ELECTRIC 2-WHEELER TRACTION MOTOR DESIGN REPORT

Vedant Sachin Shirke

TACO Prestolite Electric
Horizon Industrial Park, Chakan-II,
Pune

TABLE OF CONTENTS

1 INTRODUCTION

1.1 Requirements Defined

The requirements were defined based on the study of market trends which resulted in the following outcomes. The range of requirements was set up depending on the feasibility of design, manufacturing and customer base.

Rated Voltage: 72Vdc.

Rated Power: 9kW.

Rated RPM range: 1500 – 3000 RPM.

Maximum Diameter: 200mm

Maximum Length: 200mm

Number of Slots: 10-12 slots

Number of Poles: 8-10 poles

1.2 Application Scenarios

This motor drive can be used for regular commuter bikes in the segments of mass market bikes which are usually of the engine displacement of 100-150CC and offer a solution for the constantly growing electric scooter market which has seen continuous increase in the power figures. The OLA S1 Pro Gen2 is already having a peak power output of 11kW for a short duration, hinting the direction chosen by the biggest market shareholders in Indian EV 2-Wheeler market.

Table 1. Present-Day Market Players

Powertrain Specs	OLA Electric	OLA Electric	TVS	Bajaj	ATHER	Ampere
Model	S1 Pro	S1X & S1 Air	iQube ST	Chetak Premium	450X	Primus
Max Power (kW)	11	6	4.4	4.2	6.4	4
Rated Power (kW)	5.5	2.7	3	4	3	3.4
Rated Torque (Nm)	-	-		20		
Claimed Range (km)	195	151	150		150	107
Real Range (km)	180	125	100	126	110	
Battery Pack Energy (kWhr)	4	2 to 4	5.1	3.22	3.7	3
Battery Type	Li-ion	Li-ion	Li-ion	Li-ion + VRLA	Li-ion	LFP
Motor Setup	Mid-Drive IPMSM	Hub PMSM	Hub BLDC	Side-Mount PMSM	Mid-Drive PMSM	Mid-Drive PMSM
Top Speed	120	90	82	73	90	77
Ex-Showroom Price	1,47,499	69999 to 1,04,000	1,85,373	1,35,463	1,55,156	1,19,900

1.3 Proposed Application Solution

The following are the few solutions that can be considered as a rough estimate of vehicle specifications possible with the powertrain solution offered for Tata Autocomp Systems Prestolite Electric based on the market analysis and sentiments for an upcoming EV 2W by 2026.

These focus on Modular Powertrain layout based on the same voltage range in order to standardise the majority of E/E components when it comes to the EMC/EMI, NVH and ARAI requirements, significantly cutting down on R&D costs and engineering hours required for the same.

The architecture is based on a nominal battery voltage of 74V (84V peak), allowing for lesser heating losses and increased efficiency levels throughout the life cycle by going to the High-Voltage route.

Table 2. Solution Offerings

Specifications	Low Power Scooter	Commuter Bike	High Power Bike
Battery Energy (kWhr)	3.7	5.18	6.66
Peak Discharge Power (kW)	5	10	20
Continuous Power	3.5	6	10
Nominal Voltage (V)	74	74	74
Maximum Voltage (V)	84	84	84
Minimum Voltage (V)	56	56	56
Battery pack Capacity (Ah)	50	70	90
Battery Pack Configuration	20s10p	20s14p	20s18p
Total number of cells	200	280	360
battery pack cell weight (kg)	14	19.6	25.2
Range (km – Eco Mode)	180	220	300
Charging Time (hrs) home	4	5	6
Charging Type	Portable 1000W	Portable 1200W	Portable 1200W
Top Speed (km/hr)	85	105	150
0 to 40 km/hr (sec)	3	2.4	1.8
0 to 60 km/hr (sec)	3.5	3	2.4
Cell Type	21700	21700	21700

1.4 Method

Use of analytical approach for design of an IPMSM motor was performed which consisted of high-fidelity optimization and derivation of motor parameters which were further used to model a motor model in Ansys MotorCAD software which is a dedicated software for designing of motors.

Key Features of Ansys MotorCAD

1. **Multiphysics Simulation**: MotorCAD offers integrated multiphysics simulation capabilities, allowing users to analyze electromagnetic, thermal, and mechanical performance within a single environment. This holistic approach ensures that all critical aspects of motor performance are considered during the design process.
2. **Fast and Accurate Electromagnetic Analysis**: The software provides precise electromagnetic analysis tools to evaluate parameters such as torque, power, efficiency, and losses. Users can perform both steady-state and transient simulations to understand the motor's behavior under different operating conditions.
3. **Thermal Management**: MotorCAD includes advanced thermal modelling features to assess the thermal performance of electric motors. It helps in designing effective cooling systems by simulating heat generation and dissipation, ensuring that the motor operates within safe temperature limits.
4. **Mechanical Analysis**: The mechanical analysis tools in MotorCAD enable the evaluation of structural integrity and vibration characteristics. This is essential for ensuring the durability and reliability of the motor under mechanical stresses and dynamic loads.
5. **Design Optimization**: MotorCAD provides optimization algorithms that help in refining motor designs to meet specific performance targets. Users can optimize various design parameters, such as geometry, materials, and winding configurations, to achieve the best possible performance.
6. **User-Friendly Interface**: The software features an intuitive user interface that simplifies the setup and execution of simulations. It includes pre-defined templates and libraries for different motor types, making it accessible to both novice and experienced users.
7. **Integration with Other Tools**: MotorCAD seamlessly integrates with other Ansys simulation tools and third-party software, allowing for a comprehensive design workflow. This integration enables users to perform detailed system-level simulations and leverage the strengths of multiple tools.

2 FRAMES OF REFERENCE

The reference frame which was selected was the OLA S1 Pro Motor as a benchmark in terms of power output and performance, since it's a mass market superhit in terms of sales and engineering.

Within a short span of time, it has achieved a market share of 50%+ in the Indian EV 2-Wheeler market segment against the likes of legacy automakers like Bajaj, TVS and Hero.

Market Overview

1. **Market Size and Growth**: The Indian EV 2W market has seen significant growth over the past few years. In 2023, the market size was estimated to be over 1.5 million units, with a compound annual growth rate (CAGR) of around 20% projected for the next five years. This growth is fuelled by the increasing demand for affordable and sustainable transportation solutions in urban and semi-urban areas.
2. **Key Players**: Several domestic and international manufacturers are actively competing in the Indian EV 2W market. Prominent players include Hero Electric, Ola Electric, Ather Energy, Bajaj Auto, TVS Motor Company, and Revolt Motors. These companies are investing heavily in research and development to enhance battery technology, motor efficiency, and overall vehicle performance.
3. **Government Initiatives**: The Indian government has implemented various policies and initiatives to promote the adoption of electric vehicles. The Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme provides financial incentives for the purchase of EVs, including two-wheelers. Additionally, state governments offer subsidies, tax benefits, and infrastructure support to encourage EV adoption.

Drivers of Growth

1. **Environmental Concerns**: Increasing awareness of air pollution and its impact on health and the environment has led consumers to seek greener alternatives. Electric two-wheelers, with zero tailpipe emissions, offer a sustainable solution to reduce urban air pollution.
2. **Cost Savings**: The lower operating costs of electric two-wheelers compared to ICE vehicles are a significant driver for consumers. EVs have fewer moving parts, leading to reduced maintenance costs, and the cost of electricity is lower than that of petrol or diesel.
3. **Technological Advancements**: Improvements in battery technology, such as lithium-ion batteries, have enhanced the range and performance of electric two-wheelers. Additionally, advancements in motor design and charging infrastructure have made EVs more practical and convenient for daily use.
4. **Urbanization and Traffic Congestion**: With the rapid urbanization and increasing traffic congestion in Indian cities, electric two-wheelers offer a practical solution for short commutes and last-mile connectivity. Their compact size and ease of manoeuvrability make them ideal for navigating congested urban roads.

The Ola S1 Pro uses an IPM motor that is capable of producing 11kW at peak power output demands, usually experienced while climbing a gradient with a heavy payload and is rated for 7-8kW of continuous power output. The entire E-Powertrain of this vehicle is based on 48-Volts architecture featuring a non-removable battery pack in the footwell board which allowed for compact packaging of the entire vehicle assembly.

The motor is cooled via air-vents and ducts that circulate the air on the fins of the motor housing, allowing for continuous duty cycle, delivering higher rated performance than any other scooter currently available on the market. The IPMSM has been paired with a belt drive system with a reduction of approximately 2.5, which makes it possible to manufacture and maintain over a long duration. Belt drives do have benefits like reduced noise and vibrations, enabling a comfortable and smooth ride. It also benefits from the fact of being lighter than a chain drive, thus reducing the effects induced by inertia at high speed.

