Slotless-Halbach Lightweight Electric Machines and Unconventional Multi Layer Winding

Md Sariful Islam
Graduate Student
Department of Electrical and Computer Engineering
North Carolina State University
Raleigh, NC, USA

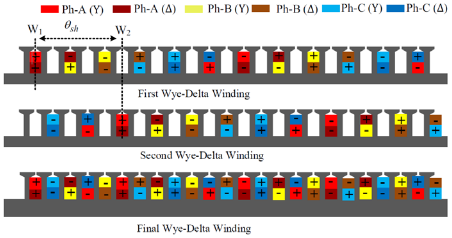
Presentation Outline

Introduction

- Motivation
- System Requirement for Drone Applications

Slotless-Halbach Lightweight Machine

- Halbach Magnetization
- Slotless-Halbach Performances
- Experimental Results



Unconventional Multi Layer Winding

- Conventional Multi Layer Winding
- Proposed Concept
- Performance Analysis

Motivation

Drone Delivery

Dubai air-taxi

Drone Delivery

- Power density & efficiency improvement of electric motors-
  - Flight time
  - Fuel Efficiency

Research Objective

Developing an electric machine topology to **maximize power density** compared to a conventional PM topology

System Requirement

Drone System Requirement

- Total mass: 8 kg
- Flight time: 30 minutes
- Four Electrical Motors

Power Requirement

$$F_{lift} - W - F_{drag-profile} = ma$$

$$P_{lift} = 500\ \text{W}$$

Propulsive power

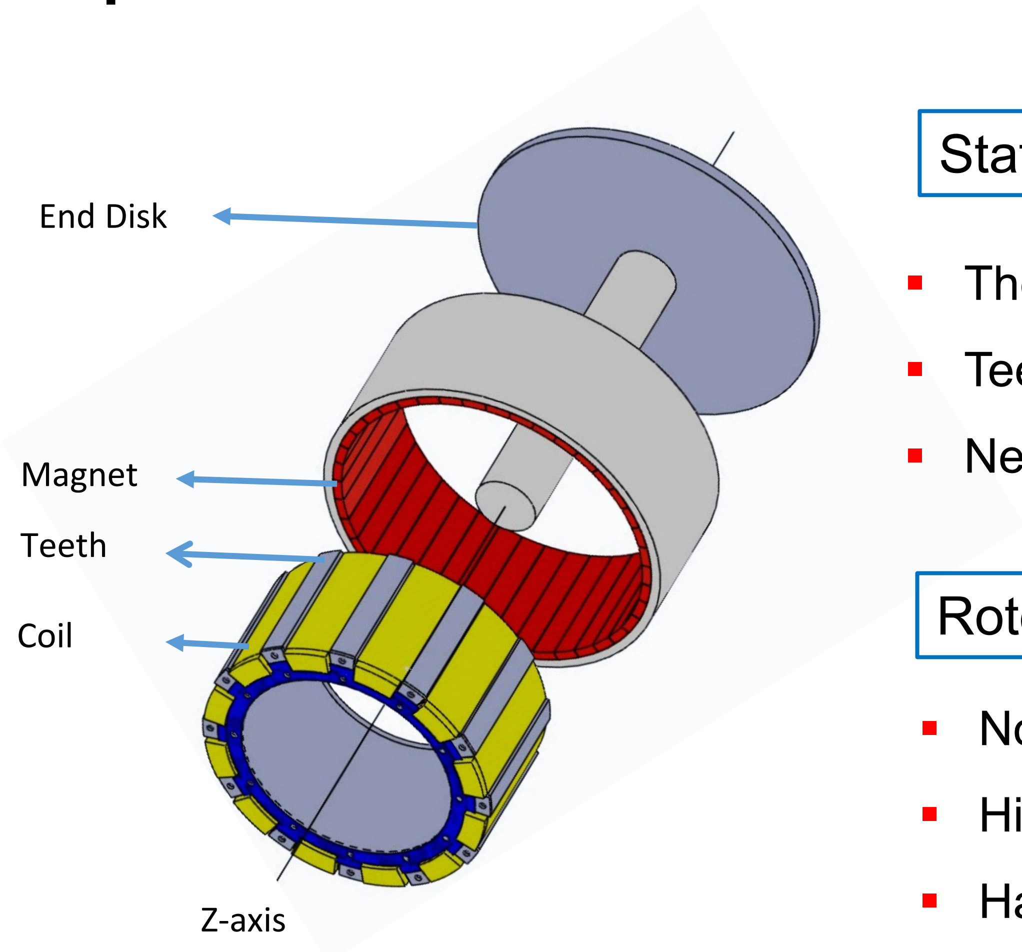
$$F_{lift} = W, \qquad Thrust = F_{drag-profile}$$

