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# MECHATRONIC CONTROL ALGORITHM FOR AN AUTOMOTIVE COOLING SYSTEM FAN

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**Abstract:**
This paper investigates a mechatronic control algorithm aimed at improving the operational efficiency and optimizing the energy consumption of a passenger car cooling system fan. The negative impacts of the conventional ON/OFF (switching) method on system stability, electrical grid current surges, and the mechanical durability of motors are analyzed. To simultaneously ensure the operational economy and thermal stability of the system, an adaptive mechatronic control algorithm is considered, which modifies control parameters in accordance with the current operating modes of the engine. In the proposed mechatronic system, the fan voltage and rotation speed are controlled in a stepped and smooth manner according to temperature variations. The advantages of the proposed algorithm are evaluated for high ambient temperatures and heavy urban traffic conditions. The results indicate that mechatronic control allows for reducing mechanical loads on fan motors, saving electrical energy, and maintaining the engine temperature stably within the optimal operational range.

**Keywords:** cooling system, fan, mechatronic control, ON/OFF algorithm, adaptive control, thermal stability, energy efficiency, passenger car, voltage regulation

## 1. Introduction

A mechatronic-controlled cooling system enables real-time management of engine and radiator heat exchange processes. The primary objective of the system is to maintain the engine temperature within an optimal range, matching the coolant flow through the pump and fan with the heat dissipation capacity of the radiator. Through this approach, excess heat is rapidly rejected, energy consumption is optimized, and the engine operates stably.

The cooling system features a closed control loop to manage engine temperature and coolant temperature in real time. The mathematical model of the system takes into account the engine heat balance, fluid flow, radiator and fan efficiency, and control signals.

To simultaneously ensure the operational economy and thermal stability of the system, an adaptive mechatronic control algorithm that modifies control parameters according to the current operating modes of the engine is synthesized in this section.

The main objective of the algorithm is to track the optimal temperature trajectory in real time, minimizing fuel consumption and component power losses.

## Literature Review

In the automotive industry, managing the thermal state of internal combustion engines and reducing energy consumption are ongoing, critically important areas of continuous improvement [1]. Particularly, the operation of passenger cars at low speeds in urban conditions or under high ambient temperatures drastically increases the load on the cooling system [2]. Fan control algorithms play a crucial role in mitigating these challenges [3]. Although conventional ON/OFF (relay) control systems, which have been widely used in automobiles for many years, are structurally simple, they fail to fully satisfy modern efficiency requirements [4]. International studies demonstrate that the abrupt activation of the fan only at minimal or maximal modes in the ON/OFF system induces several operational drawbacks [5]. Firstly, the frequent and sharp switching of the fans causes significant current surges (initial inrush currents) in the electrical system, imposing an excessive load on the onboard electrical network [6]. Secondly, such drastic changes in mechanical loads severely reduce the service life of fan motors and increase noise levels [7]. To address these issues, stepped and smoothly adjustable mechatronic systems are being actively studied in reputable scientific journals [8]. In the mechatronic approach, the fan rotation speed is continuously adjusted using pulse-width modulation (PWM) or electronic voltage regulators in accordance with real-time temperature signals obtained from sensors [9]. Such flexible (adaptive) control algorithms ensure that the fan operates at the minimum power required to dissipate the current heat flux without consuming excess energy [10]. Foreign researchers note that by activating the fan step-by-step and in anticipation (before the temperature reaches a critical point), the thermal inertia of the system is successfully compensated [11]. This prevents sudden spikes or excessive dropping of the engine temperature [12]. Consequently, the coolant temperature is maintained within a narrow and optimal range, which enhances the mechanical efficiency of the engine and reduces harmful exhaust emissions [13], [14], [15].

Scientists in our Republic have also conducted specific scientific research on improving the thermal balance and enhancing the operational characteristics of automobiles. However, scientific justification of the flexibility characteristics of algorithms and comparative analysis of mechatronic fan control efficiency against conventional systems—specifically accounting for local climate conditions (extreme summer heat and urban traffic congestion)—warrant more extensive research.

