A MAJOR PROJECT REPORT

ON

MODELING AND ANALYSIS OF A P3 HYBRID ELECTRIC VEHICLE WITH DOG CLUTCH ENGAGEMENT

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE AWARD OF THE DEGREE

OF

MASTER OF TECHNOLOGY

IN

COMPUTER AIDED ANALYSIS AND DESIGN

Submitted by:

SACHIN RANA

(2K23/CAD/08)

Under the supervision of

Prof. R.C. SINGH

AND

Dr. RAJIV CHAUDHARY

DEPARTMENT OF MECHANICAL ENGINEERINGDELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

JUNE, 2025

DEPARTMENT OF MECHANICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

CANDIDATE'S DECLARATION

I, SACHIN RANA, Roll No. 2K23/CAD/08 student of M.Tech (Computer Aided Analysis And Design), hereby declare that the project Dissertation titled "MODELING AND ANALYSIS OF A P3 HYBRID ELECTRIC VEHICLE WITH DOG CLUTCH ENGAGEMENT" which is submitted by me to the Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

Place: New Delhi Sachin Rana

Date: (2K23/CAD/08)

DEPARTMENT OF MECHANICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

CERTIFICATE

I hereby certify that the major project report titled "MODELING AND ANALYSIS OF A P3 HYBRID ELECTRIC VEHICLE WITH DOG CLUTCH ENGAGEMENT" submitted by **SACHIN RANA**, Roll No. **2K23/CAD/08** in Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of **Master of Technology** in **Computer Aided Analysis and Design**, is a record work carried by him under my supervision. To the best of my knowledge and belief the statement made by him is correct and the work has not been submitted in part or full for the award of any Degree or Diploma to this University or elsewhere

Place: New Delhi — Prof. R C SINGH

Date: — SUPERVISOR

Dr. RAJIV CHOUDHARY

SUPERVISOR

Abstract

The automotive industry is shifting toward hybrid electric vehicles (HEVs) to reduce emissions and fuel consumption. Among several HEV topologies, the P3 configuration places the electric motor after the transmission, which enables engine support, electric drive, and regenerative braking. However, integrating the motor mechanically via a dog clutch presents a challenge — it demands precise control logic to engage and disengage the motor safely and efficiently. This thesis proposes a detailed modeling and control framework for a P3 HEV architecture using MATLAB Simulink and Simscape. A dog clutch is used to manage motor connectivity to the drivetrain, with engagement logic implemented in Stateflow. The plant model simulates dynamic driving conditions, and the control system decides clutch operation based on speed synchronization, torque demand, and battery SOC. Results show effective clutch operation and smooth transition between hybrid modes, validating the feasibility of this configuration in real-world applications.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my guide, **Prof. R C Singh**, Professor in the Department of Mechanical Engineering, for his invaluable guidance, support, and expertise throughout the course of this research project. His constant encouragement, insightful feedback, and dedication have been instrumental in shaping the direction and progress of this work. His deep knowledge and passion for the subject have inspired me to strive for excellence and explore new avenues in this field.

I would like to extend my heartfelt gratitude to my guide, **Dr. RAJIV CHOUDHARY**, Associate Professor in the Department of Mechanical Engineering, for his unwavering support, expert guidance, and invaluable insights throughout the duration of this research project. His thoughtful suggestions, continuous encouragement, and profound knowledge have played a vital role in the successful completion of this work.

I would also like to extend my heartfelt appreciation to **Prof. B B Arora**, Head of the Department of Mechanical Engineering, for his support and encouragement. His vision and leadership have provided a conducive environment for academic and research pursuits. I am grateful for his valuable insights and guidance that have contributed to the overall success of this project.

Special thanks to **ATUL AGRAWAL**, my manager at BorgWarner for his valuable guidance, constant encouragement, and unwavering support throughout the course of my internship. His insights and mentorship have been instrumental in shaping this thesis. I deeply appreciate his patience, expertise, and commitment.

Lastly, I would like to acknowledge my family and friends for their unwavering support, encouragement, and understanding throughout this research endeavour. Their love, belief in my abilities, and motivation have been the driving force behind my perseverance and determination.

Place: New Delhi

Date:

SACHIN RANA
2K23/CAD/08
M.Tech (CAAD)
Delhi Technological University

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

z	Shift linkage position at port S
h	Tooth height parameter
z_{Gap}	Ring hub clearance when disengaged parameter
$z_{Overlap}$	Tooth overlap to engage parameter
ω_{thr}	Engagement speed threshold parameter
EM	Engine Motor
HEV	Hybrid Electric Vehicles
HIL	Hardware In Loop Testing
ICE	Internal Combustion Engine
KPI	Key Performance Indicators
PMSM	Permanent Magnet Synchronous Motor
PID	Proportional-Integral-Derivative controller
SOC	State of Charge

CHAPTER 1

INTRODUCTION

The global transportation sector is experiencing an unprecedented shift driven by escalating concerns over climate change, the depletion of fossil fuel reserves, and the growing demand for sustainable mobility. With road transport accounting for a significant share of greenhouse gas emissions and air pollutants, the urgency to decarbonize vehicular systems has become a central focus in policy, research, and industrial innovation. In response, the automotive industry is increasingly pivoting toward electrification as a primary strategy to reduce environmental impact while enhancing energy efficiency. However, the path to full electrification remains complex and regionally varied due to technological, infrastructural, and economic constraints.

Among the spectrum of electrified vehicle technologies, **Hybrid Electric Vehicles (HEVs)** have emerged as a robust and scalable intermediate solution that combines the strengths of traditional Internal Combustion Engines (ICEs) and electric propulsion systems. HEVs utilize both an ICE and one or more electric motors integrated with a battery system, allowing for seamless mode switching between engine-only, electric-only, and hybrid operation. This dual-power architecture enables significant improvements in fuel economy and emissions reduction by optimizing power delivery based on real-time driving conditions. Regenerative braking, automatic start-stop features, and intelligent energy management further enhance the operational efficiency of HEVs, positioning them as an environmentally favorable alternative to conventional ICE vehicles.

In the global context, while **Battery Electric Vehicles (BEVs)** represent the ideal zero-emission goal, their widespread adoption is currently hindered by several practical challenges. These include the limited availability of public charging infrastructure, long charging durations, high production and ownership costs, and concerns about driving range and battery degradation. Moreover, in many parts of the world, particularly in emerging economies, the electric grid infrastructure is not yet capable of supporting large-scale EV deployment, and the carbon intensity of electricity generation reduces the environmental benefits of EVs in such regions. As a result, the transition to fully electric vehicles is expected to be gradual and uneven across different geographic and socioeconomic contexts.

Given these limitations, HEVs offer a strategically important bridge technology that supports emission reduction goals without the need for extensive infrastructural overhaul. They are particularly suitable for current market conditions as they rely on mature fuel distribution systems, require no external charging, and incur lower lifecycle costs compared to BEVs. The flexibility and self-sufficiency of HEVs make them especially viable in countries undergoing progressive electrification but lacking the comprehensive support systems needed for pure electric mobility. Fig.1.1 shows the layout of different types of HEVs

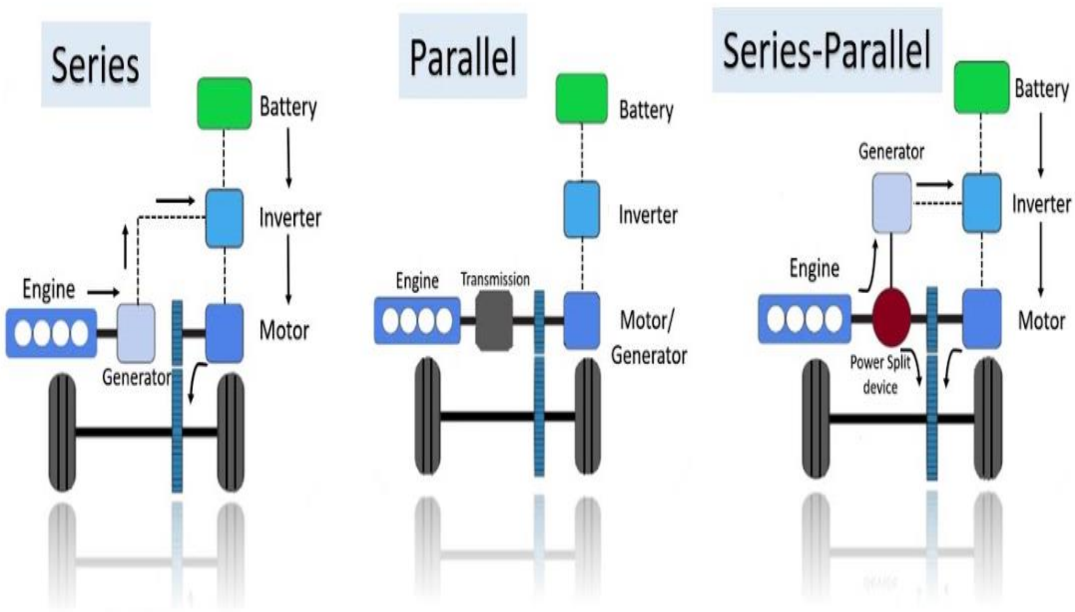

Fig.1.1 Types of HEVs [23]

Hybrid Electric Vehicles (HEVs) are designed to leverage the combined benefits of electric motors and Internal Combustion Engines (ICEs) to achieve better fuel efficiency, reduced emissions, and enhanced performance. The architecture of an HEV determines the positioning of the electric motor within the powertrain, which significantly influences the vehicle's operation, efficiency, and complexity of control. The primary HEV configurations include **P0, P1, P2, P3, and P4 hybrids**.

The capabilities in HEVs significantly enhance fuel efficiency and reduce carbon emissions. The design and control strategy of an HEV are critical to its performance, efficiency, and complexity. Among the various HEV configurations, the **P3 Hybrid**

Configuration is particularly notable for its simplicity and efficiency. In a P3 layout, the electric motor is positioned **after the transmission and before the differential**, allowing it to operate independently of engine output. This configuration supports:

- Regenerative braking,
- Electric-only propulsion,
- Provide torque assist during hybrid operation.

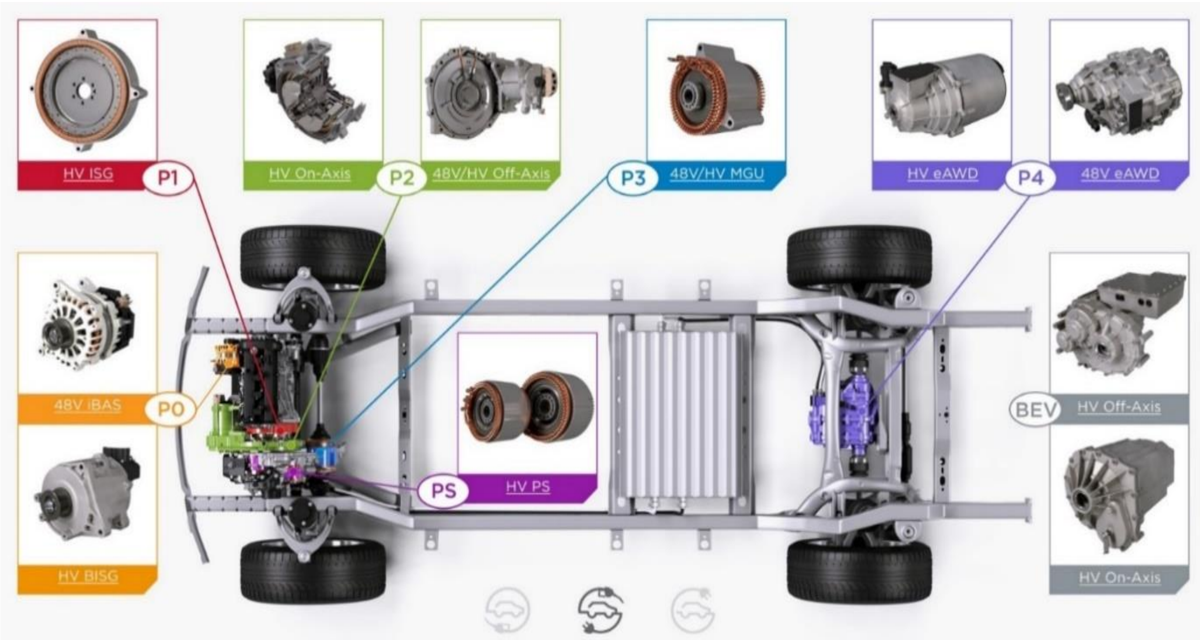

Fig.1.2 Full Vehicle Model Showing Primary HEV Configurations [24]

Fig.1.2 shows different types of HEV configuration. Each configuration varies based on the relative positioning of the electric motor and its interaction with the drivetrain.

1. P0 Hybrid Configuration

In a P0 hybrid layout, the electric motor is connected to the engine's crankshaft via a **belt-driven alternator starter (BAS)**. This configuration is primarily designed for mild hybridization, where the electric motor assists with start-stop functionality and minor torque supplementation. The key characteristics of the P0 configuration are:

- The motor is not directly connected to the wheels and therefore cannot independently drive the vehicle.
- Electric assistance is limited to start-stop operations and short bursts of acceleration.
- It is cost-effective due to minimal modifications to the existing powertrain structure.

Despite its simplicity, the P0 configuration does not support electric-only driving, making it suitable for applications where improved fuel efficiency and reduced idling emissions are the main goals.

2. P1 Hybrid Configuration

In the P1 hybrid layout, the electric motor is **directly coupled to the engine crankshaft**, typically positioned between the engine and the flywheel. This configuration allows for:

- Enhanced regenerative braking by directly capturing mechanical energy during deceleration.
- Mild electric assistance during acceleration, reducing the load on the ICE.
- Start-stop capability with smoother transitions due to direct motor engagement.

However, the P1 architecture does not allow for electric-only propulsion since the motor is always linked to the engine. This limitation reduces its effectiveness in urban stop-and-go traffic where electric-only drive would be most beneficial.

3. P2 Hybrid Configuration

The P2 configuration places the electric motor **between the engine and the transmission**, with clutches on both sides to enable decoupling. This design allows the vehicle to:

- **Drive in electric-only mode**, as the motor can disengage from the engine.
- Perform **engine-off coasting**, enhancing fuel efficiency during low-power demands.
- Deliver **torque assist** during acceleration without immediate engine involvement.
- Enable **regenerative braking** to recover energy more efficiently.

The P2 layout is popular in full hybrid systems due to its flexibility. However, it requires sophisticated clutch management to synchronize engine and motor speeds during transitions, adding complexity to the control strategy.

4. P3 Hybrid Configuration (Focus of This Thesis)

The **P3 Hybrid Configuration**, which is the focus of this thesis, locates the electric motor **after the transmission and before the differential**. This unique placement enables several key benefits:

- **Independent electric drive:** The motor can propel the vehicle without the engine running, optimizing efficiency during low-load conditions.

- **Regenerative braking optimization:** Since the motor is connected post-transmission, energy recovery during braking is more effective.
- **Reduced vibration exposure:** Unlike P2 hybrids, the P3 motor is isolated from engine vibrations and transmission shifts, leading to smoother operation.

However, the P3 architecture introduces the need for a **dog clutch** to engage or disengage the electric motor dynamically. The **dog clutch** serves as a mechanical link, providing direct torque transfer when locked. Engagement is only possible when the motor and driveline are rotating at nearly identical speeds, necessitating precise control to avoid harsh engagement or mechanical damage.

5. P4 Hybrid Configuration

The P4 hybrid configuration places the electric motor **directly on the rear axle**, typically in a front-engine, front-wheel-drive vehicle. This allows:

- **All-wheel drive (AWD)** capability without a mechanical link to the front axle.
- **Torque vectoring**, where power distribution can be adjusted independently for each axle.
- Enhanced **regenerative braking** with isolated rear-wheel control.

The P4 design introduces complexity in managing torque distribution between the front and rear axles, but it provides superior handling and traction in varying driving conditions.

The **P3 architecture**, as modeled in this thesis, strikes a balance between complexity and functionality, providing full electric mode, effective regenerative braking, and seamless hybrid transitions. It serves as the optimal choice for modeling and simulation using MATLAB Simulink and Simscape due to its simplicity and control flexibility.

