

# Design and development of a compact powertrain system for all-terrain vehicles

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## ABSTRACT

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All-terrain vehicles (ATVs) are designed to navigate rough terrains, demanding robust and efficient powertrain systems. ATVs are used predominantly for recreational purposes and even in racing events. ATVs are popular for their rugged, compact, but lightweight structure. The powertrain system in an electric ATV is the heart of the vehicle. It is also responsible for providing power output, vehicle dynamics, maximum speed, and acceleration. The powertrain system, which is pivotal for performance, faces several challenges such as weight, dynamics, inertia, and heat management. These issues impact durability and efficiency of the powertrain system and the ATV. The present research attempted to address these issues with a compact and efficient powertrain in electric vehicles (EVs). Featuring a permanent magnet synchronous motor, motor controller, driveshaft, and optimized gearbox, the system aims to maximize power output while ensuring structural integrity through rigorous mechanical analysis. An EV-driven ATV was successfully designed, developed, tested and validated in competitive events like SAE BAJA2023 and MEGA ATV2023. Overall, the system demonstrates enhanced performance and reliability.

**Keywords:** all-terrain vehicles; ATV; compact; powertrain; dynamics; driveshaft

## 1. INTRODUCTION

In the context of all-terrain vehicles (ATVs), the powertrain system encompasses various components that collaborate to transmit power from the engine to the wheels, thereby facilitating movement across diverse terrains. The specific configuration can vary based on the ATV's design and intended application. The fundamental components typically found in electric ATV powertrains that collectively form the powertrain system include the engine, transmission, drivetrain, axles and final drive; they enable the ATV to navigate rugged terrain effectively. An earlier study (Karki et al., 2020) discussed the technological aspects of the different power train systems

of electric vehicle (EV) technology and focused on those technological areas where there is a likelihood of progress by adopting optimization techniques, and future developments as green mobility. Also, (Budală & Șoica, 2019) analyzed the power losses involved in the drivetrain system. They conducted experiments for vehicle performance considering various factors and the isolated influence of each factor contributing to power loss. It is particularly important to reduce all the losses in the powertrain to improve the driving range; this applies in particular to the temperature-dependent motor and inverter losses. Subsequently, a thermally controlled, high-fidelity motor model was presented using an economic model predictive control (MPC) approach to reduce the

temperature-dependent losses (Wahl et al., 2023). The major outcome was that the majority of those motor savings originated from reduced AC-copper losses at elevated temperatures. Another study examined the temperature effects on the torque production and on the efficiency of the permanent magnet motors. It covered components such as the engine, clutch, transmission and driveline (Lungoci & Stoia, 2008). The design process involved selecting suitable components, determining gear ratios, optimizing power transmission efficiency, and ensuring proper torque distribution to the wheels. The same study elucidated how the effect of higher temperature on the demagnetization characteristic degrades the motor performance. Furthermore, Mohanraj et al. (2022) discussed the power losses that occur in the mechanical transmission of a motor vehicle engine. They tested an entire vehicle on a chassis dynamometer and thoroughly reviewed the critical aspects of electric motor drive controllers and mitigation of torque ripple. They also discussed EV design by a critical selection of motors and their control techniques to minimize the torque ripple, along with identifying other research opportunities to enhance the performance of EV. The paper presents some of the causes and effects of power loss based on experimental measurements of power losses on a transmission. In addition, Garniwa et al. (2019) demonstrated that an increase in motor temperature in the motor test in the laboratory with a fixed load resulted in a decrease in the current in controller, motor phase current, and motor torque. Moreover, the increase in motor temperature at that load in the laboratory resulted in an increase in motor rotation speed. From when the vehicle was stationary until it reached a constant speed, the controller current, the motor phase current, and the motor torque decreased with temperature. Whereas in a vehicle with a constant speed of the controller, the motor phase current, motor torque increased with a rise in temperature. The ambient temperature rise resulted in an increase in motor rotation speed when the ultra-compact eco-friendly EVs (KARLING) reached a constant speed. While at KARLING with a constant speed, the increase in temperature caused a decrease in the motor's rotational speed. Some researchers (Walker et al., 2017) performed several simulation and experimental studies of the shift transient behaviour of dual-clutch transmission-equipped EV powertrains and their theoretical and experimental results validate sensible agreement between both outcomes. Furthermore, Jazar (2017) discussed the theory and practical application of vehicle dynamics including various aspects of vehicle dynamics, such as tire dynamics, suspension systems, vehicle handling, and stability control. An in-depth explanation of the fundamental principles, mathematical models, and analysis techniques used in vehicle dynamics were also furnished. It offers insights into the behaviour and performance of wheeled vehicles, aiding in the understanding and design of vehicle systems for optimal performance and safety. In another study about the design of a drivetrain specifically for a SAE Baja racing off-road vehicle (Jain & Ranjit, 2015), the authors discussed the various considerations and challenges involved in developing a high-performance drivetrain for off-road racing. These aspects were gear selection, power transmission, torque distribution, and suspension system integration. The above study provides valuable insights and recommendations for designing a robust and efficient

