Chapter 4

Electromagnetic launch under constant voltage excitation

4.1 Introduction

The previous chapter dealt with the electromagnetic launch under constant current excitation based on the steady state Thrust-speed behavior. This chapter concerns with the comparative studies of different types of three phase windings of SLIM under constant voltage excitation from the view point of its suitability for the use of SLIM as a thruster machine used in electromagnetic launching applications.

4.2 Three phase windings of SLIM for Energy Machines

The windings are the heart of any electrical machine which plays a crucial role in converting three phase pulse power into active thrust useful for thruster or launcher applications. When an induction motor having an unstable portion (positive slope) at higher slip region of steady-state torque-speed characteristics is impressed upon with high voltage three phase pulse power, severe oscillations (positive and negative thrust magnitudes) in the transient toque-speed and torque-time characteristics occur. It may also over speed beyond its synchronous speed causing serious thrust-speed oscillations near the synchronous speed [57]. The thruster application of linear machines requires high voltage pulse power for a very short time (few cycles of the desired frequency) utilizing just its initial thrust of the transient period much before realizing the steady-state speed. The thrust-speed characteristics of SLIM and torque-speed characteristics of a rotary induction motor are almost similar in nature. The machines having unstable portion of toque-speed or thrust-speed characteristics will take a longer time for achieving the desired speed, which is aggravated in the presence of severe oscillations during starting period [58]. Here four different types of windings have been studied from the perspective of SLIM for thruster or launcher applications which are denoted by as shown in Table 4.1.

Table 4.1 Types (cases) of windings being analyzed and studied

	Tooth winding	Distributed winding
Single layer	A	C
Double Layer	AA	CC

The details of these winding are given in Table 4.2. Stator windings having single turn coils only has been given emphasis and presented here with the simulation results on ANSYS Maxwell Transient model when, phase voltage of 70.7 V r.m.s. (100 V amplitude) is suddenly applied to the SLIM. Windings with multi-turn coils have not been given heed to, the reasons for which would be stated and portrayed in the due course of the chapter. Further, composite secondary i.e. German silver as secondary conductive sheet backed by iron plate has only been considered for analysis as plain secondary is deemed inferior. The true synchronous speeds are 6.6 m/s and 13.2 m/s corresponding to 8 pole (pole pitch τ = 6.6 cm) and 4 pole (τ = 13.2 cm) formations. The translation limit of the mover is set to 1.2 m. A continuous secondary case has been realized in the simulation by developing model in Maxwell 2D transient solver. The design details of the SLIM for simulation are shown in Table 4.2. The following subsections deals with the results of FEM simulation on Maxwell

Table 4.2 Design details of the SLIM for 2D FEM Simulation

Parameter	Value	Unit
Secondary back iron width	85	mm
Primary core length	560	mm
Secondary conductor length	1800	mm
Primary core width	85	mm
Secondary conductor width	85	mm
Air gap clearance	10	mm
Thickness of secondary conductive sheet (Gs)	3	mm
Thickness of secondary back-iron	10	mm
spp	1	-
Number of slots	24	-
Turns per coil	1	-
Cross-section size of the conductor in coil	290	sq.mm
Power supply frequency	50	Hz
Primary voltage max. Peak /RMS	100 /70.7	V

for studying the operation of SLIM with Pulse three phase power. The details of physical generation of three phase pulse power is beyond the scope of the current research. This can be obtained by using flywheel type of three phase compulsators to supply momentary huge current at high three phase voltage. The FEM models for single layer toothed winding / distributed windings and double layer toothed winding / distributed windings are shown in Fig. 4.1 to Fig. 4.4 respectively.

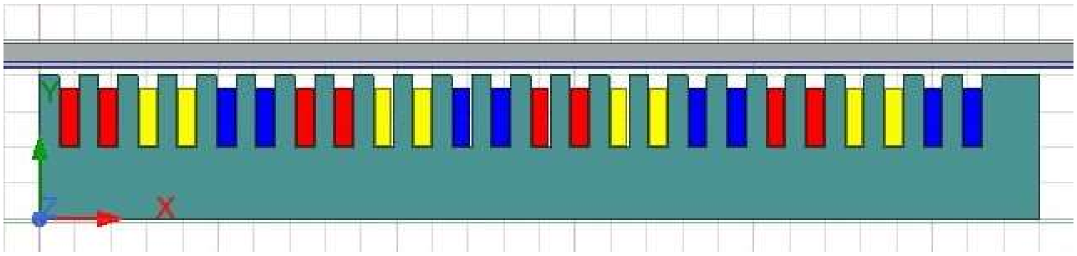

Fig. 4.1 Single Layer tooth winding [Case A]

Fig. 4.5 and Fig. 4.6 show the flux lines and flux density in the LIM for Case [A].

The aim of the study is to determine a suitable winding for the energy machine (LIM) such as thruster or launcher, which can give minimum oscillatory thrust-speed and thrust-

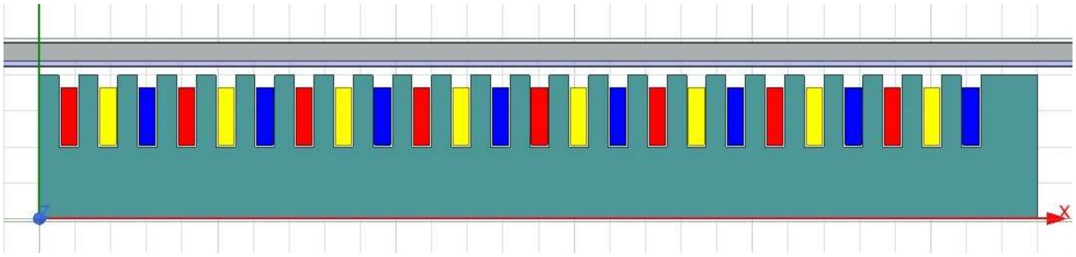

Fig. 4.2 Single layer distributed winding [Case C]

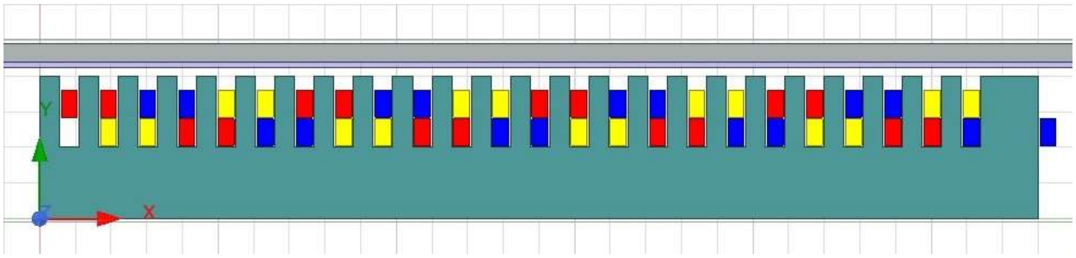

Fig. 4.3 Double Layer tooth winding [Case AA]

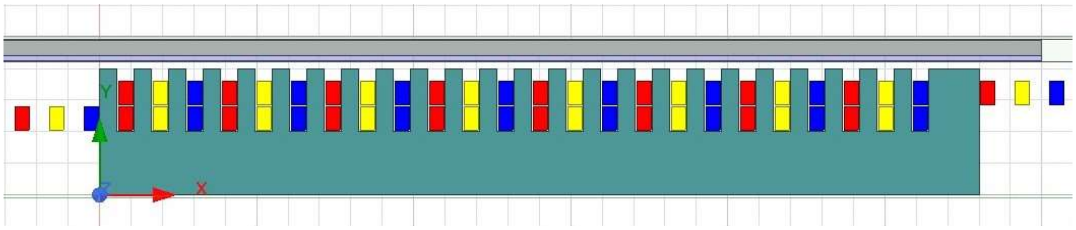

Fig. 4.4 Double layer distributed winding [Case CC]

