HYBRID HYDRAULIC-ELECTRICAL ENERGY RECOVERY AND PROPULSION SYSTEM

***Project Reference No.:** 49S_BE_1817*

College : JAIN (Deemed-to-be) University, Faculty of Engineering & Technology, Bengaluru South
Branch : Department of Mechanical Engineering
Guide : Dr. I Kantharaj
Student(s) : Mr. Vishaal S Ganesh
Mr. Prashant Umesh Chodankar
Mr. Ahmed Rabie

Keywords:
Hybrid energy system, Hydraulic regeneration, Supercapacitor, Model Predictive Control, Energy efficiency, Tesla turbine, Suspension energy harvesting.

Introduction:
Traditional electric drivetrains rely heavily on battery systems for both high-power delivery during acceleration and absorption of regenerative braking energy. This imposes significant electrical stress on the battery, accelerating aging and limiting overall efficiency. Furthermore, significant recoverable energy from continuous vehicle suspension movement remains unutilized. To address these challenges, this project presents the development of a Hybrid Hydraulic-Electrical Energy Recovery and Propulsion System (HEERP System). It integrates a hydraulic suspension-based energy harvester, a hydraulic-to-electrical generator (Tesla turbine), a fast-response supercapacitor bank, and a hybrid battery. The system is governed by a Model Predictive Controller (MPC) that dynamically routes energy based on real-time vehicle conditions, thereby optimizing performance, enhancing energy capture, and maximizing component durability.

Objectives:
1. Develop a fully analytical, theoretically-validated hybrid hydraulic-electrical energy recovery model.
2. Implement MPC-based switching logic to route energy between supercapacitors and batteries.
3. Validate improvements in fuel efficiency, battery load reduction, and conversion efficiency.
4. Demonstrate a digital twin model that replicates real drive-cycle behaviour.

Methodology:
The project adopted a structured three-phase simulation and analytical methodology to develop and validate the system:
1. System Design and Analytical Modelling: Subsystems were mathematically modelled using physical laws. The hydraulic circuit was designed utilizing the vehicle's suspension strut as a cylinder, channelling rod-displaced fluid to a diaphragm reservoir that regulates pressure. The fluid drives a 10-disc Tesla turbine selected for its efficiency with viscous fluids, which is coupled to a 24V PMBLDC generator.

2. Algorithm Integration: An Intelligent Power Distribution Algorithm driven by Model Predictive Control (MPC) was developed. The MPC uses parameters like supercapacitor SOC, battery SOC, propulsion demand, and predicted braking to dynamically switch energy pathways (e.g., routing high-power regen to the supercapacitor and low-power sustained generation to the battery).
3. Validation and Extraction: The digital twin was validated across multiple driving conditions. Kinematic analysis was performed using ISO 8608 Class C urban driving profiles and IRC:99-2018 speed hump cases. Energy balance equations evaluated the hydraulic-to-electrical conversion efficiency, system pressure limits, and the consequent reduction in battery load during transient propulsion bursts.

Result and Conclusion:

In conclusion, the analytical results validate the efficacy of the HEERP system in capturing and distributing suspension-induced energy. Under ISO 8608 Class C urban driving, the system successfully recovered 0.6751 Wh of electrical energy per UDDS drive cycle, translating to an estimated annual saving of 202.5 Wh. The integrated Tesla turbine and PMBLDC generator achieved a combined theoretical conversion efficiency of 52.8%. The supercapacitor bank provided a usable energy buffer of 5.495 Wh, capable of instantly absorbing high-intensity bursts and delivering propulsion boosts. This hybrid approach reduced battery peak current demands by approximately 25%, significantly lowering battery stress. The project successfully demonstrates a robust multi-domain architecture that optimizes next-generation electric vehicle performance and energy utilization.

References:

1. [1] M. Ehsani, Y. Gao, and A. Emadi, Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design. CRC Press, 2018.
2. [2] A. Santucci, A. Sorniotti, and C. Lekakou, "Power split strategies for hybrid energy storage systems in electric vehicles: A review," Applied Energy, 2017.
3. [3] Y. Hung and C. Wu, "Regenerative Suspension Systems for Vehicles," Energies, 2018.
4. [4] P. Li, M. Yang, and J. Wang, "Hydraulic Energy Regeneration System for a Hybrid Electric Vehicle," Energy Conversion and Management, 2017.

Future Scope:

The future scope of this project includes:

1. Real-world hardware prototyping and bench-testing of the hydraulic suspension unit, Tesla turbine, and BLDC generator.
2. Scaling the system to a four-wheel harvesting architecture to potentially quadruple recovered power output.
3. Embedding the MPC algorithm onto a production-grade ECU for live real-time switching validation on a test vehicle.
4. Optimizing the Tesla turbine geometry (disc count, gap spacing) and experimenting with varying fluid viscosities to enhance the 52.8% base efficiency.
5. Filing a patent for the unified hydraulic-electrical dual-path architecture and its predictive switching matrix.