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DEVELOPMENT OF AN INTELLIGENT ENERGY OPTIMIZATION SYSTEM FOR RESIDENTIAL SPLIT-UNIT AIR CONDITIONING SYSTEM

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Abstract

The growing energy usage of residential air-conditioning units is an increasing concern, particularly in hot and humid climates. For example, in Malaysia, air conditioners can be indoors for extended durations to achieve thermal comfort. In addition, typical systems typically do not have adaptive control methods, thus resulting in compressor operation at times on and off, and unnecessary energy waste. These systems are still limited. Although recent developments in inverter air-conditioning technology have advanced efforts to improve energy efficiency when the ambient conditions dynamically shift, there are still some limitations. The aim of this paper is to re-evaluate these challenges, by developing and simulating a control logic system to improve isolating compressor performance by considering real-time ambient outdoor properties. This was achieved by developing control logic equations with the intent to provide a framework for system architecture and using a MATLAB simulation, created reactor units - 1.5 HP split-unit air-conditioner, situated in 30m³ space, to mimic real-world performance. The first step was to test the simulation model without the control logic, in order to obtain performance baseline data. The second step was to apply the control logic, and assess empirical performance data via the three configurations, including the non-inverter, inverter units, bi-directional changes in temperature and humidity; then compare performance to the control. Findings revealed that developed control logic can increase compressor speed variation and change output and reduced energy consumption without affecting space comfort. The developed control logic setup successfully achieved energy saving of 10% compared to a conventional inverter air-conditioning units system.

Keywords:, Control logic, Energy efficiency, MATLAB, Residential buildings, Split unit air-conditioning.

1. Introduction

Because of Malaysia's tropical climate and rising urbanization, there is a greater need than ever for energy-efficient air conditioning systems [1, 2]. One of the biggest sources of household energy consumption is residential air conditioners, particularly split-unit models [3]. In addition to putting strain on the national grid, the ongoing increase in cooling-related electricity consumption also adds to greenhouse gas emissions from fossil fuel-based power generation [4]. This circumstance highlights how urgent it is to use intelligent and adaptive control techniques to enhance the energy efficiency of current air conditioning systems [3, 5].

The typical Malaysian household uses air conditioning extensively, especially in the warmer months, and prolonged use results in high energy costs [2, 6]. Traditional fixed-speed air conditioners run on a temperature-only on/off cycle, which frequently results in inefficiencies like excessive compressor cycling, overcooling, and needless power consumption [3, 5]. The performance of inverter-type systems is still constrained by static control logic that ignores environmental factors like humidity and outdoor temperature, even though variable compressor speeds have increased efficiency [5, 7]. As a result, when systems continue to operate in less-than-ideal conditions, energy is frequently wasted [8].

In Malaysia, national energy initiatives, including the National Energy Efficiency Action Plan (NEEAP) and the National Energy Transition Roadmap (NETR), aim for sustainable integrated systems and improvements to existing systems that decrease electricity use and carbon emissions [9, 10]. In this sense, smart control has strong practical implications for realizing national sustainability objectives by increasing the energy efficiency of residential split-unit air-conditioning systems [3, 7].

Cooling performance is greatly influenced by environmental conditions (relative humidity, ambient temperature, and changes in heat load), but conventional air-conditioners usually only integrate feedback from the indoor temperature measurement (thermostat) [11]. This results in several operational inefficiencies, including compressor cycling too often, temperature overshoot, and excessive power consumption [3]. By using live environmental data as data input into the air-conditioning control logic, greater control can be exercised over cooling intensity, based on live environmental conditions, and limit energy consumption without compromising comfort [7, 12].

In order to combat these issues, the intended intelligent control framework uses sensor-based monitoring to respond and control the compressor and fan operation based on continually changing conditions [7, 8]. Algorithms are capable of interrogating various factors (indoor and outdoor temperature, humidity, occupancy) and providing predictive praise to the cooling load requirements for optimizing energy consumption [7, 12].