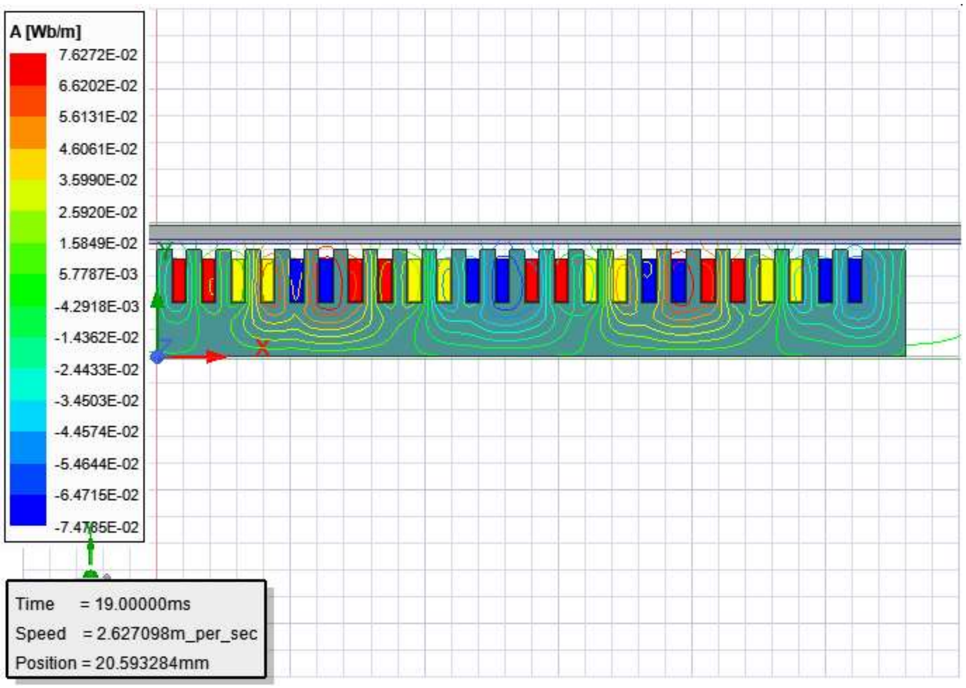

Fig. 4.5 Single layer tooth winding flux lines [A]

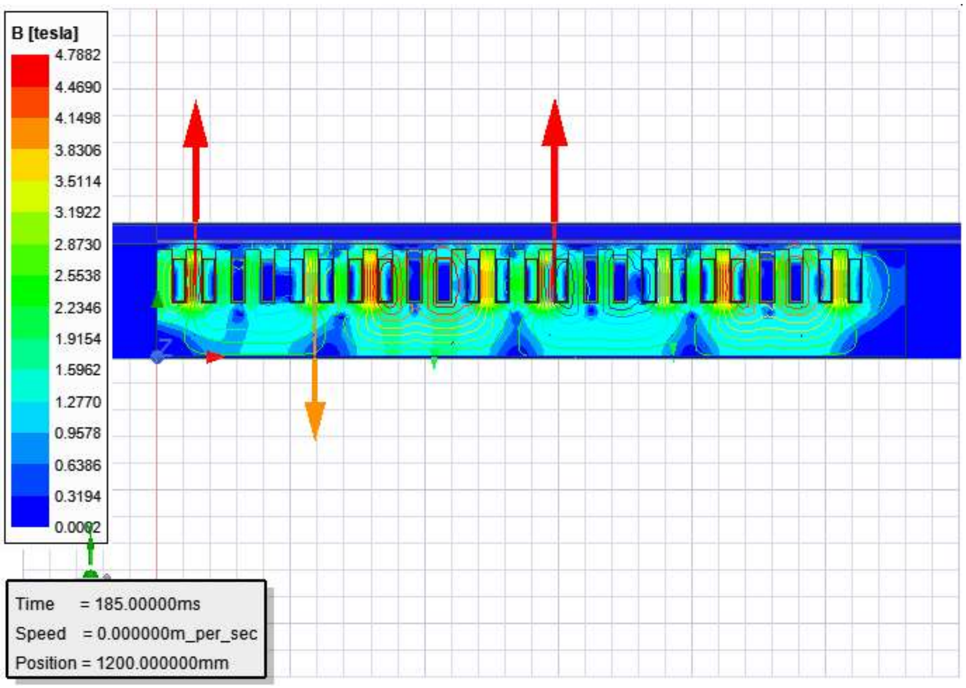

Fig. 4.6 Single layer tooth winding flux density [A]

time responses when full voltage is momentarily applied across its three phase windings. Here we have chosen German silver as the conducting plate material. The thrust oscillatory response also depends on choice of material properties, physical dimensions of the SLIM and windings types. Here only winding types and material of conducting plate have been studied thoroughly.

4.3 Single-layer tooth windings with composite secondary

Fig. 4.7 depicts the voltage and current relationship of one phase for Case A.

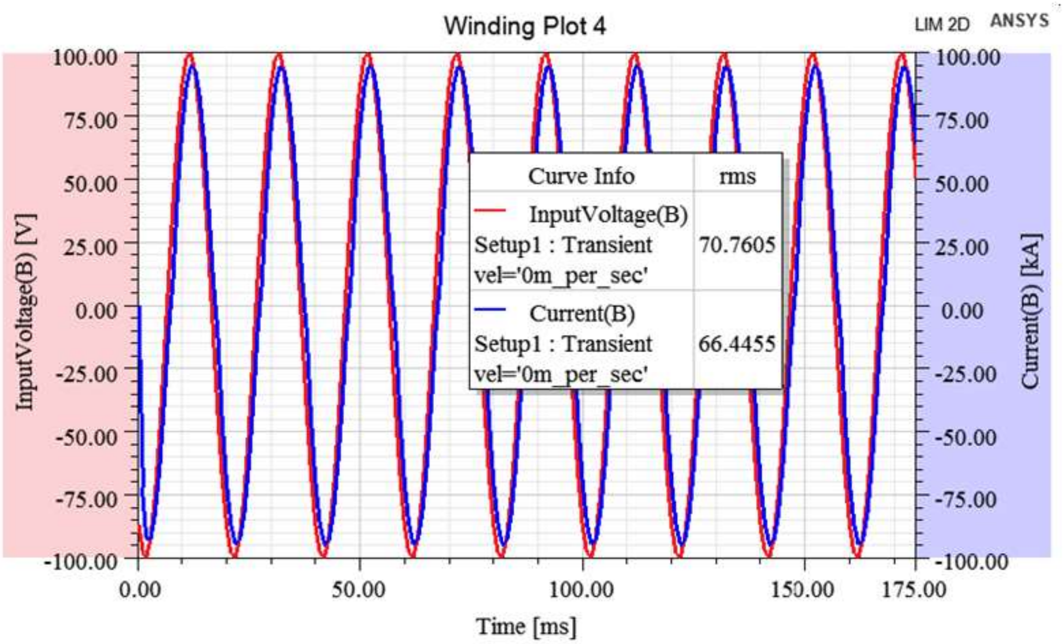

Fig. 4.7 Single layer tooth winding voltage and current relationship [A]

Fig. 4.8 and Fig. 4.9 show respectively the three phase current responses on application of the voltage for 100 ms for single layer composite secondary tooth winding with single turn (Case A) and 50 turns (Case B) per coil. The magnitude of peak current in Case A is around 93 kA, whereas that of peak current for Case B is 0.6 kA. This translates to the net peak ampere-turns per slot as 93 kAT (Case A) and 30 kAT for Case B. The lower current