## Materials and Methods

For many years, conventional relay control circuits based on automatic on/off (ON/OFF) logic have been utilized to organize the operation of fans in passenger car cooling systems. In this traditional system, only the coolant temperature of the internal combustion engine is accepted as the input parameter. The operation algorithm of the system and the output control voltage are determined based on conditions featuring two strictly fixed values:

$$\begin{cases} T_e \leq 96\ ℃, \quad bo'lsa \quad U = 8\,V \\ T_e \geq 103\ ℃, \quad bo'lsa \quad U = 14{,}5\,V \end{cases} \tag{1}$$

If the engine temperature is 96 °C or lower, the fan operates in an 8 V voltage mode, which ensures the minimum rotation speed. In the event that the engine load increases and its temperature reaches 103 °C or higher, the control signal abruptly switches to the maximum voltage level of 14.5 V. The system continues to operate in this high-power mode until the temperature drops back down to 96 °C. Such a discrete transition characteristic does not allow for a smooth acceleration of the fan motor, which induces severe inductive current surges in the onboard electrical network and drastically increases the mechanical load imposed on the structural elements of the fan (Figures 1 and 2).

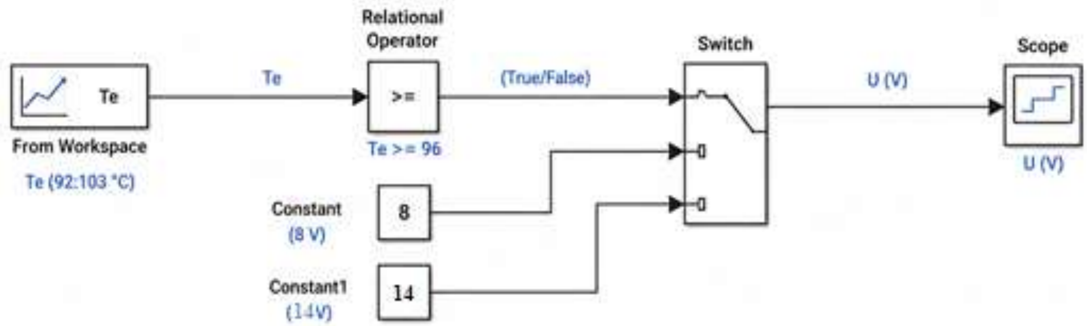



**Figure 1.** Simulink model of the conventional cooling system engine fan control algorithm

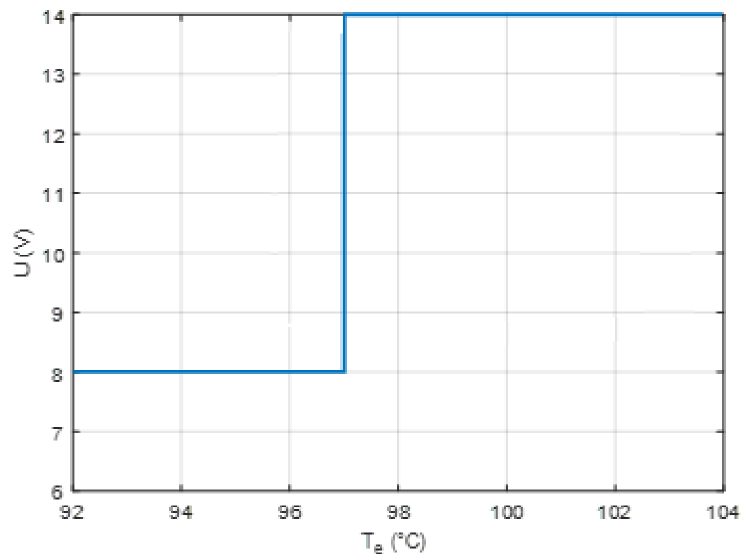


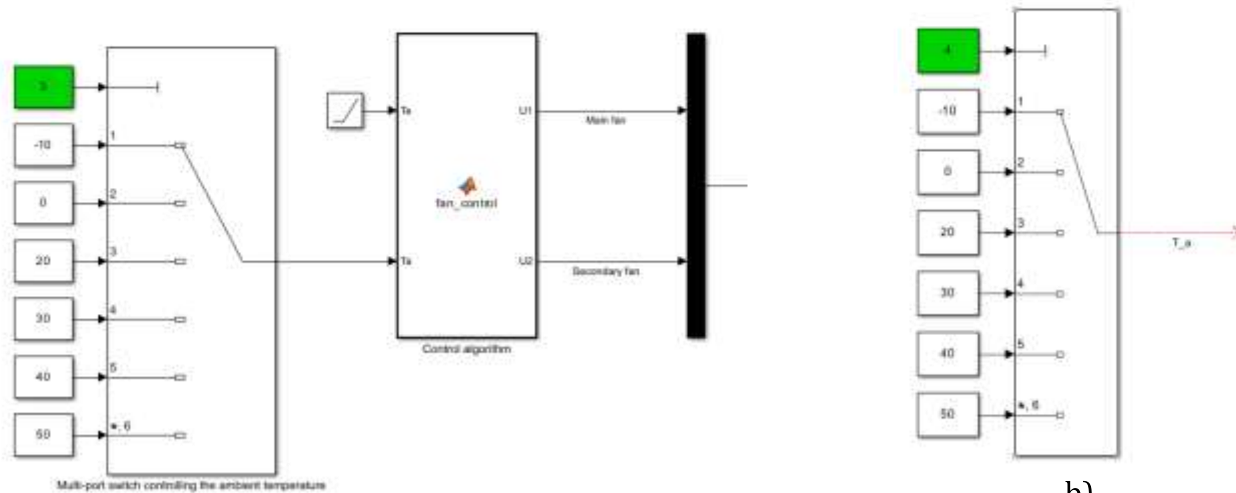

**Figure 2.** Description of the conventional cooling system engine fan control algorithm

In investigating the cooling system dynamics of vehicles, identifying the optimal operational ranges for various driving modes through experimental methods can be highly time-consuming. A robust system simulation tool can significantly reduce the development time and costs associated with these complex systems. Such tools must also be capable of co-simulating effectively with vehicle simulation software and be applicable for evaluating different control algorithms [16].