$$P_{propulsive} = 300\ \text{W @ 5000 rpm}$$

Electric Motor rating -

- 0.5 kW at 5,00 rpm
- Maximum speed: 10,000 rpm

Proposed Slotless-Halbach



Stator

- Thermal plastic teeth in the stator
- Teeth winding
- Negligible lamination to close the flux path

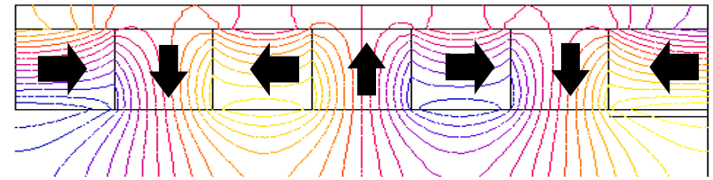
Rotor

- Non-magnetic rotor
- High number of Pole (14)
- Halbach magnetization

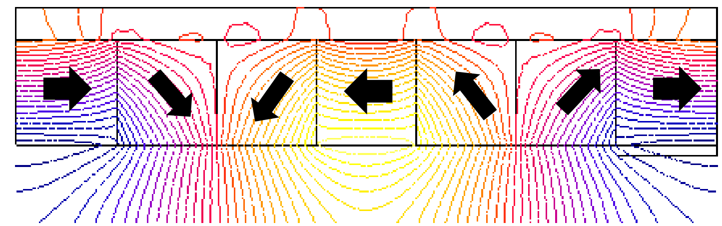
Halbach Magnetization

- Flux opposes in one side.
- Supports in other side.
- Magnet provides the flux path.
- Circumvent the need of rotor core.
- Ideal Halbach magnetization distribution is sinusoidally distributed.
- Higher segment number increases the air gap flux density.
- 2s/per pole magnet orientation changes by $90°$.
- 3s/per pole magnet orientation changes by .
- Magnetization for each segment,

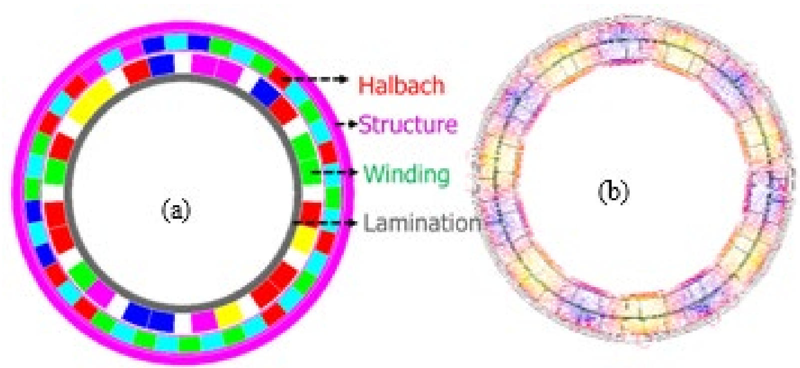
$$\theta_m = \left(1 \pm \frac{P}{2}\right) \theta_n$$



2s/per pole



3s/per pole



FEA model and Flux path

Performance Analysis

- Large effective airgap requires higher electrical loading.
- Improves power density by 60%.
- Reduces the rotor inertia by 20%.
- Increases active volume density.
- Zero cogging, and negligible ripple.
- Negligible core and magnet loss.
- However, ac conductor loss needs to be minimized using thin wire.