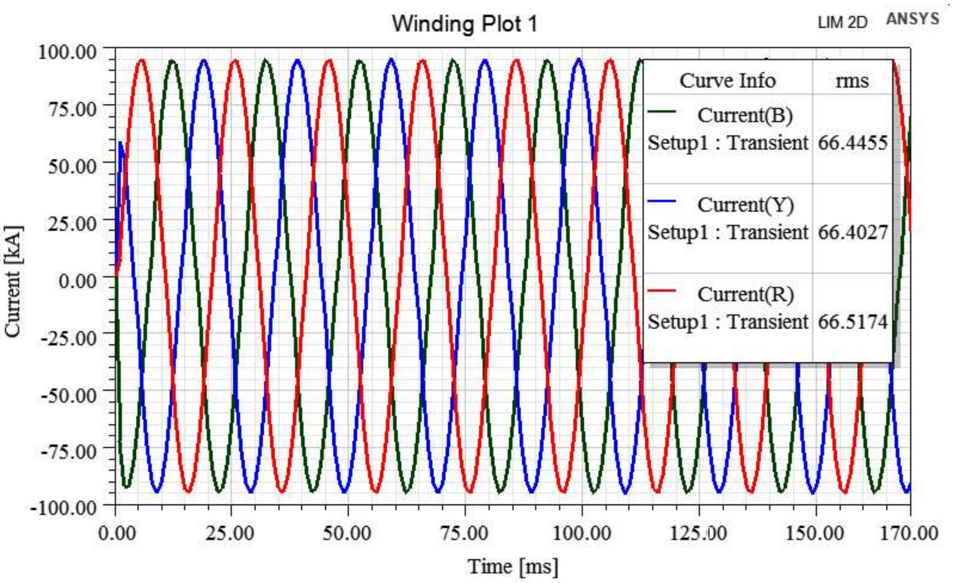

Fig. 4.8 Single layer tooth winding Current [A]

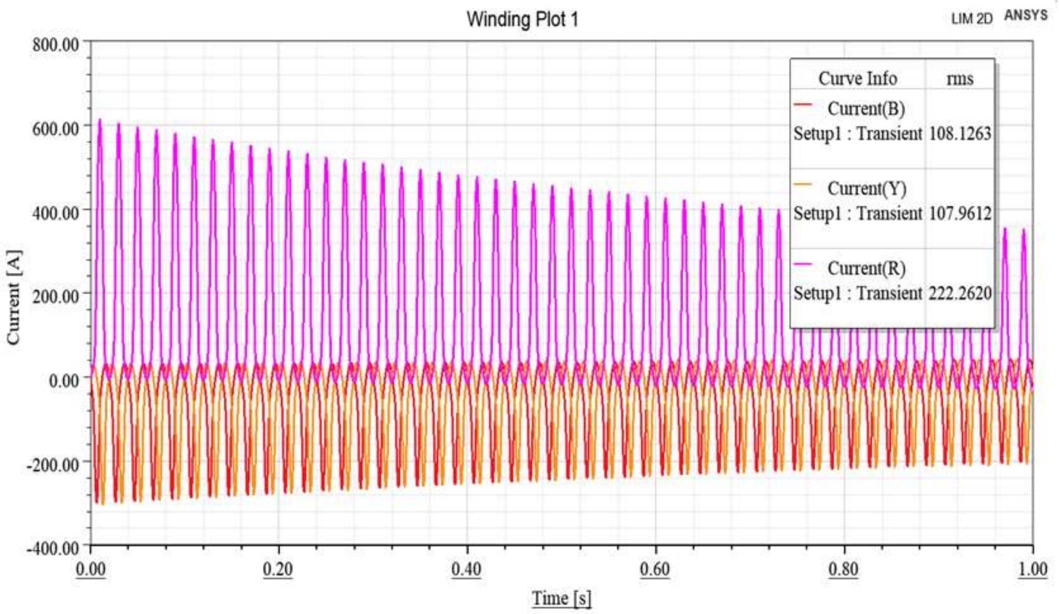

Fig. 4.9 Single layer tooth winding Current [B]

drawn by the LIM in Case B is owing to the increased inductance and resistance of the coils. Also, severe current oscillations are observed in Case B.

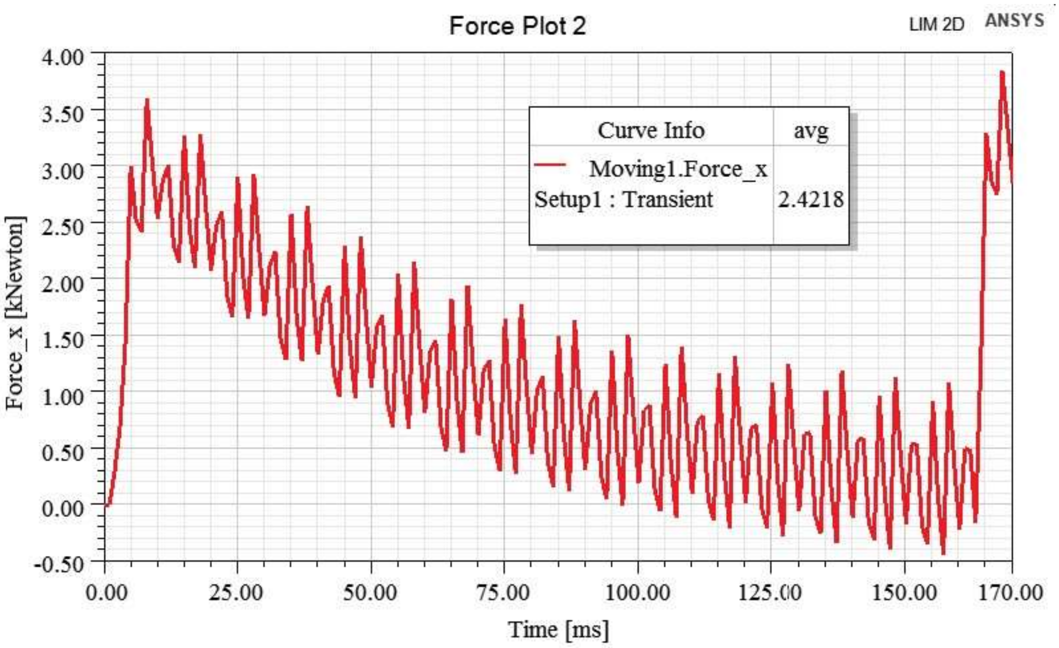

Fig. 4.10 Thrust-Time Single Layer tooth winding single turn composite secondary [A]

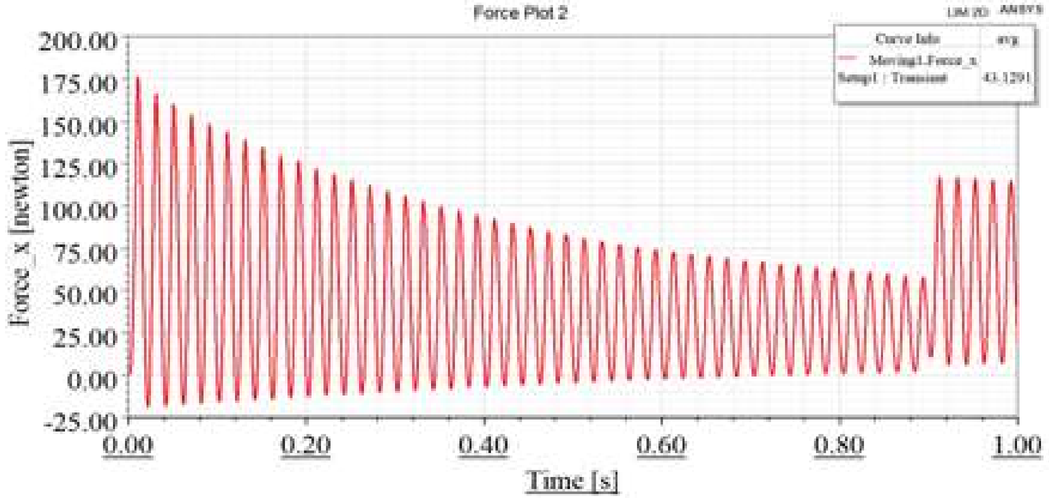

Fig. 4.11 Thrust versus Time Single Layer tooth winding 50 turn composite secondary [B]

