Journal of Engineering Applications December 2024 Vol.11 No.32 20-25
Article

Inverter technology and the role of the user behavior: Towards a more efficient use of energy

La tecnología inverter y el rol del comportamiento del usuario: Hacia un uso más eficiente de la energía

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CONAHCYT classification:

Area: Engineering
Field: Technological sciences
Discipline: Mechanical technology and engineering
Subdiscipline: Refrigeration equipment

https://doi.org/10.35429/JEA.2024.32.11.20.25

History of the article:
Received: September 01, 2024
Accepted: December 26, 2024

Check for updates

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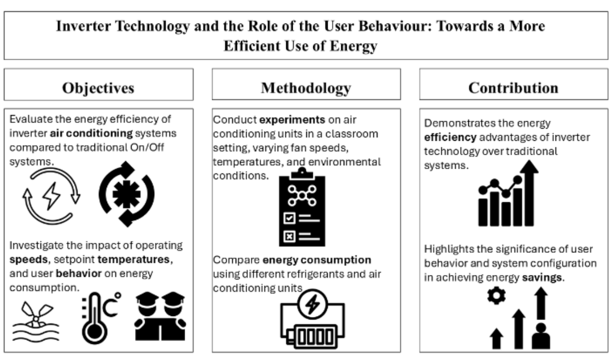
Abstract

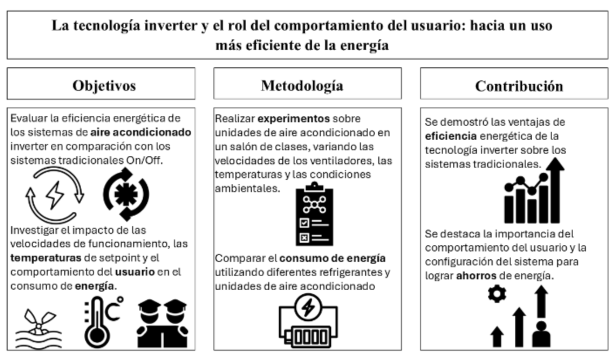
The article analyzes the energy efficiency of air conditioning (AC) systems with inverter technology compared to On/Off systems, highlighting the importance of user behavior in energy consumption. AC is essential for comfort and health, but it also contributes significantly to CO_2 emissions due to high energy consumption. Inverter technology can reduce energy consumption by maintaining a more stable internal temperature and reducing operating costs and emissions in comparison with On/Off systems. However, incorrect use by users, such as turning the AC to maximum capacity and then reducing it, lead to energy inefficiencies. Thus, users play a crucial role in the control to improve energy efficiency. It has been studied that the participation of users in temperature management and the advanced technologies use optimize energy consumption and reduce environmental impact. i.e., the adoption of inverter systems and user education are essential to achieve a more sustainable and efficient use of energy in hot climate areas.



Energy efficiency, Inverter technology analyzes, Energy consumption comparison.

Resumen

Se examina la eficiencia energética de los sistemas de aire acondicionado (AC) con tecnología inverter frente a los sistemas On/Off, subrayando el papel del usuario en el consumo de energía. Aunque el AC es vital para la comodidad y salud, también contribuye a las emisiones de CO_2 debido a su alto consumo energético. La tecnología inverter reduce el consumo de energía al mantener una temperatura interna estable, disminuyendo los costos y las emisiones comparado con los sistemas On/Off. Sin embargo, un mal uso, como ajustar el AC a máxima capacidad y luego reducirlo, provoca ineficiencias energéticas. Por lo tanto, el comportamiento del usuario es crucial para mejorar la eficiencia energética. Se estudió que la participación activa en la gestión de la temperatura y el uso adecuado de tecnologías avanzadas optimizan el consumo energético. La adopción de sistemas inverter y la educación del usuario son esenciales para un uso más sostenible y eficiente en climas cálidos.



Eficiencia energética, análisis de tecnología inverter, comparativo de consumo energético.

Citation: Vidal-Santo, Adrián, Campos-Domínguez, Armando, Vázquez-Guzmán, Aldo G. and Castillo-Toscano, William A. Inverter technology and the role of the user behavior: Towards a more efficient use of energy. Journal of Engineering Applications. 2024. 11-32: 20-25.

