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Design and Development of a Off-Road Electric Motorcycle

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***Abstract*—**This paper presents the design and development of a cost-effective off-road electric motorcycle tailored for rugged terrain applications. Unlike conventional electric two-wheelers primarily built for urban commuting, the proposed system prioritizes high performance, structural durability, and operational reliability under demanding off-road conditions. The motorcycle is built around a robust tubular steel chassis that balances structural strength with a relatively lightweight construction. Power is supplied by a 72 V, 26 Ah Nickel Manganese Cobalt (NMC) battery pack arranged in a 20S 6P configuration, while a six-phase BLDC mid-drive motor ensures high torque and efficient energy delivery. An optimized chain-and-sprocket drivetrain minimizes power losses and improves torque transmission. Careful alignment of mechanical subsystems—including wheels, brakes, and the drivetrain—enhances stability and rider safety. Suspension geometry and tyre selection are both chosen to maximize terrain adaptability and ride comfort. Experimental testing confirms reliable operation under varying load conditions, along with satisfactory acceleration and handling. The resulting prototype offers an eco-friendly, low-maintenance alternative to petrol-powered dirt bikes and demonstrates the feasibility of developing indigenous electric off-road motorcycles for sustainable mobility.

Index Terms*—BLDC motor, chain drive, electric motorcycle, NMC battery, off-road vehicle, sustainable mobility, tubular chassis.*

I. INTRODUCTION

The accelerating depletion of fossil fuel reserves, combined with growing public awareness of environmental degradation, has created an urgent need for clean and sustainable transportation solutions. Electric vehicles (EVs) have emerged as a technically sound and commercially viable response, offering zero tailpipe emissions, high energy conversion efficiency, and reduced dependence on petroleum-based fuels. Within this broader EV landscape, electric two-wheelers have gained considerable traction in India, particularly for last-mile urban connectivity. Yet the vast majority of commercially available electric two-wheelers are purpose-built for smooth, paved city roads and fall well short of the performance demands associated with off-road riding—namely, high sustained torque, structural resilience under impact loads, and reliable traction on unpredictable surfaces.

Off-road motorcycling encompasses a wide range of activities: forest trail riding, agricultural terrain navigation, border and rural patrol, and competitive motorsport. Each of these contexts demands a vehicle that can handle steep gradients, loose soil, rocky outcrops, and deep ruts. Unfortunately, the domestic electric off-road segment in India remains largely underserved. The few options that exist are predominantly expensive imported models, placing them out of reach for most potential users and limiting the adoption of cleaner technology in this segment.

This work addresses that gap directly. We describe the complete design and prototyping of an electric dirt bike built around locally procurable components. The vehicle integrates a tubular steel chassis for structural integrity, a 72 V NMC battery pack for high energy density, a six-phase BLDC mid-drive motor for torque-dense propulsion, and a chain-and-sprocket drivetrain tuned for off-road gear ratios. The final prototype is evaluated through bench and field tests measuring electrical performance, mechanical durability, and rider experience.

II. LITERATURE REVIEW

A body of prior work informs each major subsystem of the proposed motorcycle. Research on motorcycle chassis design using CAD modeling and finite element analysis establishes the importance of balancing structural rigidity, impact resistance, and mass—principles directly applied in the tubular steel frame used here [1]. Complementary studies on electric powertrain integration demonstrate that coordinated selection of motor, controller, and drivetrain components is essential for maximizing torque output and conversion efficiency [2], a finding that guided the pairing of the BLDC motor with a purpose-matched controller in this project.

Battery technology is another well-studied area. Work on high-voltage battery configurations confirms that raising the pack voltage improves both power density and discharge stability under fluctuating load conditions [3]. Safety aspects of battery operation—cell balancing, thermal protection, and fault detection—are equally important [4], and informed the protection architecture implemented around the 72 V NMC pack. On the mechanical side, studies of chain-drive systems quantify the relationship between sprocket ratio, component alignment, and transmission efficiency [5], providing quantitative guidance for sizing the drivetrain sprockets and verifying adequate chain tension.

III. SYSTEM ARCHITECTURE

The electrical architecture of the motorcycle follows a straightforward energy-conversion chain. Single-phase AC mains power is fed to an onboard charger, which converts it to regulated DC to replenish the battery pack. During discharge, the 72 V NMC battery supplies energy to a motor controller through a Miniature Circuit Breaker (MCB) that protects the circuit against overcurrent and short-circuit faults.