Fig.4.10 and Fig. 4.11 depict respectively the thrust versus time for Case [A] and Case [B]. The first zero thrust dip refers to the speeds at which thrust crosses the x-axis (speed axis or zero thrust) for the first instance in the course of transient thrust oscillations. The overshoot in thrust at the end seen in the figures is because the mover has completed its translation limit and gets stopped at that time, while the simulation run time had been kept a little more than the time at which the translation limit is reached. The magnitude of this overshoot thrust at standstill condition is almost equal to the magnitude of the thrust at the very beginning when the mover has just started to move. In Case [A], though the oscillations are there, the transient thrust goes below zero after 100 ms when the machine is nearing its synchronous speed and finally achieves a steady state speed before the mover (secondary) has traveled its target translation limit of 102 m as can be seen in Fig. 4.12. In Case [B] the transient oscillation in thrust below zero creeps in very early impeding the progress of the mover which is unable to achieve a steady state speed as shown in in Fig. 4.13.

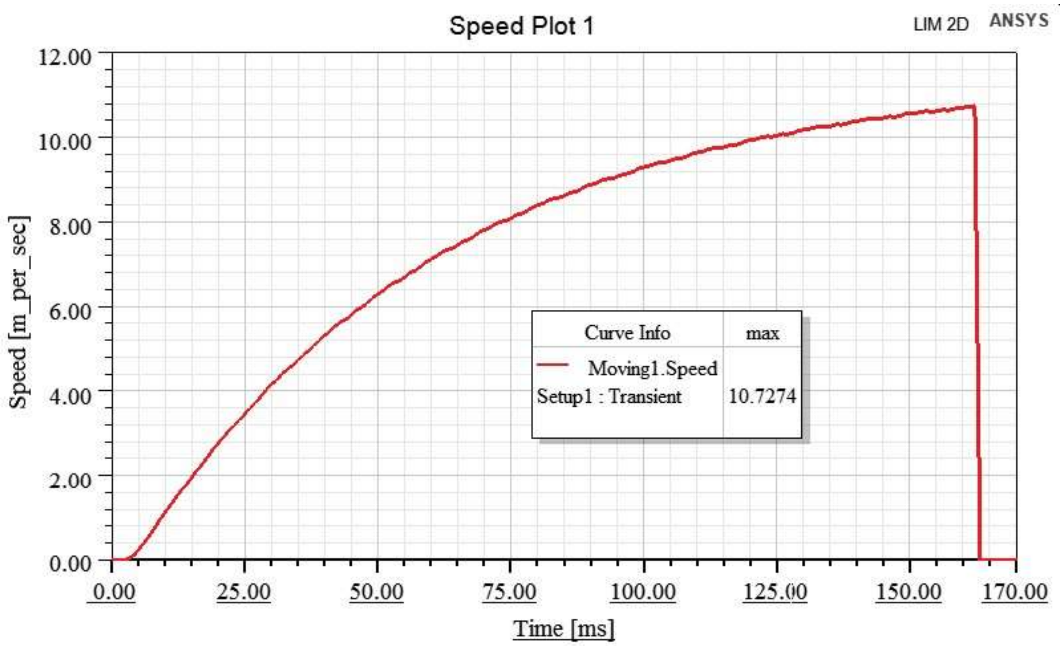

Fig. 4.12 Speed-Time of Single layer tooth winding [A]

The oscillation in the transient thrust in positive direction contributes to the forward movement, whereas the oscillations in thrust in negative direction hampers the movement severely when present during initial conditions. The manners in which the SLIM advances

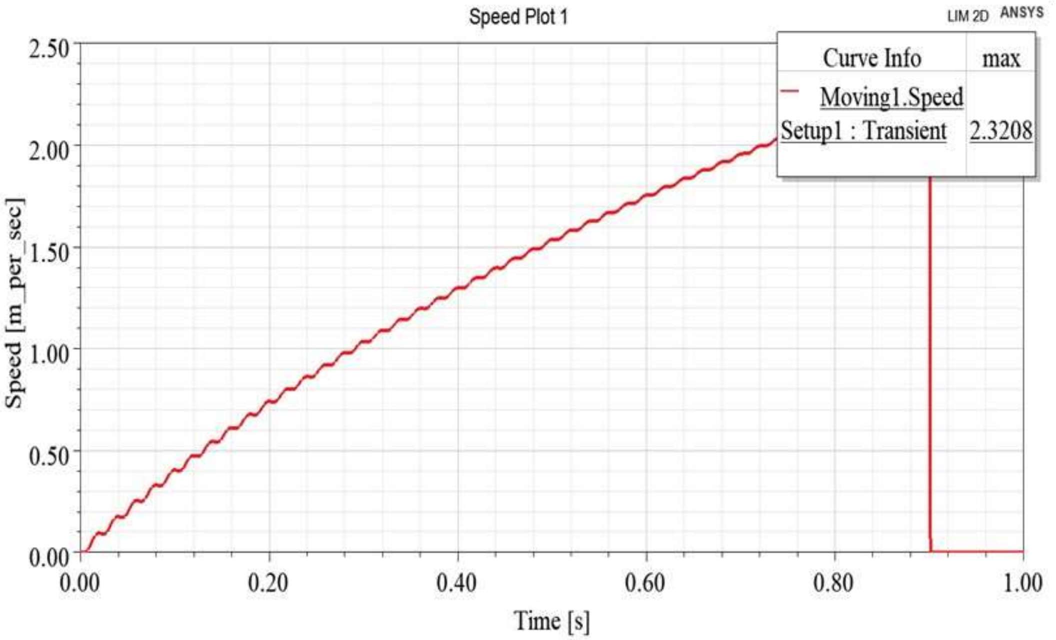

Fig. 4.13 Speed-Time of Single layer tooth winding [B]

in Case [A] and Case [B], are portrayed respectively in Figs. 4.14 and 4.15. It can be observed that in Case [A] the target is reached in 166 ms, while it is 900 ms for Case [B].

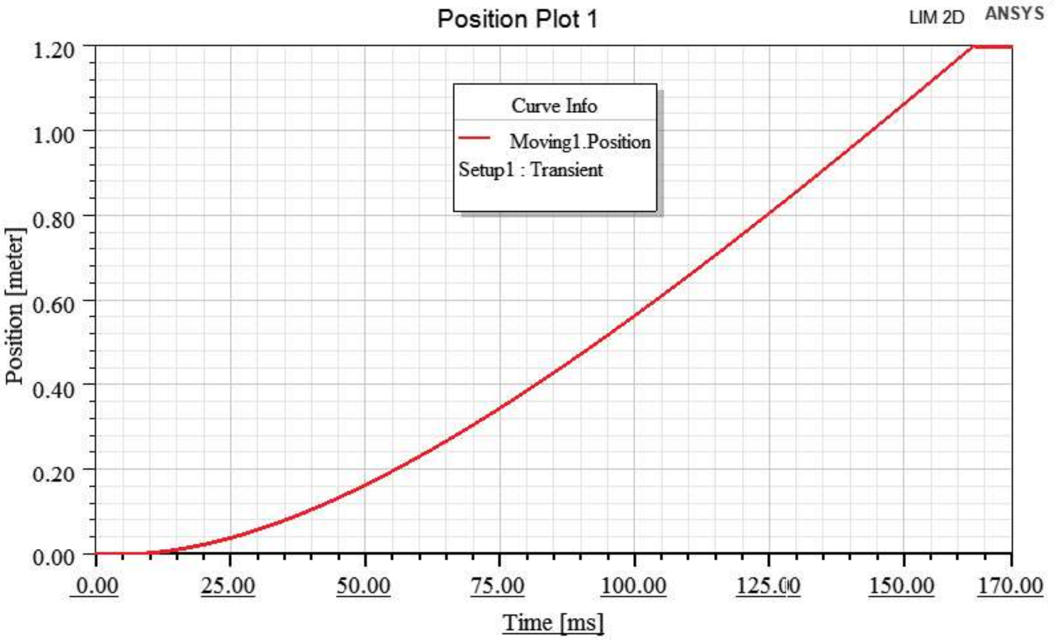

Fig. 4.14 Position-Time for Single layer tooth winding [A]