The MATLAB Simulink environment serves as a convenient platform for modeling automotive mechatronic systems. Utilizing this software environment, it is possible to develop virtual representations of complex technical systems, test control algorithms, model sensor and actuator behaviors, and perform real-time signal analysis. One of the primary advantages of the Simulink environment is its graphical modeling capability, which allows the user to represent complex mathematical formulas through block diagrams. Consequently, modeling automotive cooling systems in Simulink is widely applied in scientific research and practical engineering problem-solving [17], [18].

This Simulink model was developed to investigate the mechatronic control logic of an internal combustion engine cooling system. The system determines the operating modes of the cooling fans based on two primary input parameters: engine temperature and ambient temperature.

The control model consists of the following functional blocks (Figure 3a).




a) b)

**Figure 3.** Simulink model of the mechatronic-controlled cooling system:
a) fan control algorithm; b) multi-port switch controlling the ambient temperature

The ambient temperature generation section consists of six constant value blocks and a single multi-port switch. This group of blocks allows the researcher to model various climatic conditions, namely temperature ranges of -10÷0 °C, 0÷10 °C, 10÷20 °C, 20÷30 °C, 30÷40 °C, and 40÷50 °C. A specific temperature range is selected using the switch and transmitted to the control block (Figure 3b).

A ramp signal generator is utilized in the section representing the engine temperature. This block simulates the engine temperature rise over time. This serves to observe how the system behaves under dynamic conditions and the sequence in which the fans are activated when the temperature reaches critical points.

A specially programmed functional block serves as the central part of the control system. Complex logical conditions (the algorithm) are integrated within this block, which analyzes the incoming temperature signals. The function of the block is to calculate the most optimal voltage level for each specific temperature pair. Here, the control does not merely consist of switching on or off, but is instead implemented by varying the voltage step-by-step.

The output section features two independent channels, which are routed to the main and auxiliary fans. The signals passing through these channels are transmitted to a visualization device via a combining block (Figure 4).

