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A THERMAL-ANALYSIS GUIDED REDESIGNING OF UNINTERRUPTIBLE POWER SUPPLY FOR ENERGY STORAGE APPLICATIONS
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Abstract. *This study proposes a redesign of a commercial line-interactive sinusoidal UPS of 1400VA with an output RMS voltage of 115 V (60 Hz) based on a thermal analysis. The focus of the analysis is on key components such as the transformer, power transistors affixed to heat sinks, and a cooling unit. The first round of thermal analysis was conducted using Ansys simulation calibrated with experimental data obtained from a temperature analyzer and Type K thermocouples. The simulation results suggested internal layout changes such as rotating the transformer by 90°, replacing the core windings with aluminum, and increasing fan intake velocity, among others. A second round of simulations was performed, taking the layout changes into account. The results showed a marked decrease in temperature, as the novel configuration optimized airflow by enabling smoother, uninterrupted flow and increased turbulence while minimizing energy losses. Although this approach improved heat transfer between components and air by promoting turbulence and forced convection, at higher velocities, a sudden airflow deviation near the intake caused a temperature increase due to disrupted forced convection in the transistor region. Nonetheless, this study demonstrates how engineering design based on modeling and simulations increases product maturity, diminishes rework, and engineering hours.*

Keywords: *UPS, energy storage, thermal analysis, heat dissipation.*

1. INTRODUCTION

In an increasingly connected world reliant on constant power availability, the need for reliable and uninterrupted power supply is paramount. That's where UPS, or Uninterruptible Power Supply, comes into play. UPS systems serve as a crucial backup power solution, ensuring the continuity of electrical power in the event of disruptions, outages, or voltage fluctuations [1].

UPS systems also have an additional application as energy storage devices. By leveraging their battery capacities, UPS systems can store excess electrical energy during times of low demand or when renewable energy sources generate surplus power. Furthermore, UPS energy storage can contribute to load shifting and peak shaving. During times when energy demand is high, such as during peak hours, UPS systems can discharge the stored energy, reducing the strain on the grid and potentially lowering electricity costs. This load shifting capability helps balance the supply and demand dynamics and optimizes energy utilization. UPS systems also play a vital role in supporting the integration of renewable energy sources. As renewable energy generation, such as solar or wind power, is intermittent by nature, the ability to store excess energy becomes crucial. UPS systems can store the surplus renewable energy produced during periods of high generation and release it when the renewable sources are not producing electricity, ensuring a consistent and reliable power supply. [2-8]

Nevertheless, during the operation of electrical equipment, the generation of heat is inevitable as a result of the functioning of internal components. This heat needs to be properly dissipated to prevent the temperature from rising to harmful levels, which can compromise the lifespan and functionality of the devices. As a result, thermal analysis plays a crucial role in ensuring the performance and reliability of uninterruptible power supply (UPS) systems, as excessive heat can lead to equipment failures and even disruptions in power supply [9].

Thermal analysis in UPS also allows for the sizing and design of efficient cooling systems, taking into account the amount of heat generated by the equipment within enclosed spaces and other sources of heat present in the environment. This analysis is essential to ensure that the temperature of internal components remains within acceptable operational limits.

Furthermore, with technological advancements, thermal simulation tools are increasingly being used in UPS development. These tools enable preliminary studies and simulation of different heat dissipation scenarios, aiding in cabinet design and proper component positioning. In this way, potential hotspots can be identified, and measures can be taken to reduce heat generation [10].

Based on this scenario, this project aims to analyze and optimize the thermal performance of a UPS (Uninterruptible Power Supply). The research involves the complete transposition of the UPS to the Ansys simulator in order to compare experimental temperature results with the values provided by the simulator. We will also present a proposal to change the UPS design, aiming to reduce the temperature and enhance its operational safety.

2. METODOLOGY

2.1 Uninterrupt power supply

Fig. 1 presents the configuration of a typical line-interactive UPS. During normal operation (this mode was considered in this paper), the UPS continuously charges its battery and passes the AC power line through to the connected devices (load), passing through the transformer. It includes automatic voltage regulation (AVR) to correct minor fluctuations in voltage without switching to battery power, which helps to extend the battery life and improve the efficiency of the UPS. In the event of a power outage, the UPS switches to battery power within milliseconds, providing uninterrupted power to the connected devices.