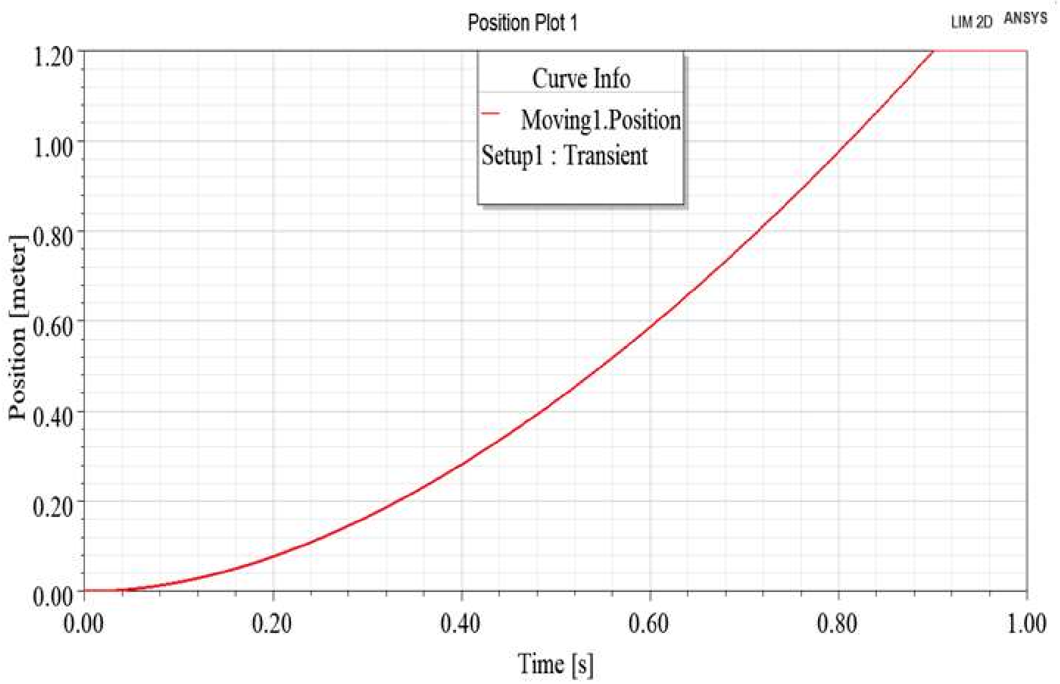

Fig. 4.15 Position-Time for Single layer tooth winding [B]

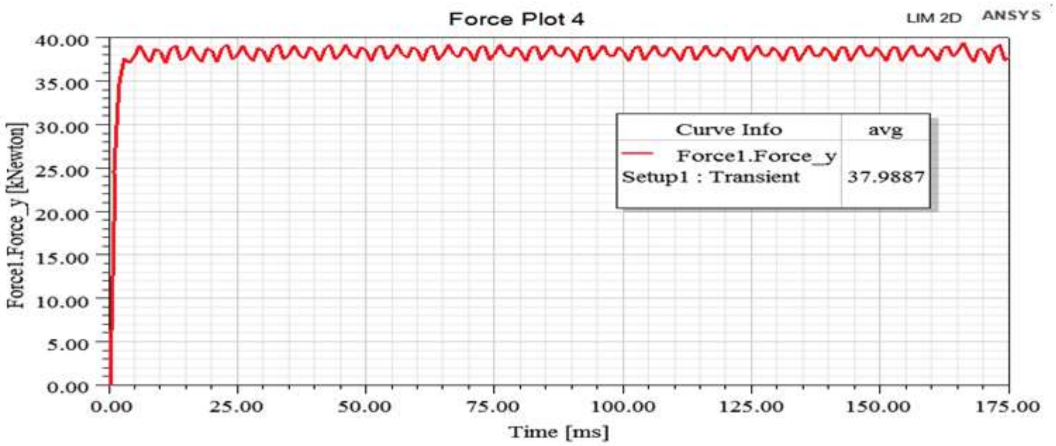

Fig. 4.16 Normal Force-Time for Single layer tooth winding [A]

Fig. 4.16 and Fig. 4.17 show Normal force versus time for Case [A] and Case [B]. The positive *y*-directed Normal force on the secondary (situated above the primary stator) indicates that the force is repulsive in nature. While the Normal force immediately settles to a steady value in Case [A], the oscillatory normal force variation in Case [B] results in

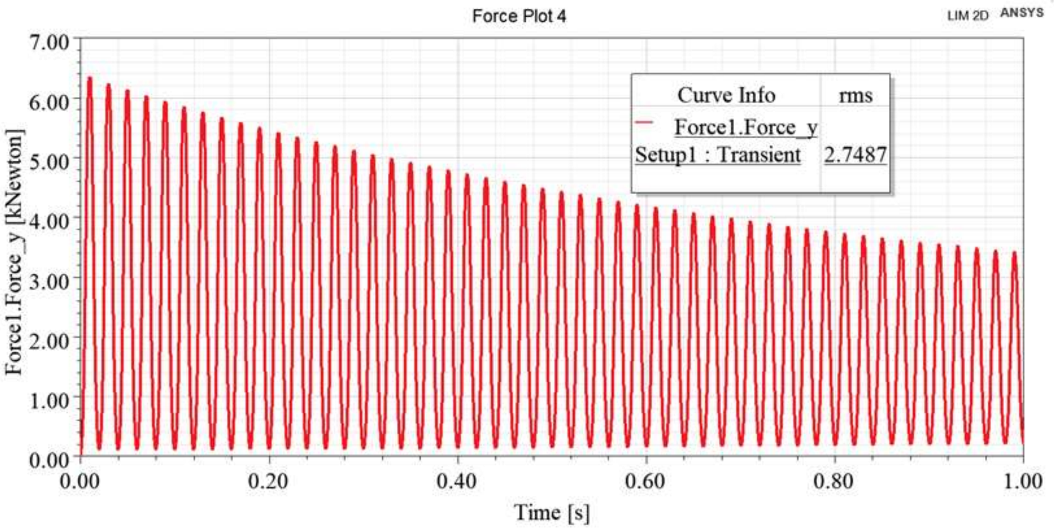

Fig. 4.17 Normal Force-Time for Single layer tooth winding [B]

generation of vibration and noise and eventually contributes to fluctuation in the virtual mass of the mover. It may be noted here that the magnitude of Normal force is more than 10 times the magnitude of thrust in both the Cases.

From the above simulation results it is evident that the performance of LIM in Case [B] with 50 turns coils is far inferior to that of Case [A] with single turn coil. Hereafter, LIM with single turn coils will only be given heed to.