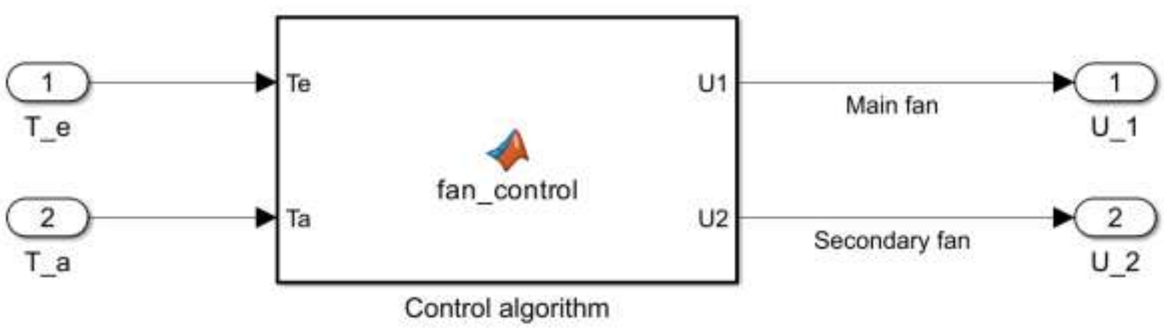



**Figure 4.** Diagram of signal transmission from the control block to the fans and the control algorithm

The developed mechatronic control system executes adaptive control in accordance with the ambient temperature. At low ambient temperatures, the fans are utilized minimally to save energy, whereas under high-temperature conditions, the cooling system operates with maximum efficiency. The stepped control of the fans reduces electrical energy consumption, lowers mechanical loads, and extends the operational lifespan of the cooling system.

## Results and Discussion

The mathematical imitation modeling results obtained in the MATLAB/Simulink environment theoretically prove that the mechatronic cooling system possesses higher efficiency in both static and dynamic operating modes compared to conventional mechanical systems. The transient characteristics and timing diagrams obtained within the scope of the study allowed for a comprehensive analysis of how the thermal balance of the engine is maintained under various vehicle operational conditions.

The results obtained for the automotive mechatronic cooling system based on ON/OFF control and mechatronic control are illustrated (Figure 5). The graphs provide a comparative analysis of the changes in the main fan, auxiliary fan, and ON/OFF control signals relative to variations in the engine temperature.