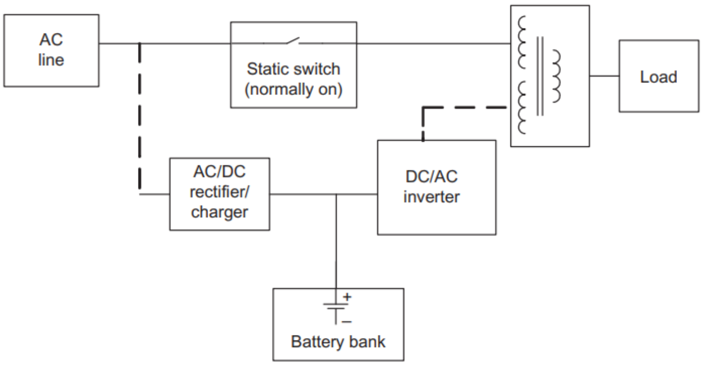
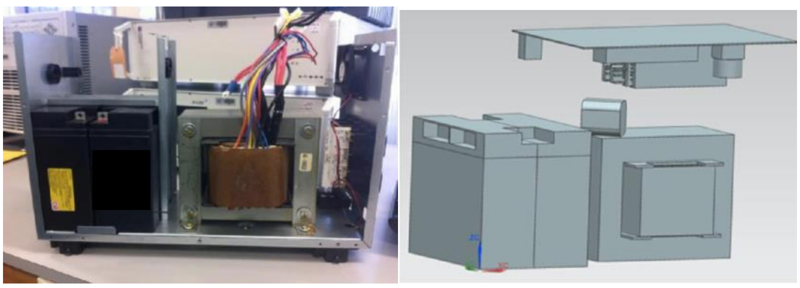


Figure 1. Configuration of a typical line-interactive UPS [11].

In this analysis, a commercial line-interactive sinusoidal UPS of 1400VA with an output RMS voltage of 115 V (60 Hz) was employed. The UPS utilizes 12Vdc 17Ah lead-acid batteries. The transformer features internal and external copper windings and a silicon steel core. To harness the stored energy in the battery, a full bridge DC/AC voltage converter was implemented, comprising power transistors and an aluminum heat sink. The UPS is ventilated by a fan operating at a speed of 12.5 m/s. Initially, the three-dimensional design of the UPS was created using the NX software. Fig. 2 displays a photograph of the UPS and the final design.



(a) (b)

Figure 2. (a) Photograph and (b) three-dimensional drawing from the UPS.

2.2 Experimental setup

In order to extract the temperature of different components of the no break and to calibrate the simulations, experimental data was extracted from the UPS. Fig. 3 shows the experimental setup. To maintain a high-quality energy and avoid interruption during the tests, the UPS was powered by a programmable alternating power source (Chroma Programmable AC Power Source 6500). A resistive load of 800W was used, thus making the UPS work with 80% of its total capacity. For this, a programmable AC/DC electronic load from Chroma model 63804 was used. Finally, to extract the operating temperature of the transformer, a Keysight 34970A Data Acquisition was used together with Type K thermocouple, that were positioned in the transformer, battery and converter.

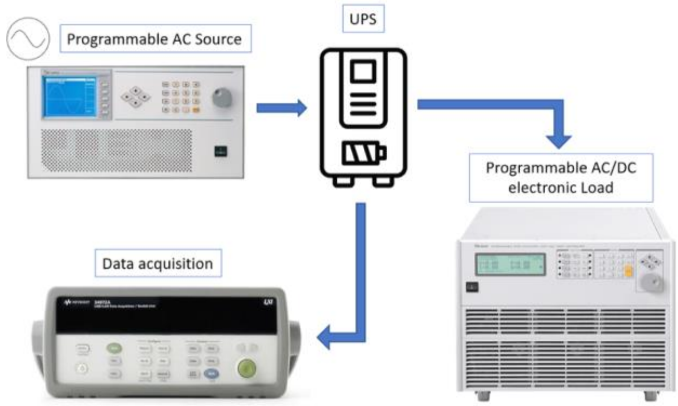


Figure 3. Experimental setup configuration.

