IMPROVING ON-OFF CONTROL SOLUTIONS TO ENHANCE ENERGY EFFICIENCY FOR RESIDENTIAL AIR CONDITIONERS

CẢI TIẾN GIẢI PHÁP ĐIỀU KHIỂN ON-OFF NHẰM NÂNG CAO HIỆU QUẢ NĂNG LƯỢNG CHO MÁY ĐIỀU HÒA KHÔNG KHÍ DÂN DỤNG

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(Received: January 16, 2026; Revised: April 01, 2026; Accepted: April 17, 2026)

DOI: 10.31130/ud-jst.2026.24(5A).037

Abstract - ON-OFF control was widely used in older air conditioning systems due to its simplicity and low cost. However, choosing an inappropriate temperature fluctuation range can lead to longer operating times, increased power consumption, frequent on/off cycles, and reduced lifespan. This paper proposes an improved control solution that increases the temperature fluctuation range while maintaining comfort. A mathematical model of room thermal balance is constructed and used to evaluate the effectiveness. The results show that the improved control solution can reduce operating time, reduce the number of starts, and save energy while maintaining a reasonable temperature fluctuation range. The proposed method is simple, effective, highly applicable, and does not require changes to the system hardware.

Key words - ON-OFF control; air conditioning; energy saving, control solutions; residential HVAC

Tóm tắt - Điều khiển ON–OFF được sử dụng rộng rãi trong các hệ thống điều hòa không khí trước đây do đơn giản và chi phí thấp. Nhưng nếu chọn biên độ dao động nhiệt độ không phù hợp có thể dẫn đến thời gian vận hành dài, tiêu thụ điện tăng, máy đóng ngắt nhiều lần và tuổi thọ giảm. Bài báo này đề xuất một giải pháp điều khiển cải tiến, điều chỉnh tăng biên độ dao động nhiệt, nhưng vẫn đảm bảo yếu tố tiện nghi. Một mô hình toán học cân bằng nhiệt của phòng được xây dựng và dùng đánh giá hiệu quả làm việc. Kết quả cho thấy giải pháp điều khiển cải tiến có thể giảm thời gian vận hành, giảm số lần khởi động, tiết kiệm điện năng trong khi vẫn duy trì biên độ dao động nhiệt độ hợp lý. Phương pháp đề xuất đơn giản, hiệu quả và có tính ứng dụng cao, không đòi hỏi thay đổi phần cứng của hệ thống.

Từ khóa - điều khiển ON-OFF; điều hòa không khí; tiết kiệm năng lượng; giải pháp điều khiển; HVAC dân dụng.

1. Introduction

Electricity consumption by residential air conditioning systems accounts for a significant proportion of the total electricity consumption of households, particularly in regions with hot and humid climates. Among the control methods currently in use, ON–OFF control remains a fairly common method due to its simple structure, high reliability, and low investment cost. In this method, the compressor operates at its rated capacity when the room temperature exceeds a specified threshold and stops when the temperature drops below another threshold.

Despite its structural advantages, traditional ON–OFF control has several limitations, such as long daily operating time, frequent compressor switching, and low energy efficiency, especially under part-load conditions. These limitations not only increase electrical energy consumption but also affect thermal comfort and compressor lifespan.

In recent years, many studies have focused on advanced control methods such as inverter control, fuzzy control, and control with a cooling anticipator. However, these methods often require more complex hardware and higher investment costs. Therefore, improving the ON–OFF control algorithm to enhance operating efficiency without increasing cost is a research direction with high practical significance.

This paper proposes an improved ON–OFF control solution based on a mechanism that increases the hysteresis band while still ensuring comfort conditions, with the aim of reducing operating time, decreasing the number of starts, and saving energy.