4.4 Performance of LIM for Case C, AA and CC.

The performance of LIM for Case C, AA and CC are portrayed in the following figures. The behavior of the performance responses would be found to be quite identical in behavior, though with varied magnitudes of the quantities. The transient thrust versus time have been reported in Fig. 4.18, Fig. 4.19 and 4.20 for Cases AA, C, CC respectively. Similarly, speed-time curves, position versus time characteristics and Normal force versus time behaviors have been portrayed in Fig. 4.21, Fig. 4.22, Fig. 4.23; Fig. 4.24, Fig. 4.25, Fig. 4.26 and Fig. 4.27, Fig. 4.28, Fig. 4.29 respectively. The salient features of these figures are tabulated in Table 4.3. In single / double layer toothed windings the coil is wrapped around a single tooth, whereas in distributed windings other side of a coil is placed at slot one pole pitch apart. Although short pitching is possible in distributed windings, but it cannot be incorporated in single layer distributed winding. Double layer distributed three phase windings are normally preferred for conventional induction motors used in most of the applications. These types of windings are having lesser spatial DC flux density in air gap in comparison to single layer three phase winding [5]. Due to this, normal component of force is more repulsive in nature than that of single layer distributed winding. Toothed winding has smaller magnitude of normal force as that of distributed single / double layer windings.

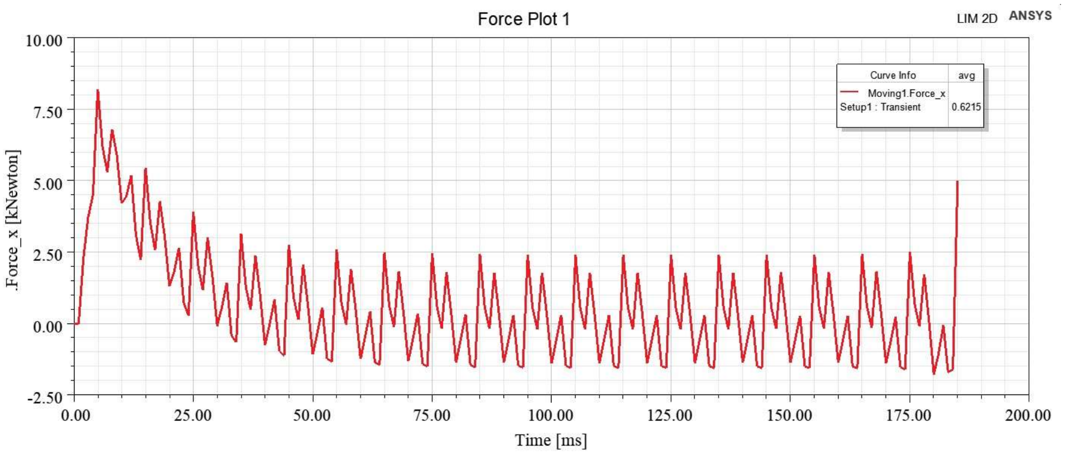

Fig. 4.18 Thrust-Time for Single Layer distributed winding [C]

A summary of the comparison of the performance of the four machines for achieving the translation limit target of 1.2 m is depicted in Table 4.3.

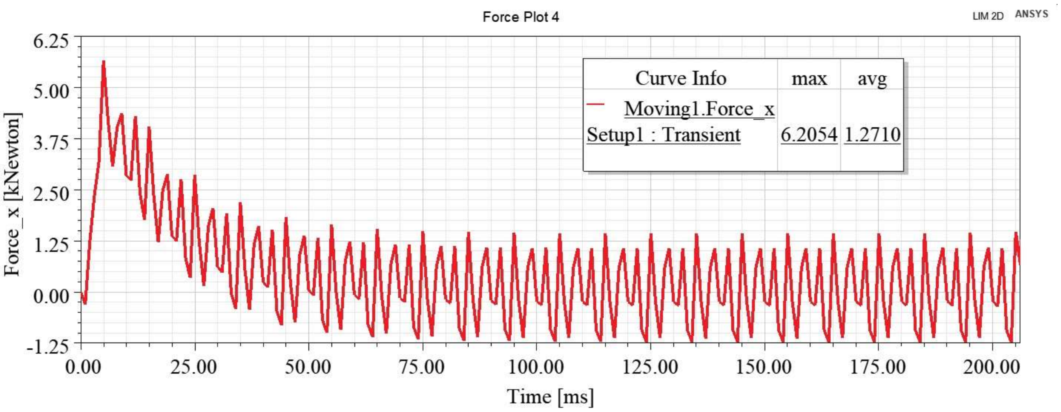

Fig. 4.19 Thrust-Time for Double layer tooth winding [AA]

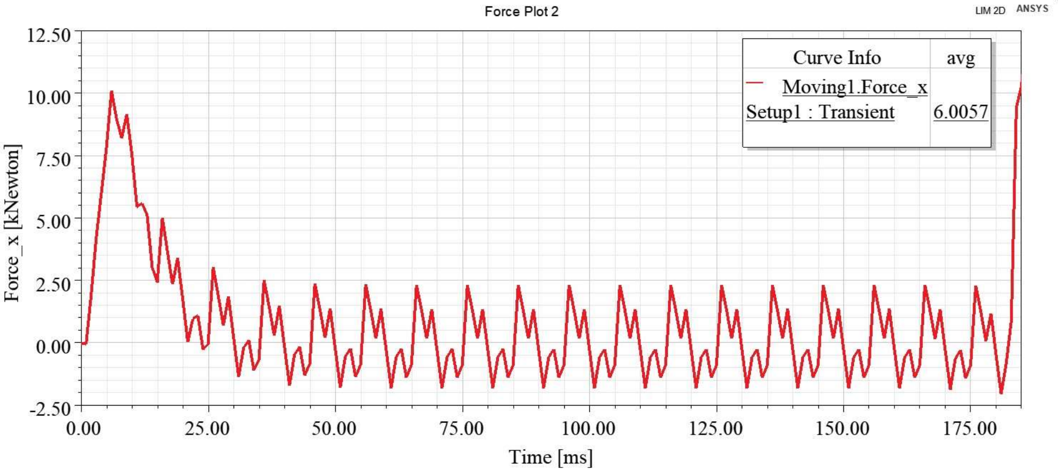

Fig. 4.20 Thrust-Time for Double layer distributed winding [CC]

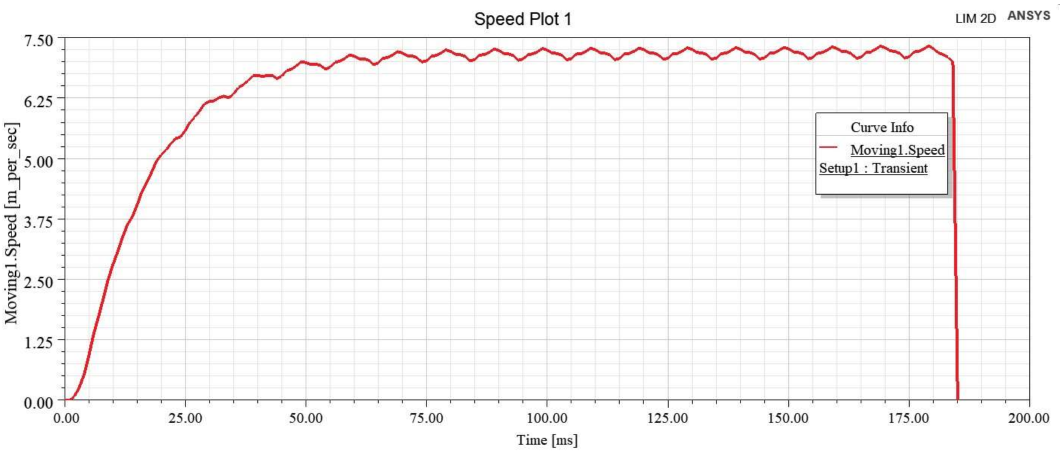

Fig. 4.21 Speed-Time for Single layer distributed winding [C]