Although comparable or similar technologies exist in buildings with large-scale building management systems [11], the adapted modifications to apply to a residential setting is somewhat limited based on some validity concerns, costs, and practical constraints [3]. The establishment of both cost-effective and scalable intelligent controller for residential split-unit systems has the potential for significant energy savings at the consumer level [5, 7]. Accordingly, the proposed framework suite aligns with Malaysia's overall low carbon transition to energy [9, 10], noticeably provides a low impact solution to peak load demand, facilitates compressor efficiency and durability, resulting in decreased energy consumption for the household ratepayer; thereby providing a line of meaningful contribution to Malaysia's longer-term energy sustainability goals [10, 13]

In Malaysia, the residential sector is characterised by increased electricity demand, especially during dry and inter-monsoon periods [2, 6]. Energy consumption in a household where the primary cooling source is air conditioning can exceed 40% or more of total energy use [1, 3]. The temptation to rely heavily on cooling puts a strain on peak load plants, resulting in blackouts and voltage reduction during the hottest periods. The fact that electricity prices are limited through substantial subsidies creates disincentives for consumers to conserve energy or purchase efficiency technologies [6]. The increased demand for cooling from an environmental or policy perspective also drives an increase in greenhouse gas emissions due to the country's dependency on fossil fuels [4]. Even though inverter-based systems are deemed to be more efficient than fixed-speed systems [5], they do not consider real-time influences, such as occupancy, weather, or humidity [7, 12]. This leads to energy being wasted, or conversely over-cooling. Finding solutions to meet the objectives of Malaysia's National Energy Policy (2022-2040) will require going towards more intelligent and adaptable cooling technology [14, 15]. Figure 1 illustrates that, based on a household survey, air-conditioners account for the largest share of energy consumption.

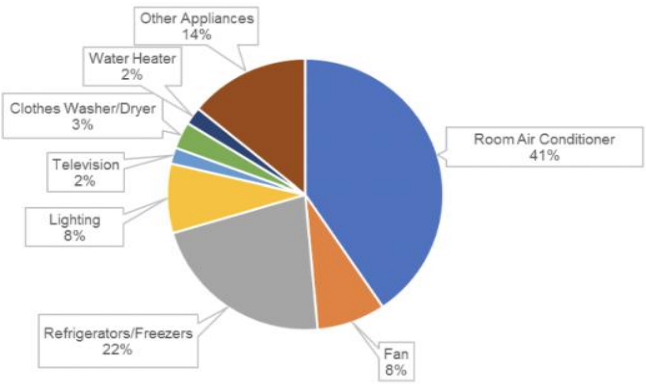

Fig. 1. Energy use from a survey done in 15 households.

The growing availability of microcontrollers, inexpensive sensors, and wireless communications systems has opened the door for the intelligent control of home air conditioning systems to improve their efficiency [7, 8]. Intelligent controllers can use real-time information (such as temperature and humidity data as well as occupancy data) to manage compressor and fan activity to dynamically adjust to real cooling needs [7, 12]. Low-cost variants can use Relative Humidity and Temperature (RHT) sensors to build low-cost systems and use platforms such as Arduino or Raspberry Pi to monitor localized environments and intelligently modulate indoor air quality based on real conditions as opposed to fixed schedules [8].

In parallel, advances in artificial intelligence (AI) and machine learning (ML) are enabling predictive control systems to use inputs such as user behaviours, weather patterns, and occupancy patterns to optimize controls and setpoints to enhance system performance [12]. Smart AC systems provide real-time feedback through mobile and web interfaces that provide users with opportunities to attempt to make choices that will lead to improved energy efficiency [7]. In Malaysia, this connects directly to current national initiatives, including the National Energy Efficiency Action Plan (NEEAP) and the National Energy Transition Roadmap (NETR), adopting smart home technologies to reduce peak-load demand and carbon footprint while optimizing household cost savings without sacrificing comfort [2, 10].

To present against the background of increasing energy requirements and poor performance of present residential air conditioning systems this project puts forth a smart and responsive energy solution. This project idea is geared towards introducing a system which is able to smartly vary its performance based on real time environmental data, which in turn will reduce energy waste and report in terms of improved performance. The put forth goals which structure the development, roll out and assessment of the presented intelligent control model and also its practicality.

The principal objective of this project is to design and simulate a smart energy optimization system for residential split-unit air conditioning units. However, there are limitations to this research. Due to safety concerns, high voltage use, and limited access to real AC components, full-scale physical implementation will not be possible. The only route to validate the research will be executed in MATLAB/Simulink using either virtual environments or prototypes which are scaled down. With this limitation in mind, this project has been inspired through the warrant for addressing rising household energy consumption in Malaysia, whereby air conditioning units use more than 21% of the electricity used in the country. Moreover, to this energy waste, many users still depend on manual timers or on fixed temperature settings which leads to inefficient operation and overcooling.

A technological adoption gap exists, as high-end smart control systems are still beyond the capability of the average household. Hence, this project aims to develop an intelligent, scalable, and cost-effective control system that will work with existing residential air conditioning systems with a focus on providing an affordable and retrofittable solution. The main component is the integration of real-time environmental sensing and adaptive control logic. The purpose of this approach is to bridge the disconnection between advanced control strategies and useful home use in countries in tropical climates such as Malaysia, while promoting energy efficiency, reducing greenhouse gas emissions and support more general sustainability aims.