drivetrain for off-road vehicles. Another study discussed the modeling and simulation techniques specifically applicable to electric vehicles and the significance of accurate modeling and simulation in understanding performance characteristics of EVs (Schaltz, 2011), including power electronics, motor drives, and control algorithms. The paper provides an overview of different modeling approaches and simulation tools employed in analyzing and optimizing the performance of electric vehicles. Strategies to select gear material in automobiles were discussed and key factors to choose gear materials, such as strength, wear resistance, cost, and manufacturing process compatibility, were studied earlier (Shastri et al., 2008). These authors presented various material options and their properties, along with guidelines for material selection based on specific application requirements. Their research provides recommendations for gear material selection to enhance performance, durability, and cost-effectiveness in automotive gear systems. Another study characterized the effect of regional temperature differences on battery electric vehicle (BEV) efficiency, range, and use-phase power plant CO<sub>2</sub> emissions and concluded that efficiency of a BEV varies with ambient temperature due to battery efficiency and cabin climate control (Yuksel & Michalek, 2015). Kanase et al. (2017) discussed the design considerations and challenges involved in developing the 2-stage speed reducer and elaborated the process of designing gears, shafts, and the casing of the gearbox, considering maximum acceleration and road resistances, for optimizing power transmission efficiency. These authors employed CAD software for virtual prototyping and simulation to ensure the functionality and performance of the speed reducer and described manufacturing techniques such as CNC machining, welding, and assembly, thereby providing insights into the practical aspects of constructing the speed reducer. They also discussed the materials and manufacturing processes employed to achieve a robust and reliable design. Later on, an integrated thermal management system based on heat pumps took into account the cooling and heating needs, which is suitable for pure electric vehicles with low energy density and poor driving range, and is of great significance for improving the driving range of electric vehicles (Wang & Liang, 2023).

To improve the driving range, it is particularly important to reduce all losses in the powertrain in an ATV. This applies in particular to the temperature-dependent motor and inverter losses. The shift towards electric ATVs introduces advancements in battery technology, power electronics, and motor design, thereby focusing on enhancing vehicle range, efficiency, and sustainability. As technology evolves, these components will continue to undergo innovation to meet the demands of modern ATV applications and environmental considerations.

The weight and design considerations in ATV powertrain systems significantly impact their performance, efficiency, and durability. Several key points related to weight, strength, and thermal management need to be considered. For example, excessive weight in dynamic components such as the engine, transmission, drivetrain, and wheels can lead to increased losses and reduce overall power output and efficiency. Higher weight requires more power to accelerate and maintain speed, which can strain the powertrain and reduce battery range in electric ATVs. The powertrain system must also be robust enough to

withstand the loads encountered during off-road use. This includes handling steep inclines, rough terrains, and heavy payloads without compromising performance or safety. Choosing materials with high strength-to-weight ratios, such as lightweight alloys or composites, helps maintain structural integrity while minimizing weight.

During operation, powertrain components generate heat due to friction and energy losses. Excessive heat buildup can lead to reduced efficiency, accelerated wear, and potential damage to components. Excessive heat and friction contribute to wear and tear on moving components, necessitating regular maintenance and potentially reducing the lifespan of the powertrain system. Effective cooling systems, such as radiators or cooling fans for internal combustion engines, and heat sinks or thermal management systems for electric components (such as batteries and inverters), are crucial. They dissipate heat and maintain optimal operating temperatures to ensure efficient performance and longevity of the powertrain. Components like bearings, gears, and seals experience frictional losses, which can reduce overall power efficiency.

