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ENHANCING ENERGY REDUCTION IN BUILDING MULTI-CIRCUIT AIR CONDITIONING SYSTEMS USING A HIGH-PERFORMANCE DIGITAL CONTROLLER

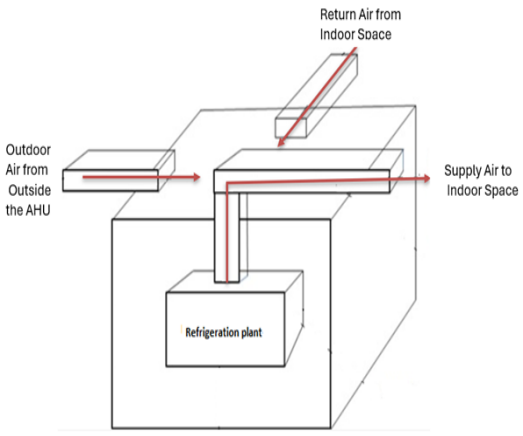
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Graphical abstract



Abstract

The substantial energy consumption of heating, ventilation, and air conditioning (HVAC) systems in buildings presents a critical challenge for global energy reduction and operational cost minimization. While extensive research addresses energy management in air conditioning, a significant gap persists in studies involving the practical application and evaluation of control strategies on operational centralized multi-circuit air conditioning systems. This paper addresses this gap by investigating the efficacy of a novel high-performance digital on/off control system. We implemented this digital controller on an installed and operational multi-circuit centralized air-cooled air-conditioning system and conducted a comparative analysis against its baseline energy usage. Experimental results demonstrate that the digital controller achieved significant energy savings of 12.6%, 18.9%, and 21.8% at temperature setpoints of 23°C, 24°C, and 25°C, respectively. These findings highlight the controller's capability to substantially improve the energy performance of existing multi-circuit centralized air conditioning systems, offering a practical and effective solution for enhanced building energy reduction.

***Keywords*:** Air Conditioning, Digital Controller, Energy Management

Abstrak

Penggunaan tenaga yang besar oleh sistem pemanasan, pengudaraan, dan penyaman udara (HVAC) dalam bangunan merupakan cabaran kritikal bagi pengurangan tenaga global dan peminimuman kos operasi. Walaupun penyelidikan meluas menangani pengurusan tenaga dalam penyaman udara, jurang yang signifikan masih wujud dalam kajian yang melibatkan aplikasi praktikal dan penilaian strategi kawalan ke atas sistem

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penyaman udara berpusat pelbagai litar yang sedang beroperasi. Kertas kerja ini menangani jurang tersebut dengan menyiasat keberkesanan sistem kawalan digital hidup/mati berprestasi tinggi yang baharu. Kami telah melaksanakan pengawal digital ini pada sistem penyaman udara berpusat sejukan udara pelbagai litar yang telah dipasang serta beroperasi, dan menjalankan analisis perbandingan terhadap penggunaan tenaga garis dasar. Keputusan eksperimen menunjukkan bahawa pengawal digital tersebut mencapai penjimatan tenaga yang signifikan sebanyak 12.6%, 18.9%, dan 21.8% masing-masing pada titik set suhu 23°C, 24°C, dan 25°C. Penemuan ini menonjolkan keupayaan pengawal tersebut untuk meningkatkan prestasi tenaga sistem penyaman udara berpusat pelbagai litar sedia ada secara substansial, sekali gus menawarkan penyelesaian praktikal dan berkesan bagi peningkatan pengurangan tenaga bangunan.

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1.0 INTRODUCTION

The escalating global energy demand necessitates more efficient energy consumption management [1], [2]. Buildings are significant energy consumers, accounting for approximately 40% of total global energy use, a figure projected to rise to nearly 50% with increasing population and energy requirements [3], [4], [5], [6]. A substantial portion of this consumption is attributed to Heating, Ventilation, and Air Conditioning (HVAC) systems [7], [8]. Therefore, effective energy management in building HVAC systems is crucial for mitigating operational costs and promoting environmental sustainability. Efficient HVAC operation leads to reduced utility bills, lower maintenance costs, and extended equipment lifespan. Furthermore, optimized HVAC management enhances indoor comfort by maintaining consistent temperature, humidity, and air quality, which is vital for occupant satisfaction and productivity.

Beyond cost and comfort, energy-efficient HVAC operations contribute significantly to environmental and regulatory objectives. Decreased energy usage directly translates to a reduction in greenhouse gas emissions and a minimized carbon footprint [10]. Many regions enforce stringent energy codes and green building standards, such as ASHRAE, which mandate effective HVAC energy management. The integration of smart technologies and building management systems facilitates real-time monitoring, predictive maintenance, and seamless integration with renewable energy sources, thereby increasing a building's value, resilience, and appeal to environmentally conscious occupants. The widespread adoption of air conditioning has notably impacted overall energy consumption [11], [12], [13]. Air conditioning systems function by transferring heat from the indoor environment to the outside air. This process involves the transfer of heat from the evaporator to the refrigerant, and subsequently from the refrigerant to the condenser. The compressor plays a pivotal role in this cycle, facilitating the movement of refrigerant from the evaporator to the condenser. Often referred to as the 'heart' of the HVAC system, the compressor's primary function is to compress the refrigerant gas, thereby increasing its pressure and temperature to enable heat rejection. This mechanism allows the HVAC system to extract heat from indoor air (in cooling mode) or transfer heat indoors (in heat pump mode), effectively conditioning the space.