2. System description and mathematical model

2.1. Hermal model of the conditioned space

The conditioned space is modeled as a lumped thermal system with a uniformly distributed temperature. For the ON–OFF control system, during a day, the air conditioner alternately operates and stops; therefore, different heat balance equations are obtained:

- The energy balance equation of the room when the air conditioner is operating:

$$C_p \frac{dt_T(\tau)}{d\tau} = Q_{load}(\tau) - Q_{AC}(\tau) \tag{1}$$

- The heat balance equation when the air conditioner is stopped:

$$C_p \frac{dt_T(\tau)}{d\tau} = Q_{load}(\tau) \tag{2}$$

where: C_P is the thermal capacity of the room (J/°C);

$t_T(\tau)$ is the indoor air temperature, varying with time (°C);

$Q_{load}(\tau)$ is the heat load, varying with time (W);

$Q_{AC}(\tau)$ is the cooling capacity of the air conditioner, varying with time.

Thus, in order for the room temperature to decrease, $Q_{AC}(\tau)$ must necessarily be greater than $Q_{load}(\tau)$, and the difference between these two values determines the operating time of the unit.

2.2. Heat load model

The heat load consists of heat transfer through the building envelope and internal heat gains, and is determined by the following expression:

$$Q_{load}(\tau) = k.F.[t_N - t_T(\tau)] + Q_T \quad (3)$$

k is the equivalent heat transfer coefficient of the enclosing structure, W/m^2K;

F is the envelope area of the room, m^2;

$t_N(\tau)$ is the outdoor air temperature, ^oC;

$t_T(\tau)$ is the room temperature, ^oC.

$Q_T(\tau)$ is the internal heat load of the room, W.

2.3. Rule of room temperature variation

Substituting Equation (3) into Equation (1), we obtain:

$$C_P \frac{dt_T(\tau)}{d\tau} = kF\left[t_N - t_T(\tau)\right] + Q_T - Q_{AC}(\tau) \quad (4)$$

$$dt(\tau) = \left[A_1 - B.t(\tau)\right]d\tau \quad (5)$$

Solving Equation (5), the relationship between room temperature and time is obtained as follows:

- During the operating process (ON):

$$t(\tau) = \frac{A_1}{B} - C_1 e^{-B\tau} \quad (6)$$

- During the stopping process (OFF):

$$t(\tau) = \frac{A_2}{B} - C_2 e^{-B\tau} \quad (7)$$

where: $A_1 = \frac{k.F.t_N + Q_T - Q_{AC}}{C_P}$, $A_2 = \frac{k.F.t_N + Q_T}{C_P}$ and $B = \frac{k.F}{C_P}$

Based on Equations (6) and (7), the cooling time, stopping time, and number of stops of the unit can be determined.

3. Control solution

3.1. Traditional ON–OFF control

In traditional ON–OFF control, the compressor operates based on a fixed hysteresis band around the temperature setpoint:

$$Q_{AC}(\tau) = \begin{cases} Q_o, & \text{when } t_T(\tau) > t_d + \Delta t \\ 0, & \text{when } t_T(\tau) < t_d - \Delta t \end{cases} \quad (8)$$

where:

t_d is the room temperature setpoint, ^oC;

Δt is the temperature hysteresis, or one half of the control differential, ^oC;

Q_o is the rated cooling capacity of the air conditioner.

3.2. Proposed improved ON–OFF control solution

In this study, an improved ON–OFF control solution is proposed by adjusting the hysteresis band according to the degree of temperature deviation, which indirectly reflects the heat load condition of the room. The effective temperature hysteresis is determined as follows:

$$\Delta t_{hd} = \Delta t_{min} + m.\left|t_T(\tau) - t_d\right| \quad (9)$$

where:

Δt_{min} is the minimum temperature hysteresis. It is recommended that Δt_{min} = 0.3 ÷0.5 ^oC, as this range is suitable for sensors and corresponds to a temperature variation that humans cannot perceive.

m is the adjustment coefficient. Typically, m = 0.2 ÷ 0.6, and m =0.4 is selected in this study.

In the proposed solution, the control differential is not a fixed quantity but is dynamically adjusted through the control algorithm in the digital controller. This differential value depends on the instantaneous temperature deviation between the room temperature and the setpoint temperature, thereby allowing the system to adapt to the heat load state of the room.