Parameter	Slotless	Slotted
OD (pu)	1	1
L (pu)	1	1
Slot/pole	12/14	12/14
Speed (rpm)	5,000	5,000
Density (kW/kg)	1.05	0.67
Core loss	3	21
DC conductor	33	13
Efficiency	93	93
Torque/Inertia $(kg-m^2)$	1300	1100

Slotless-Halbach is feasible to provide higher power density compared to the conventional machine.

M. S. Islam, I. Husain and R. Mikail, "Slotless lightweight motor for drone applications," 2017 IEEE Energy Conversion Congress and Exposition (ECCE), Cincinnati, OH, 2017, pp. 5041-5048.
M. S. Islam, R. Mikail and I. Husain, "Slotless lightweight motor for aerial applications,“ IEEE Trans. on Industrial Application (In Review).

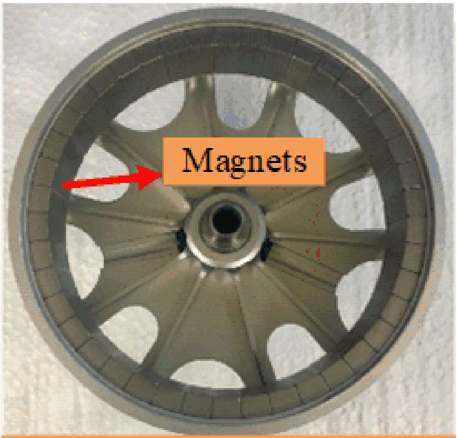
Prototyping and Test Results

Thermal plastic teeth
(a)

Stator without winding
(b)

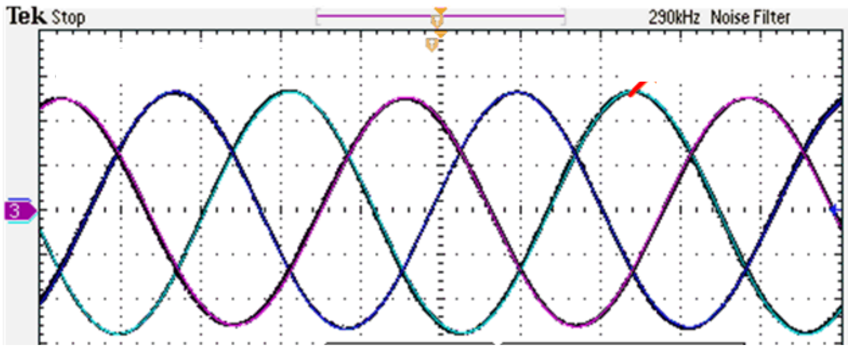
Stator with winding
(c)

