Design and Analysis of a Novel Linear Flux Reversal Wound Field Machine Considering Multiple MMF Working Harmonic Effect

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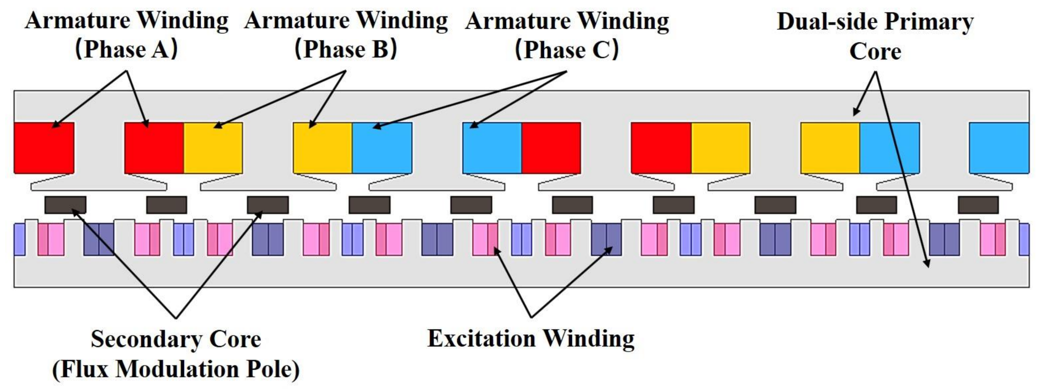
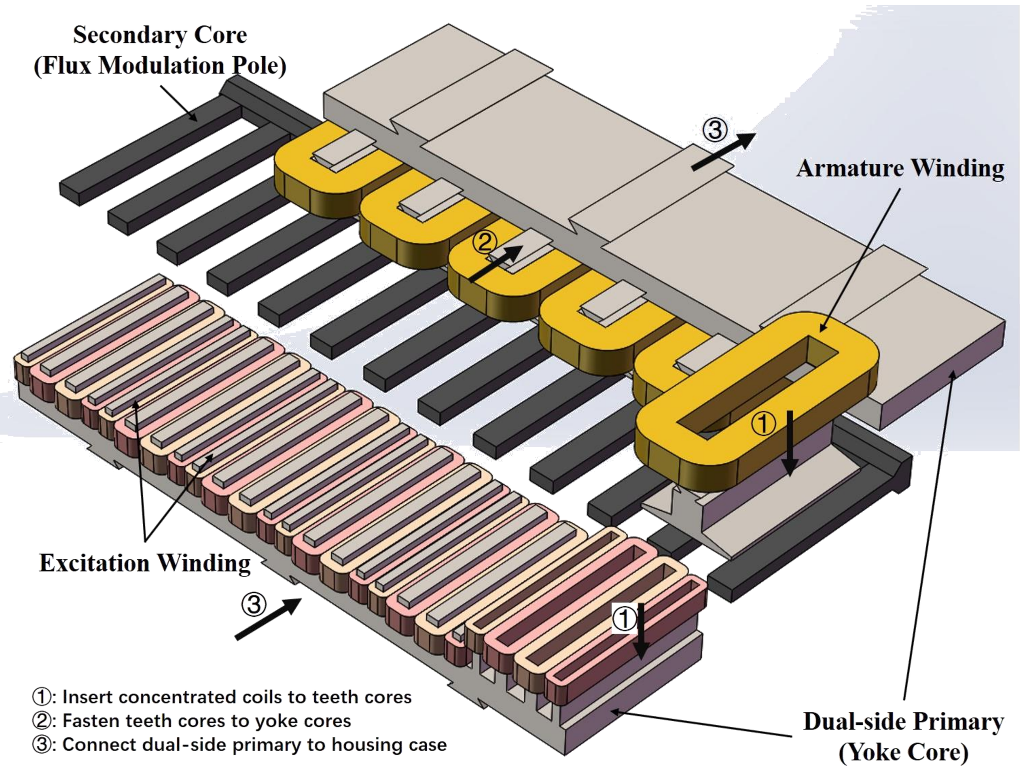
Introduction

In this paper, a novel dual-side LFRWFM has been proposed and designed considering the multiple MMF working harmonic effect, which not only retains the advantages of flux adjustment capability and low cost of the conventional wound-field machine, but also offers improved force capability as compared with the conventional counterpart by fully utilizing the multiple MMF working harmonic effect. According to FEA, the proposed LFRWFM yields 10% higher back-EMF and greatly reduce the normal force, and thus offer 34% more thrust force than the single-side LFRWFM. In addition, the dual-side structure dramatically reduces the normal force between the primary and secondary, thus the proposed machine has an improved control precision. Hence, the proposed machine, which is designed based on the multiple MMF working harmonic effect, can be an excellent solution to improve the thrust capability of the LFRWFM, and has a bright future for low-cost linear direct-drive applications.