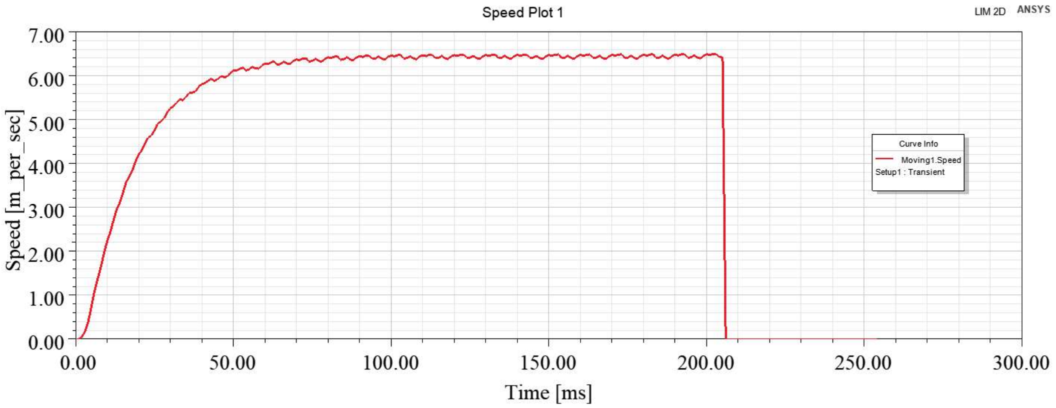

Fig. 4.22 Speed-Time for Double layer tooth winding [AA]

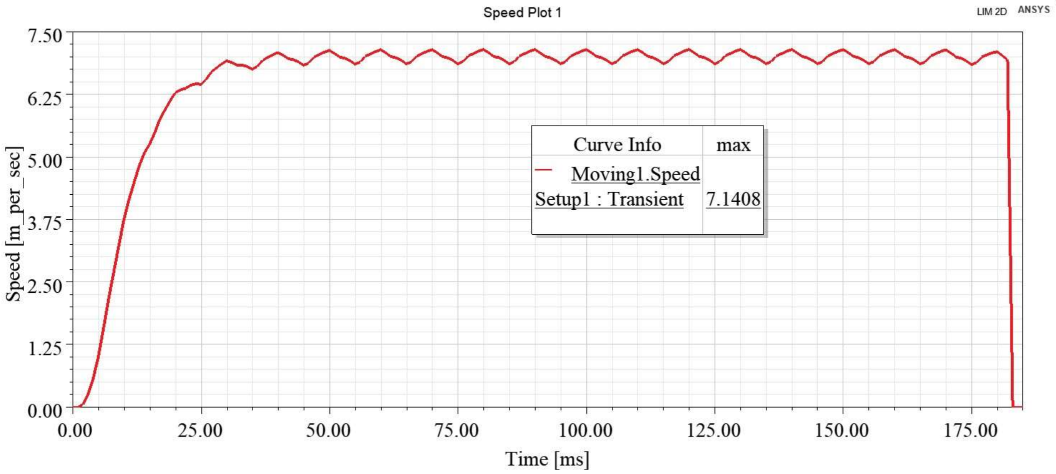

Fig. 4.23 Speed-Time for Double layer distributed winding [CC]

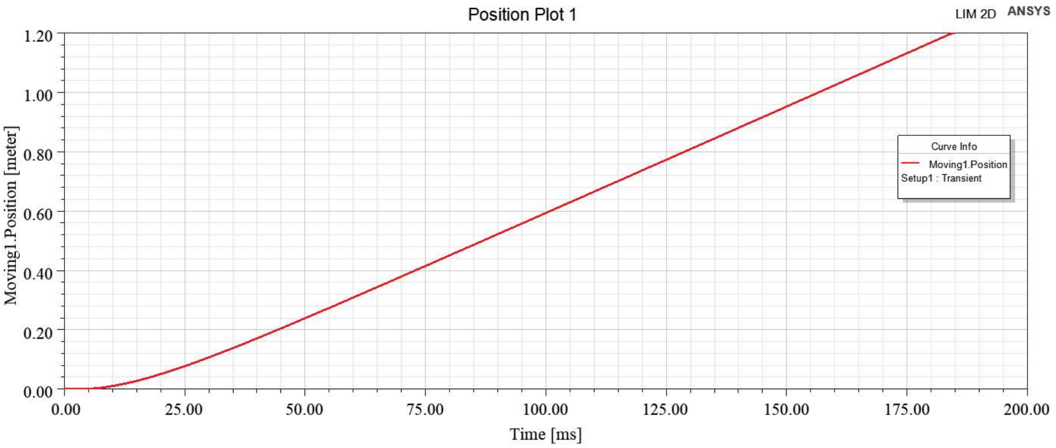

Fig. 4.24 Position-Time for Single layer distributed winding [C]

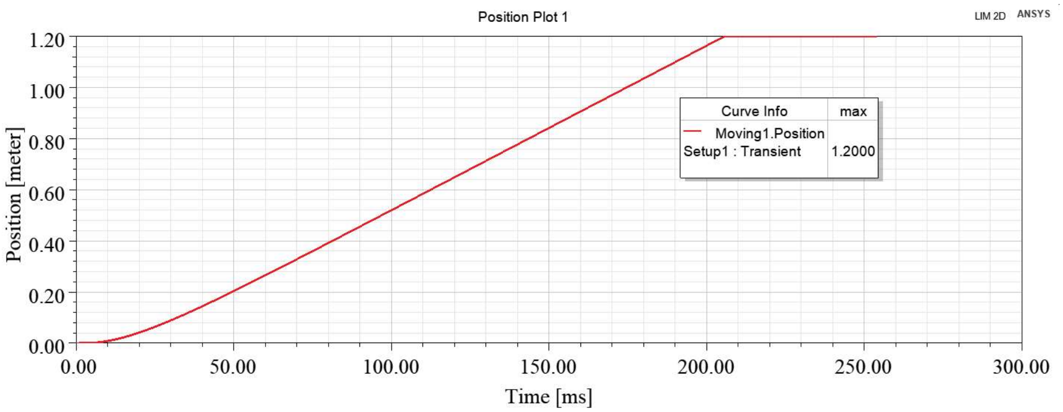

Fig. 4.25 Position-Time for Double layer tooth winding [AA]

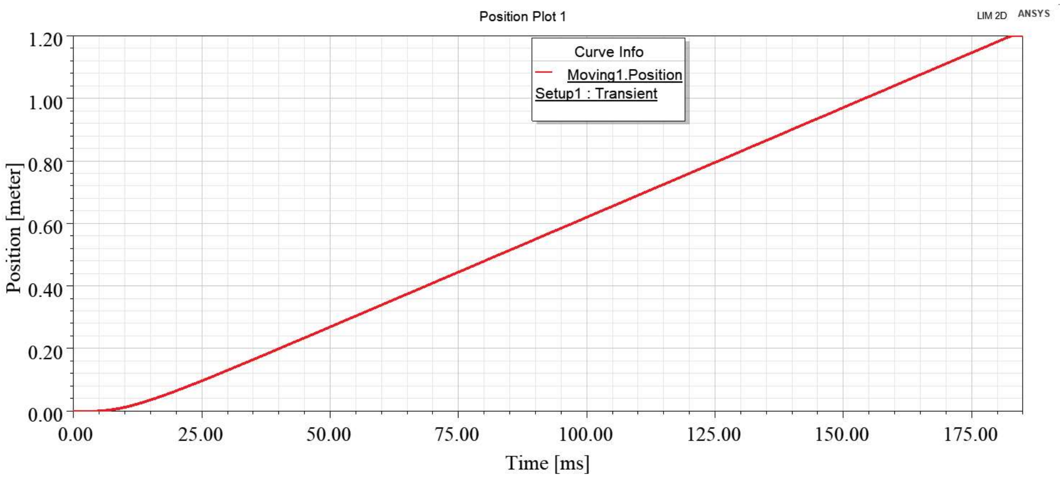

Fig. 4.26 Position-Time for Double layer distributed winding [CC]