2. Methods

This study compares three air conditioning configurations: non-inverter, inverter, and a proposed intelligent control logic. Unlike the inefficient on/off cycling of non-inverter units, the proposed system utilizes an intelligent approach in MATLAB/Simulink to dynamically adjust compressor speed based on indoor temperature and environmental variables.

2.1. Development of control logic equation

The control logic is implemented via a state-based chart subsystem shown in Fig. 2. The system transitions between four states which are OFF, LOW, MEDIUM, and HIGH, based on the effective temperature difference (ΔT_eff). This value is calculated using indoor temperature (T_cmpt), setpoint (T_setpoint), and ambient conditions (T_env, RH_env) relative to baseline "mild" constants (26°C, 60% humidity). Sensitivity factors kT and kRH calibrate the system's response to outdoor thermal stress. ΔT_eff increases, the system shifts to higher cooling modes; as it decreases, the logic downshifts to conserve energy shown in Fig. 3.

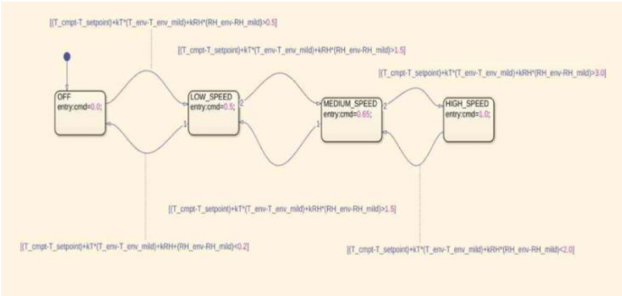

Fig. 2. The Chart Subsystem with all Equations used for different modes.

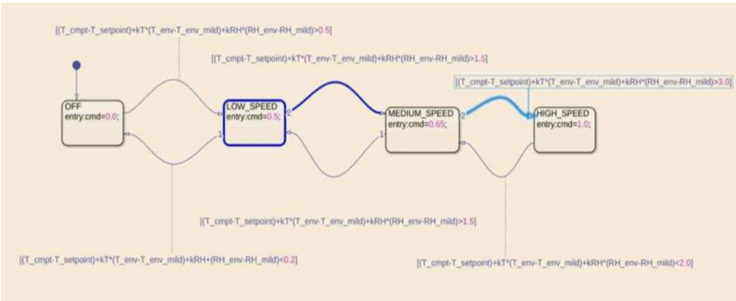

Fig. 3. Control logic chart transitioning from LOW to MEDIUM speed.

2.2. Architecture and simulation model

The system architecture shown in Fig. 4 defines the signal flow between the compressor, condenser, evaporator, and expansion valve. This was translated into a complete Simulink model shown in Fig. 5 that operates as a closed-loop system, where environmental feedback directly drives the control logic.

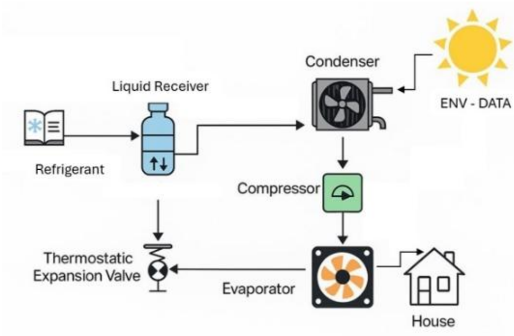

Fig. 4. A draft of an architecture design used to build the Simulink system.

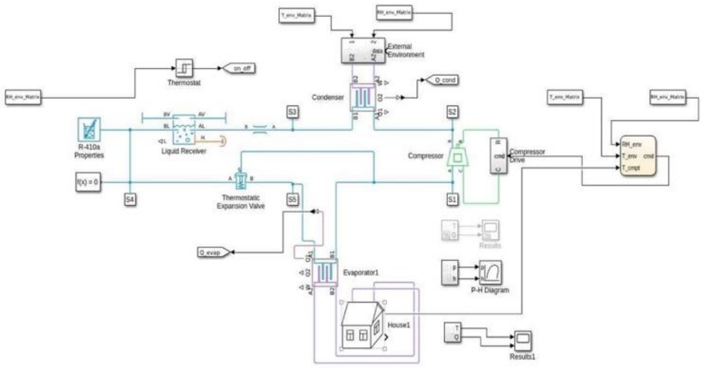

Fig. 5. The full aircon system built using MATLAB Simulink software

To ensure realistic testing, ambient data was collected via a DHT22 sensor and Arduino Uno, Fig. 6. These readings were logged to Excel and imported into MATLAB matrices (T_env_Matrix) and (RH_env_Matrix) to drive the External Environment Subsystem, Fig. 7. This subsystem simulates psychrometric air properties and airflow behaviour to interact realistically with the cooling components.