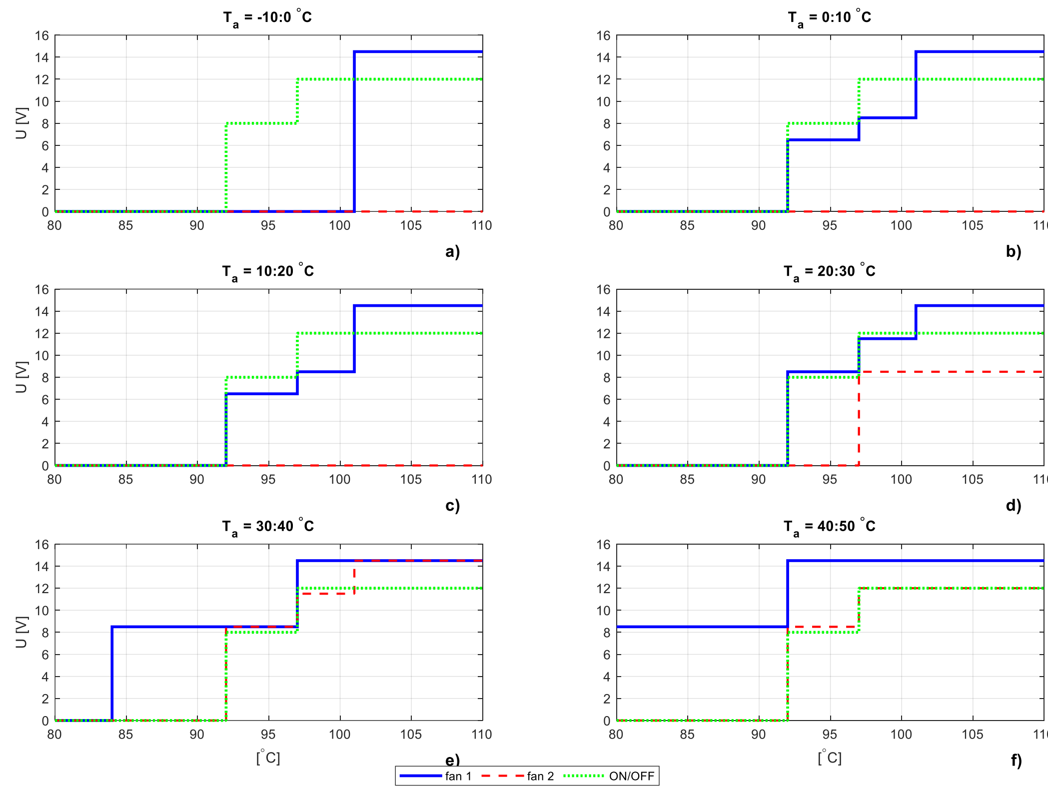



**Figure 5.** Comparative analysis of results obtained based on ON/OFF control and mechatronic control of the automotive mechatronic cooling system

Each graph is plotted for a specific ambient temperature range, covering the intervals of −10÷0 °C, 0÷10 °C, 10÷20 °C, 20÷30 °C, 30÷40 °C, and 40÷50 °C. In the mechatronic control system, the fans are managed in a stepped manner corresponding to the engine temperature. At the initial temperature, the fans operate in a minimal mode or do not start at all. As the temperature rises, the rotation speed and voltage of the main fan gradually increase. At critical temperature values, the auxiliary fan is also activated, and the cooling intensity is significantly enhanced. Consequently, the engine temperature is maintained within the optimal range, and overheating is prevented. In low ambient temperature ranges (Figures 5a, b, c), namely within the −10÷0 °C and 0÷10 °C intervals, a delayed activation of the fans is observed. This ensures that the engine reaches its operating temperature more quickly and prevents overcooling under cold conditions. Conversely, in high ambient temperature ranges, the fans are activated much earlier (Figures 5d, e, f). Especially within the 30÷40 °C and 40÷50 °C ranges, the main fan begins to operate actively around 80÷84 °C. This enables the cooling system to engage before the engine reaches critical temperatures. In the ON/OFF control system, however, the fans operate in only two states, meaning they are either fully turned on or completely off. As seen from the graphs, the ON/OFF control signal abruptly shifts to a high value when a certain temperature threshold is reached (Figure 5a). As a result, the fan operates at its maximum mode. The primary disadvantage of this method is the frequent switching on and off of the fans and the increased electrical energy consumption. Furthermore, the sharp fluctuations in mechanical loads reduce the service life of the fan motors.

## Conclusion

The mechatronic control system distinguishes itself by operating much more efficiently than the ON/OFF control. In mechatronic control, the fan voltage changes in a stepped and smooth manner, ensuring a smooth cooling process. Consequently, the mechanical load imposed on the fan motors is reduced, current surges in the electrical system are minimized, and the overall operational stability of the cooling system is enhanced. The advantages of mechatronic control are vividly manifested under high ambient temperature conditions. This is because, in this system, the fans are activated progressively in anticipation, and the cooling intensity is automatically regulated according to temperature variations. This prevents sudden spikes in engine temperature and ensures the thermal stability of the system. Another significant advantage of the mechatronic control system is its energy efficiency. Since the fans are utilized only in the required modes, the load on the vehicle's alternator and battery is reduced. As a result, the overall efficiency of the automotive electrical system increases. Additionally, the smooth regulation of the fans minimizes acoustic noise and enhances system operational comfort.

Moreover, a smooth and stable variation of the control signals was observed in the obtained results. The absence of sharp oscillations indicated that the system is dynamically stable. This confirms that the mechatronic cooling system possesses a suitable and efficient control algorithm for real vehicle operation. The results demonstrate that the developed Simulink model works effectively in optimizing the thermal state of the automotive engine.

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