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Introduction

Air conditioning in hot areas is mainly used for thermal comfort and public health reasons. In regions where temperatures reach high levels, especially during the summer, air conditioning provides a comfortable and safe environment by reducing the temperature and humidity of the indoor air. This is crucial for preventing heat-related health problems, such as heat stroke and dehydration, which can negatively affect vulnerable populations such as young children, the elderly, and people with chronic illnesses (Ebi et al., 2021).

However, the widespread use of air conditioning carries significant consequences for global climate change. The main impact comes from energy consumption (Hilmiyati-Mas'adah et al., 2023). Fossil fuels make up 80% of current global primary energy demand, and the energy system generates around two-thirds of global CO_2 emissions (Adu et al., 2024).

This additional demand for electricity to power air conditioning systems can directly contribute to greenhouse gas emissions, exacerbating global warming and climate change. Therefore, while air conditioning is crucial for human well-being in hot areas, it is imperative to develop and adopt more efficient and sustainable technologies, such as less energy-intensive refrigeration systems (Foster & Elzinga, 2024).

An alternative is inverter technology, which adjusts the compressor speed according to the thermal demand. This reduces energy consumption by up to 35% compared to traditional systems, maintaining a more stable indoor temperature and reducing operating costs and CO_2 emissions (Siriwardhana & Namal, 2017). Implementing this technology in air conditioning systems is a step towards greater energy efficiency and sustainability (Ebeed et al., 2024).

Although the inverter system in air conditioners is an advanced technology that promises energy efficiency, its incorrect use by users can generate contrary results. Many users turn the air conditioner on to full capacity at first and then reduce it, which can lead to periods of overcooling or overheating, thus increasing unnecessary energy consumption.

This pattern of manual use, where the user sets the air conditioner to its maximum power and then decreases it, creates considerable energy inefficiencies. According to Liu et al. (2021), the lack of use of automatic control in these systems results in higher energy consumption due to human intervention and inconsistent usage patterns. It is crucial to highlight the importance of including occupants in the control system of air conditioners to improve energy efficiency. Research has shown that including users in this process is not only an economical methodology but also effective for detecting occupancy and collecting data on user behavior (Zhou et al. 2024), thus contributing to a more efficient use of energy(Tang et al., 2021).In particular, the energy consumption due to the use of air conditioners in hot humid areas such as the port of Veracruz, Mexico, represents around 80% of the total kWh during the spring, summer, and early season periods in the educational sector (Vidal, 2016).

Methodology

Two power grid analyzers were used to record energy consumption when air conditioning (AC) equipment was operated simultaneously. In the experimentation, the set point of the operating temperatures (Interior Comfort Temperature), the evaporator fan speeds, and of course the time evolution of the ambient temperature corresponding to each monitoring cycle, during more than a year of experimentation, were varied; since the seasonal efficiency of the equipment (Resource Efficiency and Environmental Efficiency, REEE) will depend on the uses and habits of the user and of course on the environmental conditions.

In terms of energy efficiency, R32 refrigerant is typically slightly more efficient than R410A due to its higher thermal conductivity and lower vapor pressure, allowing air conditioning systems to use less energy to achieve the same cooling capacity. It is estimated that this difference can translate into an energy efficiency improvement of around 5% isotropic efficiency compared to R410A, depending on the specific operating conditions of the equipment. The characteristics of each AC equipment that was experimented with are presented in Table 1 (Bobbo et al., 2019; Kim et al., 2023).

ISSN: 2410-3454.
RENIECYT-CONAHCYT: 1702902

Box 1

Table 1

The characteristics of each air conditioning unit used in the experiment

Characteristics	Inverter Mirago	Inverter Carrier	On/Off Mirago
Capacity (BTU/hr)	12000	12000	12000
Refrigerant	R-32	R-410A	R-410A
Reported REEE (BTUh/We)	16.8	16.8	12.1

Source: (Bobbo et al., 2019; Kim et al., 2023).

The air conditioning (AC) systems were installed in a classroom of 32 m^2 or 90 m^3, in which 32,000 BTU of thermal load is required: so. In the experimentation, the 12,000 BTU systems were complementary to the 24,000 BTU system that exists in the room. In the first stage of testing, the 12,000 BTU equipment was operated alternately and was energized to 220 V. The electrical network analyzer was configured to the voltage operated by the equipment and although many electrical parameters were monitored, this study focuses mainly on energy consumption (kWh). The period of operation, in the first stage, of the AC equipment was, in most cases, from 09 to 14 and from 16 to 19 h, with some variations, and in the second stage only from 09 to 14 h. The room contained an average of 11 people during the experimentation, in the first stage, and an average of 5 people, during the second stage.