To address these challenges, ATV manufacturers focus on optimizing the design, material selection, and cooling systems of a powertrain system. Advances in lightweight materials, efficient cooling technologies, and design optimization techniques help enhance performance, extend range for electric ATVs, and improve overall

reliability under varied operating conditions. Balancing weight reduction with structural strength and effective thermal management remains critical in achieving optimal ATV powertrain performance and longevity.

## 2. MATERIALS AND METHODS

Accelerators provide the input to the motor controller and drive the motor based on the input. Figure 1 shows a block diagram of the proposed system, which includes the powertrain components coupled with external electronic inputs such as accelerator, forward/reverse/neutral switch and ignition. The battery powers up the motor controller via contactors. The power from the motor is transferred to the gearbox and then to the wheels via drive shafts, which completes the entire powertrain system.

The process of powertrain designing starts with force calculations and the minimum power required to overcome the resistive force. Calculations of the force and torque were performed. Thereafter, the following factors were considered to select and design the drive motor and gearbox.

1. Rolling resistance
2. Grade resistance
3. Drag resistance
4. Total tractive effort
5. Achievable speed

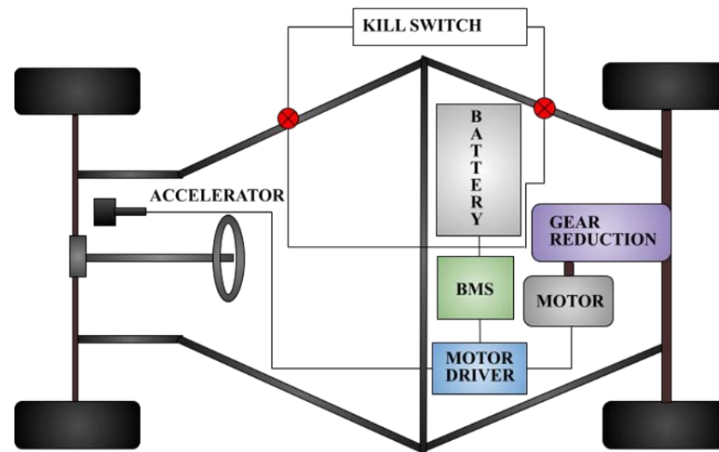


**Figure 1.** The schematic of powertrain system

### 2.1 Calculation of rolling resistance

Rolling resistance refers to the opposing force that the vehicle has to overcome due to the rolling motion between the wheels and the surface of motion of the vehicle. It depends on the coefficient of rolling friction, which varies depending on the material of the tires and the roughness of the surface of motion.

The rolling resistance can be calculated from Equation (1) given below:

$$RR = GVW \times C_{rr} \quad (1)$$

where RR denotes rolling resistance, GVW = 246.65 Kg; gross vehicle weight,  $C_{rr} = 0.6$ ; coefficient of rolling resistance =  $246.65 \times 9.81 \times 0.6$ ; coefficient of rolling resistance is = 145.17N

### 2.2 Determination of grade resistance

Grade resistance, a form of gravitational force, is the force that tends to pull the vehicle back when it is climbing an inclined surface. The grade resistance acting on the vehicle can be calculated using Equation (2) shown below:

$$GR = GVW \times (\theta) \quad (2)$$

where GR = grade resistance, grade or inclination angle =  $35^\circ$ ;  $GR = 246.65 \times 9.8 \times \sin(35)$ , and grade resistance = 1387.64N

### 2.3 Determination of drag resistance

Drag resistance refers to the force that opposes the vehicle's motion through the air. It depends on the vehicle's shape, speed, and aerodynamic features. Reducing drag

resistance improves fuel efficiency, performance, and stability. Automotive engineers use design techniques and simulations to optimize aerodynamics and minimize drag. Enhancing aerodynamic efficiency is crucial for enhancing the overall performance of automobiles.