Structure and Assembly





Proposed LFRWFM

- consisting of a dual-side primary and a sandwiched secondary.

Secondary

- simple and robust, composed of a series of silicon steel bars arranged in intervals
- offer a permeance distribution with periodic variation and have a modulation function on air-gap MMF distribution, thus called flux modulation poles (FMP)

Dual-side primary structure

- separate the field windings and armature windings on two different sides of primary
- make a dent in normal force between the primary core and secondary core.

Armature and excitation windings

- adopt non-overlapping concentrated windings for higher slot filling rate and shorter coil end
- the copper usage is saved and copper loss is reduced, thus the efficiency will rise

Pole pitch of excitation teeth

- different, then the **multiple MMF working harmonic effect** can be introduced to improve the TD.

Basic Operation Principle

Magnetic Gear Effect

- an excitation field with large pole-pair number
- flux modulation effect caused by the sandwiched FMPs or other structure like parallel teeth
- large pole-pair number excitation field modulated into a low pole-pair number one interact with the armature field produced by armature winding
- generate average thrust or torque

Slot/Pole Pair Relationship

$$P_a = |P_f \pm Z_{fmp}|$$

$$\frac{Z_a}{GCD(Z_a, P_a)} = 3n$$

$$(n = 1,2,\ldots)$$

$$PR = Z_{fmp}/P_a$$

Multiple MMF Working Harmonic Effect

MMF Distribution

$$F_f(x_s) = \sum_{i,j=1,3\ldots}^{\infty} F_{f,i}\sin(iaP_f x_s) + F_{add,j}\sin(jaP_{add}x_s)$$