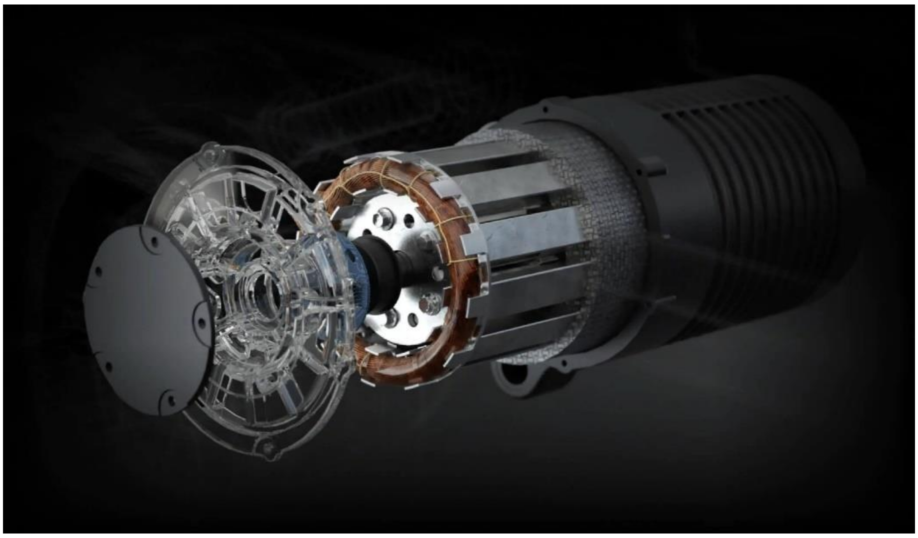

Fig 1. Ola S1 Pro Motor Image

This motor has specifications like:

Number of Stator Slots: 12

Number of Rotor Poles: 10

Number of Phases: 3

Magnet Grade: N42UH

Efficiency >90% at base speed

Weight <10kg

Axial Length < 230mm

Radial Length <200mm

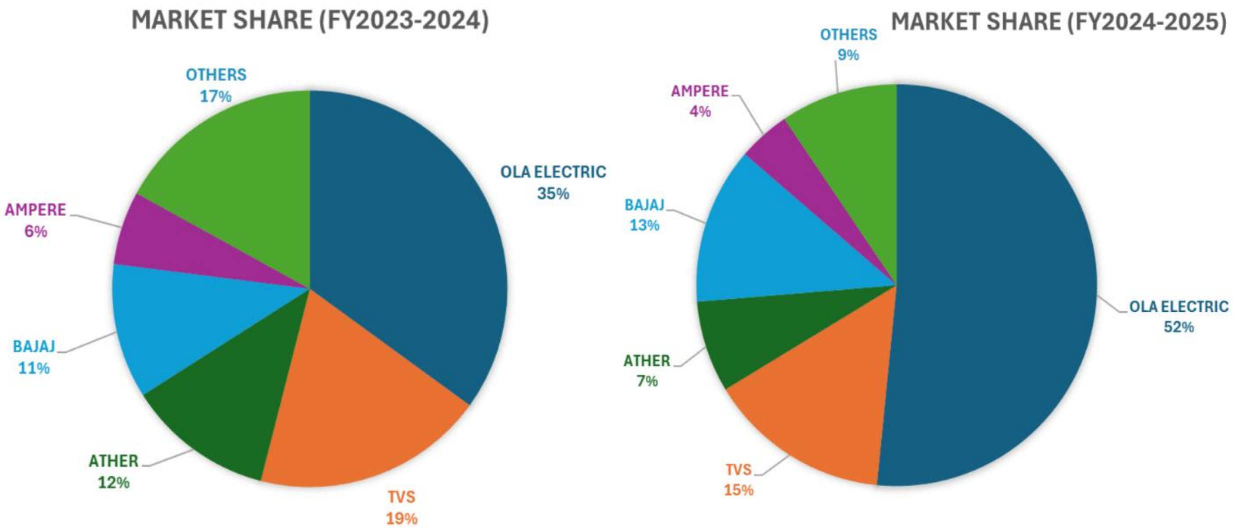

Fig 2. Market share in India ([reference]())

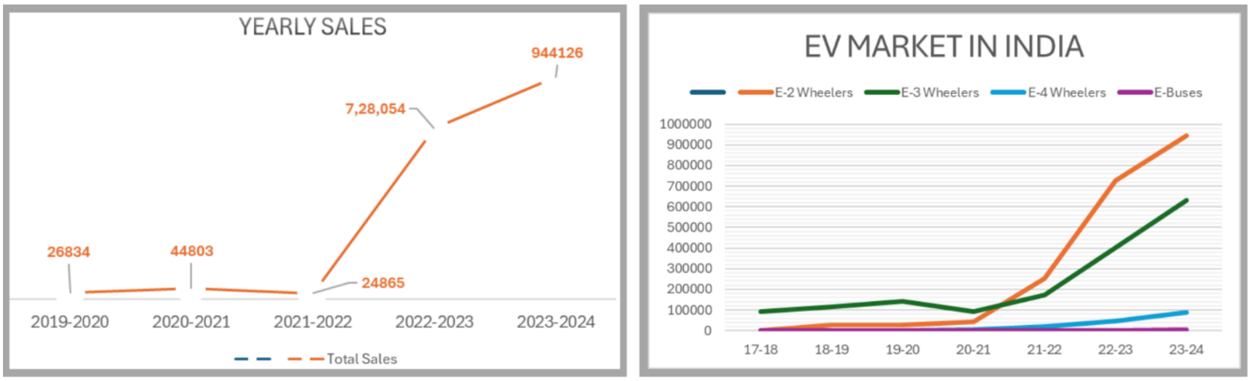

Fig 3. Market trend in India ([reference]())

After analysis of these trends, the EV 2-Wheeler market is a high volume business with a presently unmeasurable impact and growth prospect, which can be used to expand into high volume-cost effective production technologies. Presently the Indian Market for 2W is led by Ola Electric, Bajaj and TVS which is evident with the amount of market share and public sentiment towards their product.

Power Output	Brand
<1kW	Okaya, Hero Electric, Okinawa
1-3kW	BATTRE, BGauss, Okaya, Hero Electric, Okinawa, Ampere, Bajaj
3kW-6kW	Okinawa, Ampere, Bajaj, Ather, TVS, OLA Electric
>6kW	Ather, OLA Electric, River

Type of Motor	Brand
BLDC HUB	BATTRE, Okaya, Hero Electric, Okinawa, TVS
PMSM HUB	Bgauss, Bajaj
BLDC Sidemount	
PMSM Sidemount	Bajaj
BLDC Mid-Drive	Okinawa
PMSM Mid-Drive	OLA Electric, Ather, Ampere, River

OPTIMAL UNCLEAR AVOID

*Segmentation analysis is based on sales in the previous fiscal year **(2023-2024)***

Fig 4. Market research segregated based on power output and sales.

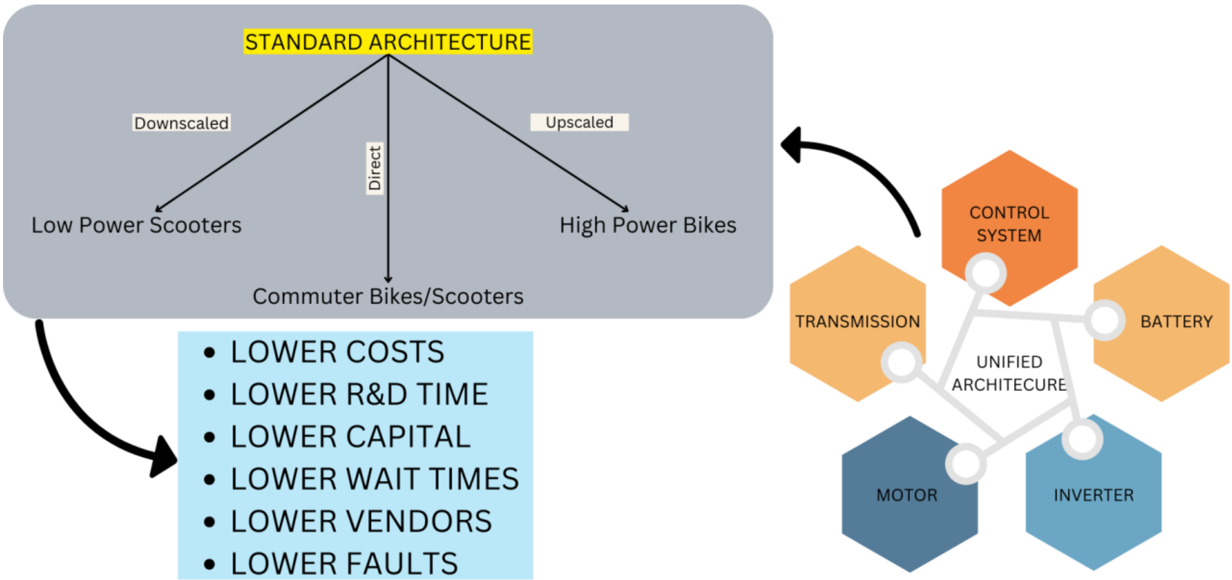

Fig 5. Modular Architecture for the development of an IPMSM

3 IMPLEMENTATIONS

3.1 Requirements Specification:

Rated Power = **7.5kW to 9.5kW**
Base Speed = **3000 RPM to 4000 RPM**
Peak Speed = **5500 to 6000 RPM**

Motor Mass = **8kg to 10kg**
Cooling = Blown Over Natural Convection via Fins

Vehicle Gross Weight = **300kg** (Kerb + 2 Healthy Adults + Payload)
(140+(2*75)+10 kg mass split-up)

Vehicle Top Speed = **80kmph +**
Acceleration **(0-60kmph) < 7 secs**

Voltage = 72Vdc

Efficiency > 90%

Fig.6 Powertrain Characteristics at Vehicle Level

These requirements were finalized based on the market trend analysis of various other vehicles as mentioned earlier in this report (*Table 1 and Table 2*).