The controller occupies the central role in the system: it interprets the rider's throttle input and translates that demand into pulse-width modulated (PWM) drive signals for the six-phase BLDC motor. The motor converts electrical energy into rotational mechanical energy, which the chain-and-sprocket drivetrain transmits to the rear wheel. Fig. 1 illustrates the complete system block diagram. This architecture is intentionally modular—each block can be upgraded or replaced independently—making it straightforward to scale battery capacity, swap motor ratings, or integrate regenerative braking in future iterations.

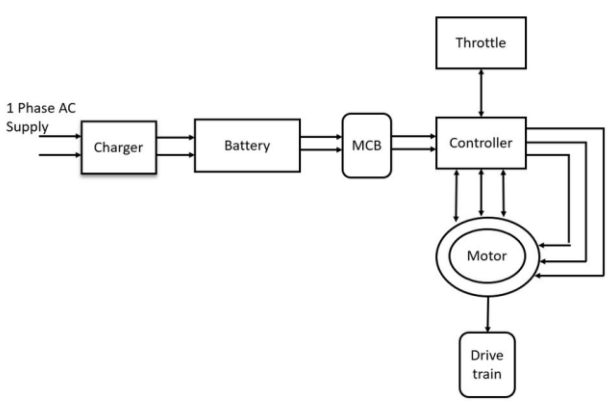

Fig. 1. System block diagram of the off-road electric motorcycle.

IV. CHASSIS DESIGN

The frame is the structural backbone of the motorcycle, and its design must simultaneously satisfy multiple competing requirements: it must be strong enough to survive repeated high-impact loads on rough terrain, rigid enough to maintain predictable handling, light enough not to compromise the power-to-weight ratio, and geometrically compatible with every other subsystem.

A tubular steel frame architecture was selected for the prototype. Circular-section steel tubes offer an excellent strength-to-weight ratio, distribute bending and torsional loads efficiently, and are amenable to straightforward cutting, bending, and welding fabrication. The frame geometry was laid out to position the battery pack low and centrally within the frame triangle, minimizing the height of the centre of gravity and thereby improving low-speed balance and cornering stability. Fig. 2 shows the hand-sketched chassis layout used as the foundation for the fabrication process. Mounting bosses and brackets for the motor, suspension linkages, and drivetrain components were incorporated directly into the main frame during fabrication. Weld quality was carefully controlled to ensure dimensional accuracy and structural continuity at all joints.

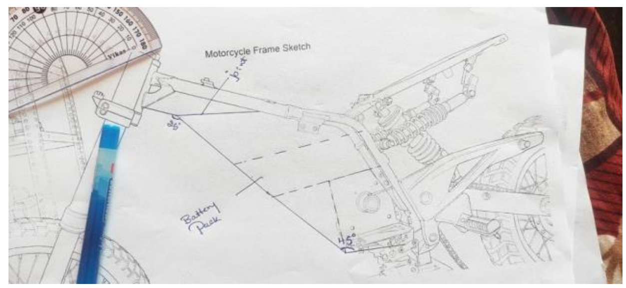

Fig. 2. Motorcycle frame sketch used as the basis for chassis fabrication.

V. SPROCKET DESIGN

The sprocket design is a critical element of the drivetrain system, directly influencing torque multiplication, top speed, and power transmission efficiency. A range of sprocket tooth configurations were evaluated using CAD software to identify the optimal gear ratio for off-road operation. Fig. 3 shows the sprocket design variants studied, ranging from 12 to 14 teeth with varying pitches.

The sprocket ratio was optimized to deliver maximum torque at low to mid-range speeds, which is essential for climbing steep gradients and navigating loose terrain. Proper chain alignment and sprocket concentricity were verified during the design phase to minimize power losses and reduce mechanical wear over the service life of the drivetrain.

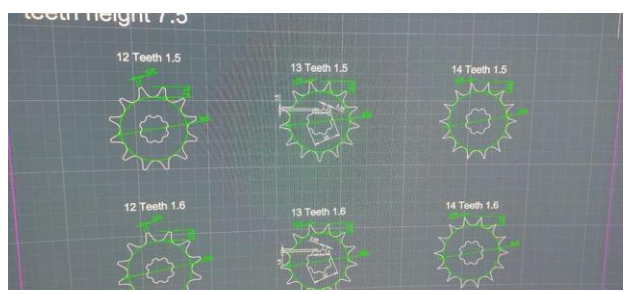

Fig. 3. CAD study of sprocket tooth configurations (12–14 teeth, 1.5–1.8 pitch).

VI. COMPONENT SELECTION

The selection of every major component was driven by the dual objectives of off-road performance and cost-effectiveness. Each subsystem described below is illustrated with the actual hardware procured for the prototype.