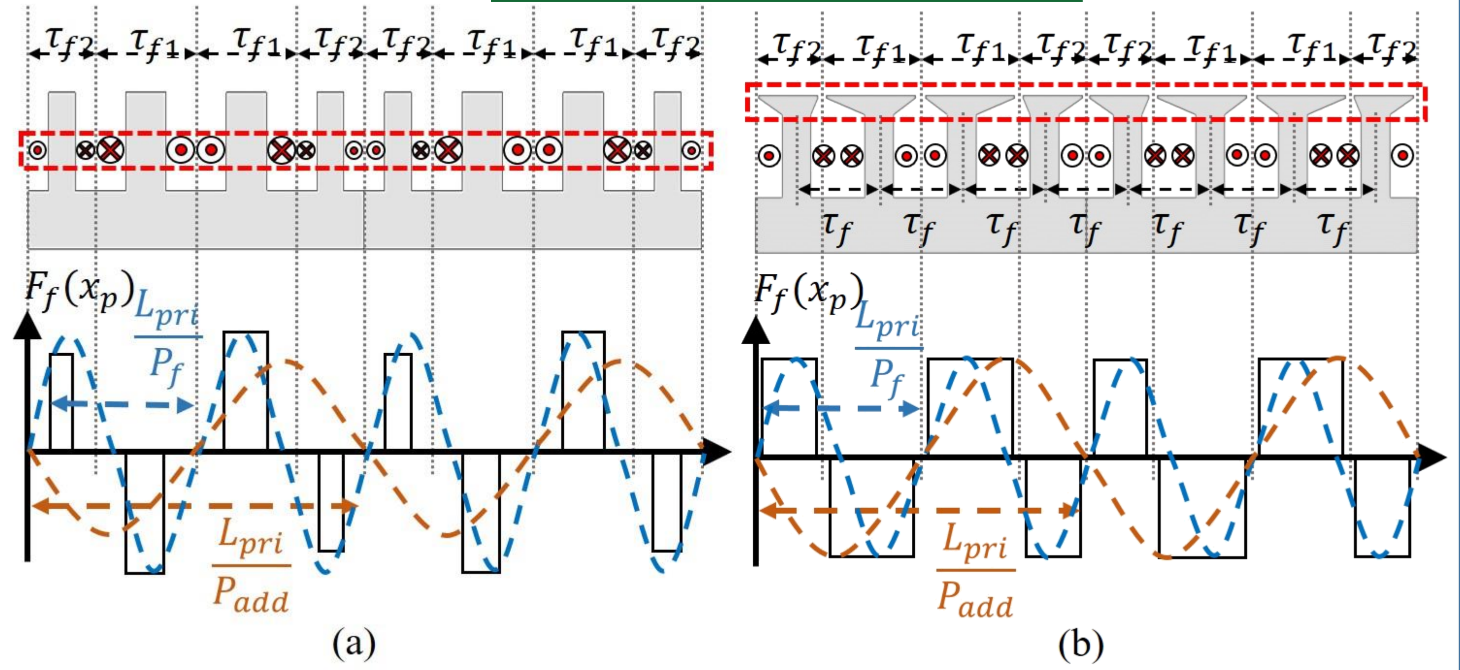
Air-gap Permeance

$$\Lambda_{fmp}(x_s, x) \approx \Lambda_{fmp,0} + \Lambda_{fmp,1}\cos[aZ_{fmp}(x_s - x)]$$

Flux Density Distribution

$$B(x_s, x) = \sum_{i=1,3\ldots}^{\infty} \frac{1}{2} F_{f,i}\Lambda_{fmp,1}\sin[a(Z_{fmp} \pm iP_f)x_s - Z_{fmp}x] + \sum_{j=1,3\ldots}^{\infty} \frac{1}{2} F_{add,j}\Lambda_{fmp,1}\sin[a(Z_{fmp} \pm jP_{add})x_s - Z_{fmp}x]$$

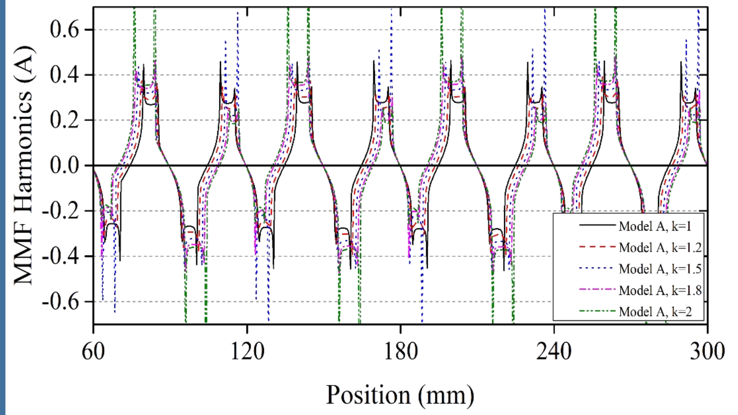
How to realize?



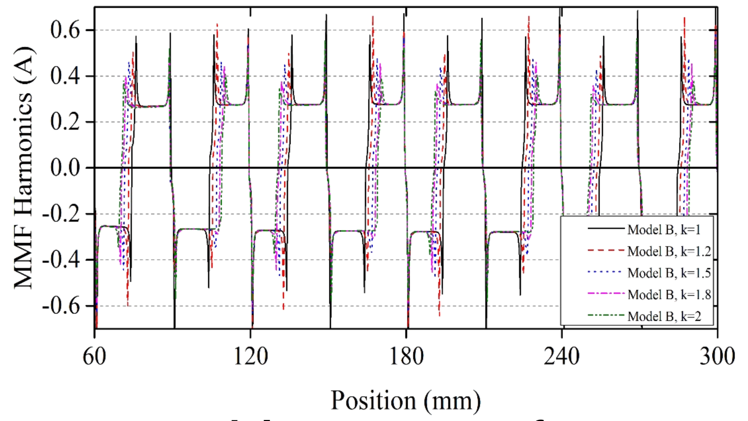
(a) **Model A: Excitation teeth with different ampere-turns**

(b) **Model B: Excitation teeth with different-pole-pitch pole shoes**

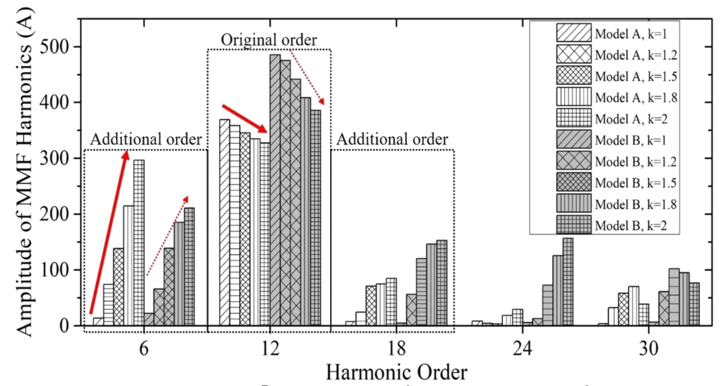
How is the effect vs K? $K = \frac{\tau_{f1}}{\tau_{f2}}$



