover conductor =2×m×Tph (14)

Actual mover conductor per slot = Zsm× total mover slot

Total conductor =2×m×Tph

Tph= total conductor /2×m 9 (15)

E. Conductor Parameter:

Output of motor in KVA Q=V× Im (16)

∴ Im= Q/V

Area of mover conductor am=Im/δ

Taking current density δ=3 to 5 mm2

Diameter of bare conductor d0= 2×√ (am/π)

Actual area of bare conductor am(act.)= (π/δ)/d02

Actual area enamelled conductor = am(act.)+enamelled covering (17)

δ (act.)=Im/am(act.)

F. Slot Dimensions:

Space required for mover conductor in slot

=Zsm×am (18)

Space required for mover conductor in slot (actual) =Zsm (act.)×am(act.)

G. Width of Mover Slot:

Wms = number of conductor widthwise × diameter of insulated conductor + 2 (width of slot insulation) + slack (19)

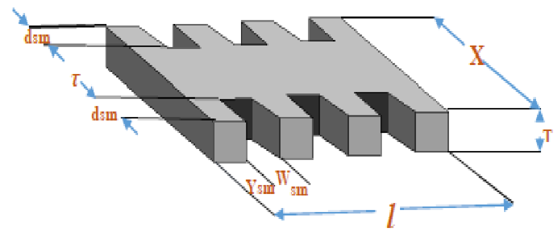


Fig. 2. Movable Core (Primary)

The actual calculated parameter of the proposed single phase core of linear induction motor with toroidal winding is shown in the following table

Table II. Design Parameter and Dimensions

Prameters	Values	Unit
Wattage	60	W
Voltage	230	V
Frequency	50	Hz
Length of core	0.20	m
Synchronouse Velocity	5	m/s
Current	0.7	A
No. of Poles	4	-
Pole Pitch	0.05	m
Thickness of core	0.03	m
Width of core	0.093	m
Number of Slots	16	-
Depth of mover slots	22	mm
Width of mover slots	6	mm

H. Depth of Mover Slot :

dms= number of conductor depth wise × diameter of insulated conductor + 3 (width of slot insulation)+depth of wedges and lip + slack (20)

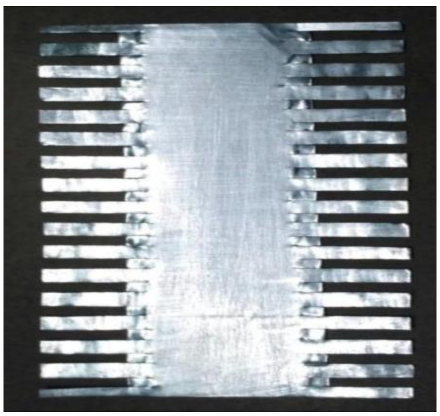
Generally, slack = 1, lip=1, depth = 3, wedges = 1 or (0.8 for Wms)

Hence width of core of proposed linear induction motor

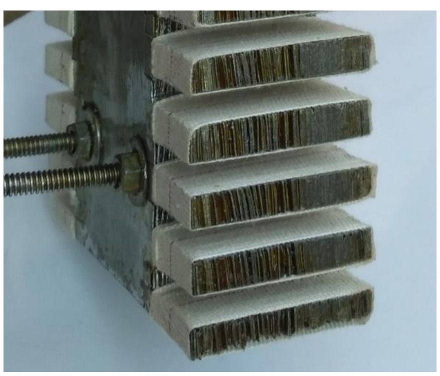
$$X=2\times dsm+\tau \quad (21)$$

I. Formation of Core:

Linear induction motor magnetic mover core is made in similar way as that of other electric machine. Number of silicon steel metal sheet are cut according to the dimension of slots depth and slot width. Stamping are formed either by laser cutting, metal stamping method , water get cutting , progressive dies, electric discharge machine [EDM] or by fine blanketing. [3]



(a)



(b)

Fig. 3. (a), (b) Stamping and Core

All above methods are useful for mass production of core. Stampings are formed by cutting the sheet by sheet cutting plier by hand into the required dimension of core. These stampings are stacked together. Then, holes are drilled by drilling machine for holding the stamping together and to form core. These stamping then bolted together. Since stamping are cut by hand, they are not in furnished form, when stacked together. So to form smooth surface core and furnished slots. These stacked cores then filed and surface of core and slots are made smooth. Care must be taken while filing the core because chances of deformation of core are there while filing. This may create uneven air gap. After creating smooth stamping and core after stacking them. These stamping of core unbolted and each stamping is then insulated from each other by providing coating of insulation varnish-insulation over them. After drying the coating of varnish then again stampings are stacked together.[1][2] The varnish coating over each stamping insulate stampings from each other and hence thereby reduce the eddy current losses inside the core. In this way core is formed cost effectively.

III. Design Of Winding

As discussed in the introduction section, toroidal winding has the advantage such as short end connection length, high slot fill factor and switchable number of poles. Toroidal winding for the main winding and auxiliary winding as in case of single phase induction motor has been proposed in this paper. Main winding and auxiliary winding are wound in toroidal manner.