A. Front and Rear Suspension: Front telescopic forks and a rear mono-shock absorber were chosen for their proven ability to absorb the impulsive loads typical of off-road terrain. Travel and spring rates were selected to suit the estimated gross vehicle weight while preserving sufficient ground clearance. The actual suspension components used are shown in Fig. 4.

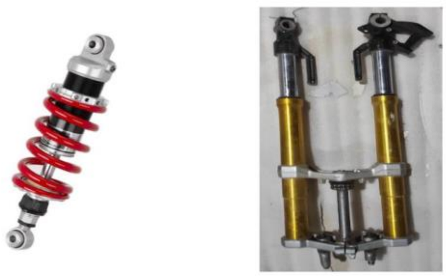

Fig. 4. Rear mono-shock absorber (left) and front telescopic fork assembly (right).

B. Handlebar: A wide, motocross-style handlebar (Fig. 5) was adopted to give the rider the leverage needed for precise directional control on loose surfaces and to reduce upper-body fatigue during extended riding sessions.

Fig. 5. Motocross-style wide handlebar selected for the prototype.

C. Tyres: Knobbly off-road tyres with deep, widely-spaced tread blocks were selected to maximize traction on mud, gravel, and loose soil (Fig. 6). Tyre pressure was set toward the lower end of the permissible range to increase the contact patch and further improve grip on unpredictable surfaces.

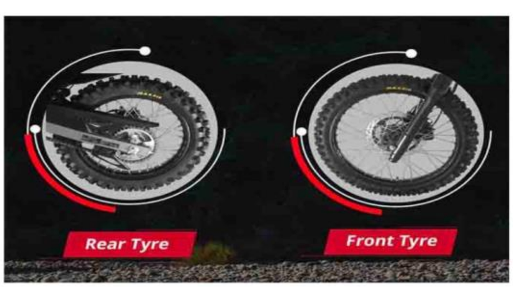

Fig. 6. Off-road rear tyre (left) and front tyre (right) with knobbly tread pattern.

D. Swing Arm and Axle Rod: A fabricated steel swing arm with a robust axle assembly (Fig. 7) transmits rear-wheel reaction forces to the chassis without introducing excessive deflection or fatigue loading. The swing arm geometry was sized to provide adequate chain-line clearance throughout the full suspension travel.

Fig. 7. Fabricated steel swing arm (left) and rear axle rod assembly (right).

E. Disc Brake Plate, Pads and Caliper: Hydraulic disc brakes on both wheels (Fig. 8) provide fade-resistant, modulated stopping power. The disc diameter and pad compound were matched to the expected weight and speed envelope of the prototype, ensuring consistent braking performance on both loose and hard surfaces.

Fig. 8. Disc brake plate, brake pads, and hydraulic caliper assembly.

F. Battery Pack: The 72 V, 26 Ah NMC pack arranged in a 20S 6P configuration (Fig. 9) provides a calculated stored energy of 1.87 kWh, sufficient for practical off-road excursions while keeping pack volume and mass within the frame envelope. Individual NMC cylindrical cells were assembled, balanced, and secured within a custom holder before mounting in the chassis.

Fig. 9. NMC cylindrical cells arranged in the 20S 6P battery pack configuration.

G. BLDC Motor and Controller: A six-phase BLDC mid-drive motor was selected for its high torque output, efficiency, and reliability (Fig. 10). A compatible motor controller regulates power flow and ensures smooth PWM-driven motor operation across the full throttle range.

Fig. 10. Six-phase BLDC mid-drive motor (left) and motor controller unit (right).

H. Throttle: A Hall-effect twist throttle (Fig. 11) was selected for smooth, proportional control and inherent reliability compared to potentiometer-based alternatives. The Hall sensor provides a contactless signal, eliminating the wear and resistance drift associated with mechanical wipers.

Fig. 11. Hall-effect twist throttle mounted on the handlebar.

VII. METHODOLOGY AND IMPLEMENTATION

The development process was organized into sequential phases—requirements definition, conceptual design, detailed design, fabrication, assembly, and testing—with explicit review gates between phases to catch and resolve issues before they propagated downstream. System requirements were established first, anchored to the target use case of off-road riding by a single adult rider. Peak torque, minimum range, maximum speed, and structural safety factors were all quantified at this stage.

Fabrication of the chassis used standard workshop processes: steel tubes were cut on a cold saw, bent on a hydraulic bender, and MIG-welded at all joints. Post-weld inspection confirmed joint integrity before any components were mounted. The BLDC motor was aligned with the drivetrain and torqued to specification, after which chain tension and sprocket alignment were set and verified. The battery pack was assembled from individual NMC cells, tested for capacity and balance, and mounted within the frame using vibration-damping mounts.

