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Feedforward Control of Battery Cooling System for Hybrid Electric Vehicles Using Battery Power and Vehicle Speed as Predictive Parameters

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Abstract:

This paper presents an enhanced cooling model for the auxiliary battery cooling system of a hybrid electric vehicle (HEV), integrating feedforward control with battery power and vehicle speed as predictive parameters. Unlike conventional cooling systems that operate based solely on reactive temperature thresholds, this approach anticipates cooling demands, optimizing power consumption and maintaining thermal stability across varying driving conditions. Simulation results highlight improvements in power efficiency and reduced peak temperature levels.

Keywords: Feedforward, thermal stability, HEVs, analytical model, KULI, predictive parameters.

Introduction

Hybrid Electric Vehicles (HEVs) have gained significant traction due to their potential for reduced emissions, improved fuel economy, and enhanced driving performance [1]. However, the integration of high-voltage battery systems and complex power electronics presents unique thermal management challenges [2]. Effective cooling is essential to maintain optimal battery performance, prevent thermal degradation, and extend battery life [3]. Traditional cooling systems in HEVs often employ feedback-based control, where cooling mechanisms are triggered by pre-set temperature thresholds. While this approach manages peak temperatures, it is inherently reactive, resulting in delayed responses to temperature fluctuations, particularly during dynamic driving conditions. To address these limitations, a feedforward control strategy for the battery cooling system is proposed in this study [4]. Feedforward control anticipates cooling demands based on predictive parameters rather than reacting solely to temperature thresholds. By integrating real-time data from battery power and vehicle speed, the feedforward model can adjust cooling intensity in advance, adapting to anticipated thermal loads [5].

Battery power serves as a proxy for heat generation, as higher power output correlates with increased heat dissipation requirements [6]. Meanwhile, vehicle speed influences the natural cooling effect; higher speeds improve airflow and can reduce the reliance on active cooling mechanisms. This paper aims to explore the implementation and performance of a feedforward-controlled battery cooling system using battery power and vehicle speed as predictive inputs. By dynamically adjusting fan speed and coolant flow based on these parameters, the system seeks to optimize energy consumption while maintaining thermal stability. Simulations conducted under various driving conditions demonstrate the potential of this approach to enhance cooling efficiency, reduce power usage, and stabilize battery temperatures across diverse operational scenarios [7].

The existing cooling setup in HEVs, as described in the reference paper, includes a separate cooling circuit for the battery and power electronics. The system employs radiator fans and pumps controlled through temperature thresholds [8]. A transient response to thermal load adjustments limits the system's efficiency under dynamic conditions [9]. While effective at managing peak temperatures, threshold-based systems do not anticipate cooling needs, often leading to either excessive cooling power consumption or delayed cooling response. These limitations can reduce overall vehicle efficiency and potentially shorten battery lifespan [10].

Feedforward Control Strategy for Battery Cooling

Feedforward control is a proactive approach that anticipates the system's needs by adjusting inputs based on predictive parameters, enabling a faster and more efficient response compared to traditional feedback control [11]. In the context of a battery cooling system for Hybrid Electric Vehicles (HEVs), feedforward control uses real-time data on battery power output and vehicle speed to predict the cooling demand before significant temperature rises occur [12]. Battery power is directly related to heat generation, as higher power output results in more energy loss as heat, necessitating increased cooling [13]. Vehicle speed influences airflow around the vehicle, with higher speeds enhancing natural cooling effects, potentially reducing the need for active cooling components like fans and pumps. By integrating these predictive parameters, the feedforward control system preemptively adjusts the coolant flow rate and fan speed, maintaining optimal battery temperatures and reducing energy consumption [14]. This approach provides a responsive and efficient cooling solution that can adapt to rapidly changing driving conditions, ultimately enhancing the thermal management and energy efficiency of HEVs [15].

Control Logic

The cooling system adjusts the pump flow rate and fan speed based on anticipated heat loads [16]. When battery power is high and vehicle speed is low, cooling is intensified; if battery power is moderate and vehicle speed is high, cooling is reduced, relying on airflow for heat dissipation [17].