During the experiment, temperatures inside and outside the room were recorded using J-type thermocouples. Data acquisition was done using trademark technology and software, and the complete design of the SCADA system is described in detail in another article written by the same authors (Campos-Domínguez et al., 2024). In the second stage of the experimentation, only inverter systems of two different brands were worked on, which were also operated alternately and simultaneously.

Results

Figure 1 shows the comparison of energy consumption as a function of ambient temperature for two devices, both with inverter technology, operating at different setpoint temperatures: 24°C (a), 23°C (b), and 22°C (c), with the fan speed in medium configuration.

In each of these scenarios, a consistent trend of reduction in energy consumption is observed in the Carriero equipment (solid blue line). This decrease in consumption could be due to the technology of each of the manufacturers concerning the compressor, evaporator, and condenser fans since the Carriero is mid-range equipment that is 30% more expensive than the Mirago.

Box 2

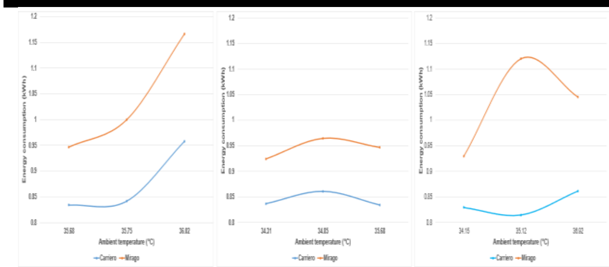

Figure 1

Comparison of energy consumption as a function of the ambient temperature of two inverter units operating at a setpoint temperature of 24°C (a), 23°C (b), and 22°C (c) and intermediate fan speed

Figure 2 explores the power consumption as a function of the setpoint temperature, again using two inverter units operating at average fan speed. The comparison between different setpoints shows a clear trend. For ambient temperatures between 36 and 37 °C, which represents a very hot day with thermal sensations of around 45°C, inverter technology is more appreciated in the AC Carriero at a set point of 24°C and this energy consumption gap is reduced as the setpoint decreases, that is, the colder the equipment is required.

Box 3

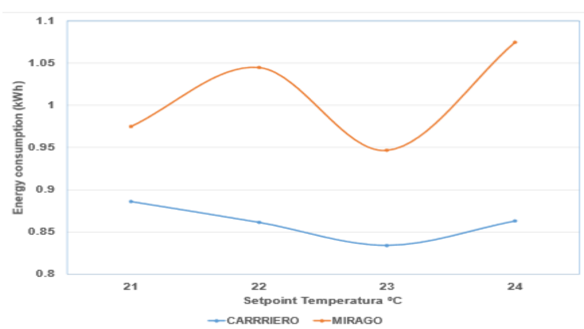

Figure 2

Comparison of energy consumption as a function of setpoint temperature of two inverter units operating at intermediate fan speed

ISSN: 2410-3454.
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Moreover, Figure 3 presents a comparison of energy consumption as a function of ambient temperature, contrasting equipment with inverter technology (blue line) and a device with On/Off technology (orange line) operating at setpoint temperatures of 22°C (a) and 23°C (b) with medium fan speed. This figure highlights the significant differences in energy performance between the two technologies. Inverter systems show significantly lower energy consumption compared to On/Off systems, particularly at higher temperatures. The blue line, representing the inverter system, shows a flatter and more stable curve, indicating a better ability to maintain energy efficiency regardless of fluctuations in ambient temperature. In contrast, the orange line of the On/Off system shows more inefficient energy consumption due to the need to turn the compressor on and off repeatedly to maintain the desired temperature.

The energy consumption behavior of two inverter air conditioning units, Carriero and Mirago, was evaluated in high and medium-speed configurations within a setpoint temperature range of 21-24°C and an ambient temperature of 36-37°C (Figure 1). The results show significant differences in energy consumption (kWh) between the two operating speeds for each unit, highlighting the importance of an appropriate selection of the operating speed to optimize energy efficiency. Under high-speed conditions, the Carriero unit maintains relatively stable power consumption through the various setpoint temperatures, with a slight increase to 22°C, followed by a gradual decrease towards 24°C. On the other hand, the Mirago unit exhibits greater fluctuation, reaching its peak consumption at 22°C and drastically reducing afterward. This variability in Mirago suggests lower operational efficiency at high speed compared to Carriero.