Drag resistance can be calculated as shown in Equation (3):

$$DF = V^2 \times C_d \times d / 25.92 \quad (3)$$

where DF = drag force,  $C_d = 1$ ; coefficient of drag,  $d = 1.168$ ; air density,  $V = 55$ ; velocity, drag resistance =  $(55^2 \times 0.62 \times 1 \times 1.168) \div 25.92$ , drag resistance =  $84.51\text{N}$

## 2.4 Total tractive effort

Total tractive effort (TTE) is defined as the total force required to move the vehicle with the desired characteristics and is the sum of the forces calculated in the above three sections. Therefore, the TTE can be calculated as shown in Equation (4):

Total tractive effort

$$TTE = RR + GR + FA \quad (4)$$

where total tractive effort =  $1617.35\text{N}$

Hence the torque ( $T_w$ ) required at the wheels is given by Equation (5):

$$T_w = R \times TTE \quad (5)$$

where R is the radius of the wheel =  $0.2921\text{m}$ ,  $T_w = 466\text{Nm}$   
Required gear ratio can be obtained from Equation (6):

$$r = T_w / (0.80 \times T_m) \quad (6)$$

where  $r$  = gear ratio;  $T_w$  = torque at wheels;  $T_m = 58\text{Nm}$  = torque at motors;  $r = 466 / (0.9 \times 58)r$ ;  $r = 8.92$

Hence, the required gear ratio of the vehicle is 9:1

## 2.5 Achievable speed

Using a ratio of 9:1 for gear reduction, the max torque output is  $480\text{ Nm}$  ( $9 \times 58 \times 0.92$ ), where 0.92 is the shaft loss factor, which is sufficient for all the terrain conditions in the track.

The maximum RPM at the output will be  $466\text{ rpm}$  ( $4200 \div 9$ ) in minimal loading conditions. The achievable speed can be calculated by the formula shown in Equation (7):

$$\text{Achievable speed (V)} = \text{wheel circumference} \times \text{RPM} \quad (7)$$

where wheel circumference =  $1.83\text{ m}$ ; output RPM =  $466.66$   
 $V = 1.83 \times 466.66$ ; Achievable speed (V) =  $852\text{ m/min}$ ;  $\sim 51.1\text{km/h}$

## 2.6 Gear design

(i) Stress calculations:

The Lewis form factor for a  $20^\circ$  involute system is given in Equation (8):

$$y = (0.124 - 0.912) \div Z \quad (8)$$

where, Z = number of teeth

Tangential force on the gear teeth can be calculated from Equation (9):

$$F_t = \pi y m b C \sigma \quad (9)$$

Where  $F_t$  is the tangential load at the pitch line;  $\sigma$  = yield stress;  $m$  = module;  $b$  = face width;  $y$  = Lewis form factor;  $C$  = velocity factor = 1

The details of the gears are shown in Table 1, and the total deformation analysis of the first gear train is shown in Figure 2. In addition, Figure 3 depicts the stress analysis of the second gear train. This analysis was done based on the force values obtained from the calculations.

**Table 1.** Details of gears

|                          |          |
|--------------------------|----------|
| Module, m                | 2        |
| Yield stress, $\sigma$   | 333.33   |
| Face width, b            | 20       |
| Number of teeth, $z_1$   | 25       |
| Number of teeth, $z_2$   | 50       |
| Number of teeth, $z_3$   | 95       |
| Number of teeth, $z_4$   | 20       |
| Lewis form factor, $y_1$ | 0.117    |
| Lewis form factor, $y_2$ | 0.135    |
| Lewis form factor, $y_3$ | 0.144    |
| Lewis form factor, $y_4$ | 0.108    |
| Force, $f_1(\text{N})$   | 4918.228 |
| Force, $f_2(\text{N})$   | 5684.868 |
| Force, $f_3(\text{N})$   | 6048.013 |
| Force, $f_4(\text{N})$   | 4534.907 |