Rotor Hub with Aluminum support

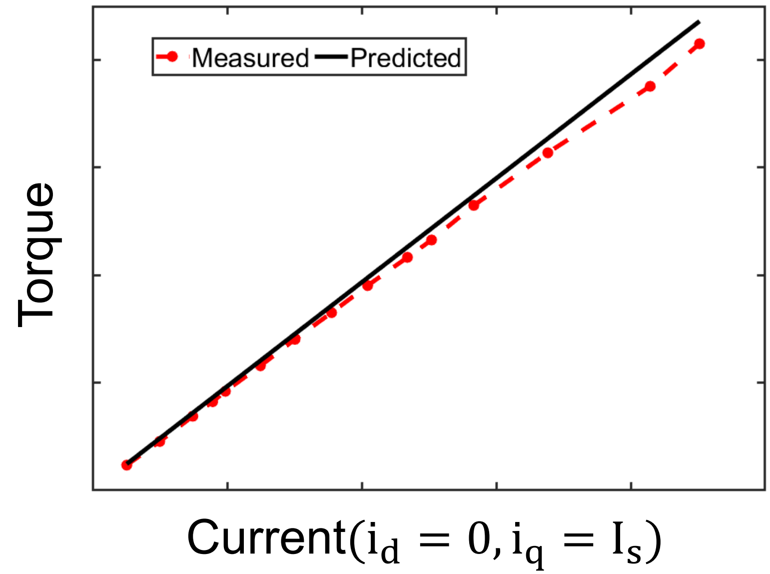


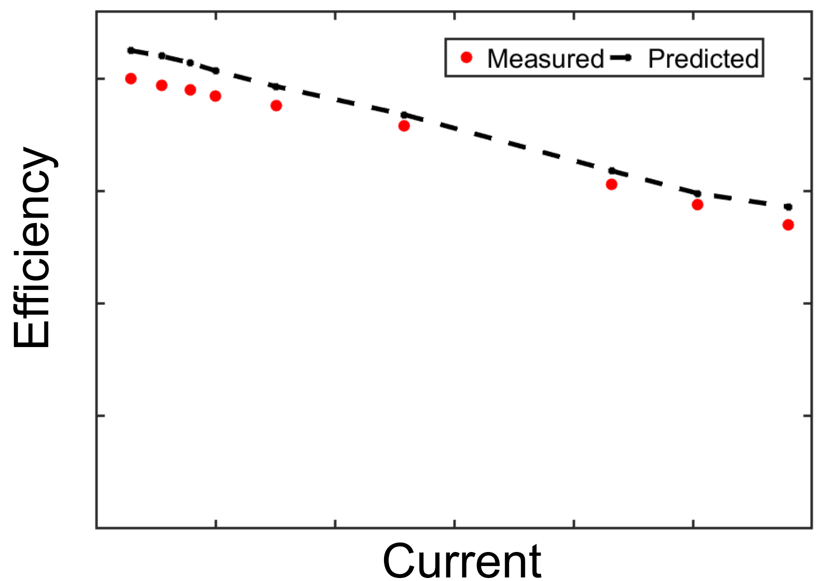
Halbach Magnets

- PWM switching frequency of 80 kHz.
- Ultra low inductance requires WBG drives as enabling technology.



BEMF profile

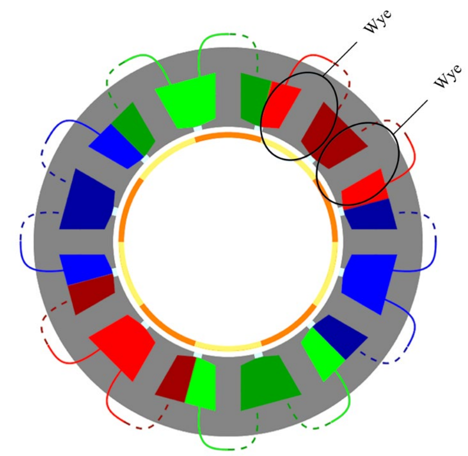




Conventional Teeth Winding

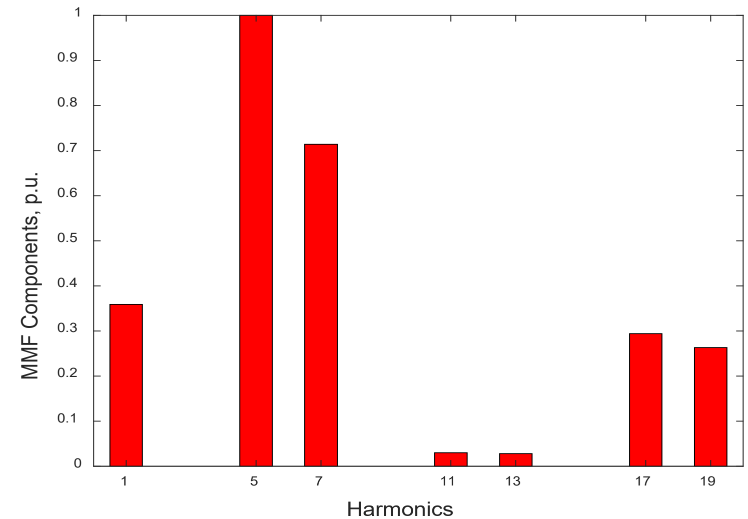
- Shorter end-turns, higher fill factor, compact
- High MMF harmonics $P_{Core}\uparrow, T_{AVG}\downarrow, PF_{IN}\downarrow$
- Lower P_{I^2R-St} but higher induced losses, η ↓

$$MMF_{YY} = \sum_{\nu=1,-5,7}^{\infty} \frac{12NI}{\nu\pi} \sin\left(\frac{\nu\pi}{12}\right)^2 \sin(\nu\theta - \omega t - \nu\pi/12)$$



12s/10p

- 1st (35%), 7th (71%), 17th, 19th are responsible for rotor loss, core saturation, PM eddy current loss.
- Problematic for ripple, and lower power factor.