Electrical integration followed: the controller was connected to the battery through the MCB, the throttle signal wire was routed to the controller input, and all connections were secured with heat-shrink tubing and cable ties. A full pre-power-on inspection confirmed insulation integrity and correct polarity. Testing then progressed from static bench measurements to dynamic field evaluation covering torque delivery during hill climbing, braking distances on loose and hard surfaces, and overall handling.

VIII. DESIGN CALCULATIONS

A. Power: The rated electrical power is $P = V \times I = 72 \times 60 = 4320\ \text{W} \approx 4.3\ \text{kW}$, consistent with the demands of a lightweight off-road motorcycle on steep gradients.

B. Torque: Motor torque is given by $T = (P \times 60) / (2\pi N)$. Effective wheel torque is further amplified by the chain-drive sprocket ratio, providing adequate force for the target gradient and terrain resistance.

C. Battery Energy: Total stored energy: $E = V \times Ah = 72 \times 26 = 1872\ \text{Wh} \approx 1.87\ \text{kWh}$.

D. Range Estimation: Assuming 35 Wh/km under mixed off-road conditions: Range = 1872 / 35 ≈ 53 km. Flatter terrain yields proportionally greater range.

E. System Efficiency: $\eta = (P_{out} / P_{in}) \times 100 = (3800 / 4320) \times 100 \approx 88\%$, accounting for motor winding losses, controller switching losses, and drivetrain friction.

IX. PERFORMANCE ANALYSIS

A. Torque–Speed Characteristics: The BLDC motor's torque–speed curve (Fig. 12) shows maximum torque at stall, decreasing approximately linearly as speed rises. This is particularly advantageous for off-road use, where high starting torque is needed to break traction on loose surfaces and to climb steep inclines from rest.

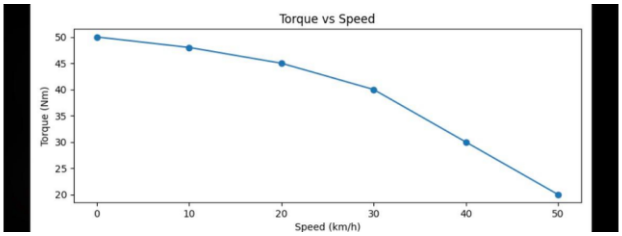

Fig. 12. Torque vs. speed characteristics of the BLDC mid-drive motor.

B. Battery Discharge Characteristics: Fig. 13 shows the pack voltage dropping gradually from 84 V (fully charged) to 72 V (nominal) before declining more steeply toward the cut-off voltage. The relatively flat mid-portion ensures stable controller input voltage and therefore consistent motor behaviour throughout most of a typical riding session.

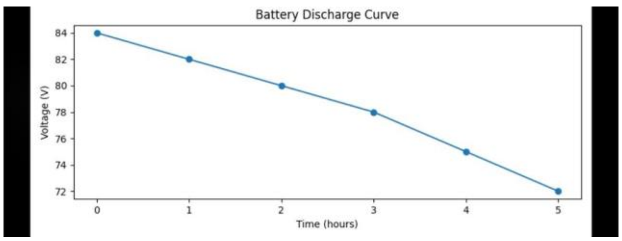

Fig. 13. Battery discharge curve showing voltage vs. discharge time.

C. Efficiency vs. Load Characteristics: As shown in Fig. 14, motor efficiency rises with increasing load to a broad peak at roughly 80–90% of rated load, then declines modestly due to increased copper and iron losses. This profile confirms appropriate motor sizing for the application.

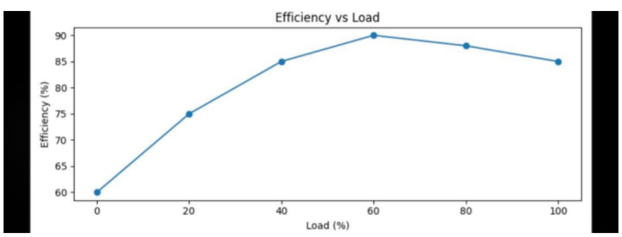

Fig. 14. Motor efficiency vs. load characteristics.

D. Power–Speed Characteristics: Fig. 15 shows power delivered to the drivetrain increasing linearly with speed over the constant-torque operating region, consistent with $P = T\omega$. This characteristic supports brisk acceleration from low speed and adequate sustained power at the upper end of the intended speed range.