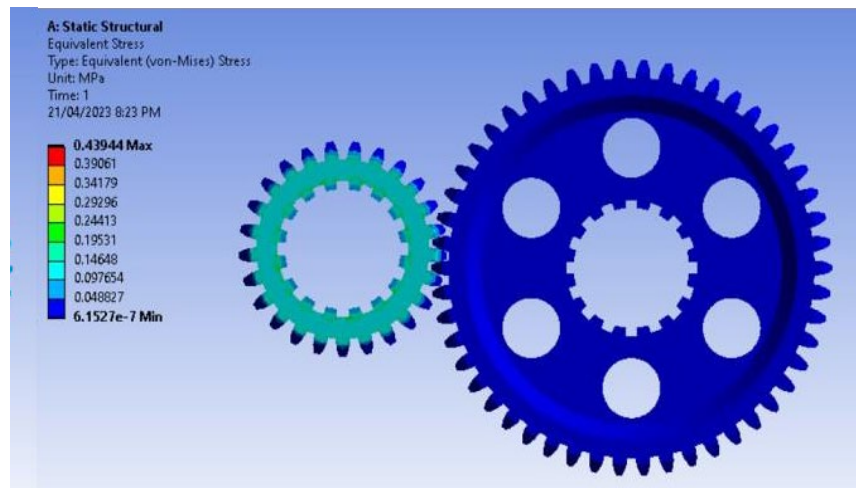


**Figure 2.** Total deformation analysis

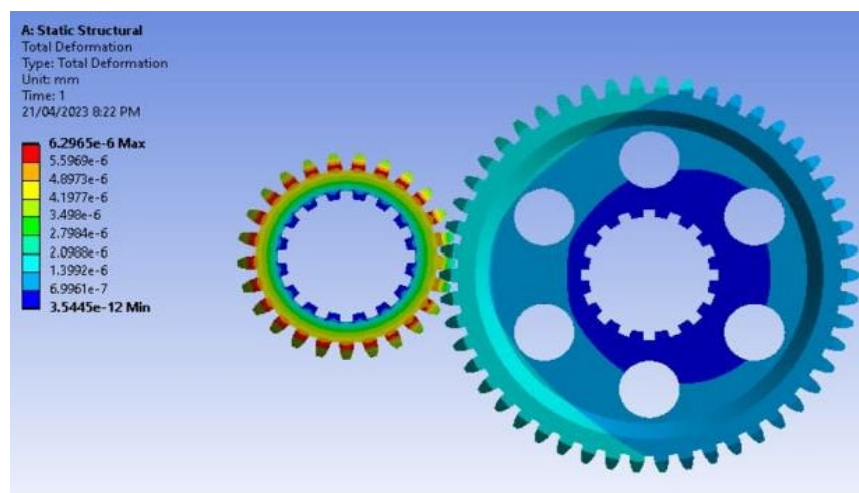


**Figure 3.** Stress analysis

(ii) Gearbox manufacturing:

After finalizing the gear ratios, the powertrain was sent for manufacturing, where the process started with machining the Aluminum 7075T6 block, as shown in Figure 4. The machining process was carried out using a CNC milling machine.

The milled gearbox was then sent for polishing to attain a smooth finish, as shown in Figure 5. The gear teeth and the shafts were then milled. They were derived from a hardened EN-24 material. Figure 6 shows the machined and polished gearbox casing.