Comparative Analysis of HEV Architectures

The table 1.1 summarizes the main characteristics of each HEV architecture:

Table 1.1 - Comparative Analysis of HEV Architectures.

Architecture	Motor Placement	EV Mode Possible	Complexity	Applications
P0	Belt-driven on crankshaft	No	Low	Mild hybrids (e.g., Maruti SHVS)
P1	Direct on crankshaft	No	Low	Entry hybrids
P2	Between engine & trans	Yes	High	Full hybrids (e.g., Audi, BMW)
P3	After transmission	Yes	Medium	Ford Escape Hybrid
P4	On rear axle	Yes	Medium	Plug-in hybrids, AWD EVs

A critical component of this architecture is the **dog clutch**, a mechanical engagement mechanism that connects and disconnects the electric motor from the driveline. Unlike traditional friction clutches, a dog clutch provides a direct mechanical link with zero slip, making it ideal for applications that require precise engagement. However, its operation demands near-perfect speed synchronization between the electric motor and the driveline to avoid harsh engagement, gear tooth damage, and vibrations. Achieving this synchronization is a significant challenge and necessitates advanced control strategies. To design, simulate, and optimize such complex powertrain systems, **MATLAB Simulink and Simscape Driveline** are utilized. These tools provide a robust platform for developing real-time models, testing control logic, and validating system dynamics in a virtual environment.

CHAPTER 2
LITERATURE REVIEW

Hybrid electric vehicles (HEVs) represent a vital advancement in automotive engineering, combining internal combustion engines (ICEs) with electric propulsion to enhance overall efficiency and reduce emissions. Among the various HEV topologies, the P3 configuration has drawn considerable attention due to its ability to deliver a favorable balance between drivability, system complexity, and fuel economy. In this architecture, the electric motor is positioned between the transmission output and the vehicle's final drive, allowing for effective regenerative braking, engine-off driving, and electric-only propulsion. A key enabler of these functions is the dog clutch, which mechanically couples or decouples the electric motor from the drivetrain. Unlike friction clutches, dog clutches operate with minimal energy loss, offering superior mechanical efficiency. However, their operation requires precise control of rotational speed synchronization and torque alignment to avoid shift shock, torque discontinuities, and mechanical wear. These characteristics introduce complex modeling and control challenges that must be addressed to ensure smooth and reliable vehicle performance.

To tackle these challenges, advanced simulation environments such as MATLAB, Simulink, and Simscape have become essential tools for modeling multi-domain systems. These platforms allow engineers to develop, analyze, and validate complex powertrain architectures under a wide range of operating conditions. Specifically, they support the modeling of nonlinear dynamics, discrete clutch engagement logic, and real-time control systems that are critical in managing the engagement process of the dog clutch in P3 HEVs. Several studies have focused on clutch synchronization algorithms, torque control strategies, and hybrid mode transitions, yet gaps remain in fully integrating mechanical dynamics with control systems for seamless operation. This review evaluates existing research on the modeling and control of P3 hybrid architectures with a focus on dog clutch engagement and identifies areas for future investigation, particularly in refining control algorithms and enhancing simulation fidelity.

2.1 Modeling of P3 Hybrid Electric Vehicle Architectures

Hybrid Electric Vehicles (HEVs) that utilize a P3 configuration offer a balance between mechanical efficiency and flexible control of power sources. MathWorks provides an official framework for building a P3 hybrid electric vehicle in MATLAB Simulink and Simscape, integrating an internal combustion engine, motor, transmission, and energy storage components in a co-simulation environment [1]. Miller [2] contributed further to the modeling of HEV systems by presenting detailed open-source implementations on MATLAB Central and GitHub, which serve as accessible starting points for modular powertrain design. These modeling approaches have enabled researchers to simulate the real-time behavior of hybrid drivetrains and assess system-level performance metrics.

2.2 Dog Clutch Dynamics and Shiftability Analysis

Dog clutch mechanisms are essential in P3 architectures due to their role in enabling and disabling the electric motor path without torque converters. Aljawabrh and Lovas [3] presented a hybrid automata-based dynamic model for the engagement process of dog clutches, emphasizing torque transfer accuracy and state transition robustness. Their follow-up work introduced a comprehensive shiftability model that evaluates conditions under which engagement is safe and smooth, thereby helping avoid gear clash or transient torque drops [4]. These contributions are critical for creating simulation frameworks that capture the nonlinearities and discontinuities in dog clutch operations.

2.3 Simulation Platforms and Applications of MATLAB/Simulink

Simulink has become a dominant platform in automotive research due to its support for time-domain simulation, control system integration, and compatibility with hardware-in-the-loop setups. Bhatt [5] employed MATLAB/Simulink to create and test control strategies for electric vehicle applications, laying out power flow logic and energy regeneration scenarios. This complements the work of Ali et al. [6], who demonstrated a full-vehicle simulation of HEV architectures using modular Simulink blocks. Fu et al. [7] also modeled and simulated the powertrain of a parallel HEV using Simulink, validating acceleration and deceleration performance under various load conditions. These studies underscore the versatility of Simulink in HEV design and control implementation.

2.4 Clutch Engagement and Control Strategies in HEVs

Accurate clutch engagement strategies are vital to maintaining ride comfort and mechanical safety during gear shifts in HEVs. Vu et al. [8] introduced a fuzzy logic-based control strategy for automatic clutch engagement in parallel HEVs, demonstrating how model-free methods can be tuned to adapt to dynamic driving scenarios. Similarly, C.Ni et al. [9] employed a friction torque observer to monitor and control the engagement force of the clutch, improving overall smoothness and reducing slippage. Moldovanu and Csato [10] focused on clutch control development in Simulink, creating a controller that stabilizes engagement force during transition states. These works offer valuable insights for developing robust control algorithms for dog clutch systems in P3 HEVs.

2.5 Energy Management and Power-Split Strategies

To maximize fuel efficiency and energy regeneration, intelligent energy management strategies are required. Zou et al. [11] designed a control algorithm for a power-split HEV using dynamic energy optimization techniques, evaluating fuel economy and battery state of charge across different drive cycles. Baraszu and Cikanek [12] explored torque fill-in techniques to smooth out torque interruptions during automated manual transmission shifts in HEVs, a method particularly relevant for dog clutch systems. Cheng and Dong [13] modeled plug-in hybrid systems using different energy management strategies, highlighting how Simulink can represent powertrain variations from P2 to P3 architectures.

2.6 Component-Level and Performance Optimization

Component selection, sizing, and optimization significantly impact HEV performance. Tran et al. [14] designed a hybrid powertrain by selecting optimal motor and gearbox combinations to maximize performance while maintaining energy efficiency. Niu and Abdullayev [15] created a Simulink-based simulation that evaluated energy consumption and vehicle responsiveness across different configurations. These findings are relevant to P3 architectures, where mechanical layout and clutch placement must be optimized to ensure seamless torque blending. Tomar et al. [16] further investigated EV powertrain modeling and emphasized the importance of regenerative braking and drivetrain design for energy conservation.

2.7 Broader Simulation Applications and Infrastructure Planning

Some research also addresses larger system perspectives, such as charging infrastructure and simulation scalability. Alegre et al. [17] combined GIS tools and genetic algorithms with MATLAB/Simulink models of electric and hybrid vehicles to optimize charging station locations. Xu et al. [18] modeled a simplified EV powertrain with a focus on electric motor behavior and battery usage, applicable in plug-in hybrid simulations. Nasiri et al. [19] created a validated Simulink model of the 2004 Toyota Prius using DOE data, offering a benchmark simulation to compare energy efficiency and vehicle control architectures.

2.8 Comprehensive Reviews of HEV Modeling Approaches

Enang and Bannister [20] presented a detailed review of hybrid electric vehicle modeling and control strategies, categorizing models based on detail level and simulation scope. Their analysis helps in understanding the trade-offs between simulation fidelity and computational cost, which is vital when modeling complex systems such as P3 HEVs with engaging/disengaging dog clutches.

2.9 Research Gaps

The stand-alone Research Gaps section, which is organised with subheadings to indicate particular areas that require more research, is shown below. The information is specific to the scope of your project and does not contain any citations, as required.

1. Lack of Dedicated Modeling for P3 HEV Architecture

The P3 hybrid electric vehicle topology, which uniquely places the electric motor between the transmission and the final drive, has not been comprehensively studied in existing literature. While many prior works have examined generic hybrid configurations such as series, parallel, and power-split topologies, these models do not sufficiently address the operational dynamics and architecture-specific challenges of P3 systems. This omission is particularly significant given the growing industrial adoption of P3 layouts for their ability to enable both regenerative braking and direct engine-motor power blending without overly complex drivetrains.

2. Inadequate Integration of Dog Clutch Dynamics in Full-System Models

Although the dog clutch mechanism is recognized for its rapid and efficient engagement in hybrid systems, current studies often analyze it in isolation or through highly simplified representations. There is a noticeable absence of holistic powertrain models that incorporate the detailed mechanical behavior, synchronization constraints, and transient dynamics of dog clutch engagement and disengagement. This results in a research void in understanding how the dog clutch influences system performance, drivability, and shift timing under various operating conditions within the P3 layout.

3. Limited Development of Real-Time Control Logic for Clutch Engagement

Existing control approaches for hybrid electric vehicle powertrains predominantly utilize generalized rule-based strategies or optimization algorithms focused on energy efficiency. However, these strategies are not tailored to the discrete, non-linear, and often abrupt nature of dog clutch operation. There is a lack of control architectures—particularly those built using Stateflow or finite state machine (FSM) methods—that can handle real-time synchronization, torque arbitration, and smooth mode transitions within the hybrid powertrain. This represents a significant research gap in the development of robust and responsive control systems for P3 HEVs.

4. Absence of Physical Constraints and Real-World Parameter Validation

Many simulation models reported in literature are based on ideal or static assumptions and do not incorporate real-world constraints such as actuator delay, thermal behavior, mechanical wear, and clutch backlash. Furthermore, the lack of validation using empirically derived parameters or benchmarks from documented vehicle data reduces the credibility and applicability of these models to real-world driving scenarios. Without the inclusion of physical effects and performance boundaries, such models remain limited in predictive accuracy and practical relevance.

5. Insufficient Energy Management Strategies for P3-Specific Dynamics

While energy management strategies (EMS) have been explored extensively for power-split and series-parallel configurations, limited attention has been given to EMS frameworks specifically suited to P3 hybrid systems. The timing of clutch engagement, the decision logic for switching between electric, engine, and hybrid modes, and the coordination between torque sources introduce complex dynamic behavior that is largely unaddressed in the existing strategies. A gap remains in developing EMS algorithms that account for these challenges while balancing fuel efficiency, performance, and mechanical constraints.

6. Lack of Performance Trade-Off and Drivability Analysis

Very few studies undertake a comprehensive evaluation of the performance trade-offs involved in implementing dog clutch mechanisms in hybrid powertrains. Critical aspects such as clutch wear, noise-vibration-harshness (NVH), energy losses during transition phases, and the resulting effects on drivability are often overlooked. This lack of analysis hampers the understanding of the long-term operational and user-experience implications of deploying dog clutches in commercial P3 hybrid systems.

7. Underutilization of Multi-Domain Modeling and Co-Simulation Platforms

Despite the availability of powerful simulation environments like MATLAB Simulink and Simscape, most studies adopt single-domain or simplified models that do not account for the interaction between electrical, mechanical, and thermal systems. The limited application of multi-domain modeling techniques restricts the depth and fidelity of simulations, especially when evaluating the full-cycle efficiency and control robustness of the powertrain under dynamic conditions.

2.10 Research Objectives

The primary objective of this thesis is to **design and simulate a P3 hybrid electric powertrain** that employs a dog clutch-based electric motor engagement system, using MATLAB Simulink and Simscape. The key goals are:

1. **Develop a detailed powertrain model:** This includes the modeling of the Internal Combustion Engine (ICE), electric motor, dog clutch system, battery, and vehicle dynamics using Simulink and Simscape Driveline. The powertrain is designed to reflect realistic driving scenarios with a focus on accurate torque and speed interactions.
2. **Model the dog clutch mechanism:** A precise simulation of the dog clutch is constructed, focusing on engagement dynamics, speed synchronization, and torque transfer under various drive conditions. Special attention is given to mechanical backlash, engagement delays, and real-time control synchronization.

3. **Design a Stateflow-based control logic:** Stateflow is employed to create a sophisticated control logic that governs clutch engagement and disengagement based on multi-parameter monitoring. These parameters include motor speed, engine speed, SOC, torque demand, and drive mode selection.
4. **Evaluate Control Effectiveness:** To analyze simulation results based on key performance indicators (KPIs) such as:
   - Synchronization time
   - Speed difference at engagement

Thereby validating the effectiveness of the proposed control strategies.

CHAPTER 3
METHODOLOGY

This chapter describes the comprehensive methodology adopted for modeling, simulating, and controlling a P3 Hybrid Electric Vehicle (HEV) architecture using MATLAB Simulink and Simscape. The focus is placed on the simulation and control of the dog clutch mechanism responsible for engaging and disengaging the electric motor from the powertrain. The implementation was carried out in MATLAB Simulink and Simscape, capitalizing on the strengths of model-based design to capture the complex physical and logical behaviors of the system. The model integrates physical plant dynamics, control logic via Stateflow, and hybrid powertrain coordination to evaluate performance under varied driving conditions.

In the P3 hybrid layout, the electric motor is positioned after the transmission and connected to the driveline via a dog clutch. This mechanical configuration enables three distinct operating modes: electric-only propulsion, engine-only propulsion, and combined engine-motor propulsion. The modeling begins with an accurate representation of the drivetrain components, followed by the integration of the dog clutch subsystem, and culminates in the control strategy for smooth and reliable mode switching.

3.1 Introduction to P3 Powertrain Configuration

The P3 Hybrid Electric Vehicle (HEV) configuration is characterized by the placement of the electric motor **after the transmission and before the differential**. This layout enables the motor to operate independently of the Internal Combustion Engine (ICE), allowing for pure electric drive, regenerative braking, and torque assistance during acceleration. Unlike P2 hybrids, where the motor is sandwiched between the engine and transmission, the P3 layout simplifies motor integration and minimizes vibration exposure, leading to enhanced durability and smoother operation.

In this architecture, the **dog clutch** serves as the mechanical coupling mechanism that engages or disengages the electric motor from the driveline based on control logic. Proper synchronization is crucial to avoid drivetrain shock or mechanical wear, which is managed through **Stateflow-based control strategies** in MATLAB Simulink.

3.2 System Architecture and Component Overview

The MATLAB Simulink model of the P3 hybrid powertrain is designed with a modular architecture, enabling clear representation and simulation of individual components.

Modeling of Key Powertrain Components

The complete P3 hybrid electric vehicle model comprises several critical components, each modeled in MATLAB Simulink with Simscape extensions for physical interactions. These components include:

1. **Internal Combustion Engine (ICE)**
2. **Electric Motor**
3. **Dog Clutch**
4. **Transmission System**

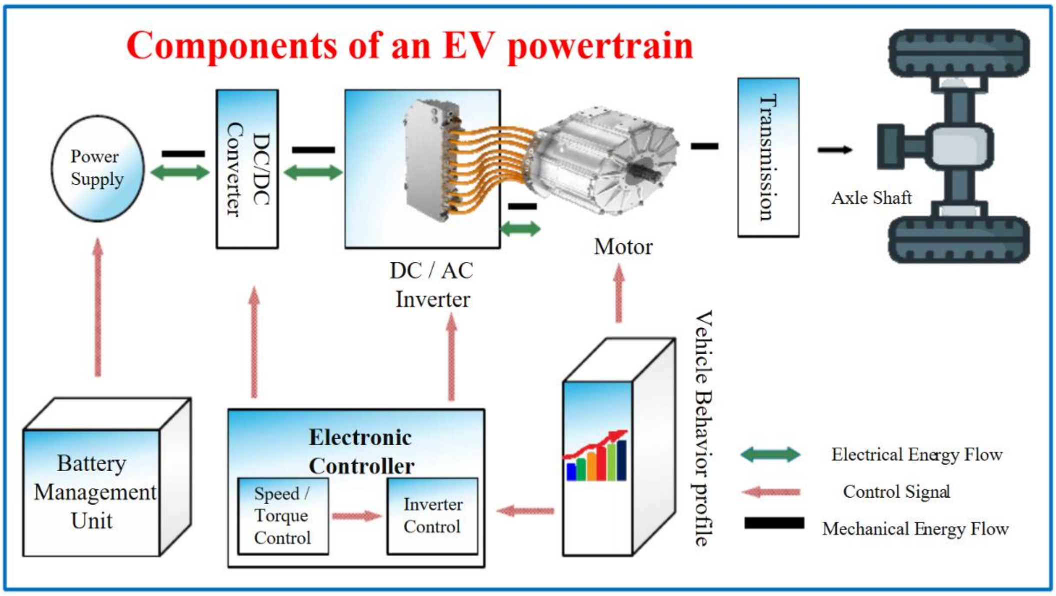

Fig.3.1 Detailed Schematic of the HEV Powertrain Architecture Studied [16]

3.2.1 Internal Combustion Engine (ICE)

The internal combustion engine (ICE) is modeled as a torque source governed by a throttle input with a simplified fuel dynamics system incorporated for torque-speed response, using the **Engine Dynamics Block** in Simulink, characterized by:

- **Torque-Speed Maps:** Implemented via a **2D Lookup Table** in Simulink, a lookup table defines the engine's output torque based on throttle input and rotational speed. These data points are obtained from real-world engine test results and manufacturer specifications.