3.2 Analytical Design Approximations

	A	B	C	D	E	F	G	H	I
1	Independent Variables					Dependent Varaibles			
2	Parameter	Value	Unit	Description		Parameter	Value	Unit	Description
3						wrm	314.1593	rad/s	
4	Rated Power	9	kW			Rated Torque	28.64789	Nm	
5	Base Speed	3000	RPM						
6						Te-overdesign	32.94507	Nm	
7	Torque Overdesign	15%				wrm-overdesign	376.9911	rad/s	
8	Speed Overdesign	20%				Speed-overdesign	3600	RPM	
9									
10	DC Link Voltage	72	V			Pout-overdesign	12.42	kW	
11	Voltage Drop	4	V						
12						VLL	53.01938	V	
13						VLL		V	
14						VLL	47.4423	V	

Fig 7. Input Parameters for Analytical Design

	A	B	C	D
1	Independent Variables			
2	Parameter	Value	Unit	Description
3				
4	Pout	12.42	kW	Rated Output Power
5	Speed	3600	rpm	Rated Speed
6	Vt	47.4423	V	Line to Line Terminal Voltage (RMS)
7	Connection	star		Winding Connection Type
8	Rounding Flag	TRUE		
9	dEff	95%		Desired Efficiency
10	dPF	0.92		Desired Power Factor
11				
12	Bav	0.604788784	T	Magnetic Loading
13	ac	40	kA/m	Electrical Loading
14	Kw	0.933		Winding Factor
15				
16	p	10		Number of poles
17	Ns	12		Number of stator slots
18				
19	ar	0.4		Ratio of stack length to pole pitch
20	g_emf	0.91		Eph/Vph
21	g_Prot			Prot/Pout
22				
23	Kf	0.76		Slot fill factor
24	Np	8		Number of parallel paths in winding
25	Lend	10	mm	End length of conductor before bending
26				
27	Bst	1.5	T	Maximum Flux Density in stator tooth
28	Bsy	1.4	T	Maximum Flux Density in stator yoke

F	G	H	I
Dependent Variables			
Parameter	Value	Unit	Description
Qin	14.21052632	kVA	Input KVA
rps	376.9911184	rps	Rated speed
Tout	32.94507322	Nm	Output Torque
It	172.9353592	A	Terminal Current
Iph_rms	172.9353592	A	Phase Current
Ic_rms	21.61691991	A	Coil Current
Vph_rms	27.39082468	V	Phase voltage
Vc_rms	109.5632987	V	Coil voltage
Ncpph	2		Number of coils per phase
G	245.0404571	J/m^3	Output Constant
D2L	153830.0746	mm^3	Volume product
D	107	mm	Bore diameter
g-offer	0.27740801	mm	An offer for the air gap length
	10		
tau_p	33.61504139	mm	Pole pitch
L	14	mm	Stack Lengths
phi_total	2.8462	mWb	Total air gap flux
phi_tooth_max	0.071155	mWb	Stator tooth flux
phi_pole	0.28462	mWb	Pole flux

J	K	L	M
Tuned Variables			
Parameter	Value	Unit	Description
Ntc	141		Number of turns in single coil (updated)
Ntph	71		Number of turns in phase (updated)
phi_pole	0.263562687	mWb	Pole flux
phi_total	2.635626872	mWb	Total air gap flux
phi_tooth	0.065890672	mWb	Tooth flux
Lstk	13	mm	Stack length (updated)
Nlammination	38		Number of laminations
cAca_ig	4.803759979	mm^2	copper Area of coil arm (initial guess)
gAca_ig	6.320736814	mm^2	gross Area of coil arm (initial guess)
SWG #	11		
SWG diameter	2.946	mm	
SWG area	6.8183	mm^2	
cAsc	6.8183	mm^2	copper Area of single conductor (update
cAca	961.3803	mm^2	copper Area of coil arm (updated)
gAca	1264.974079	mm^2	gross Area of coil arm (updated)
hs2	71.13168759	mm	slot depth
bs2	122.4251686	mm	slot bottom width
hs22	26.05862421	mm	
Do	282.5490895	mm	

Fig. 8 Analytical Design Parameters obtained but included some errors

The Analytical Solution used methods and formulas to derive the slot dimensions and winding parameters that were possible with few parametric inputs based on the output values.

As an example, the theoretical value for length of stack comes out to be “13mm” which is proved with a formula, but in terms of practicality, the minimum size needed will be above 50mm at least (from competitor data).

Pros	Cons
Accessibility: Excel is widely available and easy to use.	**Complexity Limitation**: Handling complex designs can be challenging.
Cost-Effective: Excel is cost-effective compared to specialized software.	**Manual Errors**: Higher risk of human error in manual calculations.
Customizable: Easy to customize formulas and layouts.	**Scalability Issues**: Difficult to scale for large and detailed models.
Quick Prototyping: Good for quick initial calculations and prototyping.	**Integration Limitations**: Limited integration with other advanced simulation tools.
Learning Curve: Requires minimal training for basic operations.	**Visualization**: Limited advanced visualization and 3D modeling capabilities.
Data Handling: Efficient for managing and analyzing data sets.	**Simulation Constraints**: Not suitable for dynamic simulations and real-time analysis.
Flexibility: Users can easily change and update the design parameters.	**Accuracy**: Analytical methods may not capture all real-world complexities.
Documentation: Eases documentation and reporting of results.	**Time-Consuming**: More time-consuming for iterative design processes.

Table 3. Pros and Cons of Analytical Design

These data outputs were used as a baseline for the creation of a 2-D E-Magnetic Model in Ansys MotorCAD. This software features various templates which can be modified based on simple design parameters and constraints. It allows for real-time visualization of the physical changes in parameters for quick verification of the numerical parameters and their feasibility.

Visualization

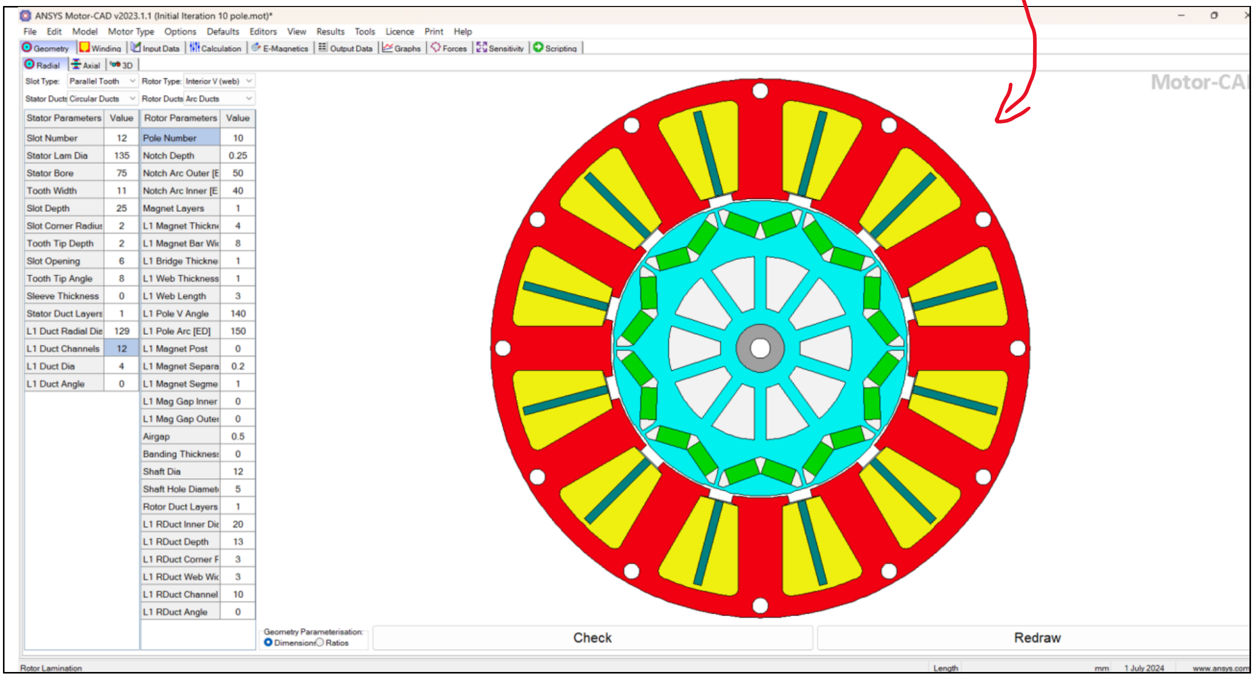

Fig 9. Radial Construction of the Motor

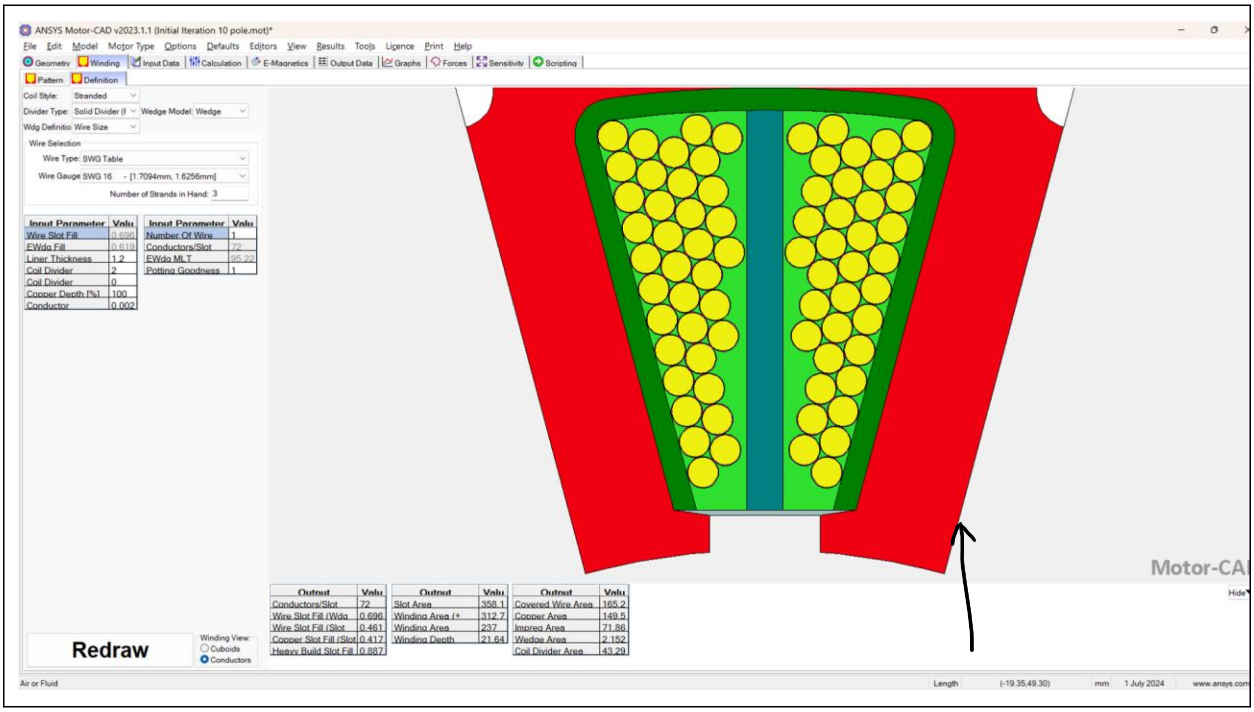

Fig 10. Slot and Winding Construction

Winding Design and Slot Fill

The output data from all these iterations was recorded in order to match with the power output characteristics and requirements but was later finalised for the following power output figures which accounted for the manufacturing and assembly's feasibility.