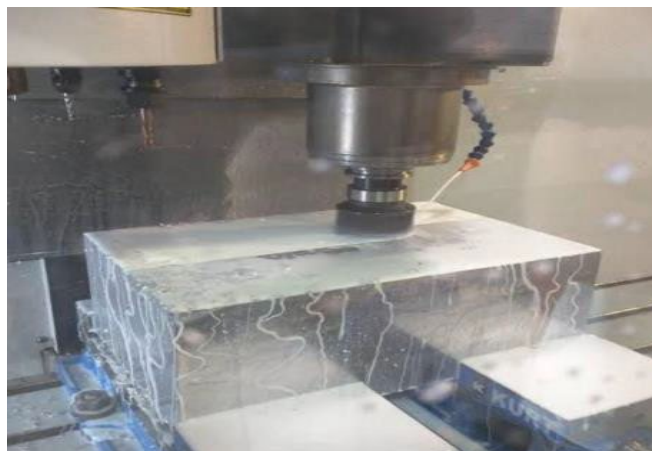


**Figure 4.** Aluminum 7075T6 block

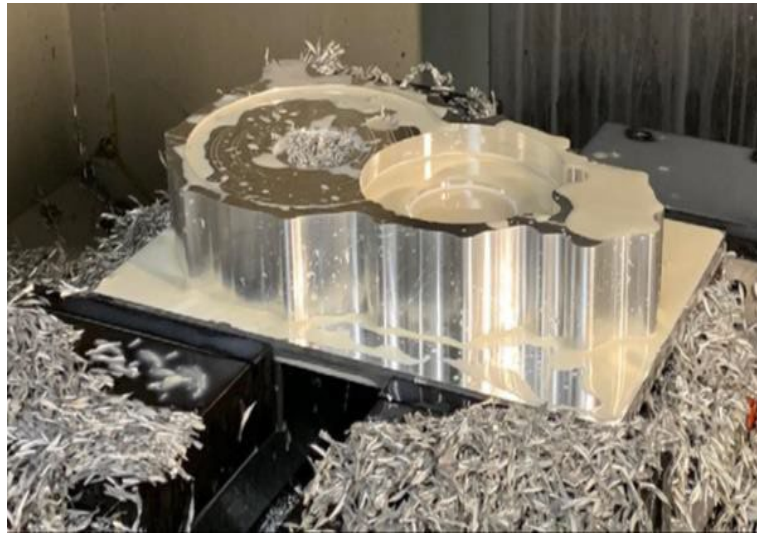


**Figure 5.** Gearbox machining in process



**Figure 6.** The machined & polished gearbox casing

(iii) Battery manufacturing:

The maximum attainable voltage was achieved by arranging 14 cells in series in a Li-ion battery pack, providing up to 58.8 V ( $3.7V \times 14$  cells). During cruising at track speeds, with an average continuous current of 55 A or an average power consumption of 2.8 KW (based on existing test results), 90 min was sufficient for the event. To achieve 1.5 h of operation, a battery capacity of 82.5 Ah was required ( $55A \times 1.5h$ ). However, from a manufacturing point of view, the available standard capacity is a 26650.5Ah lithium-ion cell. Therefore, 16 cells in parallel could be used, resulting in a total capacity of approximately 80 Ah.

Li-ion chemistry was used due to its high energy density compared to other cell types. To fit the battery inside the roll cage in the best way possible, various cell arrangement configurations were evaluated; the most suitable configuration was selected and sent for

manufacturing, as shown in Figure 7. The raw cells were checked for their health and were arranged in grids which were further spot-welded with nickel strips. The grids were then stacked as per the arrangement and the cell wiring was completed.

The battery management system (BMS) was then wired and configured as per the requirements. Later, after cycles of charge and discharge testing, it was placed inside the casing and packed with sealant that made it IP67 rated. Anderson 175 connectors were then fitted and the packs were ready to use.

The powertrain system layout is depicted in Figure 8. It begins with the motor which was mounted in a cantilever manner by 8 mm plate on the roll cage. The output shaft was coupled to the input of the gearbox with the help of a coupler. After the 9:1 reduction from the gearbox the output of the gearbox was transferred to the wheels via a drive shaft.

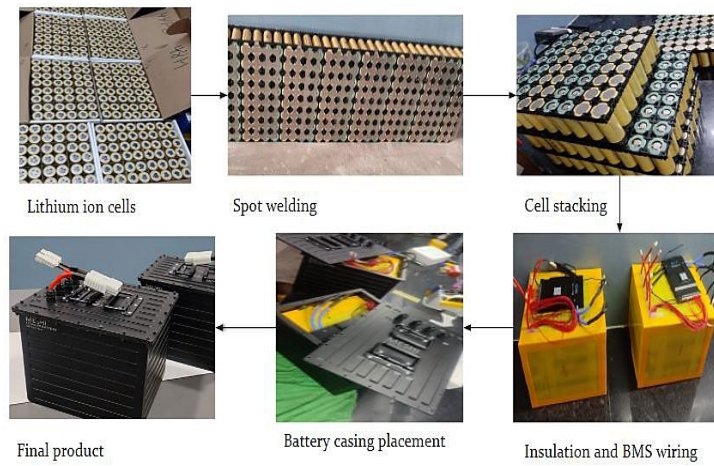


**Figure 7.** Battery manufacturing process



**Figure 8.** Assembled powertrain

Figure 9 demonstrates the CAD model of a drive train. The wheels were mounted using knuckles and hubs which were further connected to the suspension arms. Also, an inboard braking system was implemented in the gearbox at the output shaft. The gearbox was firmly mounted on the frame using L brackets which were TIG welded to the

chassis. The locking of drive shaft to the hubs and gearbox, and of the disc rotor to the gearbox output, was achieved using splines milled onto the shafts. Figure 10 shows the model of an assembled EATV, and Figure 11 depicts the rear view of the assembly.