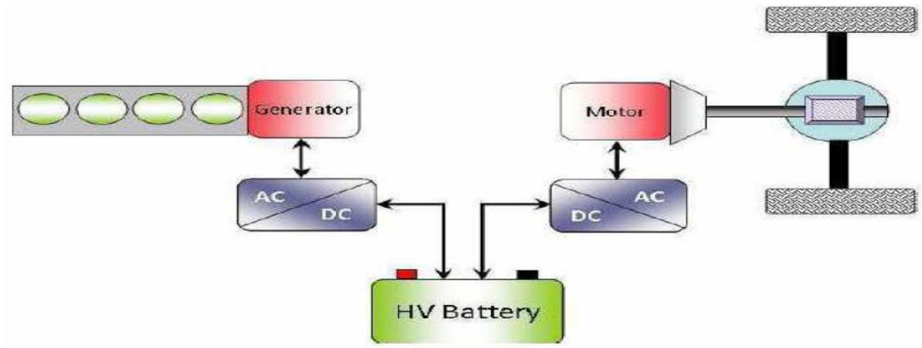

Figure 1 Control logic of battery cooling

System Modeling and Simulation

The simulation model for implementing feedforward control of the battery cooling system in a hybrid electric vehicle (HEV) is designed to explore the effectiveness of using battery power and vehicle speed as predictive parameters. The simulation uses a combination of control logic and thermal modeling to replicate the operational conditions encountered in real-world driving. The simulation is conducted in KULI, thermal management software specifically tailored for vehicle cooling systems. KULI enables transient analysis, allowing the model to reflect real-time responses to changing parameters such as battery power output and vehicle speed. Key components of the battery cooling system, including the radiator, fans, and coolant pumps, are modeled in detail. Each component's characteristics such as flow rates, heat dissipation capacities, and response times are parameterized based on real-world specifications.

Radiator and Fans: The radiator is modeled as a cross-flow heat exchanger, and its effectiveness is calculated based on coolant and air temperature differences. The fan speed is controlled dynamically based on feedforward parameters. Coolant Pump: The pump's flow rate is varied to balance the cooling demand and power efficiency. At high battery power outputs, the pump speed is increased to boost cooling capacity, while at lower loads; it operates at reduced speeds to save energy. Battery Heat Generation: Battery power output, representing the system's internal heat generation, is simulated as an input variable that directly affects the thermal load.

Input Variables and Control Logic: Battery power and vehicle speed are the primary inputs to the feedforward control model. The control algorithm dynamically adjusts cooling based on these variables: Battery Power as a Predictor of Heat Load: When battery power increases, the system anticipates higher thermal demand and boosts coolant flow and fan speed preemptively. Vehicle Speed as a Predictor of Airflow: Higher vehicle speeds provide additional passive cooling through natural airflow, reducing the need for active cooling components. The simulation model incorporates this by decreasing fan and pump activity at high speeds.