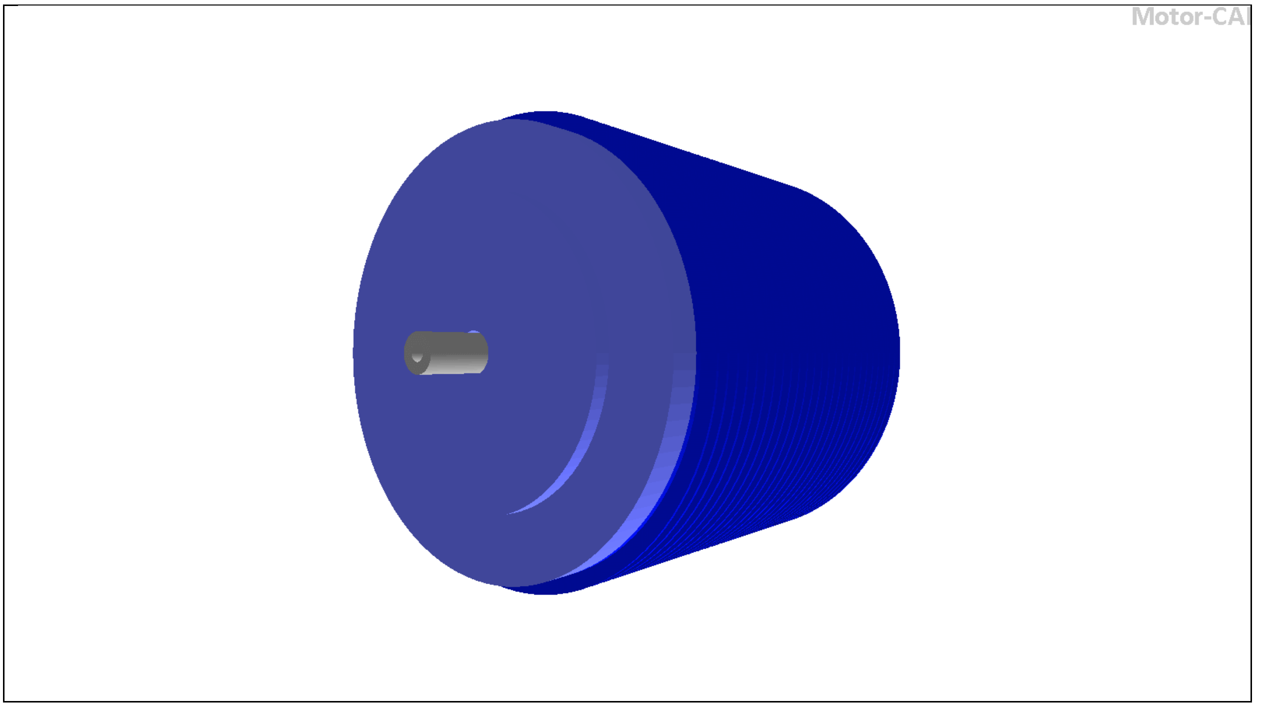

Fig 11. 3-D view of the Motor

Aspect	Analytical Design Approach (Excel)	Ansys MotorCAD
Accessibility	Widely accessible, requires only Excel software	Requires specialized software and licenses
Cost	Cost-effective, minimal software costs	Higher cost due to software licensing fees
Ease of Use	Easy to use for basic calculations and data management	User-friendly interface but requires some training
Customization	Highly customizable formulas and layouts	Customizable but within the constraints of the software
Complexity Handling	Limited to handling simpler, more straightforward calculations	Capable of handling complex, detailed motor designs
Risk of Errors	Higher risk of manual errors in calculations	Reduced risk of errors due to automated processes
Simulation Capabilities	Limited to static, analytical calculations	Advanced multiphysics simulations including electromagnetic, thermal, and mechanical analyses
Visualization	Limited visualization, mainly charts and graphs	Advanced 3D modeling and detailed visualizations
Integration	Limited integration with other design and simulation tools	Seamless integration with other Ansys simulation tools and third-party software

Accuracy	Less accurate, may not capture all real-world complexities	High accuracy due to comprehensive simulation capabilities
Optimization	Manual optimization, time-consuming	Automated optimization algorithms for design refinement
Scalability	Difficult to scale for larger and more detailed models	Scalable for detailed and complex models
Learning Curve	Minimal training needed for basic operations	Requires training to use full capabilities
Documentation	Easy to document and report results	Comprehensive reporting features
Real-Time Analysis	Not suitable for dynamic simulations and real-time analysis	Capable of real-time dynamic simulations
Thermal Management	Basic thermal calculations, often separate from main design	Integrated thermal management analysis
Mechanical Analysis	Limited mechanical stress and vibration analysis	Advanced mechanical analysis for structural integrity and vibrations
Development Cycle	Longer development cycle due to manual processes	Shorter development cycle with automated and integrated processes

Table 5. Analytical Method vs Ansys MotorCAD

4 RESULTS

The simulations were ran using default settings of the solver. The material properties were kept as per the material database in-built into the software.

The Indian drive cycle which is known as MIDC or Modified Indian Drive Cycle is a good benchmarking test but does lack the versatility shown in WLTP Class 1 or Worldwide Harmonized Test Procedure, which consists of stop-go situations alongwith steady high speeds.

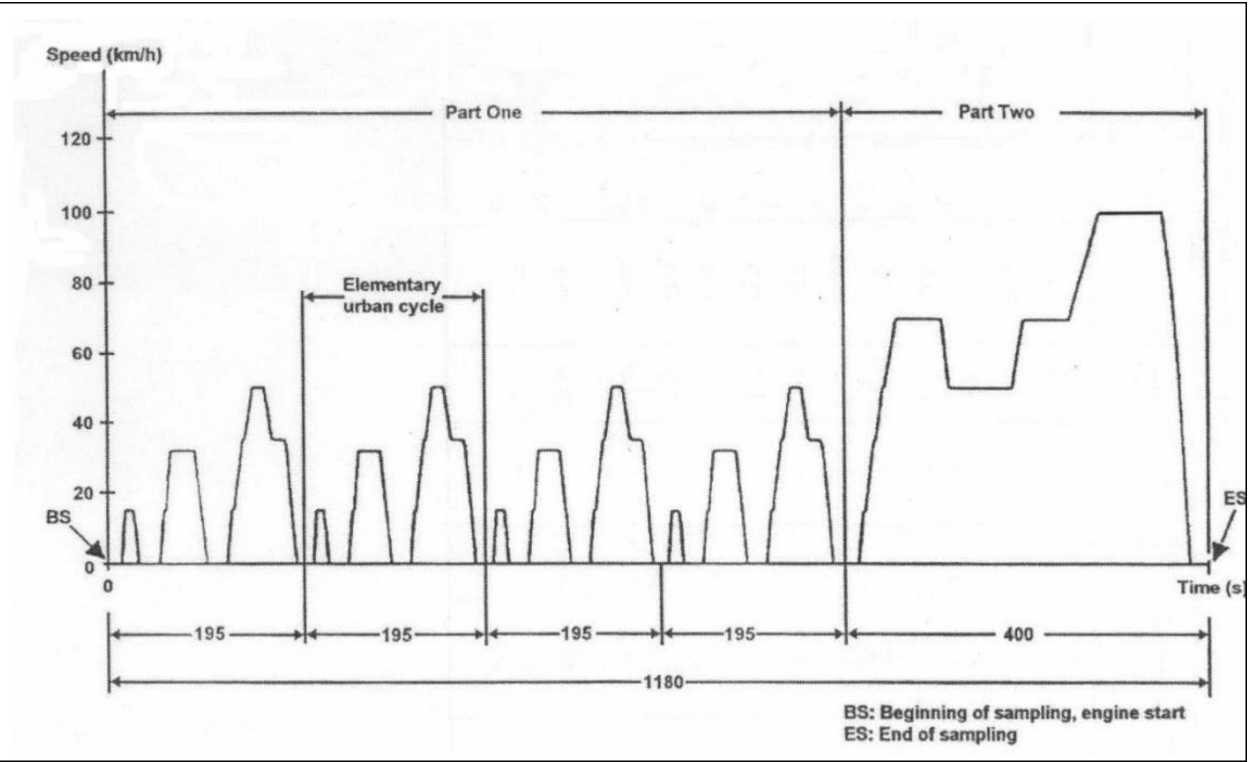

Fig 12. MIDC

Structure of MIDC

The Modified Indian Drive Cycle is structured to include a series of acceleration, deceleration, cruising, and idling phases. The cycle is typically divided into the following segments:

1. **Cold Start Phase**: This phase simulates the initial start-up of the vehicle, including idling and initial acceleration. It is crucial for assessing emissions during the cold start period.
2. **Urban Phase**: This phase represents typical city driving conditions with frequent stops, accelerations, and decelerations. It is characterized by lower average speeds and higher incidences of idling.
3. **Highway Phase**: This phase simulates highway driving conditions with steady cruising at higher speeds. It helps in evaluating the vehicle's performance and fuel efficiency during continuous high-speed travel.
4. **Hot Start Phase**: Similar to the cold start phase but performed after the vehicle has been warmed up. It assesses emissions and performance during a restart of the vehicle.