Unlike inverter control, changing the control differential in this study does not change the instantaneous power of the compressor but only affects the switching moments.

The corresponding control law is written as follows:

$$Q_{AC}(\tau) = \begin{cases} Q_o, & \text{when } t_T(\tau) > t_d + \Delta t_{hd} \\ 0, & \text{when } t_T(\tau) < t_d - \Delta t_{hd} \end{cases} \quad (10)$$

This mechanism allows the temperature hysteresis to be expanded under low-load conditions or when thermal inertia is large, thereby reducing unnecessary compressor switching while still ensuring that the indoor temperature difference remains very small.

4. Performance evaluation criteria

The effectiveness of the control solutions is evaluated through the following quantitative criteria:

4.1. Electrical energy consumption

$$E = \int_0^T W(\tau).d\tau = \int_0^T \frac{Q_o(\tau)}{COP(\tau)}.d\tau, \text{ J} \quad (11)$$

where:

$W(\tau)$ is the electrical power consumption of the air conditioner, W

$Q_o(\tau)$ is the instantaneous cooling capacity of the refrigeration system, W.

$COP(\tau)$ is the instantaneous cooling efficiency, or coefficient of performance, of the system.

If the cooling capacity of the compressor and the coefficient of performance remain constant throughout the operating period, the electrical energy consumption is given by:

$$E = \frac{Q_o}{COP}.\tau \quad (12)$$

When the operating times of the two control methods are known, their electricity costs can be compared as follows:

$$\eta_E = \frac{E_1 - E_2}{E_2}.100\% = \frac{T_1 - T_2}{T_2}.100\% \quad (13)$$

T_1 and T_2 are the daily operating times of the air conditioner under traditional control and improved control, respectively.

4.2. Room temperature fluctuation

$$\Delta t = t_{max} - t_{min} \quad (14)$$

4.3. Compressor start frequency

Let N_{start} be the number of compressor starts within one day. We have:

$$N_{start} = \frac{24x60}{T} = \frac{24x60}{\tau_1 + \tau_2} \quad (15)$$

where: τ_1, τ_2 are the operating time and stopping time of the unit in one cycle, respectively, (min).

The operating times of the unit under the two control methods within one day are expressed as:

$$T_1 = N_{start}.\tau_{11}, \quad T_2 = N_{start}.\tau_{12} \quad (16)$$

τ_{11}, τ_{12} are the operating times of the unit under traditional control and the proposed improved method, respectively, in one cycle.

5. Simulation results and discussion

5.1. Simulation parameters

The mathematical model presented above is now applied to simulate a specific case: an office room with dimensions of 12 m in length, 6 m in width, and 3.5 m in height. The room parameters are presented in Table 1.

With the values given in Table 1, substituting them into Equations (6) and (7) gives the following:

- During the operating process, the rule of room temperature variation over time is:

$$t(\tau) = -9.33 - C_1 e^{-0.000042\tau} \quad (17)$$

- During the stopping process (OFF), the rule of room temperature variation over time is :

$$t(\tau) = 38.29 - C_2 e^{-0.000042\tau} \quad (18)$$

In Equations (17) and (18), time τ is expressed in seconds.

To determine the constants C_1 and C_2 in the above equations, the boundary conditions are used:

For the operating process, at τ=0, $t(0) = t_{max}$

For the stopping process, at τ=0, $t(0) = t_{min}$

Table 1. *Room parameters*

No	Parameter	Symbol	Data
1	Equivalent heat transfer coefficient of the room	K	3.0 W/m^2K
2	The surrounding area of the room	F	126 m^2
3	Room heat capacity	C_k	9000 kJ/K
4	Internal heat load of the room	Q_T	2 kW
5	Rated cooling capacity of the air conditioner	Q_o	18 kW
6	Set-point temperature of room	t_d	24 °C
7	Outdoor temperature	t_N	33 °C
8	Initial temperature, at the time τ=0 of the cooling process	t(0)	24.5 °C
9	Initial temperature, at the time τ=0 of the machine shutdown process.	t(0)	23.5°C
10	Temperature hysteresis using the ON-OFF method	Δt	0.5 °C
11	Minimum latency using the improved method	Δt_{min}	0.5 °C
12	Average latency using the improved method	Δt_{hl}	0.6 °C
13	Air conditioner cooling coefficient	COP	3