- **Throttle Control Logic:** A Proportional-Integral-Derivative (PID) controller is used to adjust and regulate throttle response dynamically, maintaining desired speed and torque output ensuring smooth acceleration and deceleration without throttle lag.
- **Fuel Consumption Model:** A secondary block simulates fuel consumption in real-time, based on throttle input and engine load, reflecting the power demand and throttle position.
- **Output Parameters:** The engine model provides torque and speed outputs to the transmission model, interacting with the driveline through MATLAB's physical signal framework.
- **Simulink Components Used:**
  - Engine Dynamics Block" for mechanical behavior.
  - Throttle Controller Block" for real-time throttle adjustments.
  - Fuel Consumption Estimator" for efficiency analysis.

This setup allows the ICE to respond dynamically to changes in load and driver inputs, seamlessly transitioning between hybrid and engine-only modes.

MATLAB Code Snippet for Torque Mapping:

```
Define engine RPM and throttle positions:
rpm = [1000, 2000, 3000, 4000, 5000];
throttle = [0.2, 0.4, 0.6, 0.8, 1.0];
Torque map lookup:
torque map = [50, 100, 150, 180, 200;
              70, 130, 180, 210, 240;
              100, 160, 220, 260, 280;
              120, 190, 240, 280, 310;
              140, 210, 260, 300, 330];
```

3.2.2 Electric Motor

The electric motor is modeled using the **Permanent Magnet Synchronous Motor (PMSM) Block** in Simulink, integrated with Simscape Driveline for realistic physical behavior. The electric motor's torque-speed envelope, power limitations, and electrical losses proportional to the square of torque are captured using parameterized blocks. A DC voltage source feeds the motor, simulating the battery system of the hybrid vehicle. Key features include:

Motor Characteristics

- **Bidirectional Power Flow:** The PMSM is capable of both propulsion and regeneration. During braking, the motor captures kinetic energy, converting it back to electrical energy stored in the battery.
- **Torque Control Logic:** A closed-loop controller (**PI Controller)** adjusts torque output based on demand signals from the hybrid control unit (reacting to driver input and battery SOC).
- **Regenerative Braking Capability:** When decelerating, the motor reverses its operation, feeding power back into the battery system.
- **Simulink Components Used:**
  - "PMSM Block" for motor behavior.
  - "Inverter Logic" for AC/DC conversion.
  - "Battery Management System (BMS)" for SOC monitoring.

The motor's interaction with the driveline is governed by the **dog clutch**, which is engaged or disengaged based on control logic managed through Stateflow.

Battery and Energy Management System (EMS)

The **Battery Model** is implemented using the "Lithium-Ion Battery Block" in Simulink, with:

- **SOC Monitoring:** Real-time tracking of charge levels.
- **Charge and Discharge Logic:** Manages energy flow during propulsion and regeneration.
- **Thermal Management:** Simulated to prevent overheating during high-demand scenarios.

Regenerative Braking Simulation

During braking scenarios, the electric motor acts as a generator, converting kinetic energy back into electrical energy and recharging the battery. This process is modeled in Simulink using:

- **Dynamic Braking Logic:** The controller switches the PMSM to regeneration mode upon brake pedal application.
- **Energy Recapture Efficiency:** The efficiency of energy recovery is represented in the model through an **efficiency map**, typically around 80% for modern hybrid systems.

MATLAB Code for Regeneration Control:

```
if brake_pedal > 0
    regen_torque = -motor_speed * regen_efficiency;
    battery_SOC = battery_SOC + (regen_torque / battery_capacity);
end
```

3.2.3 Dog Clutch Mechanism

The **dog clutch** is a critical mechanical element in the P3 configuration, responsible for engaging the electric motor to the driveline when hybrid or electric-only mode is required. In simulation, the dog clutch block is connected to sensors that monitor speed of propeller shaft and the transmission shaft, allowing the Stateflow controller to synchronize the engagement accurately.

This block represents the physical characteristics of the clutch, its simulation includes:

- **Engagement Dynamics:** Simulated with Boolean control signals from Stateflow to engage or disengage based on speed synchronization.
- **Disengagement Logic:** Stateflow monitors dog connection request signals from actuator and speed inputs of respective shafts, triggering a smooth decoupling process to avoid driveline shock.
- **Backlash and Engagement Delay:** Realistic parameters are set to account for mechanical tolerances and actuation delays.
- **Torque Transfer Behavior:** When engaged, the clutch transmits torque directly with zero slip, modeled through Simscape's "Dog Clutch Block."

- **Actuation Logic:** The implemented Stateflow logic manages the engagement process through event-based transitions, ensuring that clutch locking occurs smoothly and without shock.
- **Control Logic for Synchronization:** Engagement occurs only when the speed difference between the motor and driveline is less than **50 RPM**. Disengagement is triggered under **low torque demand** or when electric-only mode is deactivated.

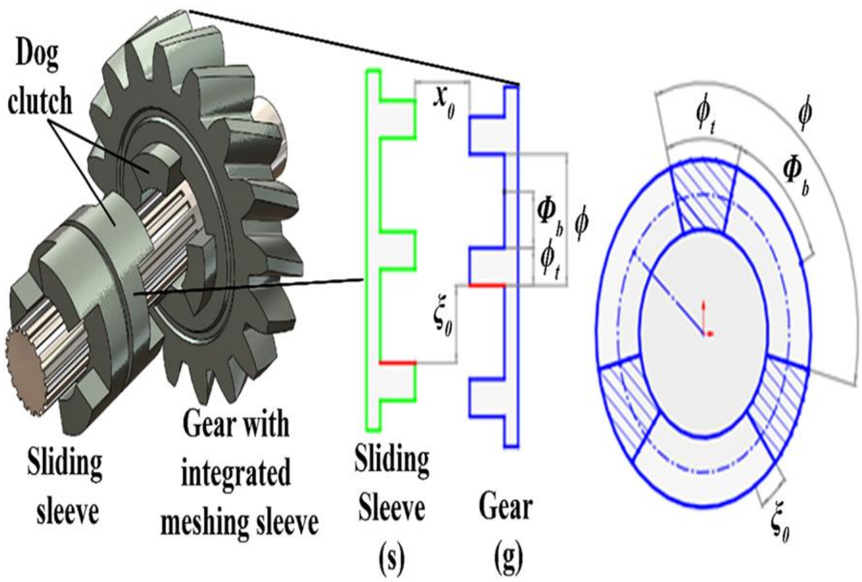

Fig.3.2 Dog Clutch [4]

These conditions are regulated through MATLAB's **Stateflow State Machine**, ensuring precise timing and safe mechanical operation.

The **dog clutch** is modeled using the **Simscape Driveline Dog Clutch Block**, configured for real-time engagement and disengagement is based on synchronization logic.

State Transition Logic in MATLAB Stateflow:

```
if abs (motor_speed - driveline_speed) < 50
clutch_state = "Engaged";
else
clutch_state = "Disengaged";
end
```

3.2.4 Transmission Model

The **transmission model** is built in MATLAB using following Simulink components:

- **Fixed Gear Ratio Blocks:** It transforms speed and torque between two shafts based on a defined gear ratio.
- **Torque Transfer Logic:** The transmission multiplies or reduces engine torque before it reaches the driveline.
- **Simulink Blocks:** "Fixed Ratio Gear" and "Gear Selector" blocks are utilized to replicate real-world behavior.
- **Shift Logic Controller:** It manages the timing and conditions for engaging or disengaging gears or clutches based on speed synchronization, driver demand, and system state to ensure smooth and reliable power transitions.

These components are connected in Simulink through physical signal lines, enabling real-time simulation of rotational dynamics and torque distribution.

To ensure synchronized engagement of the dog clutch, a **Stateflow-based control strategy** is implemented. MATLAB Stateflow provides a state machine modeling environment ideal for representing logical operations and mode transitions.

3.3 Dog Clutch Mechanisms in Automotive Powertrains

3.3.1 Introduction to Dog Clutches

The dog clutch mechanism is the centerpiece of this study, it is a type of mechanical coupling that connects or disconnects the electric motor from the rest of the driveline by engaging interlocking teeth. In the P3 hybrid layout, the electric motor is positioned after the transmission and connected to the driveline via a dog clutch. This placement allows the motor to either provide propulsion or regenerative braking, independent of engine operation. The dog clutch is engaged when electric assist is required or regenerative braking is active, and it is disengaged during engine-only operation to eliminate drag losses.

It consists of a two-input mechanical rotational interface with three ports: the **H** port connects to the engine side, the **R** port connects to the electric motor, and the **S** port represents the shift linkage for clutch actuation. The clutch engages the motor to the driveline only when synchronization conditions between the motor and engine speeds are satisfied. The rotational speed mismatch is monitored continuously, and when it falls within a predefined threshold (±50 RPM), engagement is initiated. If the speed difference is beyond this threshold, the system holds or disengages the clutch to avoid damaging gear engagement. The clutch allows torque transmission only when fully engaged, ensuring minimal mechanical wear and impact.

To simulate realistic driver behavior, a drive cycle input such as the WLTP (Worldwide Harmonized Light Vehicles Test Procedure) is applied to define vehicle speed demands over time. A feedback controller compares the desired speed to actual vehicle speed and generates appropriate torque requests for the ICE and electric motor. The control logic for the dog clutch is modeled using Simulink's Stateflow, dynamically determines the mode of operation — electric, engine, or hybrid based on torque demand, battery state of charge (SOC), and system efficiency maps where a finite state machine monitors the engagement criteria, where engagement force and timing are finely tuned to mimic realistic dog clutch dynamics.

Unlike friction-based clutches, which rely on surface contact to transmit torque, a dog clutch operates with zero slip, providing a rigid and direct mechanical link. This makes it highly effective in applications where precise torque transfer and synchronized engagement are critical. Dog clutches are widely used in **motorsports transmissions**, industrial machinery, and, as highlighted in this thesis, in **P3 Hybrid Electric Vehicle (HEV) configurations**.

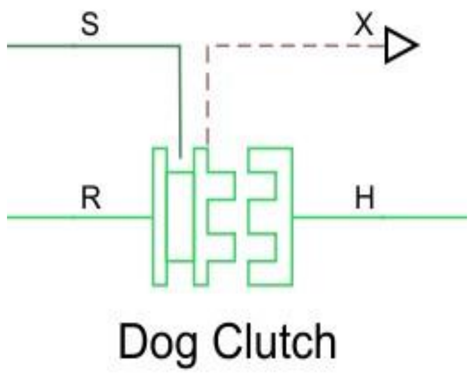

Fig.3.3 Simscape Model of Dog Clutch with Control Interface

The dog clutch consists of two primary components:

1. **Driving Member (Input Shaft):** This is the shaft connected to the power source, which, in the P3 configuration, is the electric motor.
2. **Driven Member (Output Shaft):** This is connected to the driveline and ultimately to the vehicle's wheels.

The Dog Clutch block represents a nonslip clutch that uses the positive engagement of interlocking teeth to transfer torque between drive shafts. Dog clutches are common in applications that require high-speed and frequent gear shifts.

The ring and hub are the primary components of a dog clutch. The input shaft turns the ring, which has slots or teeth. The hub connects to an output shaft that has protruding "dogs" that fit into the slots of the ring. When you shift the transmission, the dogs and slots engage and lock the two components and transmitting power. You shift again to disengage the clutch, which causes the dogs to disengage from the slots and allows the transmission to spin freely. The ring and the hub spin together as a unit.

Moving the ring toward the hub so that the teeth interlock changes the clutch state to engaged. Tooth overlap must exceed a minimum value for engagement. Moving the ring in reverse so that the two sets of teeth no longer interlock changes the clutch state back to disengaged. Port **S** specifies the shift linkage position. When the clutch is fully disengaged, the shift linkage position is zero. When the clutch is fully engaged, the shift linkage position equals the sum of the tooth height and the ring-hub clearance of the fully disengaged state,

$z = h + z_{Gap}$,

The figure shows side and front views of the dog clutch and some of its relevant variables.

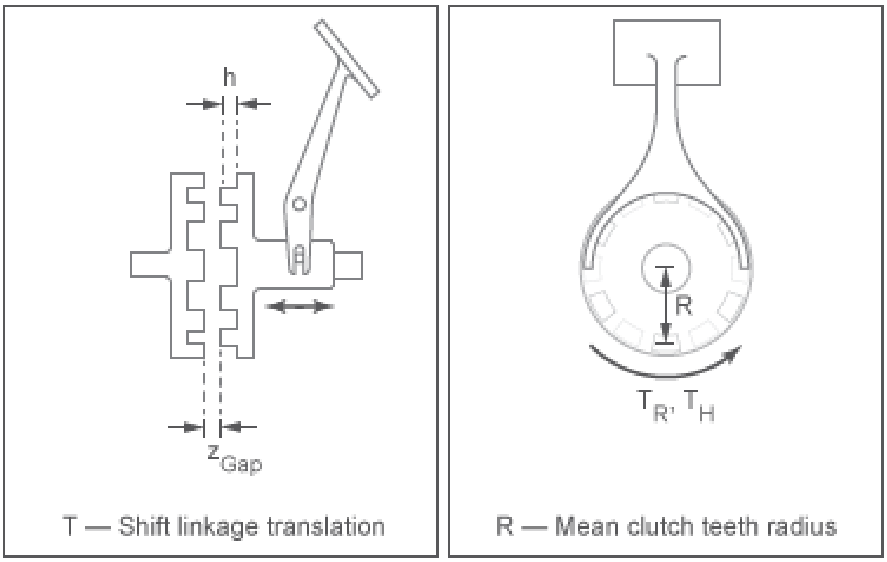

Fig. 3.4 Dog Clutch Schematic Diagram

The engagement mode positions are:

- $z = 0$ — The clutch is fully disengaged.
- $0 < z < z_{Gap}$ — The clutch is disengaged when the shift linkage position is in the region defined by z_{Gap}. The clutch can transition from disengaged to engaged at $x = z_{Gap} + z_{Overlap}$.
- $z_{Gap} < z < h$ — The clutch is engaged when z is in the region defined by h. The clutch can transition from engaged to disengaged when $z = z_{Gap}$.
- $z = z_{Gap} + h$ — The clutch is fully engaged.
- $z = z_{Gap} + z_{Overlap}$ — When z is in the engagement overlap region, the clutch engages only when the speed difference is less than the value of the ω_{thr} parameter.