2.3 Simulation

The methodology utilized in the study's development is depicted in Figure 4. Computational Fluid Dynamics (CFD) simulations for heat transfer were conducted using the Fluent CFD software within the ANSYS platform [12]. The three-dimensional design of the UPS was imported into the simulator, material properties were adjusted, the geometric mesh was defined, boundary conditions were applied, and results were processed. In this initial stage, the researchers needed to iterate through a repetitive cycle until consistent convergent results were obtained [13-15].

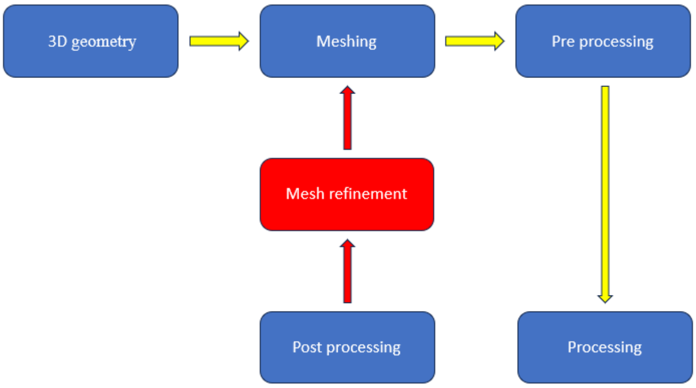


Figure 4. Schematic diagram.

2.3.1 Computational mesh refinement

A computational mesh refinement study was conducted to determine the optimal mesh resolution for solving the equations. The Ansys tool generated an initial random mesh, which was subsequently refined until achieving convergence in the results. A definitive mesh test was performed to determine the point at which the results remained consistent. Table 1 presents the key data from simulations with meshes ranging from one million to approximately three million elements.

Table 1. Simulation results from meshes ranging

Component	1209065		2762973		3197065	
	Tmax °C	Tmin °C	Tmax °C	Tmin °C	Tmax °C	Tmin °C
Transformer	46.77	27.86	46.50	27.85	47.03	27.90
Transistor	26.86	26.85	27.39	27.33	27.42	27.30
Heat sink	26.86	26.84	27.40	27.32	27.41	27.27

By analyzing the temperature data as a function of the mesh element count, it is possible to determine if the minimum number of elements satisfies the 4% difference criterion. If the difference between two quantities (of the same unit) is less than or equal to 4%, it indicates that further mesh refinement is not necessary, as the level of detail provided by the mesh is already sufficient. For the transformer it was observed a 0.58%, for the transistor 2.08% and 2.05 for the heatsink. Based on the obtained percentages, it is possible to use the mesh with 1,209,065 elements, as further refinement of the studied object's mesh would not yield significant effects.

2.3.2 Boundary conditions: Material

Table 2 represents the materials that were included, along with their respective properties.

Table 2. Materials properties used at simulation.

Parameter	**Material**	**Unit**
Heat sink – Aluminum		
Density	2697	kg/m^3
Specific heat	900	J/kg.K
Conductivity	237	W/m.K
Transformer - Silicon steel sheet		
Density	7874	kg/m^3
Specific heat	440	J/kg.K
Conductivity	80.2	W/m.K
Transformer - Copper windings		
Density	8920	kg/m^3
Specific heat	390	J/kg.K
Conductivity	401	W/m.K

2.3.3 Boundary conditions: Heat input

In the UPS operating in network mode, the component primarily responsible for the majority of the heating is the internal copper winding. It generates approximately 150,000.00 W/m^3 of heat, which in turn heats up the surrounding components and the air. Through convection, the heated air transfers this heat to the more distant components.

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2.3.4 Boundary conditions: Air flow conditions

In the subsequent step, they incorporated the actual air inlet velocity into the UPS using the fan code. By determining the maximum flow rate of the fan and having knowledge of the inlet area, it is possible to calculate the air velocity using Eq. (1).

$$v = \frac{V}{A} \tag{1}$$

Considering the variables, where v represents the air velocity, V represents the air inlet flow rate through the fan, and A represents the inlet area. The fluid used in the simulation as the system refrigerant was defined as a compressible fluid, with an ambient temperature of 25°C and a velocity of 12.5 m/s. After setting and incorporating the inlet velocity, the researchers established the outlet pressure. The pressure immediately after the outlet is atmospheric pressure, which is zero in the manometric scale.