The determined coefficients C_1 and C_2 together with the operating and stopping times of the control methods in one cycle, are shown in Table 2.

Table 2. *Results of coefficient determination*

Control method	C_1, °C	C_2, °C
Traditional ON-OFF method	-33.83	14.79
Improvement method	-33.93	14.89

Based on formulas (17) and (18) with coefficients C1 and C2 in Table 2, the room temperature change pattern in one cycle is determined, shown in Figure 1 and Figure 2.

Figure 1 shows the room temperature change pattern using the ON-OFF control method. From this figure, we see that a working cycle from the first to the second machine operation takes 39.7 minutes, the running time is 11.9 minutes, and the stopping time is 27.8 minutes. Thus, on average, the machine switches on and off 37 times a day.

While Figure 2 shows the room temperature change pattern using the improved method. The data shows that a working cycle is 46.5 minutes, the running time is 13.1 minutes, and the stopping time is 33.4 minutes. Thus, the machine switches on and off 31 times a day.

Based on the number of working cycles and the running time in each cycle, the machine's running time in a day can be determined. With the ON-OFF method, the daily running time was 7.19 hours, while the improved method was only 6.76 hours.

The reduced running time resulted in energy savings. If losses due to startup are taken into account, the efficiency is even higher.

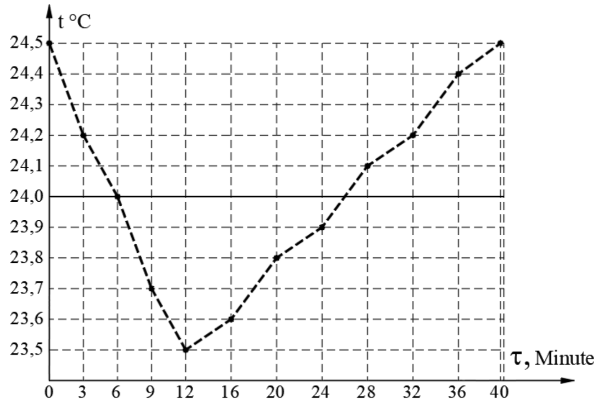

Figure 1. *Rule of room temperature variation using the traditional method in one cycle*

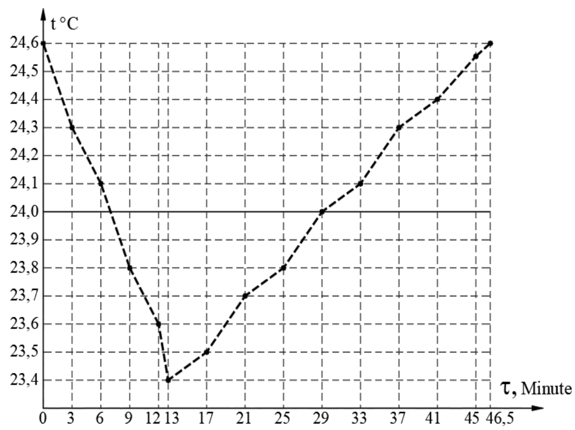

Figure 2. *Rule of room temperature variation using the improved method in one cycle*

Table 3 and Figure 3 show the calculated parameters of the two options:

- Option 1: Traditional ON-OFF control;

- Option 2: Improved ON-OFF control;

The most important parameters are the running time per cycle, the number of cycles (or the number of times the machine starts per day), the running time per day, and the daily electricity consumption for each option.