Consequently, when comparing the high- and medium-speed configurations, it is observed that both units show a reduction in energy consumption when operating at medium speed. The Carriero unit, in particular, stands out for its more consistent and lower consumption profile at medium speed, which highlights its superior efficiency in this configuration. Similarly, although the Mirago unit also reduces its consumption at medium speed, its fluctuation pattern persists, with a peak at 22°C before decreasing.

Our results show the importance of proper use of speed settings in inverter air conditioning systems to maximize energy efficiency. As Liu et al. (2021) mention, the incorrect use of these advanced technologies, such as frequent manual adjustment of maximum power, can lead to significant inefficiencies. In this context, it is crucial to promote the use of automatic control and the participation of occupants in the temperature management process, as shown by the research of Tang et al. (2021), showing that the inclusion of users as a relevant factor in energy studies not only improves energy efficiency but also optimizes occupancy detection and the collection of data on user behavior. This comparative analysis between operating speeds highlights that choosing the right speed can result in considerable energy savings and more efficient use of inverter air conditioning systems, especially in high-temperature environments.

The Carriero unit, with its remarkable performance at medium speed, demonstrates how an optimized operating setup can contribute significantly to energy efficiency as can be reported in other investigation cases (Hrouda et al., 2024; Liu et al., 2021).

Box 4

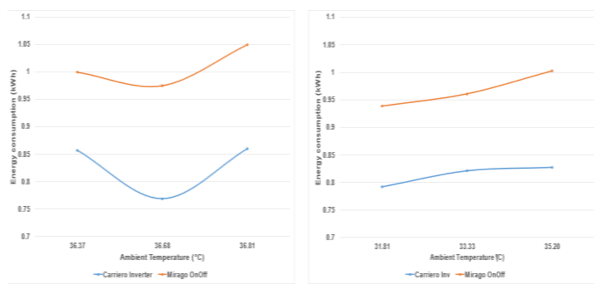

Figure 3

Comparison of energy consumption based on the ambient temperature of two units, the blue line is from the inverter and the orange line is from the On/Off operating at a setpoint temperature of 22°C (a), and 23°C (b) and intermediate fan speed

Conclusions

This study highlights the importance of choosing the right operating speed in air conditioning systems to maximize energy efficiency. It was noted that although the Carriero unit is more expensive, it provides more stable and efficient performance than the Mirago unit, especially at medium speeds.

ISSN: 2410-3454.
RENIECYT-CONAHCYT: 1702902

This superior performance is partly attributed to the use of R-410a refrigerant in the Carriero unit, which proves to be more effective in reducing energy consumption in high-temperature conditions compared to the R-32 refrigerant employed by the Mirago unit. These results underscore the need to consciously employ advanced technologies to optimize energy efficiency and mitigate environmental impact. In addition, they open the door to future research on the incorporation of emerging technologies such as machine learning and artificial intelligence into air conditioning systems. Such technologies could bring significant improvements in energy efficiency by dynamically adjusting operating speeds in real time, taking into account environmental conditions and usage patterns. By adopting these innovations, a smarter and more sustainable use of air conditioning systems could be achieved, thus contributing to the reduction of overall energy consumption and developing greener solutions.

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Author contribution

Vidal-Santo, Adrian: Contributed to the conceptualization, writing-original draft, data curation, methodology, formal analysis, and project administration.

Campos-Domínguez, Armando: Contributed to the methodology, resources and Investigation.

Vázquez-Guzmán, Aldo: Contributed to the formal analysis, writing-original draft, writing-review & editing.

Castillo-Toscano, William A.: Contributed to the conceptualization, methodology, formal analysis, and project administration.

Availability of data and materials

The data used or analyzed during the current study is available from the corresponding author upon reasonable request.

Funding

The research did not receive any financing.

Acknowledgments

The authors extend their appreciation to the Energy Systems Laboratory of the Veracruz University, Veracruz Region, for generously conceding permission to utilize their facilities. Furthermore, gratitude is expressed to the Faculty of Mechanical Engineering and Naval Sciences of the Mechanical Electrical Engineering Educational Program.

Abbreviations

AC	Air conditioner
REEE	Resource Efficiency and Environmental Efficiency
SCADA	Supervisory Control and Data Acquisition

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ISSN: 2410-3454.
RENIECYT-CONAHCYT: 1702902