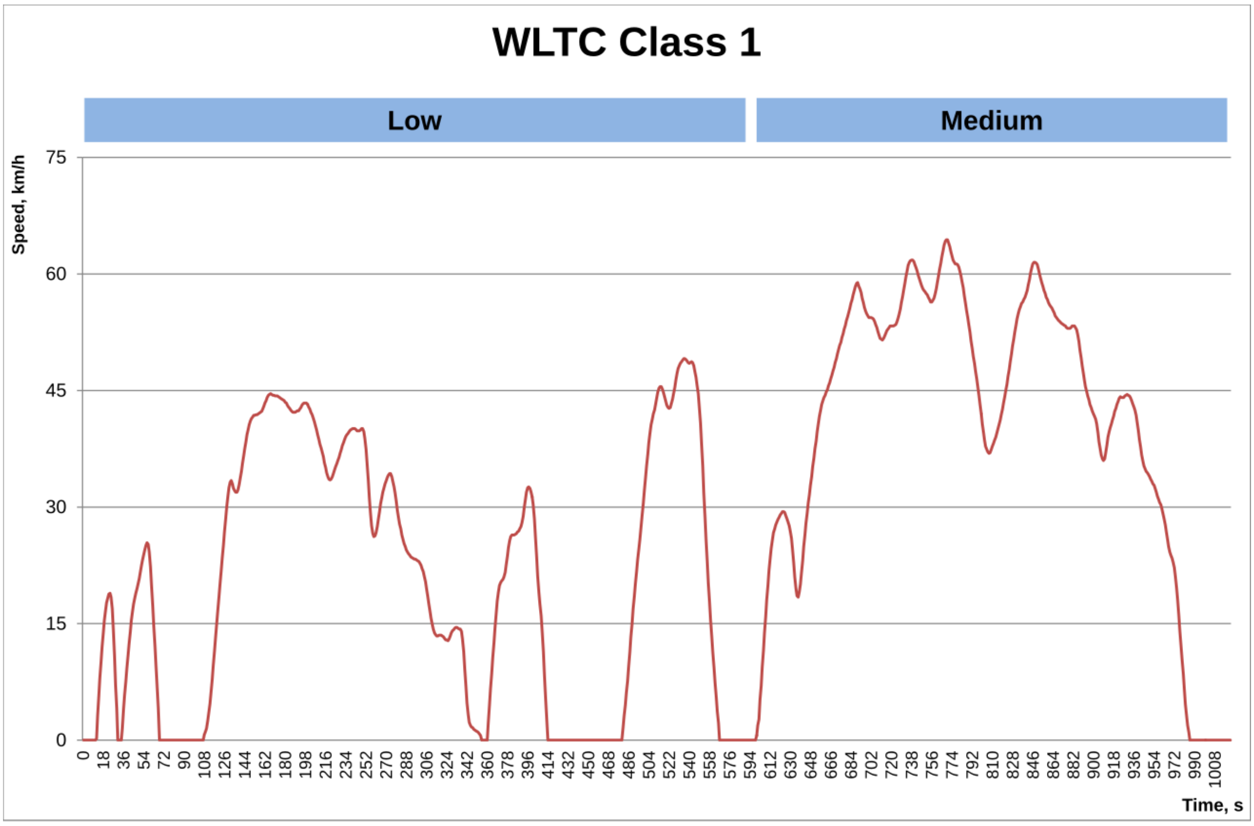

Fig 13. WLTP Class-1

The above given images clearly differ in terms of the fidelity of the test procedure and can be a big factor when translating the theoretical efficiency and performance into real-world scenarios.

The test chosen was WLTP Class-1 and all the results published in this report relies on the standard WLTP Class-1 module from Ansys MotorCAD library of drive cycles.

The Worldwide Harmonized Light Vehicles Test Procedure (WLTP) is an international standard for measuring the fuel consumption, carbon dioxide (CO2) emissions, and pollutant emissions of passenger cars and light commercial vehicles. WLTP Class 1 specifically refers to the category for vehicles with a power-to-weight ratio below 22 W/kg, typically being smaller, less powerful vehicles often used in urban environments. This classification ensures that the test cycle's parameters, such as speed, acceleration, and driving patterns, accurately reflect the typical usage of these vehicles. The WLTP Class 1 test cycle includes more dynamic and realistic driving conditions compared to the earlier New European Driving Cycle (NEDC), providing more accurate and representative data for consumers and regulatory bodies. This helps in better evaluating and comparing vehicle performance, promoting transparency and aiding in the development of more efficient and eco-friendly automotive technologies.

	Low	Medium	Total
Duration, s	589	433	1022
Stop duration, s	155	48	203
Distance, m	3324	4767	8091
% of stops	26.3%	11.1%	19.9%
Maximum speed, km/h	49.1	64.4	
Average speed without stops, km/h	27.6	44.6	35.6
Average speed with stops, km/h	20.3	39.6	28.5
Minimum acceleration, m/s^2	-1.0	-0.6	
Maximum acceleration,m/s^2	0.8	0.6	

Fig 14. Duration of WLTP Class-1

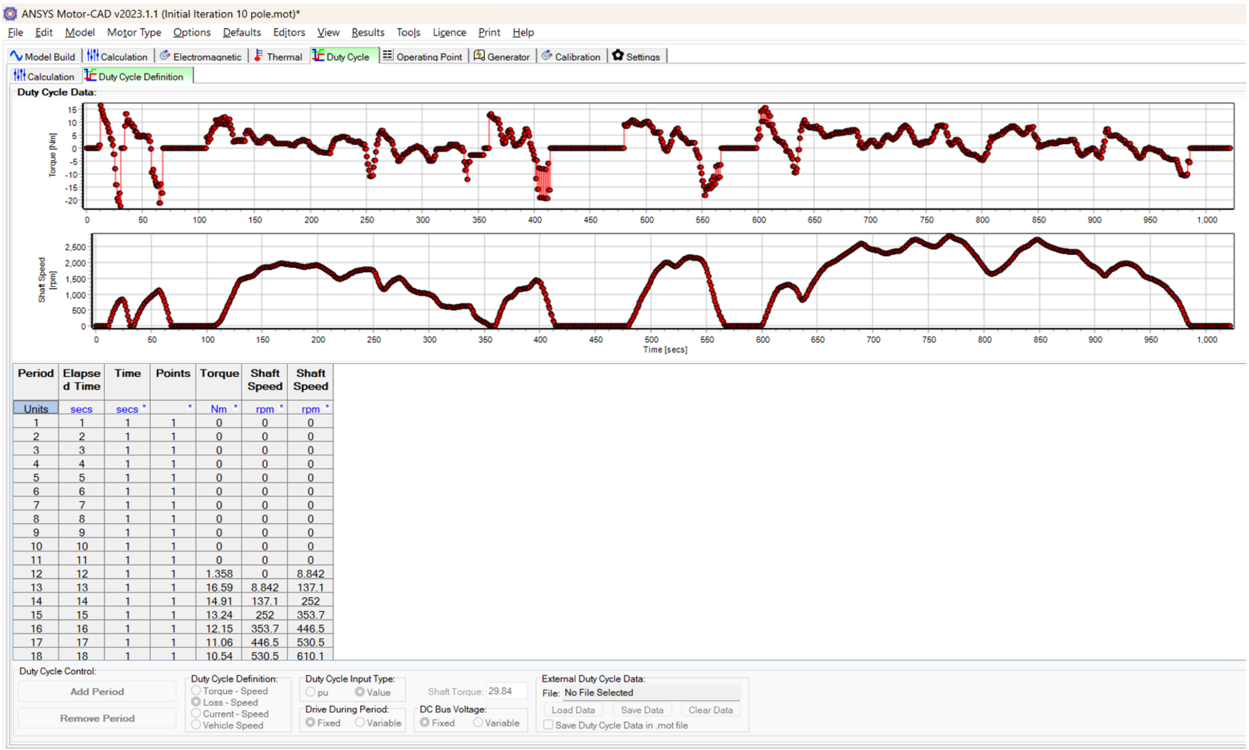

Fig 15. Duty Cycle Definition

The above is the dataset which is pre-built for WLPT Class-1 Drive Cycle, which is commonly used across the industry to test and validate low power and medium power scooters.