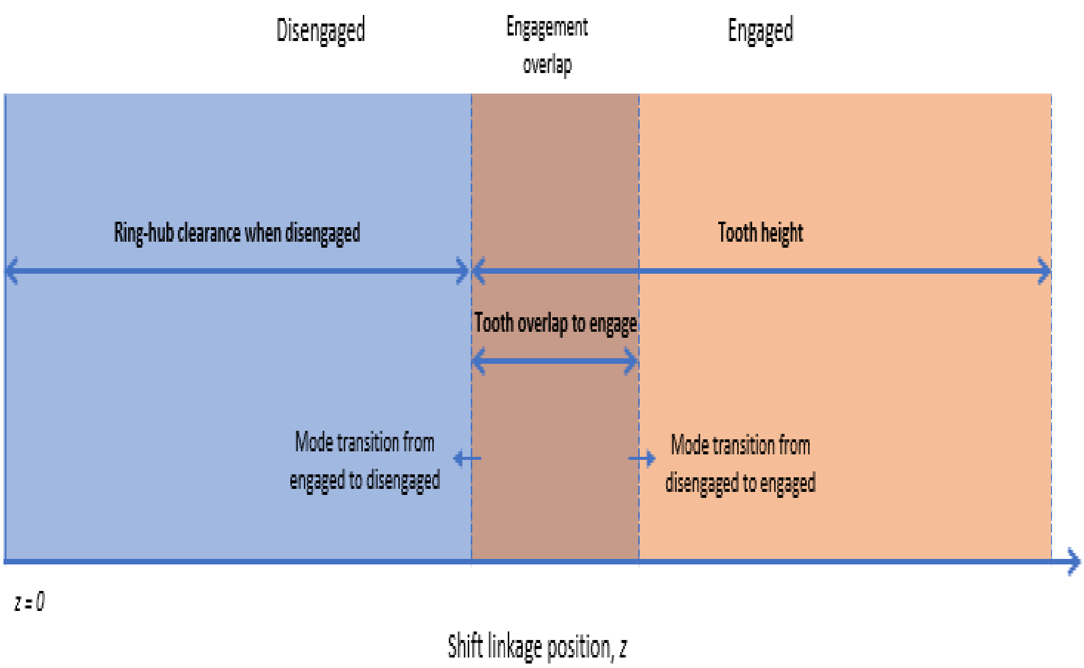

Fig. 3.5 Linkage Position

3.3.2 Synchronization Requirements for Engagement

One of the critical challenges of implementing a dog clutch in a P3 hybrid is **speed synchronization**. Unlike wet or friction clutches that can tolerate slight speed differences, a dog clutch requires near-perfect synchronization to avoid mechanical damage. Misaligned engagement can lead to:

- **Gear Tooth Chipping:** If the driven and driving members engage at different speeds, the impact force can chip the teeth, leading to premature wear and potential failure.
- **Torque Spikes:** Abrupt engagement at mismatched speeds causes sharp torque spikes, which can propagate through the drivetrain, risking component integrity.
- **Vibration and Noise:** Uncoordinated engagement results in oscillations and vibrations, affecting vehicle smoothness and passenger comfort.

3.4 MATLAB Simulink-Based Integration and Simulation Framework

The complete hybrid powertrain architecture—comprising the internal combustion engine (ICE), electric traction motor, dog clutch, transmission system, and driveline—is comprehensively integrated within the MATLAB Simulink environment. This modeling framework ensures seamless interaction between physical components (via Simscape) and logical control layers (via Stateflow), enabling rigorous system-level testing and analysis under dynamic conditions.

Simulink facilitates real-time signal monitoring and data acquisition, capturing critical system variables such as electric motor rotational speed, clutch engagement status, torque transmission values across the simulation time domain. These measurements provide essential insights for validating performance metrics and identifying control bottlenecks.

To assess powertrain behavior under real-world driving demands, standardized drive cycles are implemented. These cycles subject the hybrid system to varying speed and torque profiles, replicating typical urban and highway conditions. The vehicle response under these cycles enables evaluation of fuel efficiency, electric mode utilization, engine-on time, and regeneration potential.

The control logic developed using Stateflow is subjected to extensive testing across a wide range of scenarios, such as sudden acceleration, braking, and stop-and-go driving. This ensures that mode transition conditions, clutch synchronization, and torque coordination functions are robust, fault-tolerant, and free from logic deadlocks or undesirable transients. The physical domain interactions are modeled using Simscape Driveline, where mechanical ports and physical signal lines interconnect subcomponents, supporting accurate modeling of torque flows, inertial dynamics, gear ratios, and clutch friction effects. This allows for realistic propagation of mechanical energy and detailed simulation of driveline loading conditions.

Moreover, variables like clutch engagement delay, motor torque ramp rates, and mode switching thresholds are utilized to iteratively adjust control parameters and are also fine-tuned to balance drivability, energy efficiency, and system responsiveness. This optimization process is integral to aligning the simulation model's performance with target benchmarks and real-world operating constraints.

3.5 Consolidated Methodological Overview

The methodology adopted in this study establishes a comprehensive simulation framework for modeling and controlling a P3 Hybrid Electric Vehicle using MATLAB Simulink and Simscape platforms. The powertrain architecture is represented with high fidelity, integrating detailed physical subsystems and a robust supervisory control strategy.

One of the key technical innovations lies in the precise modeling and control of the dog clutch mechanism, which enables reliable synchronization and engagement between the engine and the driveline. The associated control logic ensures that clutch actuation occurs only under dynamically safe and mechanically synchronized conditions, preventing driveline shocks or clutch damage. The use of **Stateflow** for supervisory control introduces a modular and event-driven logic structure that governs mode selection, torque arbitration, and fault handling. This approach provides clarity in control transitions and enables scalable enhancements for future powertrain features, such as predictive energy management or adaptive learning.

Furthermore, the vehicle model undergoes validation through realistic driving cycles, allowing comprehensive analysis of energy usage, operational modes, and control robustness. The simulation environment supports both qualitative and quantitative performance evaluation, forming a strong foundation for future implementation on real-time platforms. In essence, the presented methodology not only fulfils the objectives of accurate modelling and effective control of a P3 hybrid configuration but also delivers a reusable and extensible framework for advanced hybrid vehicle research and development.

CHAPTER 4

MODELING

4.1 Introduction to MATLAB Simulink and Simscape Modeling

Model-based design has emerged as a pivotal methodology in the development and validation of complex automotive systems, particularly in the case of Hybrid Electric Vehicles (HEVs). MATLAB Simulink, when combined with the Simscape Driveline toolbox, offers an intuitive, block-diagram environment for representing and simulating dynamic systems. In this thesis, MATLAB Simulink is employed to model a P3 Hybrid Electric Vehicle (HEV) powertrain equipped with a mechanical dog clutch. The primary focus is on achieving seamless torque transfer, maximizing energy efficiency, and facilitating smooth transitions between operating modes. Simulink's integration with Simscape Driveline enables realistic simulation of mechanical interactions, especially during dynamic transitions involving the engagement and disengagement of the dog clutch mechanism.

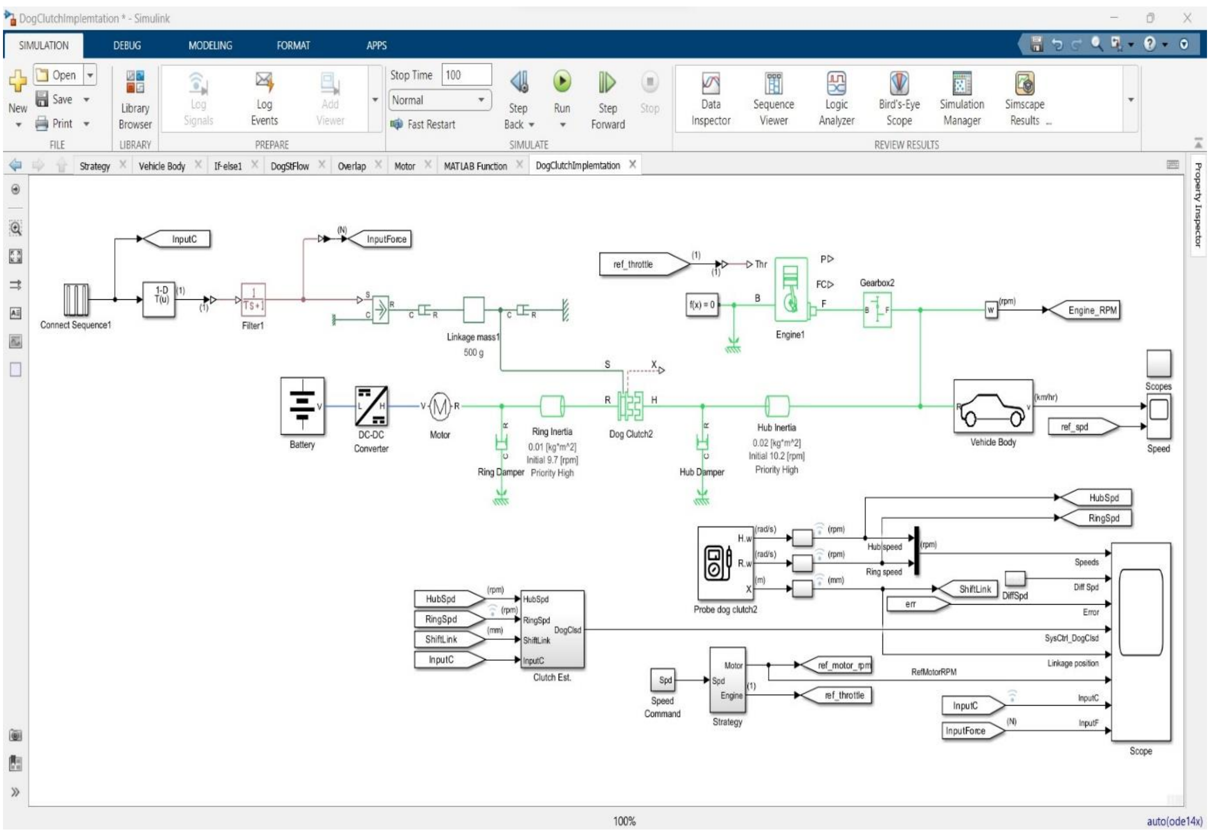

Fig.4.1 Simulink Model Overview of the P3 HEV Architecture

4.2 Stateflow Logic for Dog Clutch Engagement and Disengagement

The engagement and disengagement of a dog clutch in a P3 hybrid electric vehicle requires precise timing and coordination, especially due to the mechanical nature of the clutch which demands near-zero differential speed during synchronization. To manage the complex control logic required for this operation, a Stateflow chart is employed within the Simulink environment. Stateflow offers a graphical programming platform that is ideally suited for modeling event-driven systems, incorporating conditional transitions, state-based behavior, and time-driven logic. In this model, Stateflow is used to implement two parallel subsystems: one that governs normal clutch engagement based on actuator requests, and another that handles fallback engagement logic in the absence of valid solenoid input due to sensor or actuator failure. These two subsystems are intelligently selected based on system health and solenoid signal validity, ensuring safe operation in both nominal and fault-tolerant modes.

The core logic within Stateflow is designed around a hybrid automaton structure where clutch engagement is treated as a finite state machine with states such as "ConfirmedOpened", "PossiblyClosed", " ConfirmedClosed", and " PossiblyOpened". Transitions between these states are determined by a combination of physical conditions such as motor and engine speed difference ($\Delta\omega$), reference RPM tracking, as well as external control inputs such as solenoid actuation signals. Temporal logic and counters are integrated to ensure robustness against transient glitches or intermittent signal loss. The inclusion of fallback logic based on differential speed allows the system to maintain functional behavior even in the event of hardware faults, enhancing system reliability.

The Stateflow chart for the P3 hybrid powertrain consists of the following primary states:

1. Idle State: The vehicle is stationary, the clutch remains disengaged disengaged and the electric motor is decoupled.
2. Ready to Engage State: When the motor speed matches the driveline speed within a tolerance of **± 50 RPM**, the system transitions to the "Ready to Engage" state. Motor and driveline are synchronized; clutch is prepared for engagement
3. Engaged State: If synchronization is successful, the clutch locks, enabling torque transfer from the motor to the driveline.
4. Disengaged State: If electric assistance is not required or if the ICE takes over, the clutch smoothly disengages. Motor is decoupled; engine-only mode is active.

5. Regenerative Braking Mode: During deceleration motor operates as a generator and motor regenerates energy, with the clutch disengaged to minimize drag losses.

4.2.1 Engagement and Disengagement Logic Based on Solenoid Request

Under normal operating conditions, the dog clutch engagement and disengagement are driven directly by actuator signals originating from a solenoid valve. The solenoid is typically commanded by a supervisory hybrid control unit that determines when the electric motor needs to be mechanically coupled with the internal combustion engine via the clutch. In the Stateflow logic, a valid solenoid request is treated as the primary control input that initiates the transition from the "Disengaged" to the "Engaged" state.

When a solenoid engagement request is received, the Stateflow chart first checks whether the motor speed has been synchronized with the engine speed. This is achieved through a real-time computation of the differential speed $\Delta\omega = \omega\_engine - \omega\_motor$. If the magnitude of $\Delta\omega$ is below a specified synchronization threshold—commonly in the range of ±50 RPM—the system initiates a transition to the "PreparingToEngage" state. During this intermediate state, a short delay counter is used to verify signal persistence and ensure that the system is not reacting to noise or a spurious solenoid trigger. Once the delay period is satisfied and all conditions remain true, the clutch state transitions to "Engaged", and a digital flag is sent to Simscape through a control signal to actuate the dog clutch block.

The disengagement sequence follows a similarly structured logic. When the solenoid disengagement command is received, the chart transitions to the "PreparingToDisengage" state. Here, again, a debounce timer is used to prevent transient noise from causing unintended disengagement. Once the disengagement request is confirmed to be stable, the system moves to the "Disengaged" state, and the clutch connection is broken. This logic ensures that the actuator-controlled engagement and disengagement are both reliable and precise. The use of Stateflow for this purpose allows for graphical inspection, clear definition of conditions, and easy integration with the rest of the hybrid control architecture.

4.2.1.1 Engagement Logic and Synchronization

Engagement is achieved through **interlocking teeth** that are precisely machined to fit together with minimal tolerance. When the driving and driven members reach synchronized speeds, the teeth slide into alignment, forming a solid mechanical connection. Unlike friction clutches, which can slip during engagement, a dog clutch either fully engages or remains disengaged, allowing for immediate torque transfer.

- **Positive Locking:** The mechanical lock ensures that once engaged, there is no slip between the motor and the driveline, providing 100% torque transmission.
- **Zero Slip:** The absence of relative motion during engagement guarantees efficient power transfer without energy losses.
- **Backlash Consideration:** Small gaps between the teeth (backlash) are factored into the design to allow smooth meshing without binding.

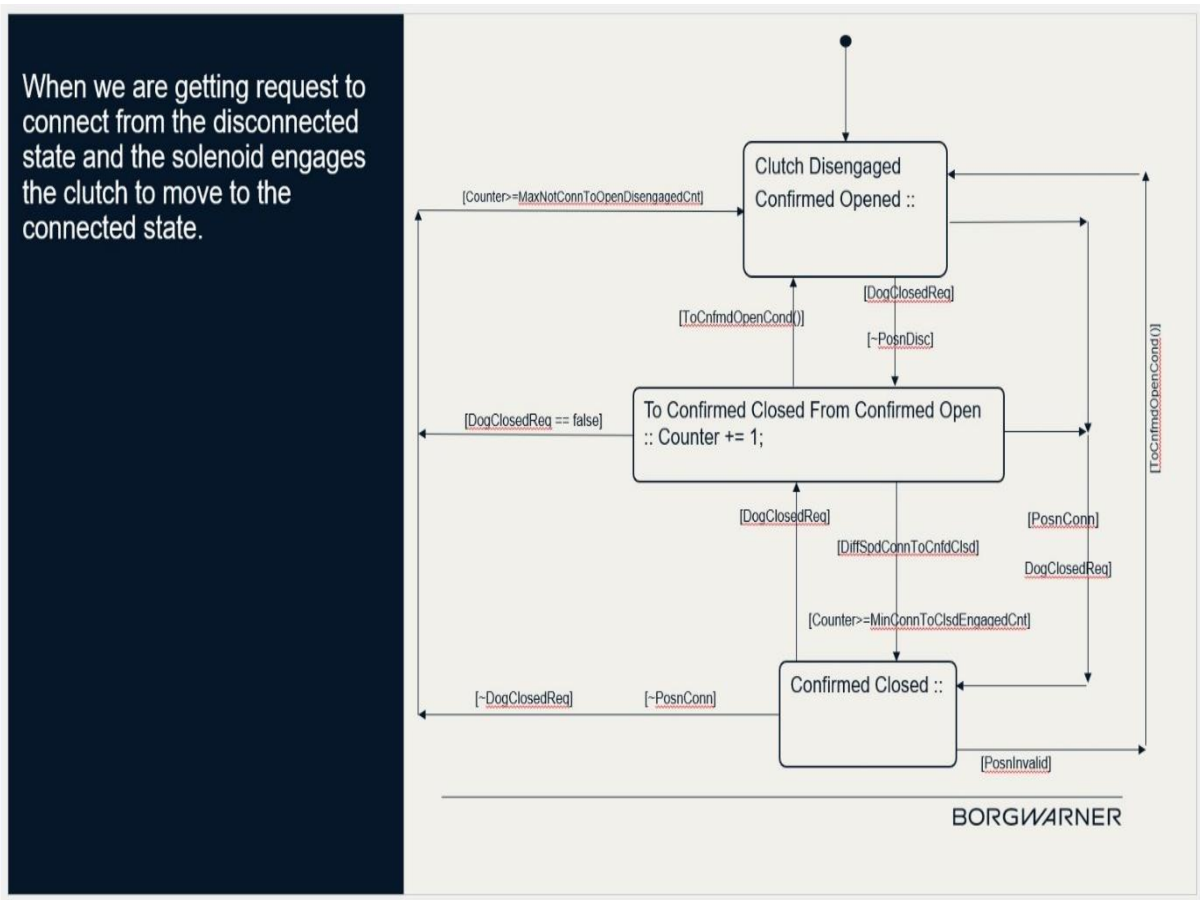

Fig.4.2 Detailed Stateflow Chart for Dog Clutch Engagement Logic.