The methodology of toroidal winding is shown in fig 4. One sided slot and other coil side is replica slot at opposite side of mover core. How coils are wound for the proposed design of double sided linear induction motor are explain in detail below[1]-[6].

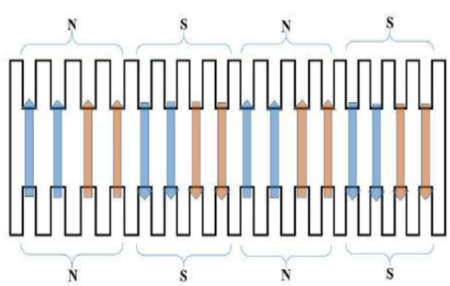


Fig. 4. Schematic of Toroidally Wound Mover

Toroidal winding is wound over core in such a way that one end of a coil is in one side Slot of the core and other coil side is in replica slot which is used to divert flux in other direction of core the methodology of toroidal winding is explain in detail in this section. Here to form one pole at both the end of core winding is wound such that main winding holds two coils in one direction [i.e. main winding in clockwise direction shown by blue arrow also two coils in same direction as that of previous to form same by red arrow. For four poles, let us discus simple way the four-coil wound in clockwise direction [i.e. upward direction shown direction shown in figure] in four consecutive slots out of which two are of main winding. Blue arrow shown in upward direction and two are of auxiliary winding. Red arrow shows in upward direction. All four coils produce one pole i.e. let us say N pole or S pole four coils are wound in anticlockwise manner arrows shown in downward direction. Where blue arrow represents main winding coil and red arrow represent auxiliary winding coil. The motor is having four poles and sixteen slots [single side core slot] and same slot are emitted by extending them in opposite direction hence only sixteen slot and not thirty-two slot. And same pole is created in both side due to toroidally wound winding.

Hence one winding contain auxiliary hold eight slots and hence two coils of each winding wound in opposite manner. Let us say two in clockwise and next two are in anticlockwise further two are of clockwise and next most in anticlockwise. For auxiliary winding same procedure is repeated. [6]

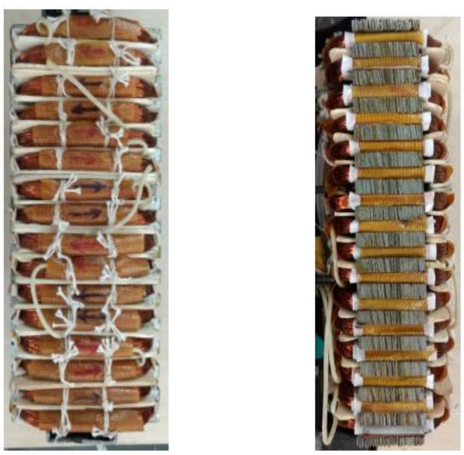


Fig. 5. Mover with Actual Winding

IV. Reaction Plate

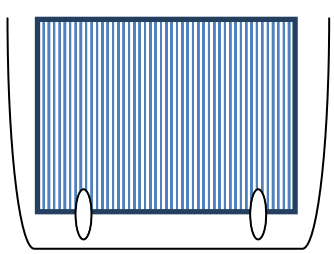


Fig 6. U Shaped Reaction Plate with Mover Core with Toroidal Windings on the Sides

In this paper, LIM with special type of reaction plate is presented. In general LIM is of two types. first single sided LIM uses reaction plate under the primary core. As the reaction plate is fixed, the primary core gets thrust force and it moves in linearly (straight). Secondly double-sided LIM uses a reaction plate in the middle & the primary core is on the both sides of the reaction plate.

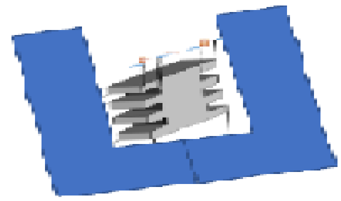


Fig. 7. Cross-Sectional View of LIM

Here a strong magnetic field is formed so that it can be operated efficiently and in this reaction plate is in u shaped or the with corners at right angle.as we are using toroidal winding of single phase reaction plate of different structure is used such that it covers the complete magnetic field and it can be used for low weight high speed applications. Due to main winding and auxiliary winding in the primary core as in case of single phase induction motor with a capacitor a travelling magnetic field is produced in primary core. Faraday law makes the reaction plate induces a emf in the reaction plate as in single phase induction motor due to this primary core starts moving in the track if the reaction plate is fixed. In hostile environments a non-magnetic stainless-steel barrier can be used between coil assembly and the reaction plate to provide a seal. Advantages of single phase special LIM are wide speed range, less maintenance & ease of control. Its applications are conveying systems, cranes drives, baggage handling, Transportation and Park rides. The LIMs are reversible so the same motor that propels the pod in one direction down the track can be used to propel the pod back to where it started. So it can be used high speed transportation of low weight goods.

V. Conclusion

This paper presents design optimization and performance evaluation of a single-phase LIM with toroidal windings. Toroidal winding has shown its merits in space-constrained applications where a LIM with much higher primary length in comparison with the primary width is required. In this case, we show that the LIM with toroidal windings provides a better performance compared to a machine with distributed windings. It provides these advantages by using special type of reaction plate. In present trend these motors have large variety of applications as mentioned above.

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