The compressor's operation profoundly influences the efficiency and performance of the HVAC system. An optimally functioning compressor ensures peak system performance, maintains desired indoor temperatures, and maximizes energy efficiency. Approximately 90% of the energy consumed by an air conditioning system is attributable to the compressor [14]. Centralized air conditioning systems, particularly those with direct expansion, are commonly employed in commercial buildings. Many of these systems traditionally utilize an on/off control approach, which operates compressors at a constant speed [3]. This often results in maximum cooling capacity, leading to overcooling in some situations due to ineffective feedback mechanisms. Such operation wastes energy and compromises thermal comfort, especially under low cooling loads. This issue is prevalent in both single and multi-circuit refrigeration systems. Digital control methods have emerged as a promising solution to maintain thermal comfort while reducing energy consumption [15], [16]. These methods enable HVAC systems to modulate their output capacity in response to conditioned space temperature demands, offering improved temperature control and significant energy savings. Capacity control ensures that the system's cooling output precisely matches the varying cooling load of the conditioned space. However, much of the existing research and technological development in this area focuses on single-circuit air conditioning systems, typically tested in laboratory settings for domestic or small-scale office applications. There is a notable scarcity of studies concerning medium or large-scale multi-circuit package air conditioning systems [3], [17], [18]. Addressing this critical research gap, this study rigorously investigates the hypothesis that a high-performance digital on/off control system can

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significantly enhance energy efficiency and operational performance in an *operational* multi-circuit centralized air-cooled air conditioning system. This novel contribution lies in the empirical validation of this control strategy within a complex, real-world HVAC environment, moving beyond theoretical or laboratory-scale investigations. Multi-circuit refrigerant systems inherently offer a degree of flexibility in capacity control. For instance, an additional circuit can provide overcapacity relative to a building's typical cooling demand. During periods of normal cooling demand, one or more refrigerant circuits can be deactivated, with the remaining circuits adequately meeting the load. The additional refrigerant circuit is activated only when required, such as during hot and humid conditions when thermal loads are high. However, providing the necessary cooling demand through additional refrigerant circuits is costly due to the associated components, and capacity management is achieved through discrete phase increases rather than continuous variable adjustment, necessitating selective and regular activation or deactivation of circuits. Consequently, this paper analyzes the practical application of digital on/off control to optimize the operation of a multi-circuit centralized air-cooled air conditioning system.

2.0 METHODOLOGY

The experimental methodology employed in this study was adapted from prior research [3] and conducted at Universiti Teknologi Malaysia's Block D06, Language Academy. This specific building was selected as a representative case study due to its typical characteristics as a modern educational facility, encompassing standard commercial office spaces and operational hours that reflect common occupancy profiles in such environments. Its accessibility facilitated direct experimental intervention and data collection, providing a realistic platform for evaluating advanced control strategies in an active building system. The building's Air Handling Unit (AHU) was integrated with a two-circuit refrigerant air-cooled package unit. This multi-circuit configuration is particularly relevant for investigation as it is widely adopted in commercial and institutional buildings to enhance system reliability, operational flexibility, and provide partial capacity in the event of a single circuit failure [19]. Such systems are critical in environments like data centers, hospitals, and certain industrial processes where continuous and reliable temperature management is paramount. Each refrigeration circuit operates independently as a vapor compression cycle, comprising a compressor, condenser, expansion device, and evaporator, ensuring that the system can maintain partial cooling capacity even if one compressor fails [3], [5], [20].

The operational profile of the building, from 8:00 am to 5:00 pm, Sunday through Thursday, corresponds to typical academic and administrative working hours. This occupancy pattern generates predictable, yet variable, cooling loads, making it an ideal scenario to test the responsiveness and energy efficiency of the digital control system under realistic operating conditions. The office space served by the AHU represents a common indoor environment where thermal comfort and energy consumption are critical considerations. The baseline temperature for the air conditioning system was established at 24°C, serving as a control parameter for comparative analysis.

The air distribution sub-system, a critical component of any centralized air conditioning system, is responsible for efficiently delivering conditioned air and maintaining a comfortable and healthy indoor environment [1], [21]. Its proper design, installation, and maintenance are essential for optimal performance and energy efficiency. This subsystem distributes cooled air from the central unit to various zones within the building. The Air Handling Unit (AHU) plays a central role in this process, controlling and circulating air throughout the building's ductwork. AHUs regulate air temperature by heating or cooling it via coils connected to a boiler, chiller, or heat pump. Air from the building's interior is drawn into return air ducts and directed back to the AHU, where it mixes with fresh outside air. This mixed air then passes over the evaporator coil for cooling before being supplied to the indoor office spaces through supply air ducts. The air distribution system of the AHU is shown in figure 1

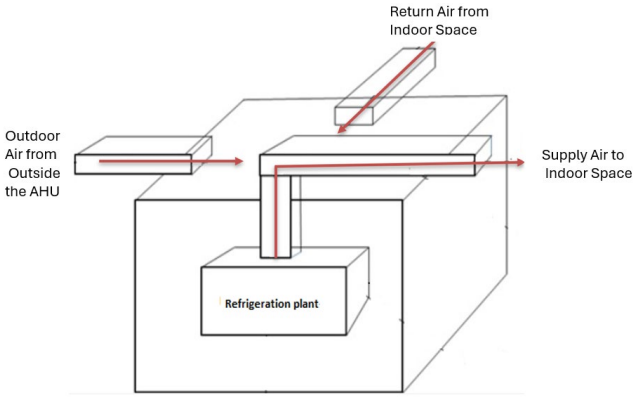


Figure 1 Schematic view of the AHU room.