Table 3. *Calculated parameters for the two control methods*

Parameter	Symbol	Unit	Option 1	Option 2
Runtime in one cycle	τ1	Minute	11.9	13.1
The stopping time in one cycle	τ2	Minute	27.8	33.4
Time of Cycle	T	Minute	39.7	46.5
Average number of machine starts per day	N	Times /Day	37	31
Machine operating time per day	$T_{1,2}$	h	7.19	6.76
Average electricity consumption	E	kWh	43.2	40.6
Reduction in electricity consumption	η_E	%	-	**6.4 %**

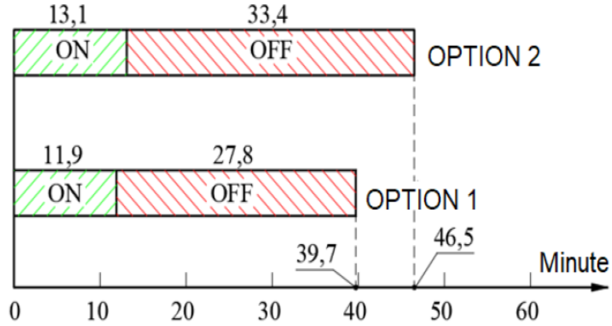

Figure 3. *Run/stop time graphs of the two options*

From Table 3 and Figure 3, it can be seen that the operating time per day under Option 2 is less. This is why the energy efficiency is 6.4% higher. If starting losses are included, the efficiency would certainly be even higher.

5.2. Results and analysis

The simulation results show that, with traditional ON–OFF control, the room temperature fluctuates within the range of 24 ± 0.5 °C around the setpoint, accompanied by a relatively high number of compressor switching operations, namely 37 times per day. When the improved ON–OFF control solution is applied, the fluctuation amplitude is increased to ±0.6 °C, but it remains within a range that humans cannot perceive, while the number of compressor starts is significantly reduced to only 31 times per day.

The analysis of electrical energy consumption shows that the proposed control method can save 6.4% of electrical energy compared with traditional ON–OFF control, depending on the heat load conditions.

5.3. Discussion

The energy savings calculated above are mainly achieved by reducing the operating time of the unit, without taking into account the losses caused by the starting process. If starting losses are considered, or if the temperature fluctuation amplitude is further increased, the effectiveness may be higher.

When the room temperature fluctuation amplitude is increased, the number of cycles decreases, and the actual operating time also decreases accordingly, contributing to energy savings. However, both energy efficiency and user comfort need to be considered. When the cycle duration increases, although the fluctuation amplitude is larger, the temperature rise rate is very slow, making the indoor environment still comfortable. Therefore, based on common practical experience, the fluctuation amplitude is often set at approximately ±1.0 °C. Another important factor is that the thermal inertia of the system may also cause the room temperature to increase or decrease beyond the amplitude set by the control device.

Although the proposed improved ON–OFF control solution does not regulate compressor capacity as inverter control does, it still demonstrates clear effectiveness in improving the operating efficiency of the system.

6. Conclusion

This paper has proposed an improved ON–OFF control solution for residential air conditioners by increasing the temperature fluctuation amplitude while maintaining it within a range that remains comfortable for users. The simulation results show that the proposed solution significantly reduces the operating time of the unit, decreases the start frequency, and saves electrical energy consumption. With its simple structure and no requirement for hardware modification, this method has high application potential in existing residential air conditioning systems.

Future studies will focus on the following aspects:

- Evaluating other modern control methods, such as inverter control in inverter air conditioners or cooling anticipators [3, 4, 5], in room temperature control to contribute to energy savings and user comfort.

- Determining the optimal room temperature fluctuation amplitude so that energy can be saved while comfort conditions are still ensured. This is a complex problem and is affected by many factors, including user physiology, room thermal inertia, and load level.

- Evaluating energy consumption costs when selecting the air conditioner capacity with a safety factor relative to the heat load, and recommending an appropriate selection range, such as $Q_o = (1{,}2\text{-}1{,}4)Q_{load}$.

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