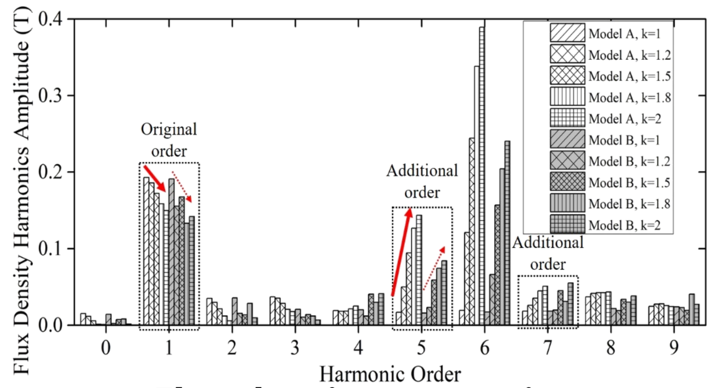
Model A: MMF waveform



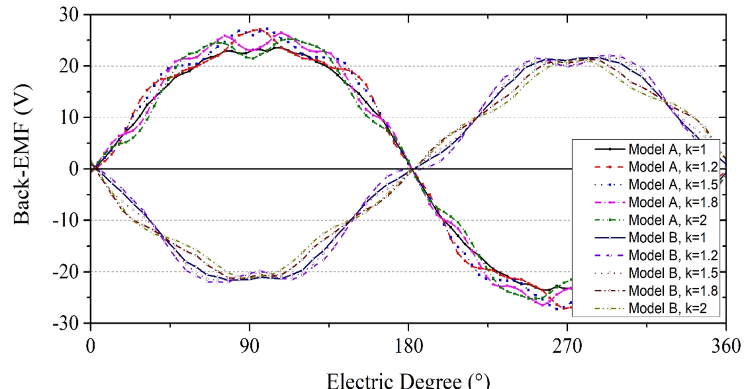
Model B: MMF waveform



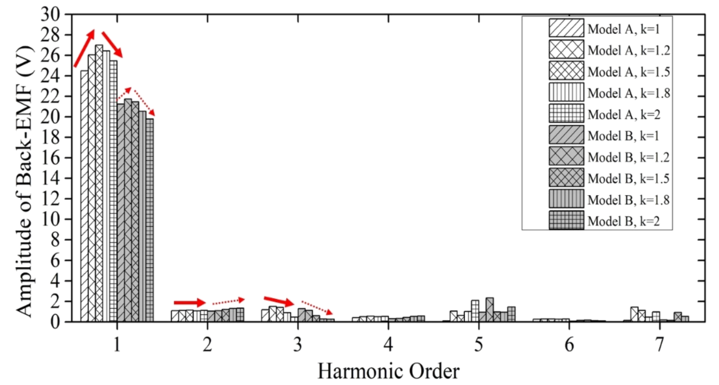
MMF harmonic comparison



Flux density comparison



Back-EMF waveform comparison



Back-EMF harmonic comparison

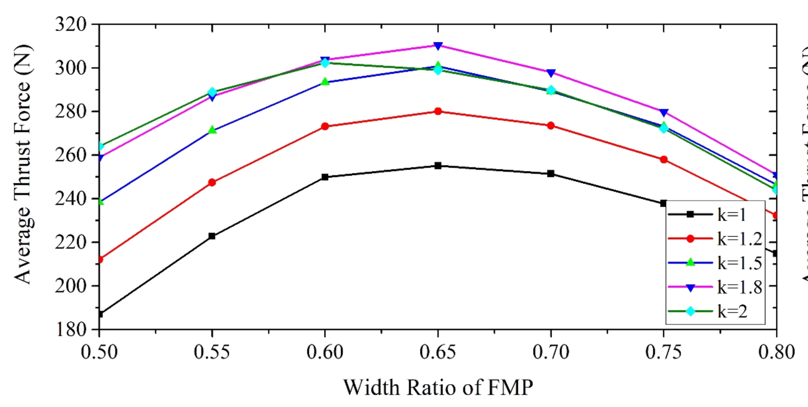
Model A:
when $K = 1.5$, the back-EMF is 26.98V, 10% higher than the original one

Model B:
when $K = 1.2$, the back-EMF is 21.72V, only 2% higher than the original one