A. Field work description

A multi-circuit centralised air cooled air conditioning system is housed in an air handling unit (AHU) room. The indoor space is an office environment for official activities and the average occupants is around 30 people. The focus of this research is to develop a control strategy for the control of temperature in a multi-circuit centralised air cooled air conditioning system, thus maintaining indoor thermal comfort whilst at the same time reducing energy consumption. The behavior of the multi-circuit centralised air-cooled air conditioning system was modelled in terms of the relationship between the indoor space air temperature and power consumption. The field measurement

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procedure was adopted from [3]. It is carried out by measuring different parameters as listed in table 1. Cloud based eazylog data loggers were used to collect data for temperature and humidity at different locations in the AHU, indoor and outdoor. The power consumption of the compressor is an important parameter, the CW240 power analyzer was used to measure the power consumption of the both compressor.

Table 1. Measured parameters.

No	Parameter
1	Power input to compressor 1 (kW)
2	Power input to compressor 2 (kW)
3	Temperature of Supply Air (°C)
4	Temperature of Mixed Air (°C)
5	Temperature of Return Air (°C)
6	Indoor Temperature (°C)
7	Outdoor Temperature (°C)
8	Supply Air Volumetric flow rate(m3/s)
9	Relative Humidity of Supply Air (%)
10	Relative Humidity of Mixed Air (%)
11	Relative Humidity of Return Air (%)
12	Relative Humidity of indoor Air (%)
12	Relative Humidity of outdoor Air (%)

B. Parameter Selection and Justification

The selection of measured parameters was meticulously designed to enable a comprehensive evaluation of the air conditioning system's energy performance, Coefficient of Performance (COP), and the effectiveness of the digital control strategy. These parameters are crucial for accurate energy modeling and for quantifying the energy savings achieved. The specific variables and their justifications are detailed below:The specific variables, their relevance to energy modeling, and their roles in COP and energy savings analysis are detailed in the table 2

Table 2. Parameters Justification.

Parameter	Relevance to Energy Modeling	Role in COP and Energy Savings Analysis
Power Input to Compressors (kW)	Direct measurement of HVAC energy consumption, crucial for baseline and model validation.	Denominator for COP (Cooling Capacity / Power Input). Quantifies energy savings by comparing consumption.
Temperatures (°C) (Supply, Mixed, Return, Indoor, Outdoor)	Critical for thermodynamic modeling; outdoor temperature influences cooling load, while indoor/supply/return define operational state.	Temperature differential with air flow calculates cooling capacity (numerator for COP). Indoor temperature indicates thermal comfort and control.
Supply Air Volumetric Flow Rate (m^3/s)	Fundamental for mass flow rate and heat/moisture transfer, a key input for AHU energy models.	Directly calculates cooling capacity. Essential for precise COP and understanding cooling load fulfillment.
Relative Humidity (%) (Supply, Mixed, Return, Indoor, Outdoor)	Enables psychrometric analysis, crucial for latent cooling loads and accurate energy models in humid climates.	Allows enthalpy calculation. Enthalpy difference with mass flow provides total cooling capacity for accurate COP. Indicates indoor air quality and comfort.

C. Digital On/Off controller design

In control systems, the on/off control is basically the easiest and simplest feedback system. They have two states in which the highest fixed state is 'ON' and the lowest fixed state is 'OFF'. The two compressors are installed with a soft starter to ensure the smooth starting and stopping of the compressors. Previously at block D06, the thermostat was installed at the AHU using the return air as feedback to control the two compressors to be in the 'ON' or 'OFF' mode. This method was found to be inefficient, thus making the system work inconsistently with the indoor condition. This resulted in waste of energy without achieving thermal comfort. In this phase of the study, the Digital On/Off controller is installed with thermocouple feedback from the indoor space to the AHU. The algorithm for the control is as stated below:

If $T_{IN} > T_{SP}$
Compressor 1: on
Compressor 2: on

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else If $T_{IN} \leq T_{SP}$
Compressor 1: on
Compressor 2: off
End

where
T_{SP} = Setpoint
T_{IN} = Feedback from indoor space air temperature

Figure 2 shows the schematic diagram of the control structure of the Digital On/Off control implemented at the AHU for digital control of both compressors, while figure 3 shows the pictures of the digital controller as installed.

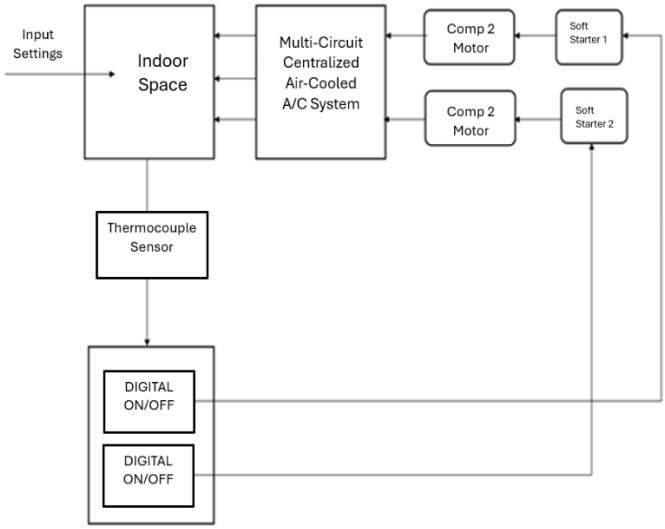


Figure 2 Digital On/Off control structure.