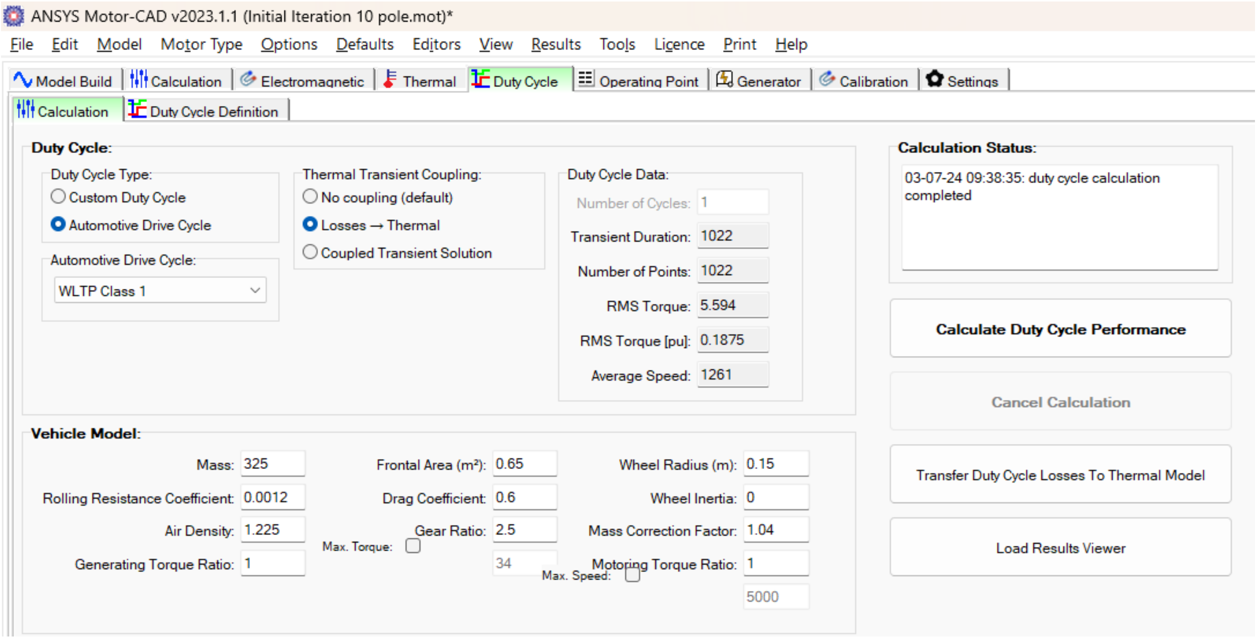

Fig 16. Duty Cycle Analysis Vehicle Model Data

The vehicle model was approximated based on the use cases commonly observed in India which included:

1. One Rider and One Pillion (75kg each)
2. Kerb Weight (125kg)
3. Luggage (25kg)

Making a total of 325kg, requiring a high tractive effort of approximately 1000N.

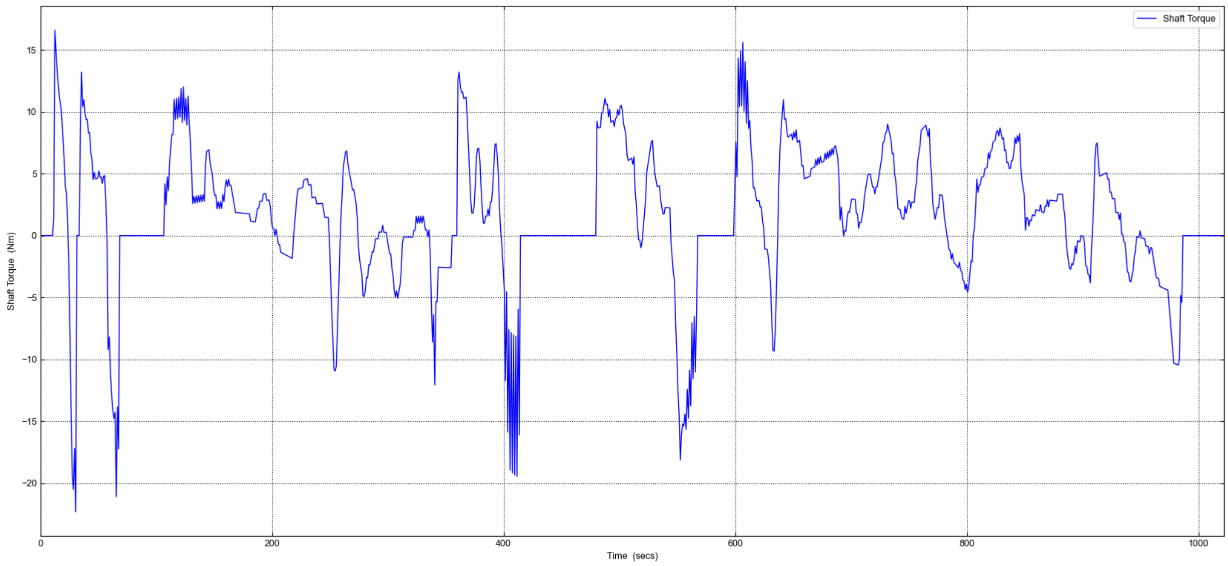

Fig 17. Motor Shaft Torque across WLTP Class-1

Duty Cycle Data

	Value
Average Efficiency (Energy Use) (%)	93.67
Average Efficiency (Point by Point) (%)	89.18
Electrical Input Energy (Wh)	132.06
Shaft Motoring Energy (Wh)	124.52
Electrical Output (Recovered) Energy (Wh)	29.26
Shaft Generating Energy (Wh)	32.11
Total Loss (Wh)	10.38
Copper Loss (Wh)	3.89
Iron Loss (Wh)	5.95
Magnet Loss (Wh)	0.02
Mechanical Loss (Wh)	0.53
Motoring Operation (%)	71.57
Generating Operation (%)	28.43

Fig 18. Drive Cycle Output Data

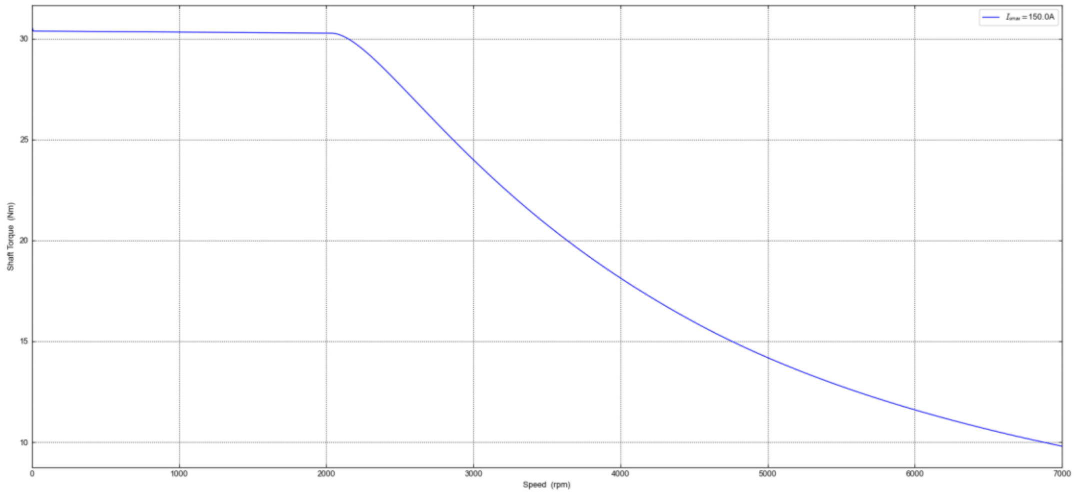

Fig 19. Torque vs Speed Curve @150A(dc)

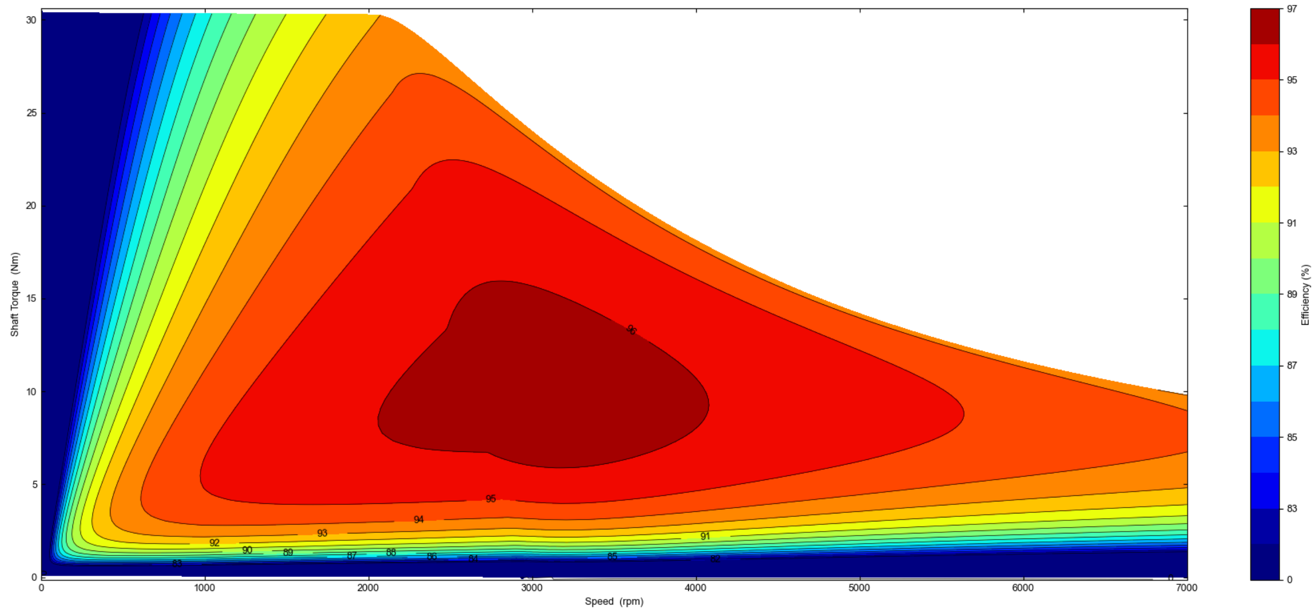

FIG 20.EFFICIENCY MAP

Efficiency maps are vital tools in the design, analysis, and optimization of machines, providing a visual representation of how performance varies across different operating conditions. By leveraging these maps, engineers and designers can enhance the efficiency and performance of motors, engines, and other machinery, leading to better, more energy-efficient products.