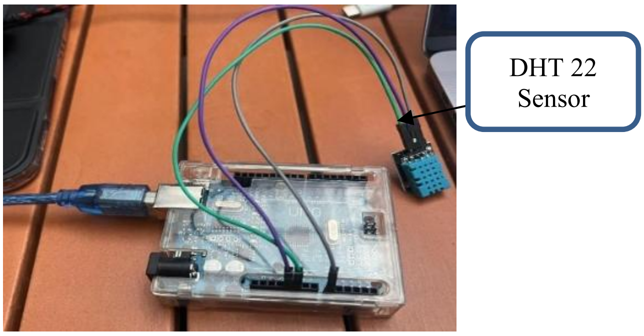

Fig. 6. The simple circuit integrated with DHT 22 sensor for data logging.

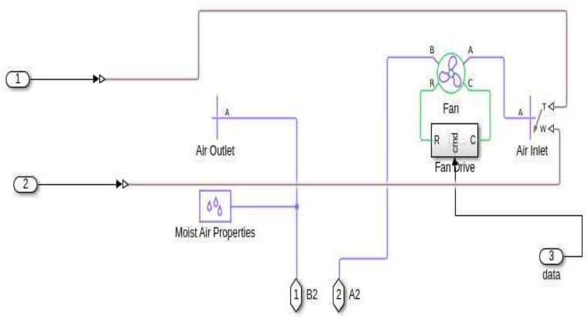

Fig. 7. Internal structure of the external environment subsystem.

2.3. Modelling approach and energy calculation

The control command (cmd) from the chart enters the compressor drive, Fig. 8, dictating speed linearly: 0 (OFF), 0.35 (LOW), 0.65 (MEDIUM), and 1.0 (HIGH).

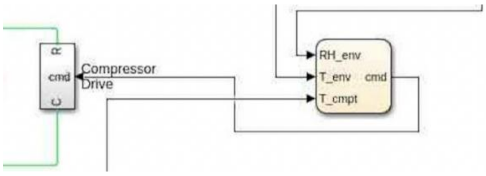

Fig. 8. CMD from chart entering compressor drive system.

Power consumption was derived from simulated RPM data. Mechanical power was calculated by converting RPM to angular velocity and applying a proportional speed-power model. These values were integrated over the simulation duration to determine total consumption in kWh. The model was validated first as a non-inverter (on/off) system before activating the control logic to simulate the proposed inverter-type performance.

3. Results and Discussion

3.1. Non-inverter system

In this section, results currently obtained from the simulation will be provided and the way it is validated will be explained. Figure 9 presents the simulated compressor operation of a non-inverter air-conditioning unit, showing its rotational speed (in revolutions per minute, rpm) over time.

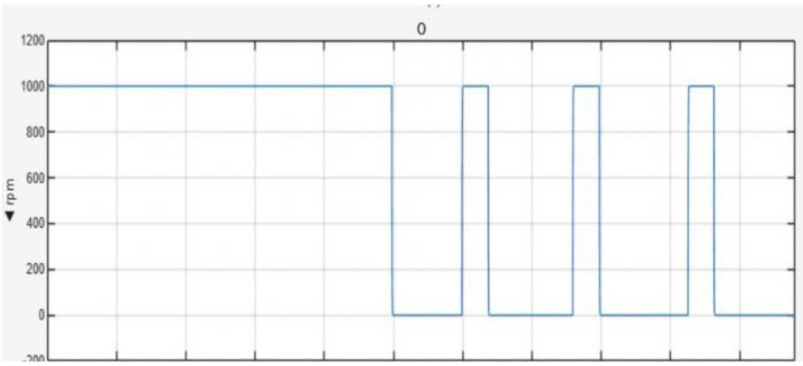

Fig. 9. RPM reading of a non-inverter aircon.

This graph acts as a reference to gauge, measure, and evaluate the performance of different control techniques.

In non-inverter air-conditioning systems, the compressor works on a simple ON–OFF control, where the compressor turns ON when the room temperature exceeds the setpoint and runs at full speed (about 1000 rpm) to achieve maximum cooling. The compressor then turns OFF once the indoor temperature is satisfied, which results in the rpm dropping to zero. This cycle continues on a repetitive loop as the unit attempts to control the room temperature within a designated hysteresis value.