Figure 3 Digital control implementation in the AHU

D. Soft Starter installation

A soft starter is an accessory that can be attached to a motor to enable the motor to employ a different manner of startup. It is an electronic device used to gradually start and stop electric motors, especially AC induction motors, in a smooth and controlled manner. Unlike a traditional direct-on-line (DOL) start, which applies full voltage to the motor immediately, a soft starter slowly increases the voltage, allowing the motor to accelerate smoothly to full speed. It permits a more gentle and effortless power-up of the motor and restricts the amount of voltage that can surge through it. This device is designed to lessen the pressure placed on the motor during the regular power-up phase of a motor. The soft starter when installed, gradually begins applying increasing voltages to the motor instead of a sudden rush of voltage. It does this by limiting the torque in the motor. This allows for smooth acceleration of power as the sudden rush of voltage frequently can cause great damage to the motor. The working principle of a soft starter reduces the overall wear and tear of the motor, thus increasing its life span. Soft starters are made up of mechanical, electrical, or both types of mechanisms. Clutches and various coupling types that use fluid, magnetic forces, or steel shot to limit torque are examples of mechanical soft starts. Any control system that briefly lowers the voltage or current input to lessen torque, or a device that momentarily changes how the motor is linked in the electric circuit, can be an electrical soft starter. The ABB compact range model was installed in this study. This model can handle more than 20 starts per hour. Figure 4 shows the circuit diagram of the soft starter, while figure 5 shows the picture of the installed soft starter at block DO6

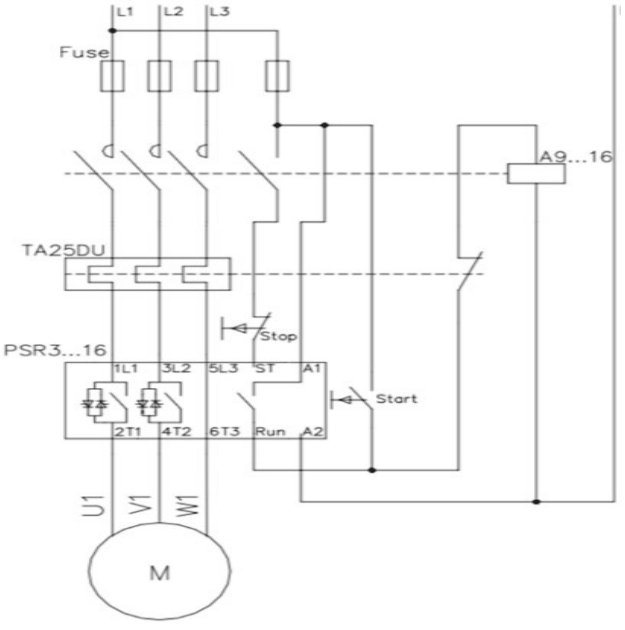


Figure 4 circuit diagram of the soft starter

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Figure 5 Soft starter installation in the AHU



Figure 6 Power Analyser to measure energy consumption

E. COMPRESSOR POWER MEASUREMENT

The power consumption of the compressor is an important parameter in determining the performance of an air conditioning system. Thus, proper measurement of the compressor power consumption is paramount in this study. The system is installed with two scroll type compressors. The CW240 power analyzer was used to measure the power consumption of the compressors. This power analyzer has a display which provides measurements for voltage, current and electric power. Figure 6 shows the Yokogawa Clamp-on Power Analyzer IM CW240E model.

3.0 RESULTS AND DISCUSSION

The effects of the controller after installation are shown in the following sections. To calculate the energy savings and the coefficient of performance, the digital controller's energy consumption is computed and compared to the on/off base case. Additionally, a setpoint tracking analysis is presented.

A. ENERGY CONSUMPTION ANALYSIS

The energy consumption for 23°C, 24°C and 25°C setpoints for the On/Off and Digital controllers were computed and the results are presented. The hourly average energy consumption is shown in table 3. The power consumption of the compressor is an important parameter in determining the performance of an air conditioning system. The system is installed with two scroll type compressors. The energy savings is calculated after implementation of the controller. This is to show the effect of the digital control strategy on the multi-circuit centralized air conditioning system, when compared to the On/Off base case. This calculation is done for the three setpoints of 23°C, 24°C, 25°C based on equation 1.

$$\textbf{Energy savings} = \frac{\text{Total On/Off energy consumption} - \text{Total Digital energy consumption}}{\text{Total On/Off energy consumption}} \text{x}100 \quad (1)$$

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Table 3 Hourly (9:00AM- 4:00PM) Energy Consumption