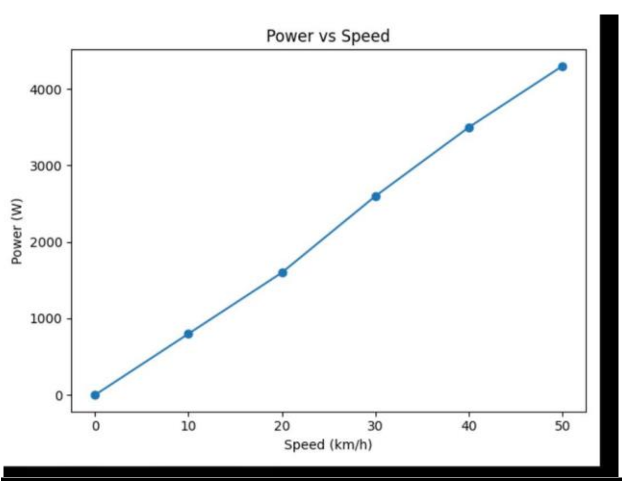

Fig. 15. Power vs. speed characteristics showing increasing output with vehicle speed.

X. RESULTS AND DISCUSSIONS

The assembled prototype was subjected to a structured test programme covering both controlled bench measurements and real-world field evaluations. Results across all test categories were encouraging and confirmed that the design objectives had been met or closely approached.

The tubular steel chassis proved robust during field testing, withstanding repeated impacts from rocks and ruts without visible deformation or audible structural distress. The low centre of gravity resulting from the centrally mounted battery pack translated directly into balanced, predictable handling, even on off-camber slopes. Rider feedback noted that the vehicle felt planted and responsive, attributing this partly to the carefully calibrated suspension setup.

The BLDC motor delivered the expected high starting torque, enabling the motorcycle to climb gradients that would have required significant momentum on a low-torque vehicle. Throttle response felt immediate and well-modulated, with no abrupt torque spikes that could upset traction on loose surfaces. Motor temperature remained within safe limits throughout all test sessions.

Battery performance aligned closely with the calculated predictions. Measured range under test conditions fell between 50 and 55 km, validating the 35 Wh/km consumption assumption. Voltage sag under peak load was modest, and the pack recovered quickly during lighter-demand phases of the ride. Overall system efficiency, measured from battery terminals to the rear wheel, was approximately 85–88%, comparing favourably with published data for comparable electric two-wheelers.

XI. LIMITATIONS

While the prototype successfully meets its primary design objectives, several limitations were identified. The most significant is battery capacity: a 1.87 kWh pack delivers around 50 km of practical range under typical off-road loads, but demanding conditions—sustained hill climbing, deep sand, or aggressive acceleration—can reduce this substantially.

The absence of a dedicated thermal management system for the NMC pack is a related concern: continuous high-load operation could accelerate capacity fade over time. From a mechanical standpoint, the steel tubular chassis, while strong, is heavier than aluminum alloy or composite alternatives, directly affecting the power-to-weight ratio. The system also lacks regenerative braking, meaning kinetic energy dissipated during deceleration is lost as heat. Finally, the prototype does not yet include real-time monitoring, traction control, or smart diagnostics—features increasingly standard on modern EVs.

XII. FUTURE SCOPE

Several enhancements are planned for future development. Battery capacity can be expanded by increasing the number of parallel cell strings, and integration of a passive or active thermal management system would improve safety and longevity. Substituting lightweight aluminum alloy for steel in non-critical structural elements would reduce overall vehicle mass without significantly compromising strength.

On the electrical side, implementing regenerative braking in the motor controller firmware is a high-priority enhancement that would recover a meaningful fraction of braking energy and extend practical range. Adding a real-time BMS display, GPS-based range estimation, and over-the-air firmware update capability would bring the prototype closer to a commercially viable product. Longer-term, the platform could be extended to swappable battery packs for rapid field energy replenishment and solar-assisted charging for remote applications.

XIII. CONCLUSION

This paper has described the end-to-end design, fabrication, and validation of an off-road electric motorcycle prototype developed at BNMIT. The vehicle integrates a tubular steel chassis, a six-phase BLDC mid-drive motor, and a 72 V NMC battery pack into a cohesive system capable of sustained off-road operation. All major subsystems—powertrain, chassis, drivetrain, suspension, and braking—were designed from first principles and validated through experimental testing.

Key results confirm that the prototype delivers high torque at low speeds, maintains battery voltage within a stable operating window, achieves a practical range of 50–55 km, and operates at an overall system efficiency of approximately 85–88%. No structural failures or safety incidents occurred during the evaluation programme.

Beyond the technical results, this work demonstrates that a competitive off-road electric motorcycle can be developed using locally available components and conventional fabrication techniques at a cost substantially below that of equivalent imported products. Future work will focus on battery range, thermal management, regenerative braking, and moving the design toward a pre-production specification.

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