Key Observations from RPM Readings:

- ON Segments: The high plateau sections at approximately 1000 rpm indicate active cooling phases.
- OFF Segments: Flat sections at zero RPM indicate that the cooling has been turned off, and the fan alone is operational.
- Binary Control: The rapid switching between full speed and zero speed indicates that the system does not have gradual speed control, which is characteristic of a non-inverter system.
- System Drawbacks: This binary system causes wear and tear and is inefficient.
- Purpose of the Baseline:

The simulation provides a baseline to measure the performance of a system that can vary speed and therefore reduce power consumption by avoiding binary control.

3.2. Intelligent system implemented in a split unit aircon system

As shown in Fig. 10, after incorporating the environmental input data (temperature and relative humidity) and the applied control logic, the simulation shows the variation of the air conditioner compressor rotational speed (RPM) for a one-hour period.

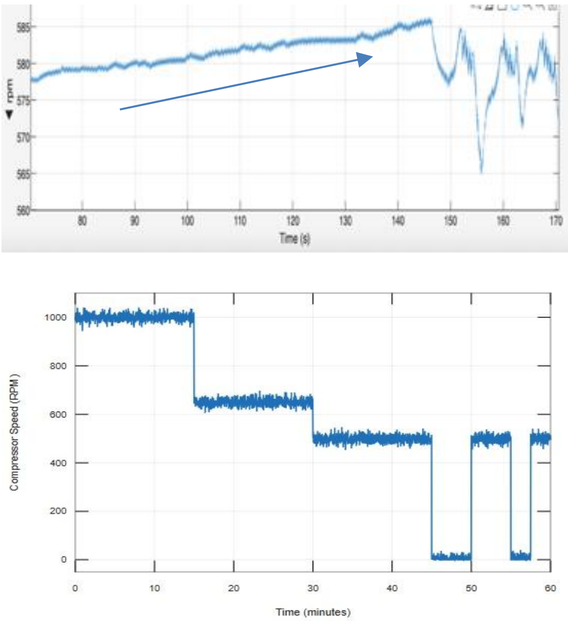

Fig. 10. Simulated RPM data after implementing new idea.

The simulation effectively illustrated an energy-efficient variable speed compressor system that adjusts its speed in real time in accordance with system demand and environmental conditions. The compressor was set to operate at maximum speed of 1000 RPM during the initial high-load period from 0 to 15 minutes to quickly cool the indoor temperature. As thermal stability was approached from 15 to 35 minutes, the compressor speed was gradually reduced to 800 RPM and then 500 RPM. Intermittent low speed operations were then applied from 35 to 60 minutes to maintain comfort while minimizing energy consumption. The simulation model was developed using a 30 m³ room volume, simulating a typical medium-sized bedroom in Malaysia, and was equipped with a 1.5 HP air-conditioning unit and four occupants to simulate a realistic heat load condition. The ability of the system to respond to changes in ambient temperature and humidity levels was effectively illustrated. The simulation results closely mimic the real-world operations of an inverter-type air-conditioning system.

Figures 11 and 12 present the compressor speed (RPM) response of the inverter air conditioning system operating under the proposed control logic for two different operating periods, namely night-time and early morning conditions.

The nighttime simulation data was taken at (11pm-12am) while morning simulation was at (5.30am-6.30am). In both cases, the same control strategy and mode-based logic were applied, and the differences in compressor behaviour are primarily attributed to variations in environmental temperature and relative humidity.

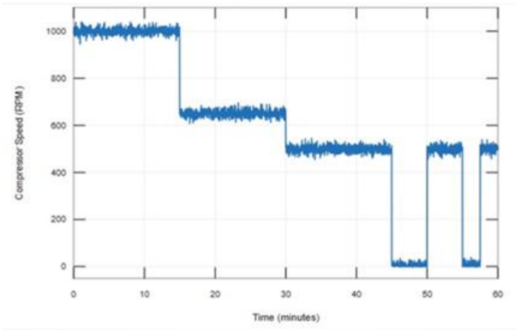

Fig. 11. RPM Reading of Inverter system with Control Logic Setup Integrated simulated during nighttime (11pm-12am).