MMF spectrum

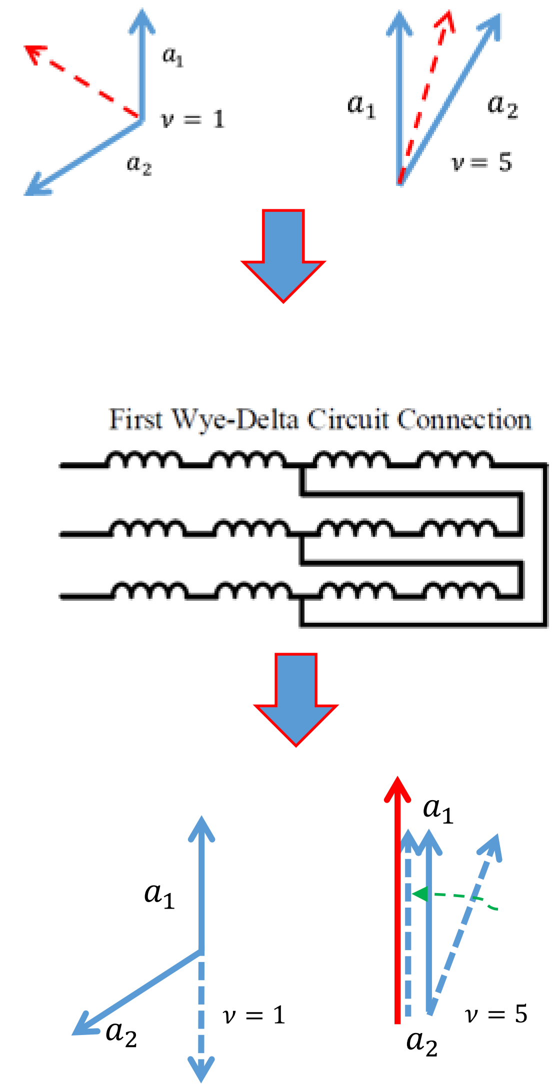
Objective

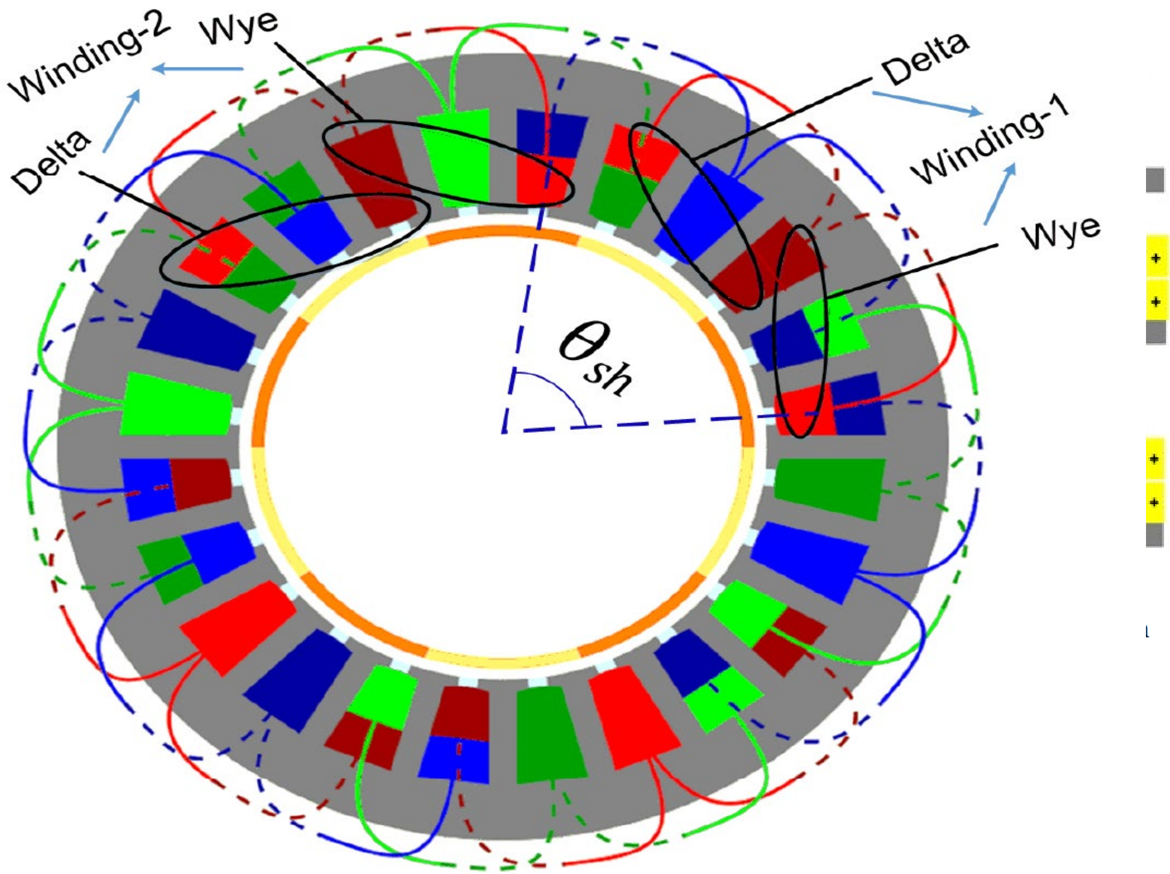
- Simultaneous cancellation of 1st (sub) and 7th (super) harmonics