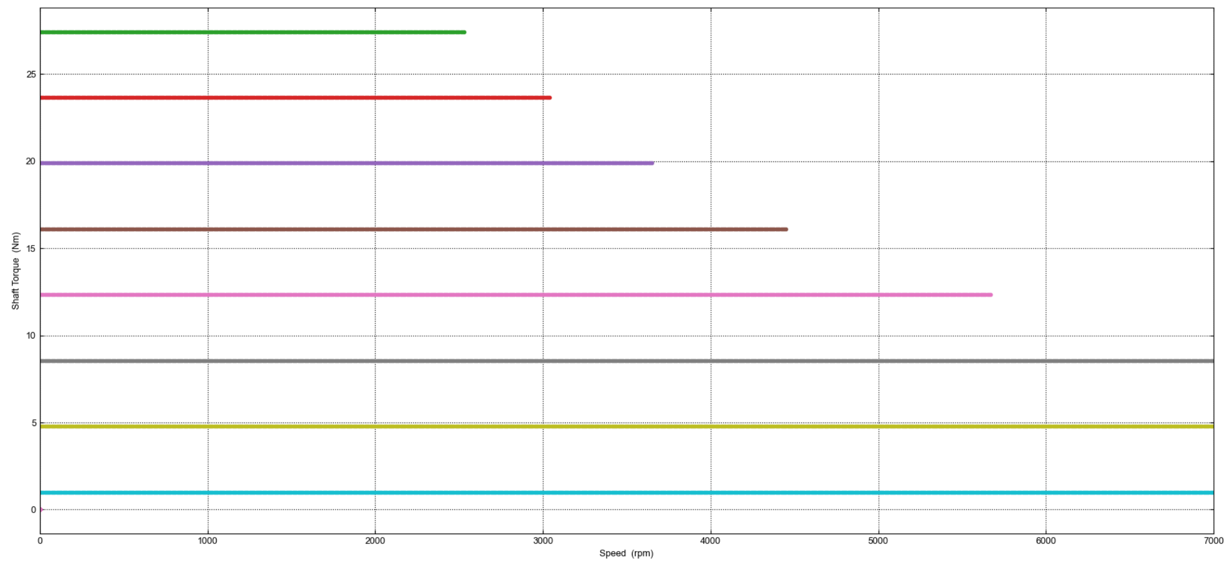

Fig 21. Torque Grid till 7000 RPM

The Torque Grid in Ansys MotorCAD is a powerful tool for analyzing and optimizing the performance of electric motors. By providing detailed insights into how torque and speed affect the motor's behavior, engineers can design more efficient, reliable, and high-performance motors tailored to specific applications. This tool is essential for ensuring that electric motors meet the demands of modern applications, from automotive to industrial uses.

Drive | E-Magnetics | Phasor Diagram | Eqosses | Win Forces

Variable	Value	Units
DC Bus Voltage	72	Volts
Line-Line Supply Voltage (rms)	50.91	Volts
Phase Supply Voltage (rms)	29.39	Volts
Line-Line Terminal Voltage (peak)	100.1	Volts
Line-Line Terminal Voltage (rms)	70.29	Volts
Phase Terminal Voltage (peak)	60.33	Volts
Phase Terminal Voltage (rms)	40.59	Volts
Harmonic Distortion Line-Line Terminal Voltage	5.001	%
Harmonic Distortion Phase Terminal Voltage	5.261	%
Back EMF Line-Line Voltage (peak)	74.72	Volts
Back EMF Line-Line Voltage (peak) (fundamental)	73.89	Volts
Back EMF Phase Voltage (peak)	43.95	Volts
Back EMF Line-Line Voltage (rms)	52.25	Volts
Back EMF Phase Voltage (rms)	30.2	Volts
Harmonic Distortion Back EMF Line-Line Voltage	1.196	%
Harmonic Distortion Back EMF Phase Voltage	4.308	%
Max Line-Line / Phase Voltage Ratio	1.732	

DC Supply Current (mean)	138	Amps
Line Current (peak)	150	Amps
Line Current (rms)	106.1	Amps
Phase Current (peak)	150	Amps
Phase Current (rms)	106.1	Amps

Phase Advance	27.27	EDeg
Drive Offset Angle (Open Circuit)	75	EDeg
Drive Offset Angle (On load)	75	EDeg
Phase Advance to give maximum torque	19.31	EDeg

Phasor Offset Angle	0	EDeg
Phasor Angle (Ph1)	0	EDeg
Phasor Angle (Ph2)	120	EDeg
Phasor Angle (Ph3)	240	EDeg
Max Angle Between Phasors	120	EDeg

Variable	Value	Units
D Axis Inductance	0.1763	mH
Q Axis Inductance	0.2481	mH
Line-Line Inductance (DQ)	0.42	mH
Self Inductance	0.2435	mH
Mutual Inductance	-0.02042	mH
Line-Line Inductance	0.5278	mH
Armature End Winding Inductance	0.003867	mH

D Axis Current (rms)	-48.6	Amps
Q Axis Current (rms)	94.28	Amps
Torque Constant (Kt)	0.2018	Nm/A
Motor Constant (Km)	1.476	Nm/(Watts^0.5)
Back EMF Constant (Ke)	0.2378	Vs/Rad
Back EMF Constant (Ke) (fundamental)	0.2352	Vs/Rad
Electrical Constant	17.04	msec
Mechanical Constant	0.4077	msec
Electrical Loading	6.482E004	Amps/m

Stall Current	2891	Amps
Stall Torque	583.4	Nm

Short Circuit Line Current (peak)	148.9	Amps
Short Circuit Current Density (peak)	11.95	Amps/mm²
Short Circuit Current Density (rms)	8.453	Amps/mm²
Short Circuit Braking Torque	-1.319	Nm
Short Circuit Max Braking Torque	-14.72	Nm
Short Circuit Max Braking Torque Speed	137.7	rpm
Short Circuit Max Demagnetizing Current	-336.9	Amps

Fundamental Frequency	250	Hz
Shaft Speed	3000	rpm

Fig 22. Electrical Input and Feedback Data

Variable	Value	Units
Maximum torque possible (DQ)	30.78	Nm
Average torque (virtual work)	30.31	Nm
Average torque (loop torque)	30.142	Nm
Torque Ripple (MsVw)	1.0527	Nm
Torque Ripple (MsVw) [%]	3.4785	%
Cogging Torque Ripple (Ce)	1.2881	Nm
Cogging Torque Ripple (Vw)	0.58004	Nm
Speed limit for constant torque	2150	rpm
No load speed	2890.9	rpm
Speed limit for zero q axis current	5.0317E005	rpm

Electromagnetic Power	9507.7	Watts
Input Power	9936.5	Watts
Total Losses (on load)	536.81	Watts
Output Power	9399.7	Watts
System Efficiency	94.598	%

Shaft Torque	29.92	Nm

Power Factor [Waveform] (lagging)	0.77064	
Power Factor Angle [Waveform]	39.589	EDeg
Power Factor [THD]	0.76957	
Power Factor [Phasor] (lagging)	0.79864	
Power Factor Angle [Phasor]	37	EDeg
Load Angle [Phasor]	64.375	EDeg
Phase Terminal Voltage (rms) [Phasor]	41.415	Volts

Rotor Inertia	0.0015714	kg.m²
Shaft Inertia	2.645E-006	kg.m²
Total Inertia	0.001574	kg.m²
Torque per rotor volume	70.368	kNm/m³

Variable	Value	Units
Phase Resistance	0.01245	Ohms

D Axis Inductance	0.1763	mH
Q Axis Inductance	0.2481	mH
Stator Slot Leakage Inductance	0.06052	mH
Stator Differential Leakage Inductance	0.006651	mH
Armature End Winding Inductance	0.003867	mH
Stator Leakage Inductance (Total)	0.07104	mH
Magnetizing Inductance (D Axis)	0.1053	mH
Magnetizing Inductance (Q Axis)	0.177	mH

D Axis Reactance	0.2769	Ohms
Q Axis Reactance	0.3897	Ohms
Stator Slot Leakage Reactance	0.09507	Ohms
Stator Differential Leakage Reactance	0.01045	Ohms
Armature End Winding Reactance	0.006075	Ohms
Stator Leakage Reactance (Total)	0.1116	Ohms
Magnetizing Reactance (D Axis)	0.1653	Ohms
Magnetizing Reactance (Q Axis)	0.2781	Ohms

Fig 23. Power and Output Data

Variable	Value	Units
Rotor Referred Resistance	1.05	Ohms

First Order Transient Reactance (D Axis)	0.1116	Ohms
First Order Transient Reactance (Q Axis)	0.3897	Ohms

Excitation Time Constant (Te)	0.0001002	secs
First Order Transient Time Constant (Td')	4.037E-005	secs
Armature Time Constant (Ta)	0.01282	secs

Variable	Value	Units
Airgap flux density (mean)	0.5303	Tesla
Airgap Flux Density (peak)	1.598	Tesla
Stator Tooth Flux Density (peak)	1.539	Tesla
Stator Tooth Tip Flux Density (peak)	2.024	Tesla
Stator Back Iron Flux Density (peak)	1.768	Tesla
Rotor Back Iron Flux Density (peak)	0.4338	Tesla