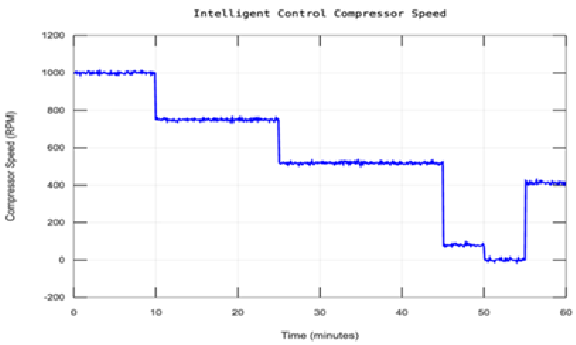

Fig. 12. RPM Reading of Inverter system with Control Logic Setup Integrated simulated in the morning (5.30am-6.30am)

During night operation, the outdoor temperature and relative humidity remained more stable around the target values for a mild environment. Consequently, the control logic held the compressor at higher operating levels for an extended period to cool the indoor compartment temperature to the desired level. There has been a gradual reduction in RPM as the system operates at reduced cooling capacity to meet the environment. Sudden changes in RPM to lower levels have been observed due to the system's reaction to reduced environmental loads while still maintaining indoor comfort.

Figure 12 displays the compressor RPM in the early morning period. As compared to the night period, the early morning period is characterized by low outdoor temperatures and lower cooling loads. For that reason, the speed dropped more sharply in the early morning period as the indoor temperatures approached the setpoint quickly.

Around 45 to 55 minutes, there was a considerable drop in compressor RPM to near-zero levels, which marked a brief shutdown operation for the compressor. This shows that the developed control logic is capable of understanding low cooling demands and transitioning to either an OFF or LOW_SPEED operation mode in order to prevent unnecessary energy consumption. Later, there was a restart operation for the compressor at a moderate RPM value due to a low increase in cooling demand.

By observing both operating modes, it is obvious that the control logic adjusts the operation of the compressor according to what is happening in the environment. During night-time, there is fixed moderate to high RPM operation because there is high thermal demand at night but after it reaches the setpoint, it manages to turn off the compressor for certain amount of time. Early in the morning, it is possible for the compressor to operate at low speed and turn off at times as well.

3.3. Response of room temperature

Although the RPM graphs were the main focus on being obtained, the focus was also to observe the room temperature graph. This is to ensure the RPM is able to fluctuate and follow the control logic setup that is created but at the same time, thermal comfort is maintained. Figures 13 and 14 clearly gives a view on the temperature response of the room/house.

Based on the temperature response graph shown from Fig. 14, there are changes to the time taken for the temperature to drop from 30 Degree Celsius down to 22 Degree Celsius. In this simulation, 30 Degree Celsius was particularly chosen to be the starting temperature because that is the optimal room temperature in Malaysian Households. The 22 Degree Celsius setpoint was chosen as a random value without a particular reason. Also, by using that particular setpoint temperature value, clear energy reduction was able to be seen. From Fig. 14, during nighttime simulation, it took about approximately 45mins for the starting temperature to reach setpoint temperature.

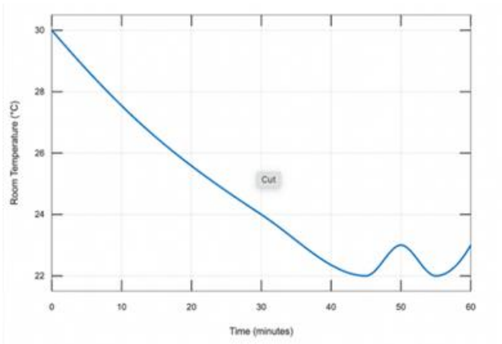

Fig. 13. Temperature response of the room/house subsystem during nighttime simulation (11pm-12am).

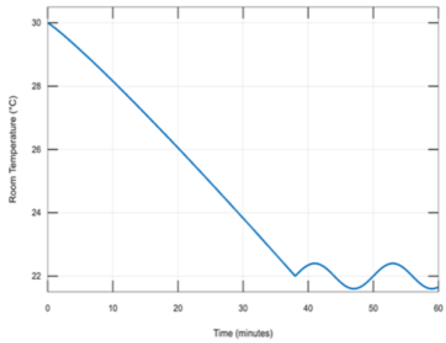

Fig. 14. Temperature response of the room/house subsystem during morning simulation

Meanwhile for the morning time simulation, it took approximately less than 40min to reach setpoint temperature. The reason for this is mainly due to the environment data input. The data collected at night and in the morning had varying temperature and relative humidity values for that 1 hour of data record. During early in the morning, the environment temperature mainly played a crucial part. The temperature values recorded were relatively low when comparing with the data obtained for nighttime. Although the nighttime data also showed low temperature values, in the morning the temperature values were even lower which made the system to run and made it possible to cool down the room even faster than nighttime.

3.4. Comparison of RPM readings

One of the main objectives of this research is to find out the power consumption of each of the aircon type through the simulation using the RPM graph and data that was obtained from MATLAB. But before calculating the power consumption, the RPM graphs that were obtained were merged into one single graph to have a clearer view on the RPM trend. This would make the RPM trend to be viewed even more clearly. Figures 15 and 16 present the merged graph.