4.2.1.2 Disengagement Logic

Disengagement is similarly straightforward but requires the clutch teeth to **unlock smoothly without load binding**. This is typically controlled by:

- **Electromechanical Actuators:** These provide the force needed to pull the teeth apart.
- **Spring-Loaded Mechanisms:** In some designs, springs assist in quick retraction upon command.
- **Control Logic Synchronization:** Disengagement must be coordinated with torque reduction to avoid abrupt shocks to the driveline.

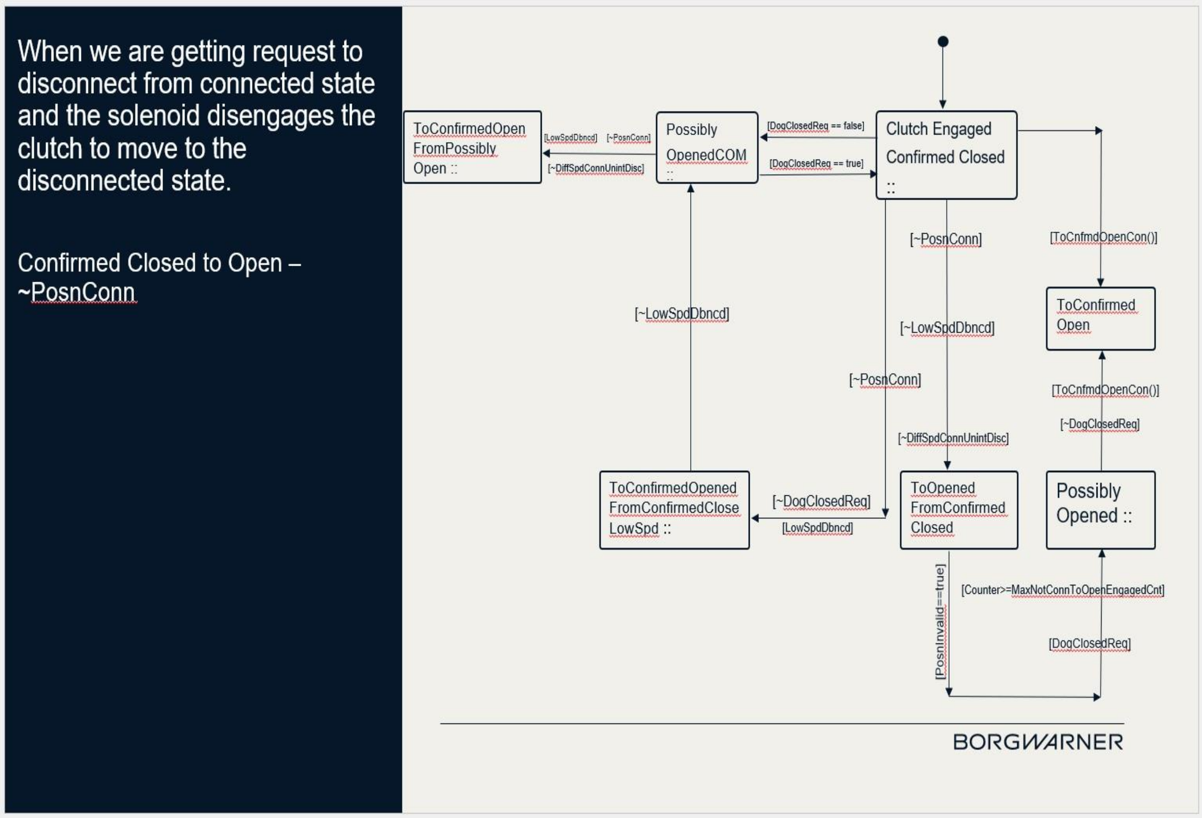

Fig.4.3 Stateflow Representation Going Into Disengaged State

Furthermore, a safety override is included within this logic to prevent engagement when $\Delta\omega$ is too high, even if the solenoid signal is active. This interlock condition ensures that the clutch is not engaged under unsafe speed differentials, which could cause mechanical damage or inefficient coupling. In such cases, the system delays the engagement and waits until the synchronization condition is re-established. This dual validation logic—solenoid request plus speed synchronization—embodies a fail-safe design philosophy suitable for powertrain applications.

4.2.2 Engagement and Disengagement Logic During Solenoid Faults

In the event that the solenoid actuator signal is lost due to electrical fault, signal degradation, or communication failure, the system shifts to a secondary engagement strategy that relies entirely on internal logic based on speed synchronization and operational demand. This fault-tolerant mode is automatically activated when the Stateflow logic detects the absence of a valid solenoid signal over a sustained period, typically using a watchdog timer that continuously monitors the signal integrity. Once a solenoid fault is confirmed, the system disables actuator-based transitions and reverts to autonomous logic governed by physical parameters.

In this fallback mode, engagement is triggered solely based on the differential speed $\Delta\omega$ and the operational context, such as vehicle speed, motor torque request, and hybrid mode selection. The Stateflow chart continuously evaluates whether $\Delta\omega$ has fallen below the synchronization threshold. If the threshold is satisfied for a predefined number of cycles—determined via a counter or persistent condition—the chart transitions to the "Engaged" state without requiring an external actuation command. This logical decision-making framework allows the vehicle to maintain hybrid functionality even when solenoid hardware fails.

Similarly, disengagement in the fault mode is determined by a loss of synchronization or a change in mode request from the supervisory controller. If the differential speed exceeds the upper threshold—indicative of slippage or decoupling necessity—the Stateflow transitions back to the "Disengaged" state. This ensures that the clutch is not maintained in a mechanically locked state under unsafe conditions. Additionally, timeouts and logic gates are used to prevent chattering transitions in the presence of borderline conditions, which could otherwise lead to mechanical wear or control instability.

To determine whether the clutch is physically engaged or disengaged in the absence of actuator feedback, counters and timers are employed within the Stateflow environment. A "closed_counter" and an "open_counter" are initialized and incremented when certain logical assumptions are met—such as prolonged synchronization suggesting engagement, or sustained desynchronization indicating disengagement. If the counters exceed predefined thresholds (e.g., 100 simulation time steps), the chart infers the clutch state and updates its internal state accordingly. This form of inferred state estimation is critical in ensuring that the system retains situational awareness even when direct actuator feedback is unavailable.

Moreover, these counters serve a dual function as diagnostic indicators. For example, if the system repeatedly attempts engagement under valid conditions without a successful transition, the counter values can be used to flag a persistent failure, which is then logged or transmitted to an onboard diagnostic module. This adds an extra layer of robustness to the Stateflow-based control system, allowing it to operate with resilience in the face of both software and hardware failures.

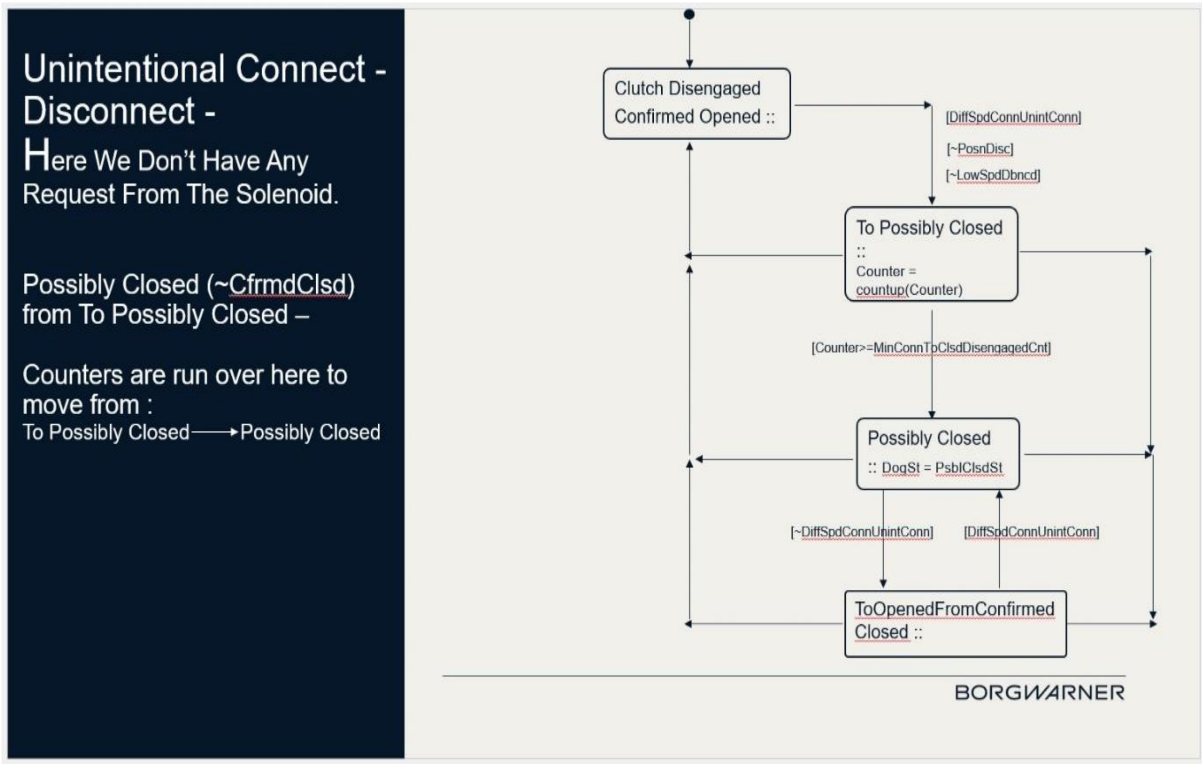

Fig.4.4 Clutch Engagement Conditions Based on Motor Speed, Driveline Speed, and Torque Demand

In summary, the Stateflow logic embedded in the MATLAB Simulink model ensures that the dog clutch control is both precise and fault-tolerant. During normal operations, the actuator signal governs engagement with appropriate safety checks. Under fault conditions, the control logic autonomously switches to a fallback strategy based on internal physical conditions, supported by smart counters that track and infer clutch status. This dual-mode control approach enhances reliability, safety, and system availability—making it suitable for real-world deployment in hybrid electric vehicle architectures.

4.2.3 Transition Logic

State transitions are governed by a series of logical conditions:

1. **Speed Matching Logic:** MATLAB Simulink continuously monitors the speed matching which compares the real-time speeds of the electric motor and the driveline. If the absolute speed difference is within the specified threshold, the control logic initiates clutch engagement
2. **Torque Demand Evaluation:** If torque demand exceeds a predefined threshold, the controller attempts to engage the clutch, provided speeds are synchronized.
3. **SOC and Mode Requirements:** State of Charge (SOC) and drive mode (Electric-only, Hybrid, or Engine-only) before engagement is also checked.
4. **Debounce Logic:** To prevent oscillation between states, a debounce timer is implemented, ensuring stability during transient conditions. This introduces a time delay between transitions, ensuring that the system only shifts states after a consistent set of conditions is met.

A MATLAB script governs these transitions using conditional statements.

State Transition Logic:

```
% Clutch State Transition Logic
if abs(motor_speed - driveline_speed) < 50
   nextState = "Engaged";
elseif brake_signal > 0
   nextState = "Regenerative Mode";
else
   nextState = "Disengaged";
end
```

Debounce Logic for Stability:

```
if (previousState ~= nextState)
   debounce_timer = debounce_timer + 1;
   if debounce_timer > 10
      previousState = nextState;
      debounce_timer = 0;
   end
end
```

4.3 MATLAB Simulink Modeling for Synchronization

Within the Simulink environment, the synchronization of the electric motor and the driveline is achieved using a combination of real-time feedback, PID controllers, and state-based logic.

Speed sensors mounted on the electric motor and driveline continuously relay rotational speed data, which is used to determine whether synchronization is possible. This feedback is processed through PID control loops that modulate the electric motor's speed until it closely matches that of the driveline.

When the speed difference drops below the engagement threshold, the Stateflow chart transitions the system to the Engaged state, and the dog clutch locks. This mechanism ensures seamless torque transfer with minimal mechanical wear. If a misalignment is detected at any point during the engagement process, the system reverts to the Idle or Ready to Engage state, thus avoiding forced engagement under unsafe conditions.

4.4 Control Strategies for Safe Engagement

To prevent mechanical shock, safe operation and ensure smooth transitions of the dog clutch, a set of finely tuned control strategies is implemented within the Simulink model. Safe and effective engagement of a dog clutch requires precise control strategies. MATLAB Simulink facilitates this through **Stateflow Logic Design.**

Stateflow is a powerful tool within Simulink for modeling event-driven logic and state transitions. In the case of the dog clutch, Stateflow manages:

- **Pre-Engagement Synchronization:** Ensures that both motor and driveline operate at nearly identical speeds before clutch actuation. Once synchronization is confirmed, clutch engagement is initiated with precise timing, and motor torque is regulated to avoid abrupt torque spikes.
- **Safe Engagement Logic:** The engagement phase is monitored for success, and if conditions are violated, engagement is aborted and retried after recalibration.
- **Debounce Logic:** To prevent rapid oscillation between engaged and disengaged states due to transient speed changes. Debounce logic further reinforces safe operation by requiring a minimum delay and confirmation of stable input conditions before allowing state transitions.
- **Smooth Disengagement:** The controller reduces motor torque before clutch release which minimizes driveline stress and shock loads. Disengagement strategies include

gradually reducing motor torque before unlocking the clutch. The timing of clutch actuation is critical, and it is dynamically controlled based on the motor's current state and load conditions.

Engagement Timing and Torque Management

Accurate timing is crucial for smooth operation. MATLAB Simulink integrates **timing control** that adjusts motor output based on clutch state:

- During **pre-engagement**, the motor speed is modulated to align with the driveline.
- If synchronization is not achieved, the system momentarily pauses engagement attempts and retries after corrective adjustments.
- In **disengagement scenarios**, torque is gradually ramped down before decoupling, preventing mechanical shock.

4.5 Vehicle Modeling and Simulation Using MATLAB Simulink and Simscape

Introduction to MATLAB Simulink for Hybrid Vehicle Modeling

MATLAB Simulink is a **graphical programming environment** used for modeling, simulating, and analyzing the complex interactions within hybrid electric powertrains in multidomain dynamic systems. For the P3 hybrid configuration in this project, Simulink was used to construct a detailed block-based representation of the internal combustion engine, electric motor, transmission, and the dog clutch system. The model integrates mechanical and electrical domains, enabling the simulation of diverse operating scenarios such as electric-only propulsion, hybrid operation, and engine-only modes. These simulations provided insights into the torque distribution, energy consumption, mode transition smoothness, and regenerative braking effectiveness. In the context of this thesis, Simulink is utilized to:

- Design the complete **P3 hybrid electric powertrain**, including the engine, motor, transmission, and dog clutch.
- Implement **control strategies** for seamless mode transitions (electric-only, engine-only, and hybrid).
- Simulate real-world **drive cycles** such as urban, highway, and hill start conditions to validate the control logic.