**Figure 9.** CAD model of the drivetrain



**Figure 10.** The assembled EATV



**Figure 11.** Rear view of the assembly

### 3. RESULTS AND DISCUSSION

The project yielded promising results in addressing the challenges associated with ATVs. Structural analysis techniques were applied to optimize the design, resulting in a lighter yet robust ATV that maintained its strength. The customized battery pack design contributed to improved performance and range, providing sufficient power for ATV use. The introduction of an aluminum casing for the gearbox reduced weight and enhanced overall ATV dynamics. Relief holes in the gears not only reduced weight but also maintained structural integrity. Effective thermal management methods were implemented to control powertrain component temperatures, ensuring optimal power output and preventing overheating issues.

The powertrain system, including components such as the accelerator, motor controller, motor, coupler, drive shaft, knuckle and hub assembly, gear reduction system, and wheels, underwent rigorous testing and evaluation. The results showed significant improvements in power output, dynamics, and overall efficiency, indicating the success of the implemented solutions. The successful utilization of the developed powertrain system in the prestigious events like SAE BAJA 2023 and MEGA ATV 2023 further validates the effectiveness of the solutions. These results demonstrate the project's ability to address the identified challenges and enhance the performance, durability, and efficiency of the ATV.

#### 3.1 Motor and controller test run

Table 2 shows that the motor gradually gains heat for the first half, but reaches a safe saturation temperature, as shown in Figure 12. Then the motor can withstand the heat and run as usual, parallelly radiating a constant amount of heat.

The rising motor temperature degrades the current and torque of motor, but increases the rotation velocity of the motor (Garniwa et al., 2019). Once the motor is on, the temperature starts rising and stabilizes after some time. Eventually, the engine efficiency may also become stabilized.

#### 3.2 Water cooling test

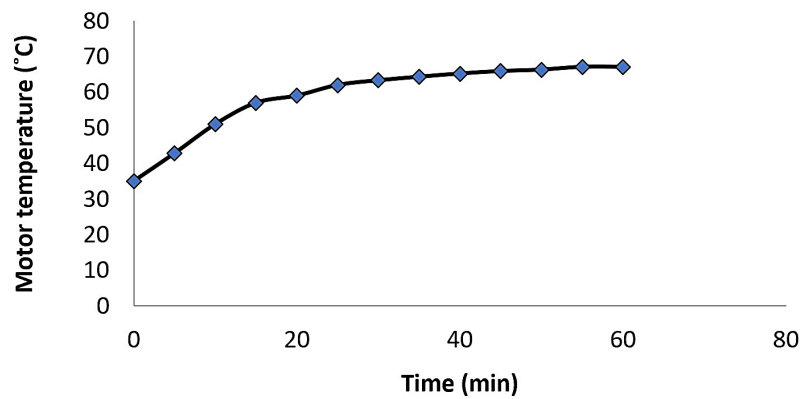
In this test, a water shower was applied to the motor to evaluate the effect of water cooling on the motor. The results are displayed in Table 3; however, only a minimal reduction in temperature was observed, and the motor regained heat quickly after the run, as shown in Figure 13.

#### 3.3 Current drain test

The current values for different load conditions were checked for the consumption and endurance time calculation. The powertrain was subjected to varying loads and the respective currents were noted in Table 4. Initially a proportional increase in the load and current was observed, but later the current lagged behind the load, as shown in Figure 14. This lag may be on account of stabilization of power output by the engine at higher loads.