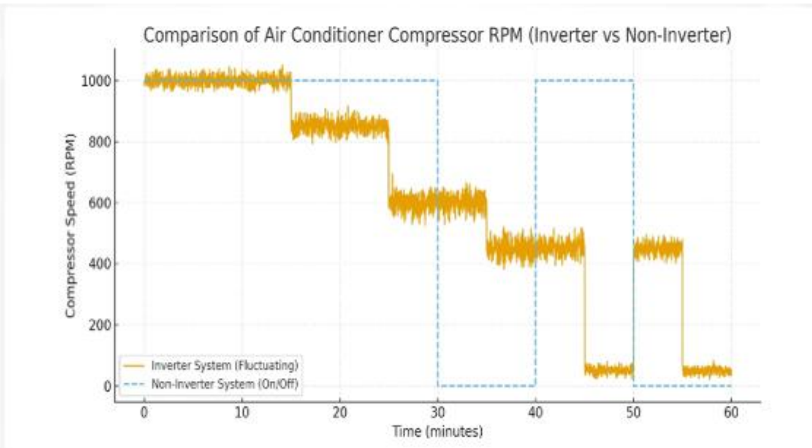

Fig. 15. Non-inverter graph vs inverter graph with control logic setup.

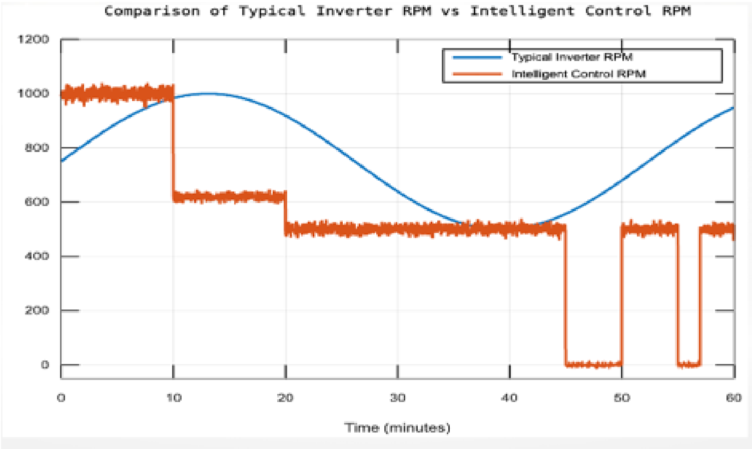

Fig. 16. Comparison of a typical inverter system and inverter system with control logic setup (night simulation).

From the comparison of the graphs in Fig. 16, clear view on the RPM trend can be seen. For non-inverter graph, the RPM starts at maximum and then turns off when setpoint temperature has been reached. This is why this type of aircon system is considered to be inefficient as it runs only in one speed. Based on Fig. 15, clear view on how different the RPM fluctuation is can be seen when a non-inverter system is compared with an inverter system with control logic setup added. In Fig. 16, a typical inverter system without the use of control logic setup was simulated and the RPM trend was compared with the inverter system with control logic setup.

The RPM of the typical inverter system do fluctuate, but it can be seen that most of the time the RPM is running at a higher speed. This is because, a typical inverter system, does not take environment inputs into its system. The main data it reads would be the compartment temperature as well as setpoint temperature. This is why the inverter system with control logic setup is proven to be more efficient as it runs on different modes by taking environment conditions into account. The efficiency although from the graph cannot be seen in numeric values, the fluctuation of the RPM visualizes the difference between these systems.

The comparison graphs were generated from simulations conducted under nighttime conditions, using environmental input data recorded at night. In addition to these, a separate set of simulations was performed using data collected in the morning, and the resulting graphs were similarly combined. These are referred to as morning simulations.

The combined graph shown in Fig. 17 is to show the difference between the RPM data that was obtained using morning environmental data and typical inverter system simulation.

The rpm data trend shown in red shows a significant difference compared to the previous graph (night simulation). The RPM trend graphs provide a visual representation of the pattern. But in the next section, power calculation will be shown to have a clear view on how varying environment data changes the power consumption of the system and reduce energy usage.