Fig 24. Motor Transient Response Time and Flux Densities

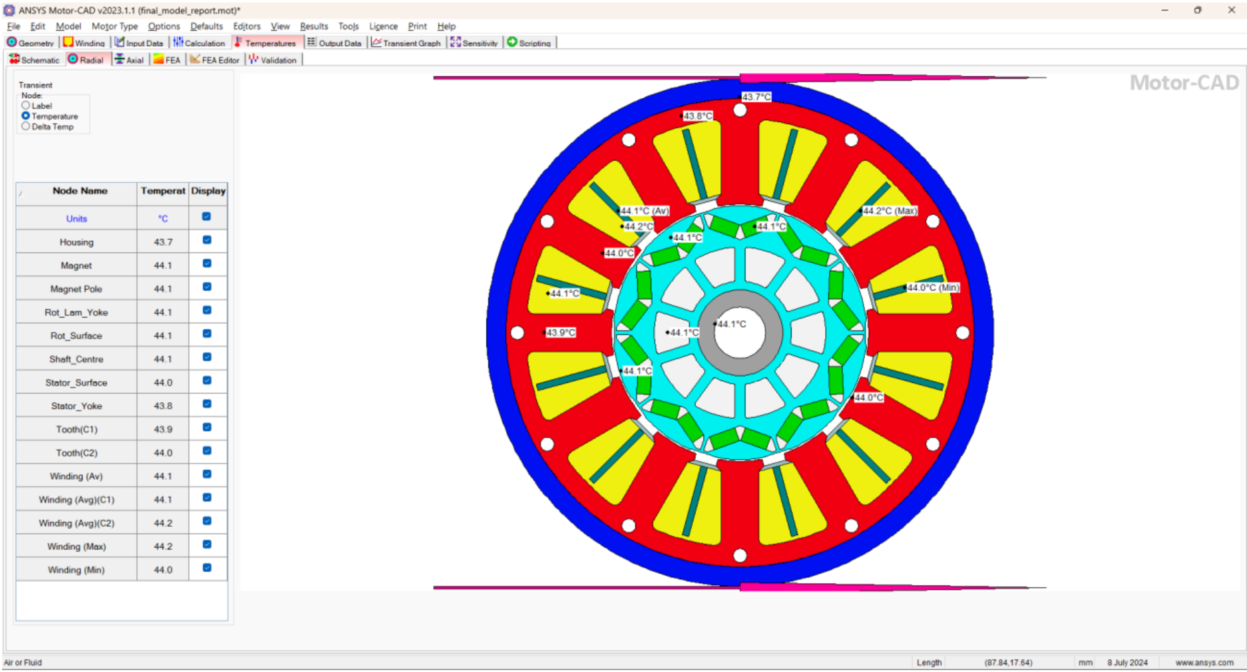

Fig 25. Radial Temperature Distribution after WLTP Class-1

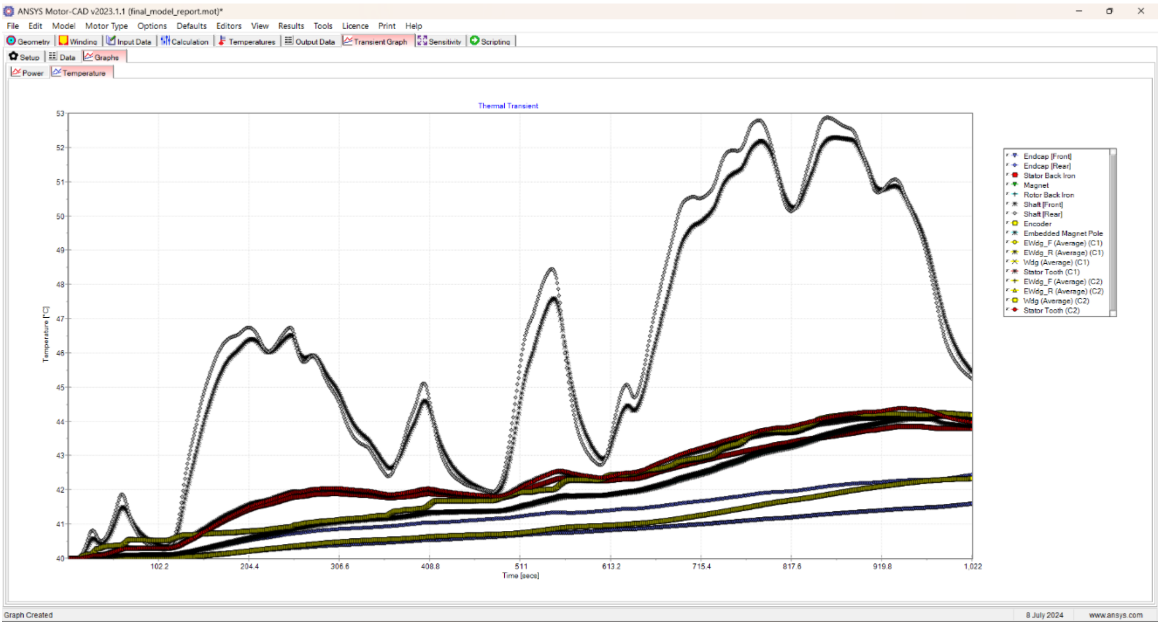

Fig 26. Transient Temperature Curve after WLTP Class-1

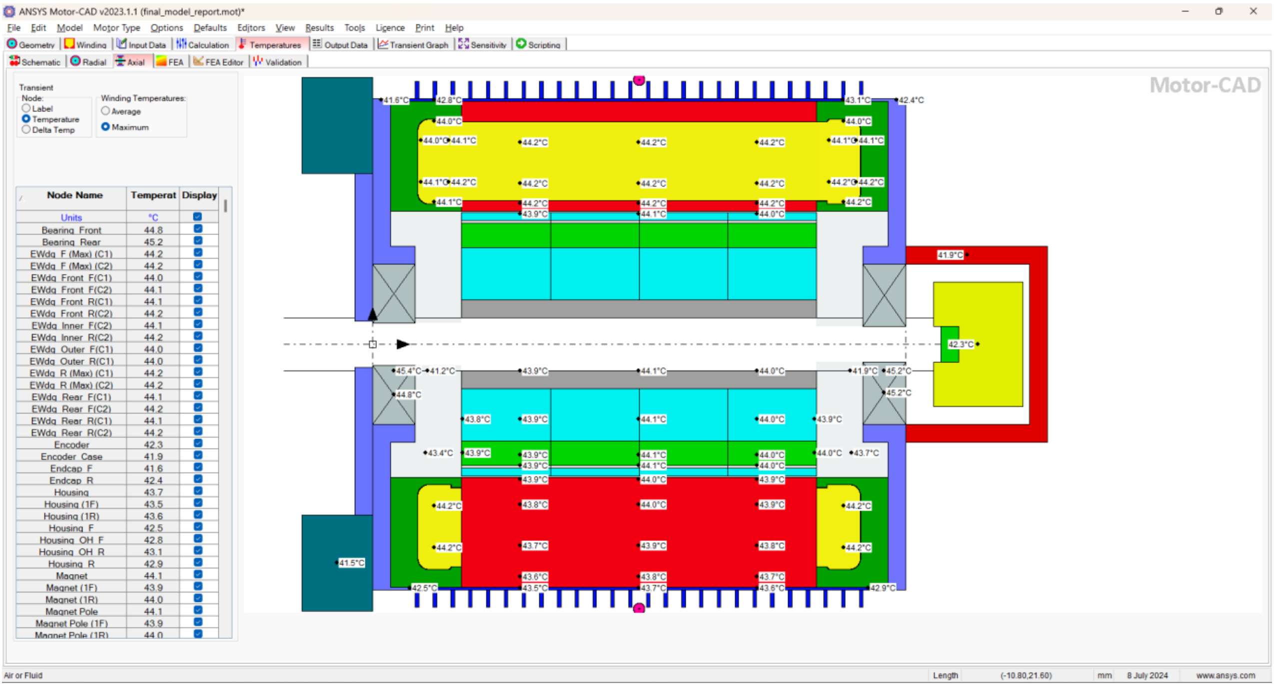

Fig 27. Axial Temperature Distribution after WLTP Class-1

The results proved that the performance lies within the operating envelope and doesnt exceed any specific parameter. The temperatures during transient drive cycles also prove that the machine can keep working for a continuous drive cycle which was tested upto 4 iterations in a sequential manner, without giving any cooling time. The results remained the same and proves that the design is a viable option.

5 CONCLUSIONS

The MotorCAD model does fall into a useful product applicable for EV 2W and 3W while being compact and lightweight. The performance does satisfy the needs of tractive effort on gradients. So, with a high gear reduction, we can easily harness the usable torque at various riding conditions.

Key Findings

1. **Efficiency and Performance**: The designed motor demonstrates high efficiency in a zone which is the RMS RPM and Torque zone according to the WLTP Class-1 simulator, which is critical for extending the range of electric vehicles. Performance testing indicated that the motor could deliver the required torque and power across the desired speed range, ensuring robust and responsive vehicle acceleration and deceleration. The regeneration power was nearly about 3-4kW, which is high enough, approximately 40-50% of rated motoring power of the electric machine.
2. **Thermal Management**: Effective thermal management strategies were implemented by maintaining a low current density in the range of 3-4A/mm^2 at its rated power value, ensuring the motor operates within safe temperature limits under various load conditions. This is crucial for maintaining motor reliability and longevity, without hampering the performance during heavy-duty usage.
3. **Compact and Lightweight Design**: The motor design achieved a compact and lightweight form factor, which is essential for EV applications to maximize space and minimize vehicle weight, thereby improving overall vehicle efficiency. The inertia of rotor was also optimized by addition of ducts that will allow for faster response to transient conditions and will reduce the current spikes in sudden acceleration and braking conditions.
4. **Cost-Effectiveness**: The design process considered the cost implications of materials and manufacturing techniques, resulting in a motor that is economically feasible for mass production without compromising on performance or durability. Usage of N-35UH magnets proved a crucial point in terms of cost reduction over the N-42UH used by other competitors.

Challenges and Limitations

The project encountered several challenges, including the need to balance performance with cost, the integration of thermal management systems, and the optimization of the motor design for various operational conditions. Additionally, while the motor performed well in laboratory settings, real-world testing under diverse environmental conditions will be essential to validate these results comprehensively.

6 RECOMMENDATIONS AND FUTURE WORK

To build on the successes of this project, several areas for future work are recommended:

1. **Extended Field Testing**: Conducting extensive field tests under a variety of real-world conditions will provide valuable data to further refine the motor design.
2. **Integration with Advanced Control Systems**: Exploring advanced motor control algorithms can enhance efficiency and performance, particularly in dynamic driving scenarios.
3. **Material Innovation**: Investigating the use of novel materials for motor components could further reduce weight and improve thermal management.
4. **Scalability**: Adapting the motor design for scalability to suit different vehicle sizes and power requirements could open new markets and applications.
5. **E-NVH**: These parameters need to comply with ISO26262 and other global standards.