CONTROL METHOD	ON/OFF			DIGITAL ON/OFF		
	23°C(kWh)	24°C(kwh)	25°C(kWh)	23°C(kWh)	24°C(kWh)	25°C(kWh)
	18/04/2021	**20/10/2019**	**29/03/2021**	**28/11/2021**	**12/12/2021**	**19/12/2021**
9:00 - 10:00	17.7	18.5	17.8	18	13.6	14.4
10:00 - 11:00	18.7	17.9	17.7	16.3	13.6	9.98
11:00 - 12:00	17.5	15.1	17.9	16.4	13.8	14.7
12:00 - 1:00	19.5	19.1	16.8	16.1	13.0	10.1
1:00 - 2:00	17.5	15.4	17.5	14.9	13.1	13.6
2:00 - 3:00	18.6	16.4	12.6	13.4	13.9	13.6
3:00 - 4:00	16.8	13.3	12.5	14.4	13.9	9.98
AVERAGE ENERGY	**18.0**	**16.5**	**16.1**	**15.6**	**13.6**	**12.3**
	19/04/2021	**21/10/2019**	**30/03/2021**	**29/11/2021**	**13/12/2021**	**20/12/2021**
9:00 - 10:00	15.9	16.7	17.3	16.3	13.8	13.7
10:00 - 11:00	16.4	17.2	17.9	16.4	13.9	11.9
11:00 - 12:00	17.6	17.5	17.5	16.5	13.1	12.0
12:00 - 1:00	18.0	15.4	17.8	16.6	12.9	12.8
1:00 - 2:00	18.1	18.4	12.2	14.3	13.0	11.3
2:00 - 3:00	18.1	14.8	10.1	13.8	13.0	14.9
3:00 - 4:00	18.0	14.6	17.7	14.1	13.0	10.9
AVERAGE ENERGY	**17.5**	**16.4**	**15.8**	**15.4**	**13.3**	**12.5**
	20/04/2021	**22/10/2019**	**31/03/2021**	**30/11/2021**	**14/12/2021**	**21/12/2021**
9:00 - 10:00	19.5	16.5	15.9	14.8	12.9	15.2
10:00 - 11:00	15.3	17.2	15.9	15.0	14.8	9.9
11:00 - 12:00	17.3	17.4	15.6	16.9	13.2	10.7
12:00 - 1:00	17.7	14.6	18.0	17.1	10.0	10.8
1:00 - 2:00	19.2	15.6	15.1	14.9	12.9	13.1
2:00 - 3:00	18.1	15.8	15.1	15.6	13.0	13.2
3:00 - 4:00	18.1	16.7	15	12.5	14.9	11.4
AVERAGE ENERGY	**17.9**	**16.3**	**15.8**	**15.3**	**13.1**	**12.1**
	21/04/2021	**23/10/2019**	**1/4/2021**	**1/12/2021**	**15/12/2021**	**22/12/2021**
9:00 - 10:00	18.0	19.0	15.1	17.0	12.9	14.9
10:00 - 11:00	17.2	16.7	15.1	17.3	14.8	14.5
11:00 - 12:00	17.4	15.6	15.4	15.4	13.2	13.1
12:00 - 1:00	16.6	14.4	17.7	16.1	12.6	10.3
1:00 - 2:00	17.9	16.4	16.1	14.9	11.9	11.8
2:00 - 3:00	17.7	17.2	16.1	13.4	13.0	11.8
3:00 - 4:00	17.7	17.3	16.3	14.8	14.9	12.1
AVERAGE ENERGY	**17.5**	**16.7**	**15.9**	**15.6**	**13.3**	**12.6**
	22/04/2021	**24/10/2019**	**4/4/2021**	**2/12/2021**	**16/12/2021**	**23/12/2021**
9:00 - 10:00	16.6	17.1	14.6	18.0	15.3	14.4
10:00 - 11:00	17.1	16.8	15.1	16.3	15.3	13.5
11:00 - 12:00	17.3	15.1	16.3	15.4	13.2	13.0
12:00 - 1:00	17.2	18.3	15.2	15.1	12.1	9.94
1:00 - 2:00	19	17.3	16.3	14.9	13.8	14.3
2:00 - 3:00	17.7	16.3	17.1	13.4	13.9	11.7
3:00 - 4:00	18.1	15.1	16.9	14.4	11.1	11.8
AVERAGE ENERGY	**17.6**	**16.6**	**15.9**	**15.4**	**13.5**	**12.7**

The daily energy consumption at 23°C, 24°C and 25°C setpoints for the On/Off and digital controller were computed from table 3 and are as shown in table 4. The above formula in equation 1 give rise to the energy savings results as indicated in table 5, these compares the effect of the digital controller with the On/Off base case for the three temperature setpoints. The energy savings at the three setpoints after implementation of the digital controller is shown in table 5.

Table 4 Daily (9:00am- 4:00pm) daily Energy Consumption

	On/Off		DIGITAL ON/OFF	
	Date	Daily Energy Consumption (kwh)	Date	Daily Energy Consumption (kwh)
	18/04/2021	126.1	28/11/2021	109.4
	19/04/2021	122.0	29/11/2021	108.2
23°C	20/04/2021	125.2	30/11/2021	106.7
	21/04/2021	122.5	1/12/2021	108.8
	22/04/2021	122.9	2/12/2021	107.4