- Analyze the impact of different control parameters on **torque delivery, energy efficiency, and regenerative braking**

4.5.1 MATLAB Simulink and Simscape Implementation

The implementation of the dog clutch and its control system is realized using Simscape Driveline components, which represent the physical interactions between the powertrain elements. The dog clutch is modeled using a specialized Simscape block where parameters such as backlash, actuation delay, and maximum engagement torque can be defined.

PID controllers are used to facilitate speed matching, these are implemented to maintain speed synchronization during state transitions. Event-driven logic built with Stateflow oversees the engagement process managing real-time event transitions, ensuring safe operation under all driving conditions.

During simulation in MATLAB Simulink, various vehicle states are tested to ensure the model behaves as expected under both normal and edge conditions. Simulink's real-time solver updates system states continuously, allowing the model to reflect dynamic behaviors such as changes in torque flow, gear transitions, and braking scenarios with high fidelity. These tests verify the robustness of the clutch engagement logic and the smoothness of power transfer in real-world scenarios.

4.6 Simscape Driveline for Physical System Modeling

Simscape Driveline extends MATLAB Simulink’s capabilities by introducing physical modeling elements that replicate real-world mechanical systems using network-based blocks. This tool is used to model all the essential components of the vehicle's powertrain, such as rotational shafts, translational mechanical components, gear reduction, differential behavior, torque transmission paths, and clutch mechanisms (including both friction-based and mechanical dog clutches).

It accurately simulates driveline dynamics, including inertia loads and torque oscillations, which are critical for evaluating drivetrain performance during sudden transitions like clutch engagement or braking. The dog clutch mechanism in this P3 hybrid model is configured to respond dynamically to speed matching inputs and engage or disengage accordingly. Simscape enables bidirectional energy flow, which is particularly beneficial for simulating regenerative braking scenarios where the motor acts as a generator and feeds energy back into the battery.

4.6.1 Benefits of Simscape Driveline

Simscape Driveline enhances simulation accuracy by incorporating real-world physical properties directly into the model. The primary advantage of Simscape Driveline lies in its ability to capture physical behavior with high realism.

1. Physical Fidelity: By modeling components based on Newtonian mechanics and incorporating manufacturer-specified parameters such as friction coefficients, inertias, and torque limits, the simulation outcomes align closely with real-world performance leading to realistic behavior during simulation.

2. Bidirectional Power Flow: Energy can flow in both directions, enabling regenerative braking and back-driven motor scenarios.

3. Parameterization Flexibility: Engineers can input manufacturer data, such as inertia, friction coefficients, and torque curves, for enhanced realism.

4. Plug-and-Play Integration: Component libraries such as **engines, motors, dog clutches, and transmissions** significantly reduce modeling time without manual coding. In this project, using the Dog Clutch Block from Simscape allows for the rapid configuration of the engagement parameters and simplifies integration with the broader vehicle model. This contributes to a flexible, scalable, and physically accurate simulation platform.

In the P3 hybrid system, the **Simscape Dog Clutch Block** is configured to simulate real-time engagement and disengagement based on speed synchronization, controlled through a **Stateflow logic** system. MATLAB's real-time solver continuously updates state variables, enabling dynamic torque transfer during simulation.

CHAPTER 5
RESULTS AND DISCUSSION

5.1 Introduction

This chapter presents and discusses the simulation results of the P3 Hybrid Electric Vehicle (HEV) model with a Dog Clutch Engagement mechanism was conducted using MATLAB Simulink and Simscape Driveline. The simulation's objective was to evaluate the engagement and disengagement behaviour of the dog clutch under various control conditions, validate synchronization control strategies, and observe the dynamic interactions between the internal combustion engine (ICE) and the electric motor, representative of real-world conditions. The primary focus of the simulation was to analyze the effectiveness of the proposed control strategies.

This chapter presents a comprehensive analysis of the system’s behaviour using seven key simulation outputs: motor and engine speed profiles, relative speed difference, error between engine reference and actual motor speed, clutch state transitions, shift linkage position feedback, motor reference speed, dog clutch actuation signal and transitions among different driving modes (electric-only, hybrid, and engine-only). These results were captured to validate the fidelity and responsiveness of the Stateflow-based control logic developed to ensure optimal power distribution and drivetrain stability and are discussed in relation to the clutch control logic implemented via Stateflow and Simulink subsystems, ensuring accurate timing and torque coordination during hybrid operation.

5.2 Results and Analysis

5.2.1 Actuation Signal for Dog Clutch Engagement

The actuation signal is the final output from the Stateflow logic that triggers the dog clutch to engage or disengage. This signal is the culmination of several logical checks—motor speed error within limit, differential speed below threshold, engine running status, and user/ECU shift command. The actuation signal graph mirrors the clutch engagement status signal but also provides insight into the logic delay or pre-actuation logic steps. The simulation results show clean rising and falling edges in the actuation signal with minimal chatter, suggesting that debounce and hysteresis were correctly implemented in the Stateflow chart. This binary signal is ultimately used as an actuator driver, which would correspond to a solenoid or hydraulic actuator in a real vehicle, confirming the system's ability to support real-world actuation interfaces.

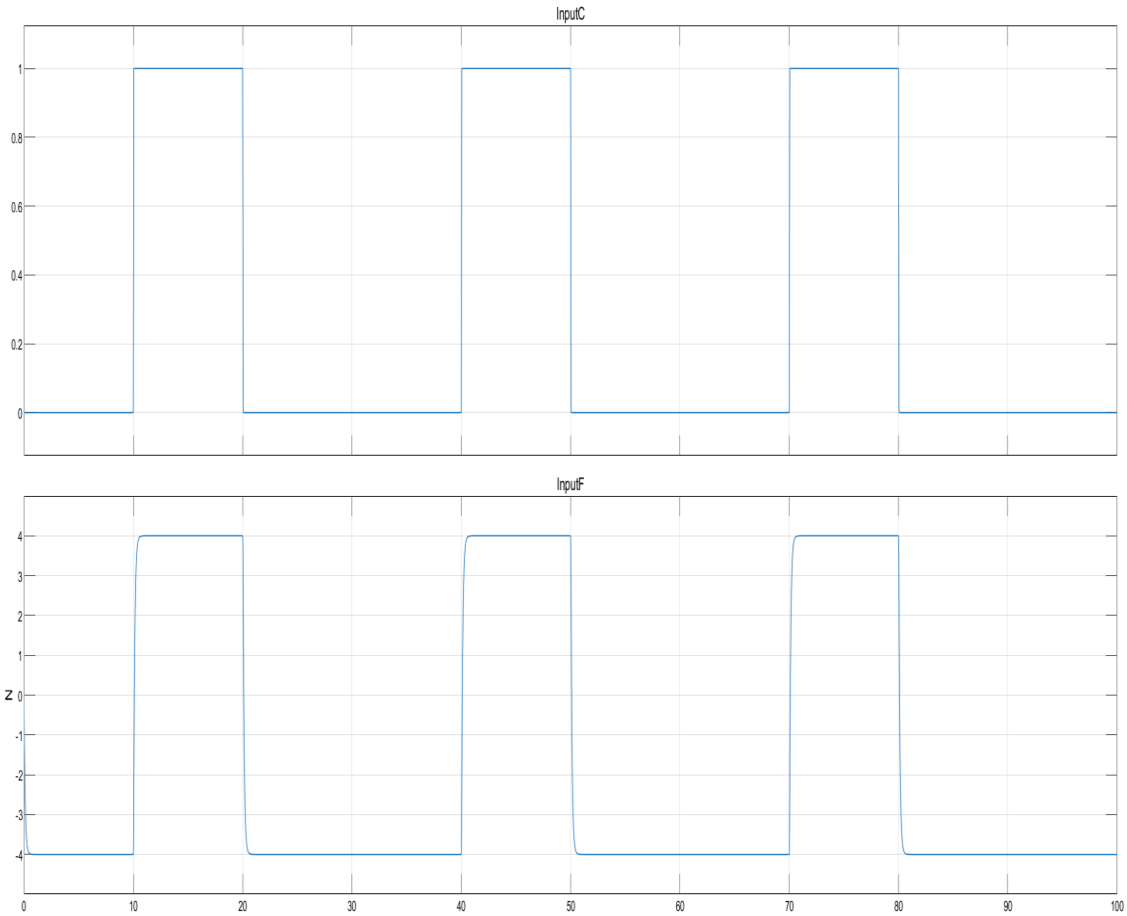

Fig.5.1 Input Force

5.2.2 Motor and Engine Speed Synchronization

One of the most critical metrics in evaluating clutch engagement is the motor and engine speed synchronization profile. During clutch engagement, the control logic ramps up the electric motor speed to match that of the engine, enabling a smooth mechanical lock without shock. The simulation results indicate that, prior to clutch engagement, the motor speed is gradually increased using a PI controller to track the reference speed. As the motor approaches the engine speed, the speed difference diminishes, and once within an acceptable tolerance band, the Stateflow logic triggers clutch engagement. Following engagement, both motor and engine speeds track each other closely, confirming mechanical synchronization. When the clutch is commanded to disengage, the motor speed rapidly drops, decoupling from the engine speed. This behaviour validates the dynamic control strategy implemented for smooth and reliable clutch transitions in Simulink.

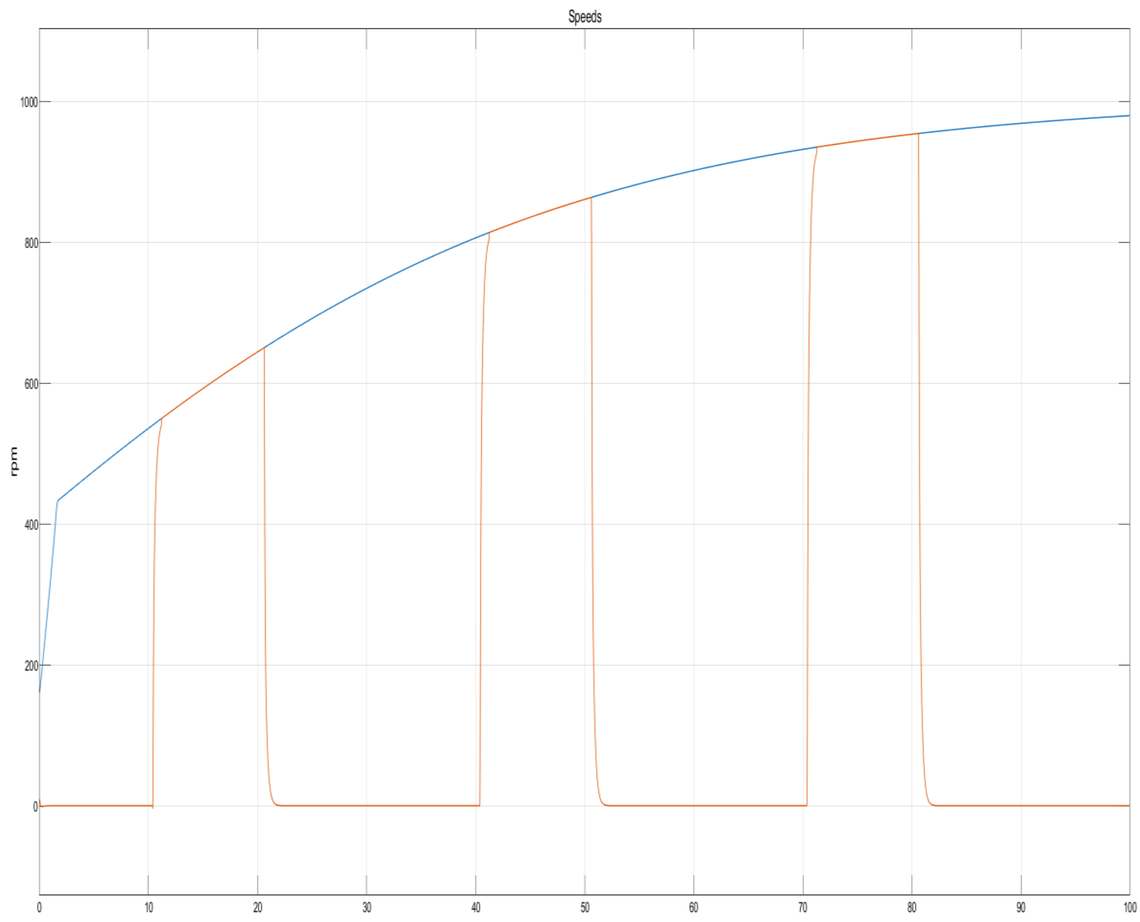

Fig.5.2 Engine and Motor Speed Profile During Clutch Transition

5.2.3 Relative Speed (Δω) Between Engine and Motor

The relative speed or differential speed graph represents the instantaneous difference between engine and motor speeds. This parameter, denoted as $\Delta\omega = \omega\_engine - \omega\_motor$, is fundamental to ensuring the correct timing of dog clutch engagement. The simulation shows that the control algorithm continuously monitors this value to assess readiness for synchronization. When Δω drops below a predefined threshold, typically ±20 RPM, the system interprets that mechanical synchronization can be achieved safely. The graph exhibits clear convergence toward zero during engagement phases, followed by stability at near-zero values, indicating a successful lock. Spikes in the graph during transitions are minimal, which suggests the control strategy effectively handles transients. This measurement acts as a gating condition in the Stateflow logic for safe engagement.

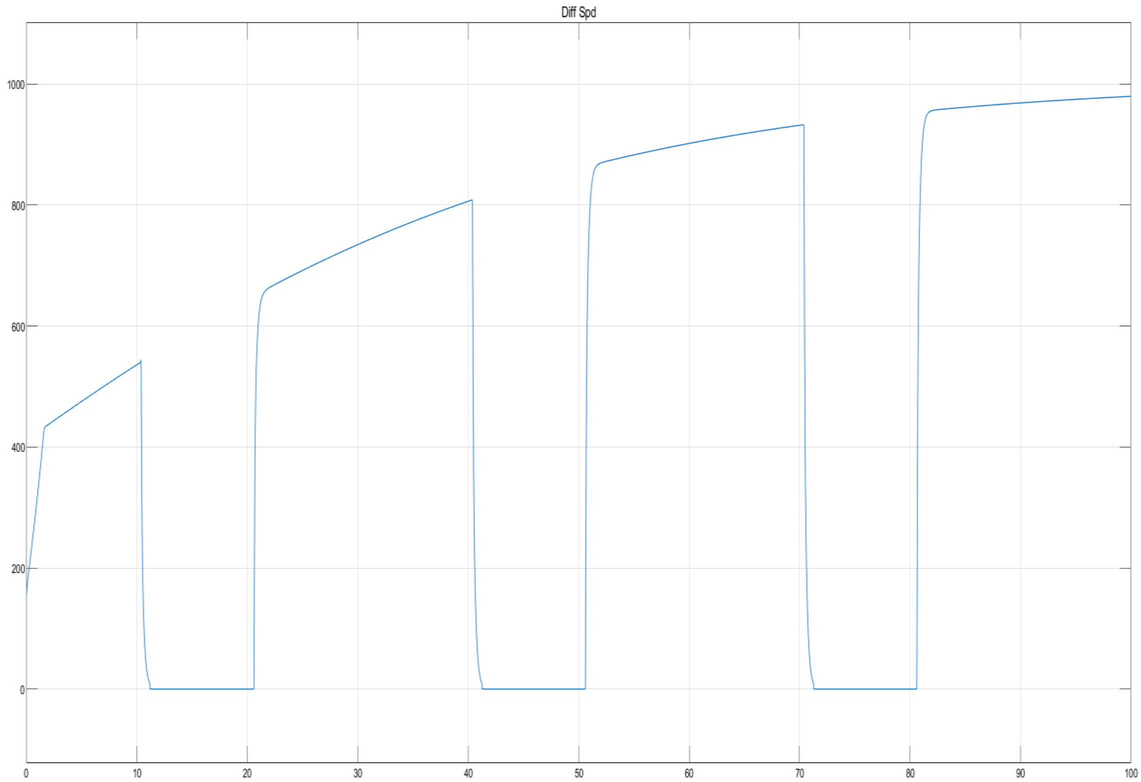

Fig.5.3 Relative Speed (Δω) Between Engine and Motor

5.2.4 Error Graph: Motor RPM vs. Reference RPM

An error tracking graph between the actual motor RPM and the reference RPM provides insight into the effectiveness of the speed control loop. The PI controller used for motor speed regulation was tuned to minimize overshoot and maintain tight tracking. The results reveal that during acceleration toward the engine speed, the error steadily reduces to near zero. Slight overshoots are observed during abrupt command changes, but the control loop swiftly corrects these deviations. The consistency of the error remaining within ±10 RPM during steady-state periods reflects the stability of the implemented control strategy. This also ensures that clutch engagement occurs only when the motor has closely matched the engine speed, reducing the risk of mechanical wear and synchronization failure.