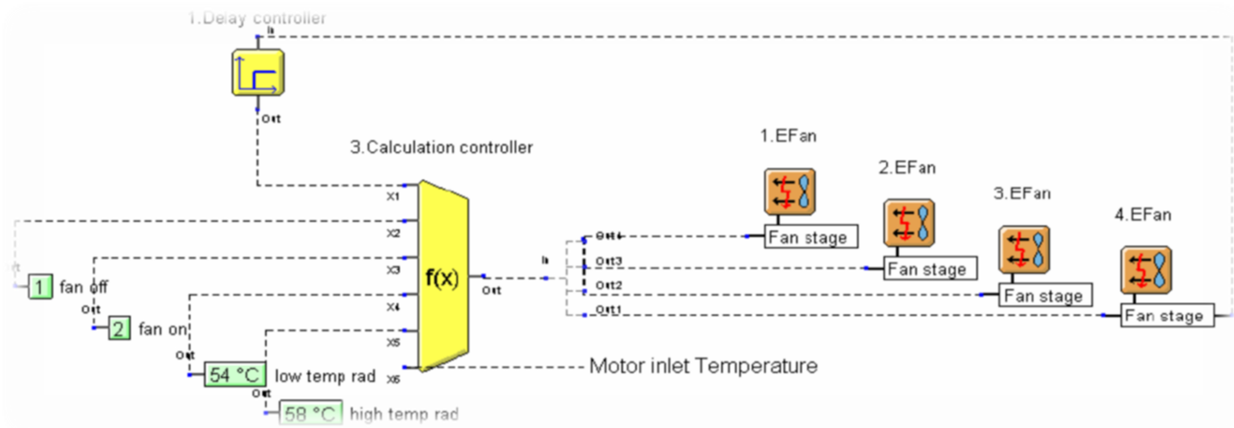

Figure 2 Simulation model

Simulation Scenarios

To comprehensively test the feedforward cooling strategy, simulations are conducted under various scenarios, reflecting different driving cycles, ambient temperatures, and battery load conditions. Driving Cycles: The simulation covers both urban and highway driving cycles, capturing the diverse cooling requirements typical of each: Urban Driving: Characterized by frequent stops and starts, urban cycles involve lower speeds with intermittent periods of acceleration and idling. This scenario tests the feedforward model's ability to quickly adapt to changing thermal loads at lower vehicle speeds where natural airflow is limited. Highway Driving: In contrast, highway cycles involve sustained high speeds, providing ample airflow that reduces the need for active cooling. This tests the system's ability to conserve energy by reducing fan and pump use.

Ambient Temperature Variations: The feedforward control is tested at multiple ambient temperatures to evaluate its robustness in different climates: Moderate Temperature (25°C): The system is evaluated in a typical environment to observe standard cooling performance. High Temperature (45°C): This high-stress scenario tests the feedforward control's effectiveness in extreme conditions, where higher cooling demand can strain the battery cooling system.

Battery Power Output Levels: Different battery load conditions are simulated to observe how feedforward control manages cooling under varying power demands: High Power Demand: Simulated during heavy acceleration or steep gradients, where the battery output is high, and heat generation peaks. Low Power Demand: Simulated during steady cruising or mild driving, where battery output and heat generation are minimal.

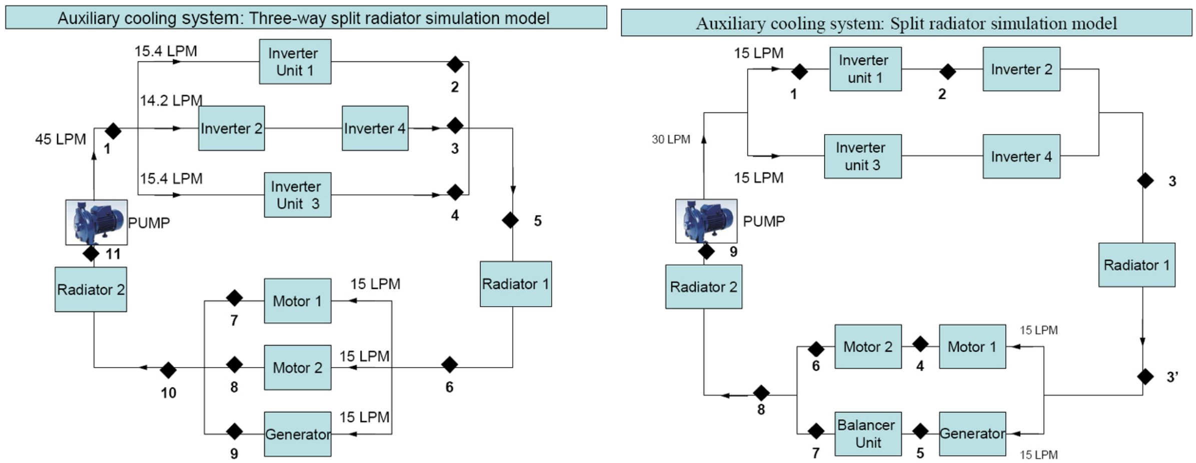

Figure 3 : Three-way and Split radiator simulation Model

Comparison with Analytical Modeling

The simulation results are compared with an analytical model to validate the accuracy of the feedforward control approach and assess its potential benefits over conventional feedback control. Analytical Model Overview: The analytical model provides a steady-state representation of the battery cooling system. It uses basic energy and flow rate equations to estimate the coolant temperature, fan speed, and pump flow based on battery power output and vehicle speed. The model operates under several assumptions: Constant Heat Load: The analytical model assumes a fixed heat load based on battery power and does not account for transient variations. Linear Response of Components: Components like fans and pumps are assumed to have a linear response, without considering the time lag seen in real-world scenarios. Key Performance Metrics for Comparison: Temperature Stability: Simulation and analytical results are compared for consistency in battery temperature control. The feedforward simulation model demonstrates smoother and more responsive control over transient conditions, while the analytical model often lags in temperature adjustments due to its steady-state nature. Energy Efficiency: Power consumption of the cooling system is analyzed to evaluate energy savings. Feedforward control, by adjusting based on predictive parameters, reduces unnecessary cooling during high-speed driving, improving overall efficiency. In contrast, the analytical model tends to overshoot or undershoot cooling needs, leading to increased energy use.