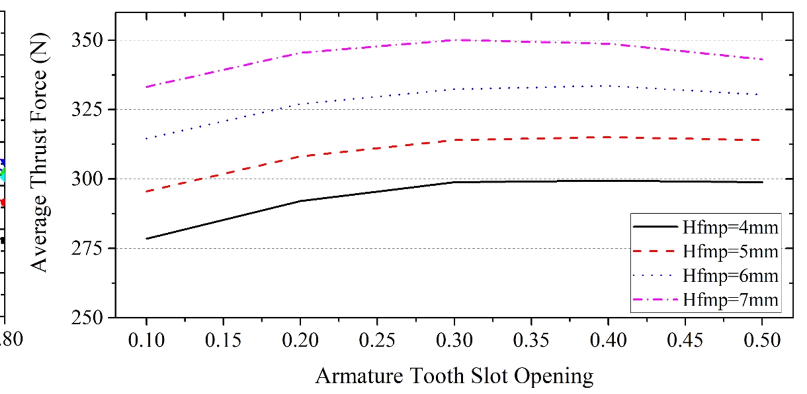
Apparently, **the excitation tooth with different ampere-turns** is much more competitive and effective than the pole-shoe design considering **multiple MMF working harmonic effect**

Last but not least, though the 10% increasement seems not large, it is under the circumstance without adding any extra electric or magnetic load

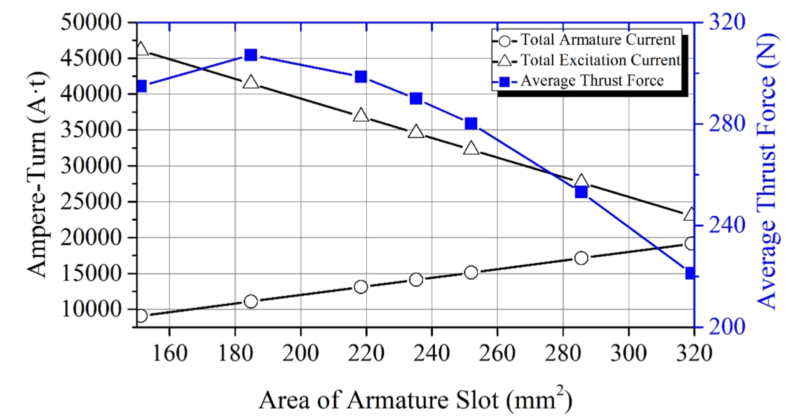
Parameter Optimization



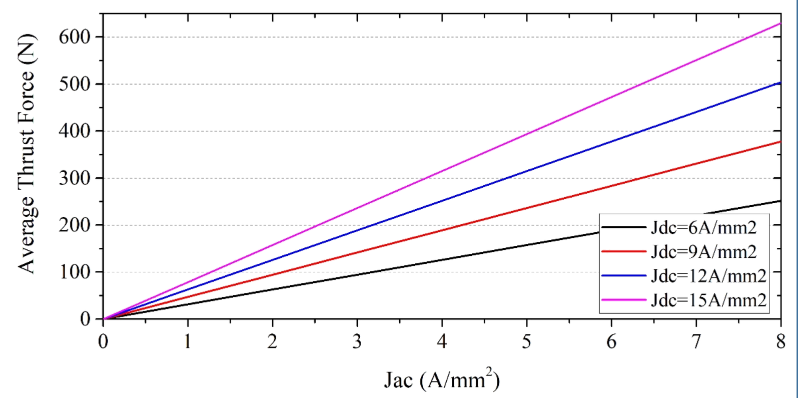
Coefficient K & FMP Width



Slot Opening Rate



The Ratio of Armature & Excitation Current



Various I_{dc} & I_{ac}

Performance Comparison to Single-side LFRWFM

Geometric Dimension & Electromagnetic Parameter

Parameter	Proposed LFRWFM	Single-side LFRWFM
Primary Length	288mm	288mm
Total Height	77mm	77mm
FMP/Stator Tooth Width	9.16mm	12mm
Air-gap	0.5+0.5mm	1mm
Stack Length	120mm	120mm
Excitation Tooth Width	6.17mm/3.43mm (K=1.8)	4.8mm
Current Density	5A/mm2 AC；10A/mm2 DC	
Velocity	60m/min	

Performance Comparison

Item	Proposed LFRWFM	Single-side LFRWFM
No-load back-EMF	54V	48
Rated Thrust Force	314N (8.6%↑)	289N
Thrust Force Ripple	62N	57N
Normal Force	300N	1920N
Friction Force due to Normal Force (α=0.02)	6N	38.4N
Final Thrust Force	308N (32%↑)	232N

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