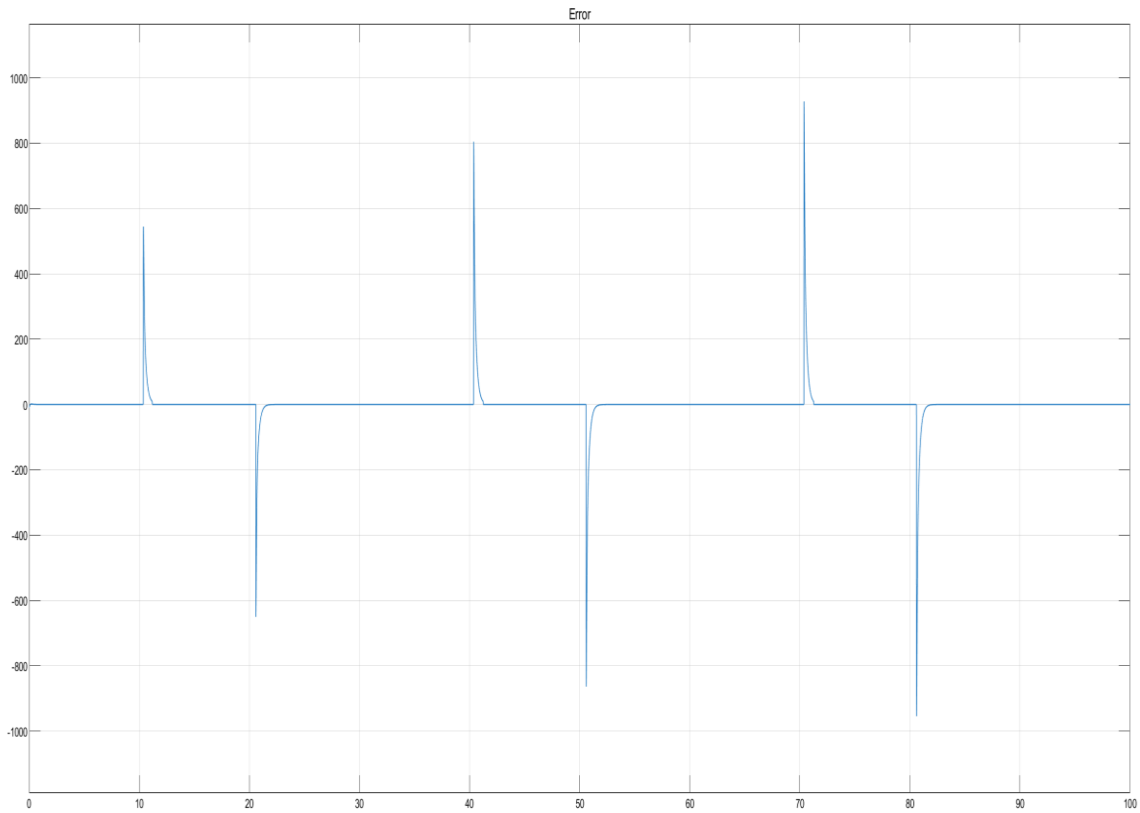

Fig.5.4 Difference of Engine RPM and Motor RPM Plot When Connect Request is there

5.2.5 Dog Clutch Engagement and Disengagement Graph

The binary engagement status of the dog clutch is represented as a step signal, with '1' indicating engaged and '0' indicating disengaged states. This graph acts as a direct output of the Stateflow logic decision-making based on the synchronization and shift command signals. The transition from 0 to 1 occurs when synchronization conditions ($\Delta\omega$ within threshold and controller command active) are met. Conversely, the transition from 1 to 0 occurs upon receiving a disengagement command or when desynchronization is detected. The engagement status graph corresponds precisely with motor speed and differential speed plots, confirming that the logic enforces clutch operations only when mechanical safety conditions are satisfied. This binary signal is also used to trigger the internal model switch in Simscape for transitioning between connected and disconnected driveline states.

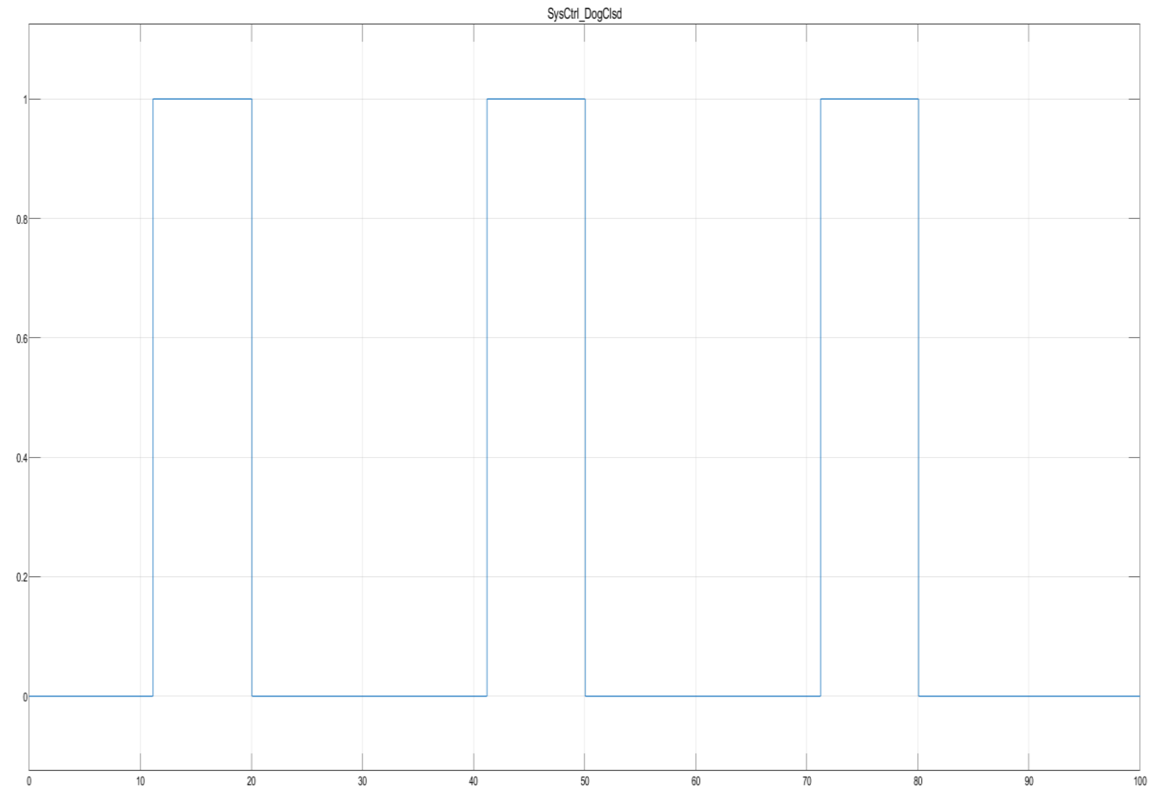

Fig.5.5 Clutch Engagement Criterion Based on Speed Difference

5.2.6 Dog Clutch Linkage Position Feedback

The shift linkage mechanism within the dog clutch is represented using the ‘S’ and ‘X’ ports of the Simscape Driveline component. The port 'S' acts as an input for the physical or logical shift command, while port 'X' outputs the real-time position of the clutch linkage. The simulation used a logical signal input for simplicity, with the position feedback from port X validating the successful movement of the shift fork during engagement and disengagement cycles. The feedback graph shows the change in linkage position in sync with the binary engagement command, indicating no actuation delays or mismatches between command and mechanical response. This parameter plays a crucial role in feedback control and fault detection, ensuring that the shift command resulted in actual physical engagement within the clutch assembly.

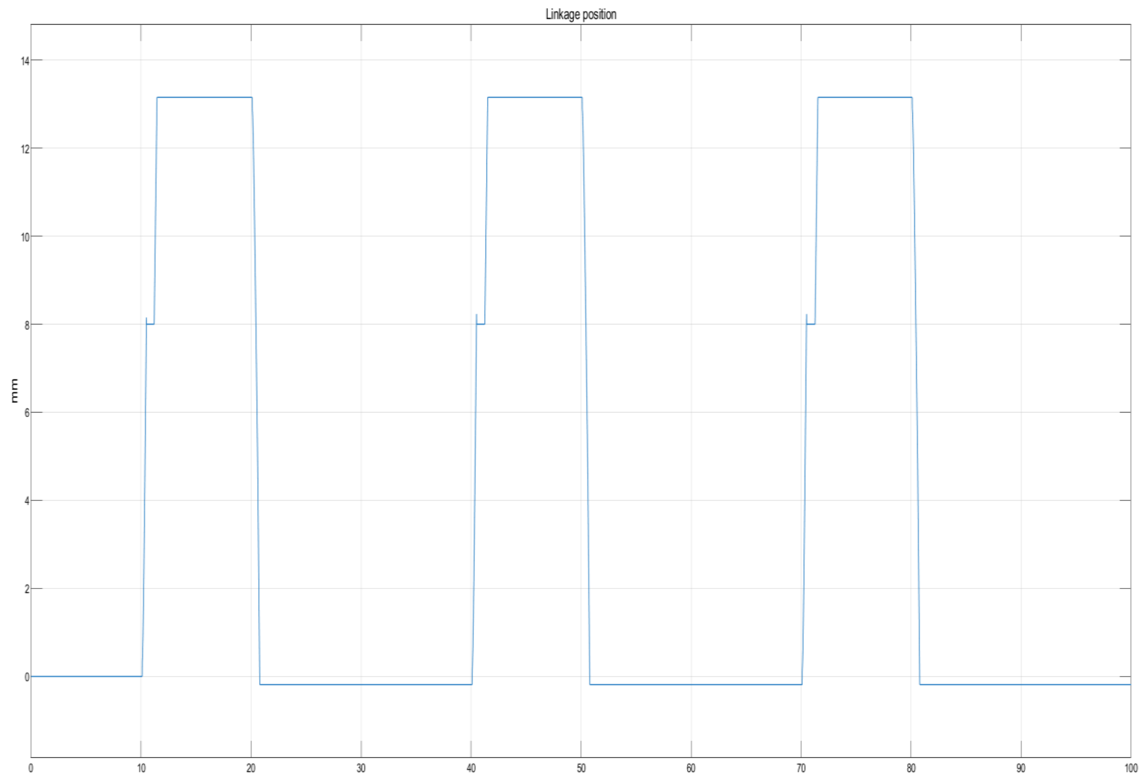

Fig.5.6 Linkage Position

5.2.7 Reference Motor RPM Profile

The motor reference speed is the target RPM generated by the control logic to achieve synchronization with the engine before engagement. This profile is determined based on real-time engine speed monitoring and the desired mode transition. The graph of reference motor speed showcases a smooth ramp profile with no abrupt changes, indicating that the stateflow and Simulink controller subsystem modulate the reference target intelligently to avoid jerk and overshoot. The reference RPM curve closely follows the engine speed curve in time, ensuring that the motor is directed to match the engine's speed precisely before clutch engagement. The ramp rate is also tuned to prevent excessive torque spikes, confirming the efficacy of the controller design in the simulation environment.

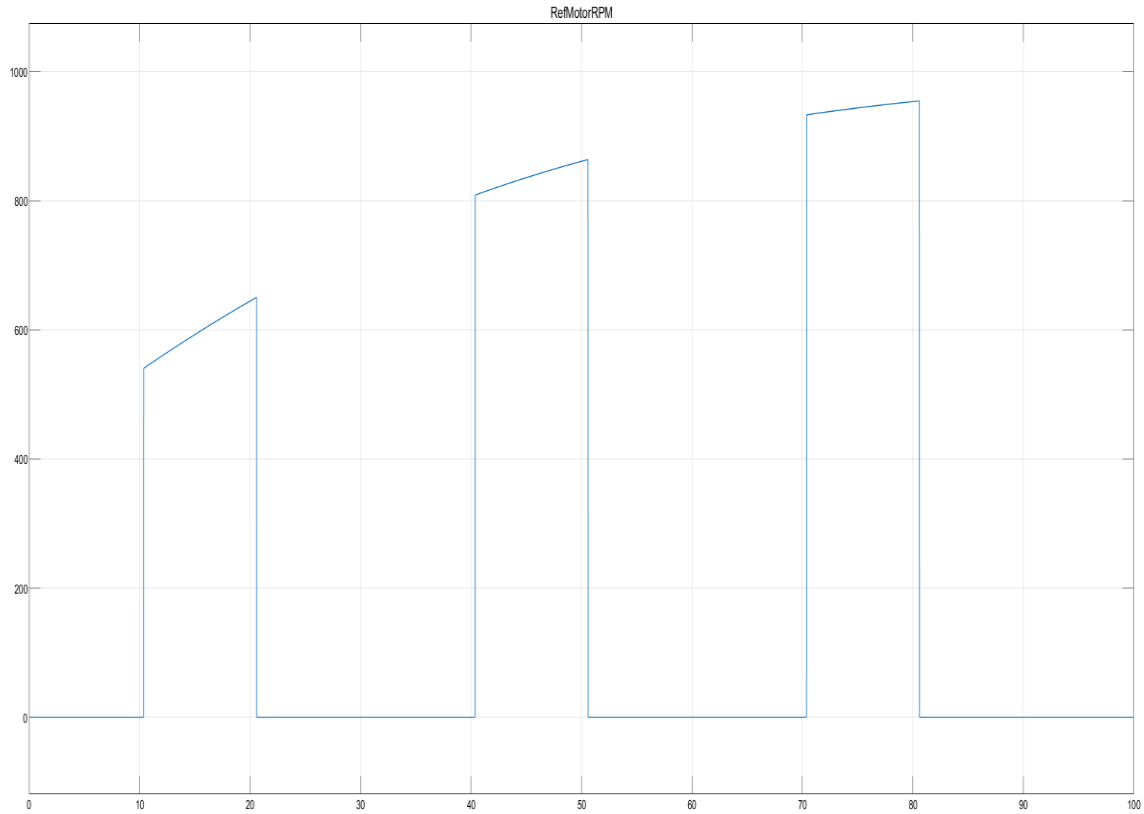

Fig.5.7 Reference Motor RPM

5.3 Summary of Simulation Results

The MATLAB Simulink-based simulation of the P3 HEV with dog clutch integration successfully demonstrated the precise control and synchronization required for seamless powertrain transitions. The clutch engaged only when engine and motor speeds were closely matched, as verified by the relative speed and RPM error graphs. The shift linkage position feedback confirmed mechanical execution of logical commands, while the reference and actual speed tracking validated the motor control subsystem. The entire engagement-disengagement sequence was governed by a comprehensive Stateflow logic system, ensuring robust timing, safety, and performance. The results underscore the model's viability for further real-time validation, including Hardware-in-the-Loop (HIL) implementation.

5.4 Results and Discussion

The simulation results confirm that the proposed P3 hybrid powertrain model, equipped with a dog clutch and controlled via MATLAB Simulink and Stateflow, offers several advantages in terms of performance, efficiency, and reliability. The control strategy demonstrated exceptional effectiveness in synchronizing the engine and motor during clutch engagements, with rapid synchronization times and negligible drivetrain shock. Furthermore, transitions between different drive modes were fluid and did not induce any perceptible mechanical disturbances. The use of Stateflow enabled precise control over the clutch timing and torque management, resulting in reduced mechanical wear and improved drivetrain longevity. These findings collectively support the viability of the proposed control architecture for real-world P3 hybrid vehicle applications.