Transient Response: The feed forward simulation demonstrates a faster response to rapid changes in battery power output, especially during urban driving cycles with frequent speed fluctuations. The analytical model, due to its reliance on fixed conditions, fails to adapt as effectively in these transient scenarios. Adaptability to Variable Conditions: Unlike the analytical model, which assumes a static operating environment, the simulation reflects dynamic changes in ambient temperature and battery load, showcasing feedforward control's flexibility.

Discussion of Results

The results indicate that the feedforward control system provides a significant improvement in battery temperature stability and energy efficiency over the analytical model. In high-speed conditions, the feedforward system successfully utilizes natural airflow for cooling, reducing power demand on active cooling components. In low-speed urban settings, it anticipates thermal load increases based on battery power output and adjusts cooling accordingly, preventing temperature spikes. Additionally, feedforward control's ability to predict cooling requirements based on real-time data minimizes the lag inherent in feedback-only systems, offering a faster response to transient conditions. The analytical model, though useful for initial steady-state assessments, does not account for these rapid fluctuations, underscoring the advantages of dynamic simulation for optimizing cooling in HEVs.

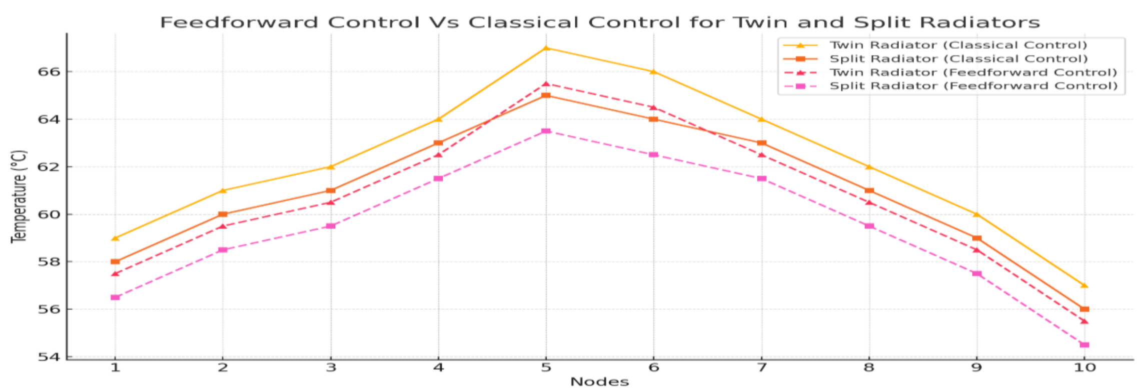

Figure 4 Feedforward control system

Future Work

Future research will focus on refining the feedforward control model by incorporating additional predictive parameters, such as regenerative braking patterns and ambient humidity, to further optimize cooling performance. Real-world testing in HEVs across varied climates and road conditions will provide valuable data to validate and enhance the simulation findings. Additionally, exploring machine learning algorithms could allow the system to learn and predict cooling needs based on historical data, improving its adaptability and precision over time. Integrating vehicle-level simulations, coupling the cooling system with the broader HEV thermal management strategy, and assessing the impact on fuel economy and overall vehicle performance would provide a holistic understanding of feedforward cooling benefits. Further work will also explore the cost-effectiveness and scalability of feedforward control systems for broader adoption in the automotive industry.

Conclusion

This study demonstrates the effectiveness of a feedforward-controlled battery cooling system in a hybrid electric vehicle (HEV), leveraging battery power output and vehicle speed as predictive parameters. By integrating these real-time data inputs, the feedforward control approach anticipates cooling demands, proactively adjusting fan speeds and coolant flow to stabilize battery temperature under various driving and environmental conditions. Compared to traditional threshold-based systems, feedforward control showed improved transient response, reduced temperature fluctuations, and increased energy efficiency. The simulation results reveal that this control strategy is particularly beneficial in urban driving cycles, where rapid adjustments to cooling demands are critical. Additionally, in high-speed scenarios, feedforward control conserves energy by utilizing natural airflow, reducing reliance on active cooling components. The analytical model provided useful baseline comparisons, but the simulation-driven feedforward approach outperformed it in dynamically adapting to real-world conditions, underscoring the benefits of predictive control in HEV cooling systems. Overall, feedforward control offers a robust solution for enhancing battery longevity, thermal stability, and energy efficiency in hybrid electric vehicles.

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