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	Total Energy Consumption (kwh)	**618.8**	**Total Energy Consumption (kwh)**	**540.5**
24°C	20/10/2019	115.7	12/12/2021	94.9
	21/10/2019	114.5	13/12/2021	92.8
	22/10/2019	113.9	14/12/2021	91.8
	23/10/2019	116.7	15/12/2021	93.3
	24/10/2019	115.8	16/12/2021	94.6
	Total Energy Consumption (kwh)	**576.7**	**Total Energy Consumption (kwh)**	**467.4**
25°C	29/03/2021	112.7	19/12/2021	86.3
	30/03/2021	110.4	20/12/2021	87.4
	31/03/2021	110.5	21/12/2021	84.3
	01/04/2021	111.7	22/12/2021	88.5
	04/04/2021	111.4	23/12/2021	88.5
	Total Energy Consumption (kwh)	**556.7**	**Total Energy Consumption (kwh)**	**435.2**

Table 5 summarized the energy savings for the three temperature setpoints in kWh and percentage as derived from table 4

Table 5 Energy Savings after Digital on/off controller Implementation

Temp Setpoint	On/Off	Digital On/Off	Energy Savings (kWh)	Energy Savings (%)
23°C	618.8	540.5	78.3	12.6
24°C	576.7	467.4	109.3	18.9
25°C	556.7	435.2	121.5	21.8

From the above results it can be observed that the application of digital controller to the multi-circuit centralized air conditioning system resulted in energy savings of 12.6% at 23°C, 18.9% at 24°C and 21.8% at 25°C.

B. COEFFICIENT OF PERFORMANCE

The coefficient of performance of the air conditioning system is the ratio of the rate of net heat removal to the rate of total energy input. A high COP value represents a high efficiency. The COP is a parameter that affects the efficiency and energy consumption of the air conditioning system. Equations 2 is used to calculate the COP for the On/Off and the digital on/off controllers at 23°C, 24°C, 25°C setpoints on an hourly basis for each day. Table 6 shows the summary of the results for the average daily COP for all the three controllers at the three different temperature setpoints of 23°C, 24°C, and 25°C.

$$\text{COP} = \frac{\text{Rate of net heat removal (Cooling Capacity, } Q_{cc})}{\text{Rate of total energy Input } (W_{input})} \quad (2)$$

$$Q_{cc} = \text{Sensible Heat} + \text{Latent Heat} = Q_s + Q_L \quad (3)$$

According to ASHRAE standard [22], the sensible heat and latent heat can be calculated as follows;
The sensible heat gain corresponding to the change in the dry-bulb temperature, ΔT for a given air flow, is determined by equation 4.

$$Q_s = (\text{mass flow rate of supply air}) \times (\text{specific heat capacity}) \times (\text{temperature change})$$
$$Q_s = \dot{m} \times c \times \Delta T \quad (4)$$

Where:
$\dot{m}$ = mass flow rate of supply air
ΔT = (Temperature of mixed air – Temperature of supply air)
c = specific heat capacity of dry air and water vapour
While the Latent Heat, Q_L can be calculated as in equation 7.
Latent heat gain = (mass flow rate of supply air in kg dry air per second) x (change in humidity ratio) x (latent heat of evaporation in kJ per kg moisture)

$$Q_L = \dot{m} \times \Delta\omega \times h \quad (6)$$

$$Q_L = \rho \times \dot{V} \times \Delta\omega \times h \quad (7)$$

Where
$\Delta\omega = \omega_{\text{mixed air}} - \omega_{\text{supply air}}$
$\dot{V}$ = Volumetric air flow rate, m3/s
ρ = the density of air at temperature T, kg/m3
h = latent heat of evaporation in kJ per kg moisture

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Table 6 Average Daily Coefficient of Performance