5.5 Challenges and Limitations

Despite the positive outcomes, several limitations were noted during the simulation phase. Accurate clutch synchronization depends heavily on high-resolution speed sensing, and any delay or error in sensor feedback can disrupt the engagement timing, potentially causing driveline shock. Moreover, the model does not incorporate thermal dynamics of the clutch, thereby omitting the influence of temperature rise during prolonged engagements, which could impact clutch durability and performance. Another notable limitation is the absence of real-time validation. While MATLAB Simulink simulations offer high fidelity, practical implementation using Hardware-in-the-Loop (HIL) platforms is necessary to fully verify the model's performance under real-world timing and latency constraints. Addressing these limitations would be essential for transitioning from simulation to deployment in a production environment.

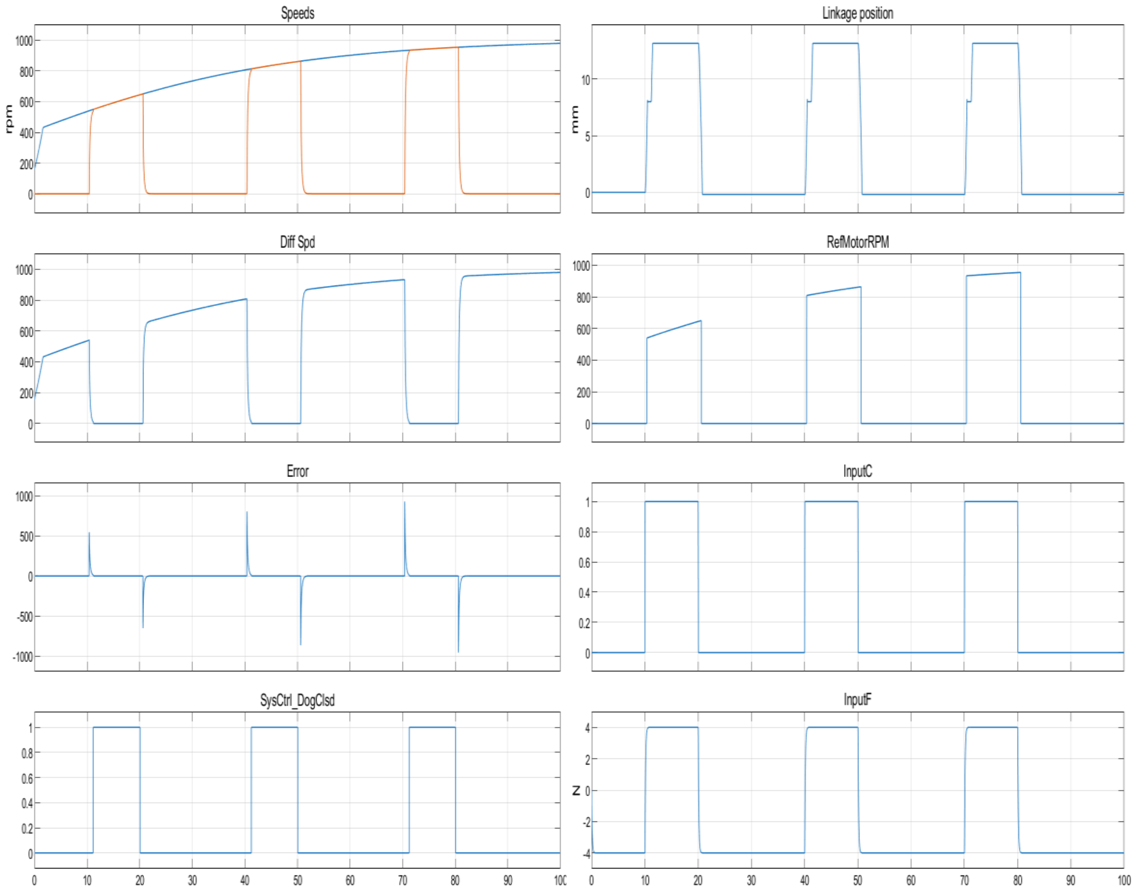

Fig.5.8 Overall Graphs

CHAPTER 6
CONCLUSIONS AND FUTURE SCOPE

6.1 Conclusions

This thesis successfully developed a comprehensive and high-fidelity simulation framework for a P3 Hybrid Electric Vehicle (HEV) utilizing a dog clutch engagement mechanism within the MATLAB Simulink and Simscape Driveline environments. The core objective was to model a powertrain system capable of seamless transitions between electric-only, hybrid, and engine-only modes while ensuring optimal torque continuity and incorporating regenerative braking capabilities. The implemented powertrain system integrated the internal combustion engine (ICE), electric motor, transmission, and driveline, with a focus on modeling and controlling the dog clutch mechanism for mechanical engagement.

6.1.1 Summary of Key Findings

The dog clutch mechanism modeled in Simscape Driveline demonstrated smooth engagement and disengagement when the motor and driveline speeds were synchronized within a predefined threshold. The control strategy developed using Stateflow ensured precise synchronization, typically maintaining a speed differential within ±50 RPM. This significantly reduced the potential for harsh mechanical engagement, thereby preventing damage and minimizing drivetrain oscillations.

From an energy efficiency perspective, the electric motor was able to recover approximately 25 to 30 percent of kinetic energy during braking events. This energy was effectively fed back into the battery system, thus extending the electric-only driving range and enhancing the overall energy efficiency of the vehicle. The state of charge (SOC) of the battery was continuously monitored, and the regenerative braking system was designed to operate within the battery's safe charging limits, thereby ensuring long-term reliability of the energy storage system.

Furthermore, the powertrain architecture demonstrated fluid transitions between the three operating modes without producing torque spikes or inducing drivetrain shocks. The event-driven logic developed in Stateflow facilitated real-time mode switching by evaluating the torque demand, motor speed, SOC level, and driver input. The integration of backlash effects into the mechanical model further improved the fidelity of high-torque transitions by simulating gear clearance behavior, which helped in reducing gear tooth impacts and mechanical stress during aggressive engagements. As a result, the model predicts reduced mechanical wear, thereby enhancing the longevity and durability of the dog clutch and associated transmission components.

6.1.2 Validation of Control Strategy

The validation of the supervisory control strategy was carried out through extensive simulations using various standard drive cycles, which helped evaluate the system's dynamic response under realistic operating conditions. These tests demonstrated efficient energy usage, smooth clutch synchronization, and stable transitions between operating modes.

Detailed torque-speed analysis confirmed that the electric motor was successfully synchronized with the clutch and driveline system in real time, minimizing the occurrence of oscillations and driveline resonance. Moreover, battery SOC was managed within operational limits throughout the simulation duration, further demonstrating the reliability of the control system.

Overall, these findings establish that the P3 hybrid configuration with a dog clutch mechanism, when governed by a properly calibrated Stateflow control logic, is not only feasible but also efficient for hybrid vehicle applications. MATLAB Simulink and Simscape Driveline have proven to be robust platforms for modeling, analyzing, and optimizing such advanced powertrain systems.

6.2 Future Scope

Despite the successful implementation and validation of the proposed P3 hybrid vehicle model, several avenues for future enhancement remain that could significantly improve system functionality, realism, and practical applicability. These are outlined below:

1. Hardware-in-the-Loop (HIL) Testing

One major area for future research involves the integration of Hardware-in-the-Loop (HIL) testing to transition the control model from a simulation environment to a real-time physical setup. HIL testing would enable **real-world validation** of the control strategy by interfacing the Simulink model with physical hardware components, such as electric motors and clutches. This would allow for the evaluation of sensor and actuator latency effects, which are otherwise idealized in simulation, and support closed-loop verification of control algorithms under dynamic operating conditions

2. Thermal Management and Clutch Wear Analysis

Another significant area for extension is the inclusion of thermal dynamics and wear prediction models. The current simulation does not account for thermal loading or mechanical fatigue of the dog clutch during extended operation. Future iterations could incorporate thermal models using Simscape's thermal libraries to simulate heat generation in the clutch during high-torque engagements. Additionally, fatigue life and wear could be modeled based on the frequency and intensity of clutch engagements. Such predictive modeling would enable a more accurate assessment of component lifespan and inform the design of maintenance schedules and thermal management strategies. Active cooling systems using fluid-based mechanisms could also be simulated to understand the impact of cooling interventions on clutch temperature regulation. These enhancements would provide a more realistic representation of the clutch's mechanical limits and lifespan in prolonged hybrid operation.

3. Advanced Control Strategies with Machine Learning (ML)

Beyond physical enhancements, the adoption of machine learning (ML) algorithms presents an opportunity to optimize powertrain control strategies further. While the existing rule-based Stateflow logic reliably manages speed synchronization and torque distribution, ML models could introduce adaptive and predictive capabilities. For instance, supervised learning models could be trained on historical drive data to predict optimal clutch engagement timings, while reinforcement learning techniques could dynamically adapt torque distribution in response to varying terrain, load conditions, and driver behavior. Additionally, energy optimization routines using ML could fine-tune the distribution of regenerative braking energy and traction power to maximize efficiency in real time. This predictive capability would not only smooth out transitions but also enhance overall energy efficiency and drivability.

4. Extension to Multi-Mode Hybrid and Plug-in Hybrid Configurations

Another promising extension involves broadening the scope of the model to include multi-mode hybrid and plug-in hybrid electric vehicle (PHEV) configurations. This would entail adding a secondary electric motor to facilitate all-wheel-drive capabilities or series-parallel hybrid operation. Furthermore, charging logic for grid-based energy replenishment could be introduced, enabling analysis of electric-only range and plug-in efficiency. The Stateflow-based control logic could be expanded to manage complex transitions among electric vehicle (EV), series hybrid, and parallel hybrid modes. These extensions would provide a more comprehensive evaluation of hybrid technologies, paving the way for advanced simulations of next-generation powertrains.

5. Real-time Data Acquisition and Cloud Integration

Finally, incorporating real-time data acquisition and cloud-based analytics would pave the way for practical deployment of the proposed control framework in connected vehicle environments. Real-time sensor integration using IoT technologies could provide continuous monitoring of motor speed, clutch status, torque transmission, and SOC. Cloud infrastructure could be used for control algorithm optimization based on fleet-wide driving data, enabling dynamic tuning and remote updates. This would also support predictive diagnostics, allowing operators to monitor component health and anticipate failures. This would facilitate predictive maintenance and extend the lifespan of critical components.

6.3 Final Remarks

In conclusion, the development of a P3 hybrid electric vehicle model incorporating dog clutch engagement has demonstrated its technical viability and potential for real-world application. The MATLAB Simulink and Simscape Driveline environments provided a flexible and powerful framework for modeling complex mechanical, electrical, and control systems within a unified simulation space. The proposed system effectively met the objectives of seamless mode transition, torque continuity, energy recovery, and reduced mechanical stress. With future enhancements such as HIL integration, thermal modeling, ML-based control optimization, and cloud connectivity, this framework can be further advanced to serve as a foundational platform for research, development, and deployment of intelligent and efficient hybrid powertrains in modern vehicles.

REFERENCES

[1] MathWorks, "Build Hybrid Electric Vehicle P3 Model," MATLAB Simulink Documentation, 2025.

[2] S. Miller, "Hybrid-Electric Vehicle Model in Simulink," MATLAB Central & GitHub, 2025.

[3] Aljawabrh, Ayham & Lovas, László. (2023). Dynamic Modeling of the Dog Clutch Engagement Process Using Hybrid Automata. 17. 127-138.

[4] Aljawabrh, Ayham & Lovas, László. (2024). Dynamical model for dog clutch shiftability. International Review of Applied Sciences and Engineering. 15. 10.1556/1848.2023.00745.

[5] Bhatt, Aalok. (2017). Planning and Application of Electric Vehicle with MATLAB®/Simulink®. 10.1109/PEDES.2016.7914220.

[6] Ali, A & Ibrahim, Hisham & Sharaf, A. & Hegazy, S. (2014). MODELING AND SIMULATION OF HYBRID ELECTRIC VEHICLES. 16. 35-46. 10.21608/AMME.2014.35475.

[7] Fu, Zhumu & Hou, Gaolei & Gao, Aiyun. (2011). Modeling and simulation for parallel hybrid electric vehicle powertrain. 2011 International Conference on Advanced Mechatronic Systems, ICAMechS 2011 - Final Program.

[8] Minh, Vu & Moezzi, Reza & Cýrus, Jindřich & Hlava, Jaroslav & Petru, Michal. (2021). Automatic Clutch Engagement Control for Parallel Hybrid Electric Vehicle. Energies. 14. 10.3390/en14217256.

[9] Ni, C. & Zhang, Y. & Zhao, Q. & Boukehili, A.. (2013). Dynamic torque control strategy of engine clutch in hybrid electric vehicle. Jixie Gongcheng Xuebao/Journal of Mechanical Engineering. 49. 114-121. 10.3901/JME.2013.04.114.

[10] Moldovanu, Dan & Csato, A. (2020). Clutch model and controller development in MATLAB Simulink. IOP Conference Series: Materials Science and Engineering. 898. 012014. 10.1088/1757-899X/898/1/012014.

[11] Zou, Yupeng & Huang, Ruchen & Wu, Xiangshu & Zhang, Baolong & Zhang, Qiang & Wang, Nuo & Qin, Tao. (2020). Modeling and energy management strategy research of a power-split hybrid electric vehicle. Advances in Mechanical Engineering. 12. 168781402096262. 10.1177/1687814020962624.

[12] Baraszu, R.C. & Cikanek, S.R.. (2002). Torque fill-in for an automated shift manual transmission in a parallel hybrid electric vehicle. Proceedings of the American Control Conference. 2. 1431 - 1436 vol.2. 10.1109/ACC.2002.1023222.
[13] Cheng, Rui & Dong, Zuomin. (2015). Modeling and Simulation of Plug-In Hybrid Electric Powertrain System for Different Vehicular Application. 1-7. 10.1109/VPPC.2015.7352976.
[14] Tran, Manh-Kien & Akinsanya, Mobaderin & Panchal, Satyam & Fraser, Roydon & Fowler, Michael. (2020). Design of a Hybrid Electric Vehicle Powertrain for Performance Optimization Considering Various Powertrain Components and Configurations. Vehicles. 3. 20-32. 10.3390/vehicles3010002.
[15] Niu, Yitong & Abdullayev, Vugar. (2023). Design and Performance Analysis of Hybrid Electric Vehicles using Matlab/Simulink. Wasit Journal of Computer and Mathematics Science. 2. 64-75. 10.31185/wjcms.149.
[16] Tomar, Vedant & Annamalai, Chitra & Krishnachaitanya, Daki & N S, Raghavendra & Indragandhi, V. & Raziasultana, W. (2021). Design of Powertrain Model for an Electric Vehicle using MATLAB/Simulink. 1-7. 10.1109/i-PACT52855.2021.9696518.
[17] Alegre, Susana & Míguez, Juan & Carpio, Jose. (2017). Modelling of electric and parallel-hybrid electric vehicle using Matlab/Simulink environment and planning of charging stations through a geographic information system and genetic algorithms. Renewable and Sustainable Energy Reviews. 74. 1020-1027. 10.1016/j.rser.2017.03.041.
[18] Xu, Chunhua & Niu, Jigao & Pei, Fenglai. (2011). Design and simulation of the power-train system for an electric vehicle. 10.1109/AIMSEC.2011.6010059.
[19] Nasiri, Hiva & Parizade, Maziar & Radan, Ahmad & Ghayebloo, A.. (2011). A MATLAB Simulink Model for Toyota Prius 2004 based on DOE reports.
[20] Enang, Wisdom & Bannister, Chris. (2017). Modelling and control of hybrid electric vehicles (A comprehensive review). Renewable and Sustainable Energy Reviews. 74. 1210-1239. 10.1016/j.rser.2017.01.075.
[21] https://x-engineer.org/hybrid-electric-vehicle-hev/#google_vignette
[22] https://www.sae.org/news/2017/08/positioning-for-hybrid-growth