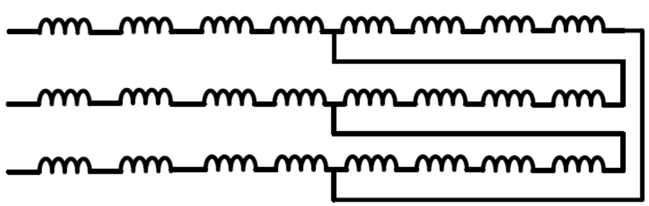
Proposed Winding

- Angular difference between adjacent coils are, $180 - v \cdot \frac{2\pi}{Q}$
- For a 12/10 motor, shifting second coils by 30^0 can cancel sub-harmonics.
- The 30^0 shift can be achieved using a $Y - \Delta$ connection.
- Two coils are connected in $Y - \Delta$ to cancel sub-harmonics.

- Two sets ($W1, W2$) of three phase $Y - \Delta$ windings are connected in series with a mechanical shift, θ_{sh}.
- $Y - \Delta$ yields a current ratio of $\sqrt{3}$ between coil groups.
- To balance the MMF, the turn number of Δ coil is $\sqrt{3}$ of Y.
- Resultant stator will have double slots (24/10 compared to a 12/10 configuration).

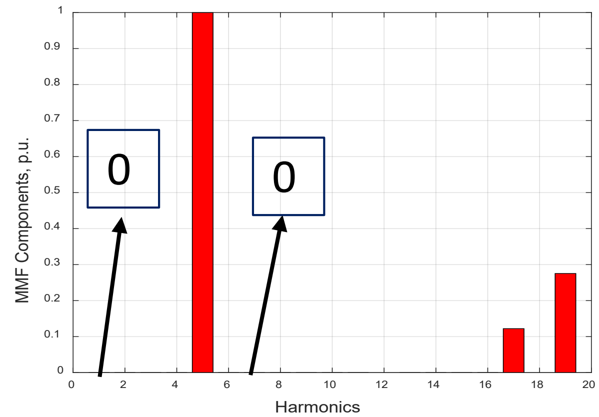



Winding-2
Wye
Delta
Delta
Winding-1
Wye
θsh



Performance Comparison

- Proposed winding yields lower core loss.
- It reduces the core loss mostly from rotor and PM.
- The reduction in core loss is 15%.
- The cancellation of sub and super harmonics reduces the leakage reactance.
- It improves the power factor, 0.96 compared to 0.9.
- However, the delta winding introduces third harmonic in delta current.
- The third harmonic in delta winding can increase the stator copper loss.
- Proper PM design and magnetization can reduce the third harmonic current in delta winding.