Time	ON/OFF			DIGITAL ON/OFF		
	23°C	24°C	25°C	23°C	24°C	25°C
	18/04/2021	20/10/2019	29/03/2021	28/11/21	12/12/21	19/12/21
9:00 - 10:00	2.3	2.4	2.9	3.5	3.8	3.9
10:00 - 11:00	2.6	2.5	3.2	3.9	3.5	4.1
11:00 - 12:00	2.7	2.7	3.2	3.7	3.5	3.8
12:00 - 1:00	2.6	2.7	3.3	3.8	3.7	3.9
1:00 - 2:00	2.6	2.8	3.0	3.5	4.0	4.0
2:00 - 3:00	2.5	3.0	2.8	3.1	4.4	3.8
3:00 - 4:00	2.3	3.0	3.2	3.4	3.3	4.2
AVERAGE COP	**2.5**	**2.7**	**3.1**	**3.5**	**3.7**	**4.0**
	19/04/2021	**21/10/2019**	**30/03/2021**	**29/11/2021**	**13/12/2021**	**20/12/2021**
9:00 - 10:00	2.5	2.5	3.1	3.8	4.0	3.8
10:00 - 11:00	3.0	3.0	3.6	3.6	3.9	3.8
11:00 - 12:00	2.3	2.9	3.3	3.5	3.5	3.5
12:00 - 1:00	2.9	2.7	3.3	3.4	3.6	4.0
1:00 - 2:00	2.4	3.2	2.3	4.1	3.5	4.1
2:00 - 3:00	2.3	2.4	2.8	3.4	4.1	3.7
3:00 - 4:00	2.9	2.8	3.3	3.4	3.5	4.3
AVERAGE COP	**2.6**	**2.8**	**3.1**	**3.6**	**3.7**	**3.9**
	20/04/2021	**22/10/2019**	**31/03/2021**	**30/11/2021**	**14/12/2021**	**21/12/2021**
9:00 - 10:00	2.7	2.5	3.3	3.4	3.6	3.9
10:00 - 11:00	2.6	2.4	3.1	3.9	3.4	3.5
11:00 - 12:00	2.3	2.3	3.1	3.8	3.7	4.1
12:00 - 1:00	2.7	2.9	3.4	3.6	4.1	4.4
1:00 - 2:00	2.3	2.7	3.4	3.6	3.5	3.5
2:00 - 3:00	2.6	3.3	3.2	3.6	3.5	4.1
3:00 - 4:00	2.6	2.6	3.3	3.6	3.6	4.1
AVERAGE COP	**2.5**	**2.7**	**3.2**	**3.6**	**3.7**	**4.0**
	21/04/2021	**23/10/2019**	**1/4/2021**	**1/12/2021**	**15/12/2021**	**22/12/2021**
9:00 - 10:00	2.5	2.8	3.2	3.7	3.7	3.6
10:00 - 11:00	2.7	3.0	3.3	3.6	3.3	3.9
11:00 - 12:00	2.6	3.2	2.8	3.5	3.4	4.0
12:00 - 1:00	2.8	3.3	3.5	3.5	3.8	3.9
1:00 - 2:00	2.6	2.9	3.7	3.5	3.7	3.9
2:00 - 3:00	2.6	2.6	3.4	3.1	4.1	3.9
3:00 - 4:00	2.6	2.9	2.9	3.3	3.6	3.8
AVERAGE COP	**2.6**	**3.0**	**3.3**	**3.5**	**3.7**	**3.9**
	22/04/2021	**24/10/2019**	**4/4/2021**	**2/12/2021**	**16/12/2021**	**23/12/2021**
9:00 - 10:00	2.2	2.8	3.2	3.9	3.8	4.2
10:00 - 11:00	2.2	2.4	3.7	3.9	3.8	3.8
11:00 - 12:00	3.2	2.7	3.3	4.0	3.5	3.9
12:00 - 1:00	3.1	2.7	3.5	4.0	3.8	3.9
1:00 - 2:00	2.7	2.7	3.4	3.5	3.9	3.3
2:00 - 3:00	2.1	3.1	3.1	3.1	3.9	4.0
3:00 - 4:00	2.3	3.4	2.9	2.8	3.6	3.9
AVERAGE COP	**2.5**	**2.8**	**3.3**	**3.5**	**3.8**	**3.9**

Graphical representations of the average coefficient of performance for each of the 23°C, 24°C, and 25°C setpoints are displayed in Figures 7 and 8. The figures as well as table 6 above, shows that the COP improved after the implementation of the digital on/off controller.

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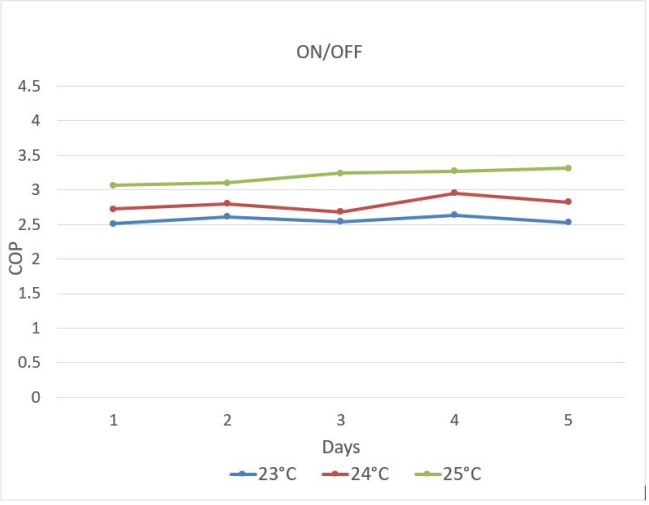


Figure 7 Effect of setpoint on COP using ON/OFF control

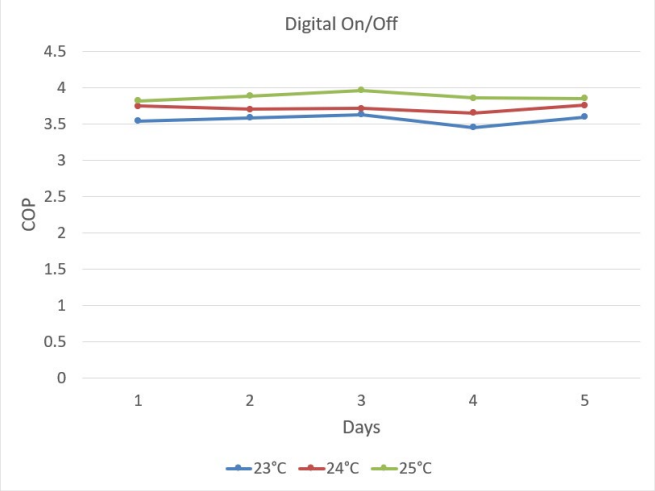


Figure 8 Effect of setpoint on COP using Digital control

The implementation of a digital controller improves the coefficient of performance (COP) of building multi-circuit air-conditioning systems by enabling continuous capacity modulation, reducing compressor cycling losses, and maintaining operation near optimal thermodynamic conditions. Unlike conventional on/off control, digital controllers minimize temperature oscillations, enhance heat exchanger effectiveness, and improve part-load efficiency. From a control theory perspective, digital control reduces steady-state error and improves system stability, resulting in lower electrical energy input for the same cooling output. Consequently, the system achieves higher energy efficiency and sustained COP improvement at both component and building levels.