**Table 2.** Temperature testing of motor at no load

| Sl.No. | Time (min) | Motor temperature (°C) |
|--------|------------|------------------------|
| 1      | 0          | 35.0                   |
| 2      | 5          | 42.8                   |
| 3      | 10         | 51.0                   |
| 4      | 15         | 57.0                   |
| 5      | 20         | 59.0                   |
| 6      | 25         | 62.0                   |
| 7      | 30         | 63.3                   |
| 8      | 35         | 64.3                   |
| 9      | 40         | 65.2                   |
| 10     | 45         | 65.9                   |
| 11     | 50         | 66.3                   |
| 12     | 55         | 67.1                   |
| 13     | 60         | 67.1                   |

**Figure 12.** Temperature versus time at no-load**Table 3.** Water cooling test

| Sl.No. | Time (Min) | Motor temperature (°C) |
|--------|------------|------------------------|
| 1      | 0          | 62                     |
| 2      | 5          | 52                     |
| 3      | 10         | 62                     |

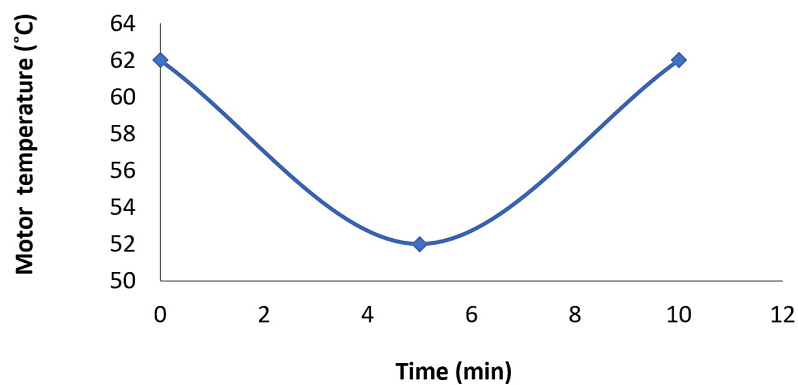
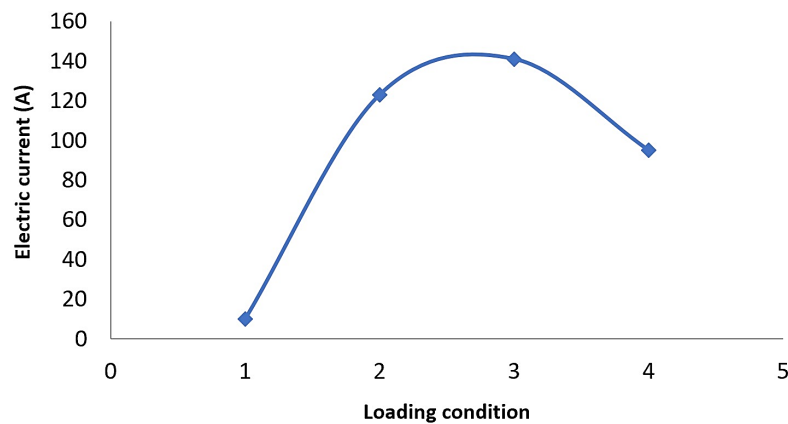
**Figure 13.** Variation of motor temperature versus duration of run

**Table 4.** Current drain test

| Sl.No. | Load            | Current (A) |
|--------|-----------------|-------------|
| 1      | No load         | 10          |
| 2      | Full load       | 123         |
| 3      | Stall condition | 141         |
| 4      | Max. speed      | 95          |

**Figure 14.** Variation of load versus current

#### 4. CONCLUSION

Overall, the project concentrated on tackling numerous ATV concerns, especially weight, engine efficiency, and thermal management. Significant progress has been achieved in minimizing these issues collectively with structural analysis, customized battery design, aluminium case for the gearbox, relief holes in gears, and appropriate thermal management techniques.

The present structural study identified weight-saving potential without sacrificing strength, resulting in a lighter yet more robust ATV design. The bespoke battery pack design maximizes energy capacity while reducing superfluous weight, resulting in increased performance and range. We can also conclude that the use of an aluminum gearbox case lowers the weight of this critical component, thereby improving the overall dynamics of the ATV.

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#### AUTHOR CONTRIBUTIONS

N.V.L. being the corresponding author and has continuously supervised the project. M.K. has written the review referring the articles and also framed the body of the article. S.A. has contributed in all work associated with machining of gear box and assembly of all terrain electric vehicle. H.P., S.K.P.N., and P.A. have involved in design, material collection, fabrication and assembly of the all-terrain Vehicle. H.P. lead the team in experimentation

on the ground and has worked on design of the vehicle. The structural analysis of gear train was conducted by S.K.P.N. and P.A.

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