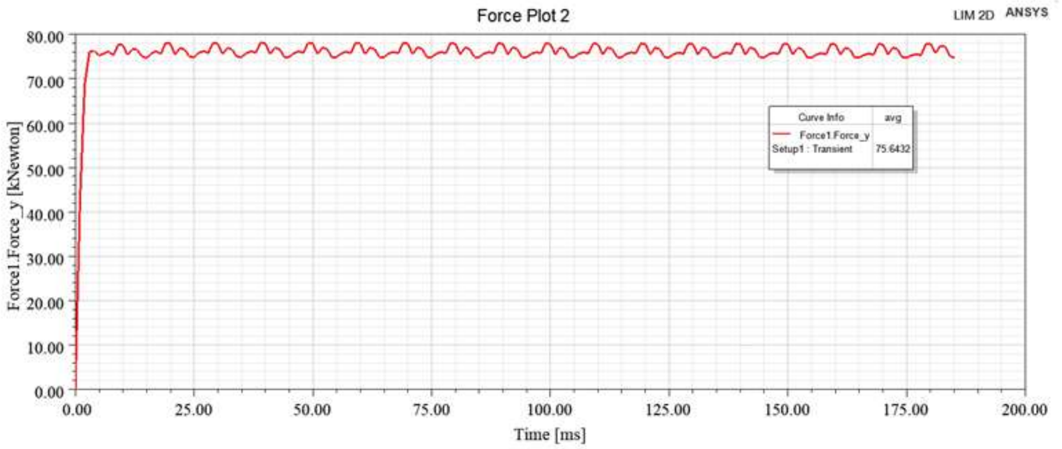

Fig. 4.27 Normal Force-Time for Single layer distributed winding [C]

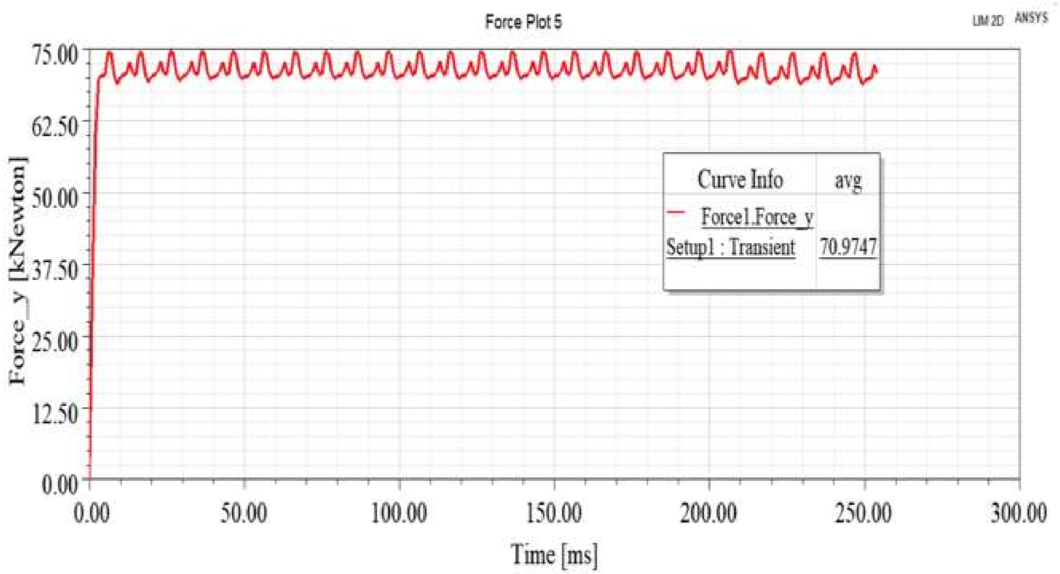

Fig. 4.28 Normal Force-Time for Double layer tooth winding [AA]

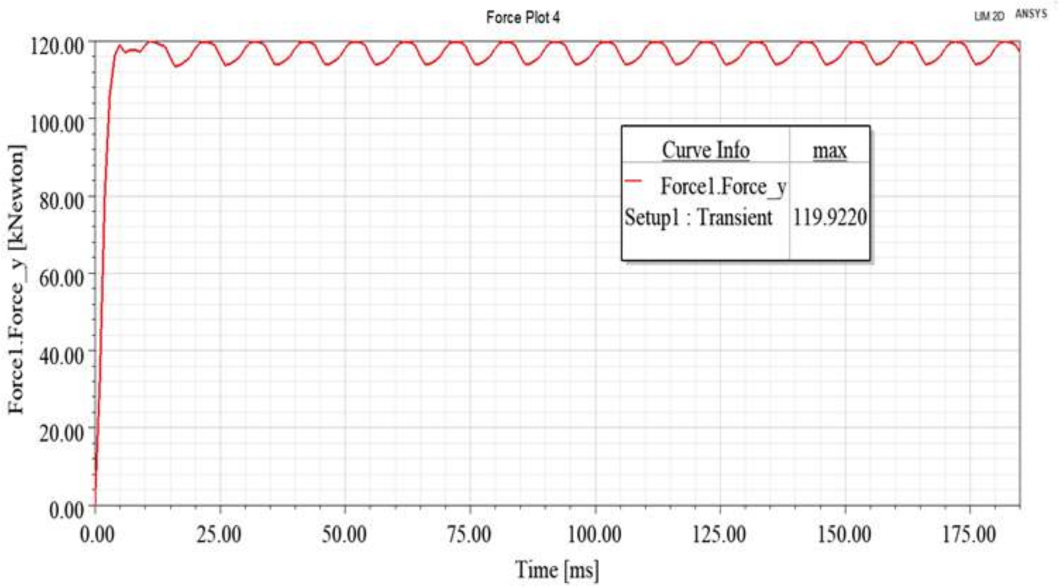

Fig. 4.29 Normal Force-Time for Double layer distributed winding [CC]

Table 4.3 Comparison of performances of the LIM with different windings

Case	Exit velocity (m/s)	Launch time (ms)	Max. Thrust (N)	Speed at first zero Thrust dip (m/s)	Peak current (kA)	Losses (kW)	Time at first zero thrust dip (ms)	Normal force (kN)
A	10.7	162.5	3600	9.13	93	600	97	37.98
C	7.14	185	8200	6.28	93	657	33	75.64
AA	6.4	205	6200	5.45	82.5	1771	33	70.97
CC	7.14	182	10000	6.44	67.5	1540	25	116.1

The first zero thrust dip refers to the speeds at which thrust crosses the x-axis (speed axis or zero thrust) for the first instance in the course of transient thrust oscillations. It signifies that the motor is nearing it's synchronous speed in the case of Tooth windings (which means the motor would be entering the generating mode before reaching synchronous speed). While in the case of Distributed windings, the motor (a low speed motor, as $V_{synch.}$ $<$ 50 m/s) would go into generating mode after surpassing the synchronous velocity (due to the longitudinal end effects). In case of toothed winding, the coil span is 1 slot, it means that if one side of coil is in slot No. 1 the other side of coil is in Slot No. 2. The shorter overhangs drastically reduces the presence of inactive copper (lesser copper being left unused in the electromagnetic thrust generation), whereas in distributed windings for spp = 1 , in case of three phase the coil span is 3 slots. With large overhang portion, copper losses are expected to be on the higher side for distributed windings.

From Table 4.3 it can be deduced that with the highest exit velocity attained by the mover at the minimum launch time, SLIM in Case [A] is the the best performer among all the cases.

4.5 Conclusion

The toothed windings with composite secondary give lesser peak thrust as compared to distributed winding with composite secondary. This is the reason that such windings did not find application in conventional electrical machines. But these machines exhibit least oscillatory transient thrust as such it is a superior machine for thruster applications. As a concluding remark, it is recommended to use single layer toothed winding of three phase Case [A] or multiphase excitation for thruster applications. It has lowest overhang portion, lowest copper requirement, the occurrence of negative thrust in the transient oscillations much later in the travel, fast response and lowest temperature rise for meeting the target. The next Chapter deals with the effects of joints in the reaction rail on the thrust of SLIM.

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