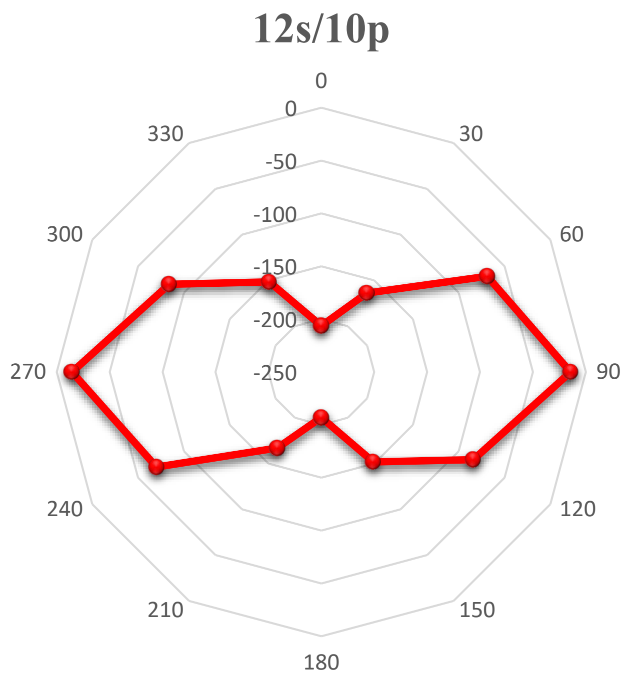
Rated Performance Comparison

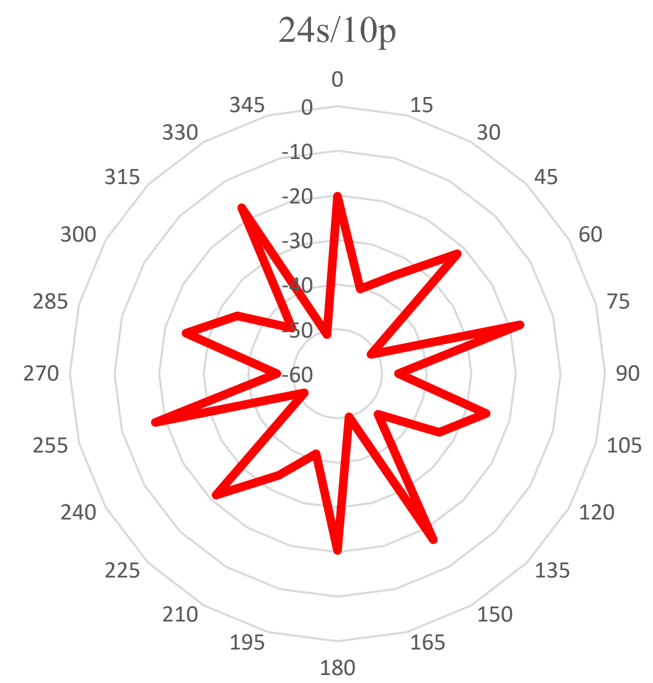
Parameters	Conventional	Proposed	[4]	[9]
T_{AVG} (Nm)	12.95	13.10	13.43	12.75
T_{Ripple} (%)	5.30	1.60	2.50	1.25
$THD_{V_{LL}}$ (%)	4.60	1.10	2.70	1.63
P_{core}	4.35	3.71	4.22	3.89
I^2R	128.4	129.8	129.8	128.4
Power factor	0.90	0.96	0.89	0.95
Harmonic in Δ	0	1.6	1.52	0

M. S. Islam, M. A. Kabir, R. Mikail and I. Husain, "A New Space Harmonics Minimization Strategy for Fractional Slot Concentrated Windings," *2018 IEEE Transportation Electrification Conference and Expo (ITEC)*, Long Beach, CA, 2018, pp. 412-417.

Radial Force

- The proposed winding also improves the radial force of the machine.





Thank You