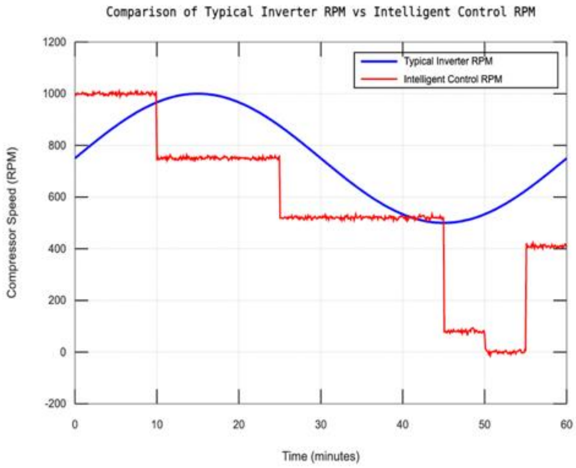

Fig. 17. Comparison of a typical inverter system and inverter system with control logic setup (morning simulation).

3.5. Power saving calculation

Once the RPM data was obtained, power calculation was done. Since MATLAB provides the RPM graph, code can be utilised to convert those graphs to power value (kWh). By simply pasting the suitable code on MATLAB workspace, will allow the RPM data conversion to power values. This makes the power saving calculation much easier to be conducted.

The particular code shown in Fig. 18 was used to paste on MATLAB workspace.

```
% Convert RPM to instantaneous power (kW)
power_kW = rated_power * (rpm ./ rated_rpm).^3;

% Convert power to energy (kWh)
energy_kWh = sum(power_kW * dt) / 3600;

% Display result
disp(['Total Energy Consumption = ', num2str(energy_kWh), ' kWh']);
```

Fig. 18. Code used on MATLAB to convert RPM data to power (kWh).

Once the power conversion was done, the data obtained was tabulated in Table 1 shown to conduct the power saving calculation to have a clear view on how much power is actually saved from each simulation that was run on MATLAB Simulink Model.

Table 1. Energy and power comparison between conventional and intelligent ac system (Night simulation).

System Type	Total Energy (kWh)	Peak Power (kW)	Minimum Power (kW)
Conventional Inverter AC	0.8200	1.4200	0.1800
Intelligent AC with Control Logic	0.7356	1.2693	0.0241

$$\text{Energy Saving (\%)} = \frac{E_{inverter-}E_{intelligent}}{E_{inverter}} \times 100 \quad (1)$$

$$\text{Energy Saving (\%)} = \frac{0.8200-0.7356}{0.8200} \times 100$$

$\frac{0.0844}{0.8200} \times 100 = 10.29\%$

Based on the calculation, it can be seen and proven that the proposed Control Logic Setup can potentially provide an additional approximate saving of 10% in terms of energy when being compared to a conventional inverter system. In Table 2, the energy and power comparison are shown for a conventional vs intelligent AC system for morning simulation.

Table 2. Energy and power comparison between conventional and intelligent AC system (morning simulation).

System Type	Total Energy (kWh)	Peak Power (kW)	Minimum Power (kW)
Conventional Inverter AC	0.8200	1.4200	0.1800
Intelligent AC with Control Logic	0.6100	1.1200	0.0000

Energy Saving (%) = $\frac{E_{inverter} - E_{intelligent}}{E_{inverter}} \times 100$

Energy Saving (%) = $\frac{0.8200 - 0.6100}{0.8200} \times 100$

$\frac{0.2100}{0.8200} \times 100 = 25.6\%$

In the early morning simulation run, the energy saving is greater than that of the night running, primarily due to the cooler and drier atmospheric conditions during that period. Due to the decrease in the external temperature and humidity, the amount of cooling required by the AC is minimal. Hence, the compressor consumes lesser time to attain the desired room temperature, after which the compressor operates at higher speeds for shorter periods, as the innovative control logic tends to switch the compressor to LOW speed or switch it off when the desired indoor temperature is attained. Moreover, during nighttime simulation, as it is cooler than during the day, the retained heat of the building causes increased cooling rates; thus, the compressor operates at medium speeds for a longer period, resulting in greater energy consumption than in early morning running.

4. Conclusion

The current research aimed to explore the concept of energy optimization in residential split system air conditioners using a smart inverter compressor control algorithm. The research objectives were achieved through the development and implementation of a smart inverter compressor control algorithm, which was then simulated in MATLAB Simulink to compare its performance with conventional non-inverter and inverter technologies. The research successfully achieved its objectives, which were to develop a dynamic control logic to control compressor speed in real-time, suppressing unnecessary compressor operation at high RPM as temperatures approached setpoint. The second objective was achieved by developing an intelligent control algorithm to control compressor speed in real-time, as well as to simulate changes in compressor speed and room temperature. The third objective was achieved by developing an evaluation using the International Performance Measurement and Verification Protocol, which confirmed that the proposed smart inverter control algorithm can achieve significant energy savings compared to conventional inverters.

The research, although simulated, provides an indication that intelligent control can be achieved without compromising cooling capacity.

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