C. TEMPERATURE SETPOINT TRACKING

A setpoint is the desired value at which a controller aims to maintain the process variable in temperature control applications [20]. Its control output power can be changed to do this. The controller's capacity to maintain the setpoint indicates effective energy management and indoor occupant thermal comfort. Figure 9 shows that the interior temperature setpoint of 23 °C could not be maintained at the correct level by the On/Off controller. The setpoint was varying between 20 and 24 degrees Celsius, usually dropping to 20 degrees. This occurs as a result of the inefficient On/Off thermostat control method. The On/Off thermostat control uses return air as the control feedback, which leads to this inefficiency. However, the controller expects a greater indoor air temperature since the return air does not precisely reflect the current indoor temperature setting. This causes the two compressors to work virtually constantly, which leads to overcooling and unnecessary energy use.

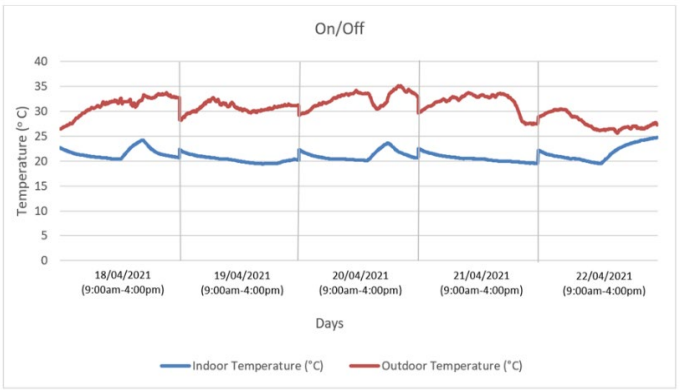


Figure 9 Effect of On/Off Control On Setpoint Tracking

Figure 10 shows the effect the digital controller has on maintaining the indoor temperature setpoint, it shows that the indoor temperature was maintained most of the time at the required setpoint.

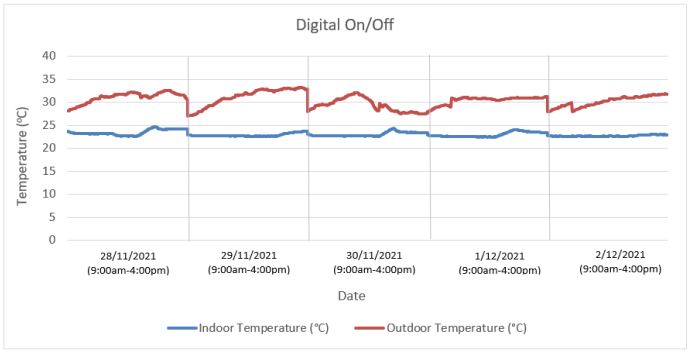


Figure 10 Effect of Digital control on setpoint tracking

This study demonstrated that the digital control strategy's capacity to deliver accurate, stable, and adaptive control makes it successful in preserving the multi-circuit centralized air conditioning systems' setpoint. The temperature of the outdoor air has an impact on both ventilation and heat transmission via

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external walls and roofing. The temperature of the outside air is what drives natural ventilation, and research has shown that building energy use is closely related to variations in the outside temperature. These two factors are highly significant. Because the outdoor conditions for both control methods are similar, as indicated by the graphs in figures 9 and 10 above, the premise for comparing the controllers' energy usage is justified.

4.0 CONCLUSION

This study successfully demonstrated the significant energy-saving potential of a high-performance digital on/off controller when applied to an operational multi-circuit centralized air-cooled air conditioning system. Our findings indicate that the digital controller not only outperformed traditional on/off thermostat control at various temperature setpoints (achieving savings of 12.6% at 23°C, 18.9% at 24°C, and 21.8% at 25°C) but also substantially improved the system's Coefficient of Performance (COP) and indoor temperature setpoint tracking. This work contributes uniquely to the existing literature by providing empirical evidence of enhanced energy efficiency in a real-world, complex multi-circuit HVAC environment, a domain where practical application studies are notably scarce.

The novelty of this research lies in the successful implementation and validation of a digital control strategy on an existing, operational system, moving beyond theoretical simulations or laboratory setups. While the study effectively showcases the benefits of the digital controller, it is important to acknowledge certain limitations. The investigation was conducted on a specific type of multi-circuit centralized air-cooled system, and the generalizability of these exact savings to other HVAC configurations or climates may require further validation. Additionally, the study focused on on/off control, and did not explore the potential benefits of more advanced control algorithms such as proportional-integral-derivative (PID) or model predictive control (MPC).

Future research could extend this work by evaluating the digital controller's performance across a broader range of HVAC system types and climatic conditions. Further investigations into integrating adaptive control algorithms or machine learning techniques could yield even greater energy efficiencies and predictive capabilities. Additionally, a long-term economic analysis, including installation costs and return on investment, would provide valuable insights for broader industry adoption. This study thus lays a crucial foundation for advancing practical energy management strategies in complex building air conditioning systems.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethics declaration

Formal ethical approval was not obtained for this study. However, the authors confirm that the research was conducted in accordance with established ethical principles and good research practices, with due consideration given to participant rights, informed consent, confidentiality, and responsible data handling.

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