2.3.5 Convergence analisy

The number of iterations that the program should execute was defined in order to attempt to obtain the desired result. Ansys uses an iterative method for calculating the results. This means that with the continuity equations (conservation of momentum, conservation of energy, and conservation of mass), the program starts the calculations with an initial assumption of values and then performs multiple calculations until these calculations begin to converge. Convergence occurs when the results of the last calculation are considerably close (if not identical) to the results of the previous calculation. Once convergence is achieved, it can be said that the obtained results are definitive and should be analyzed accordingly. The Fluent CFD software, by default, uses a convergence criterion where the residual percent error between iterations is less than or equal to 10e^{-4}. This criterion was achieved in the simulations only in the transient study regime. However, the transient mode produced similar results to the steady-state regime. The steady-state regime allows the convergence of all essential variables, except for continuity and turbulence due to the presence of numerous vortices generated within the UPS (a component whose equilibrium is unattainable in steady-state). Figure 5 presents the convergence curves for the steady-state regime.

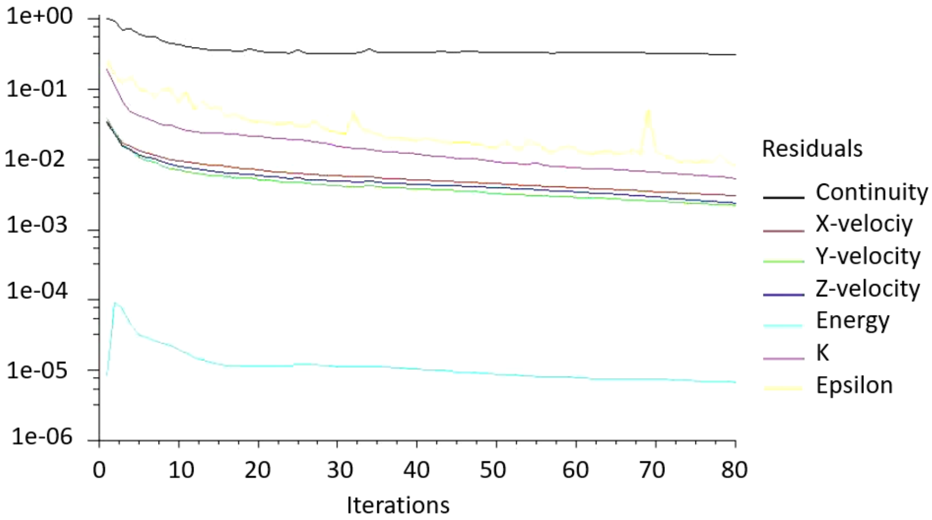

Figure 5. Permanent regime convergence curves

Table 4 compares the maximum temperatures obtained under steady-state conditions with the results obtained in the transient regime.

Table 3. Maximum temperatures obtained in the permanent and transient regime.

Component	Permanent regime	Transient regime
Transformer	46.77 ºC	47.41 ºC
Transistor	26.86 ºC	29.05 ºC
Heat sink	26.86 ºC	28.07 ºC

3. RESULTS AND DISCUSSION

3.1 Experimental analysis

The Figure 6 presents the experimental result of temperature variation over time, extracted from the main heat sources of the UPS: transformer, transistor, and battery. Immediately after the experiment, thermal images were taken using the FLUKE thermal camera for result comparison.

3.2 Simulations

After completing the calculations, Ansys provides a window where all possible simulation results are displayed. In the case of the thermal study of the UPS, our focus is on knowing the temperatures of the components and the flow lines (streamlines) to propose changes in geometry, flow, materials, component arrangement, etc. Figure 5 shows the comparison of the results considering the experimental and simulations data, for the maximum temperature.

Table 4. Experimental vs simulations comparisons of the maximum temperature.

Components	Experimental data[ºC]	Simulations results[ºC]
Transformer	43	46
Transistor	28	27
Heatsink	28	27

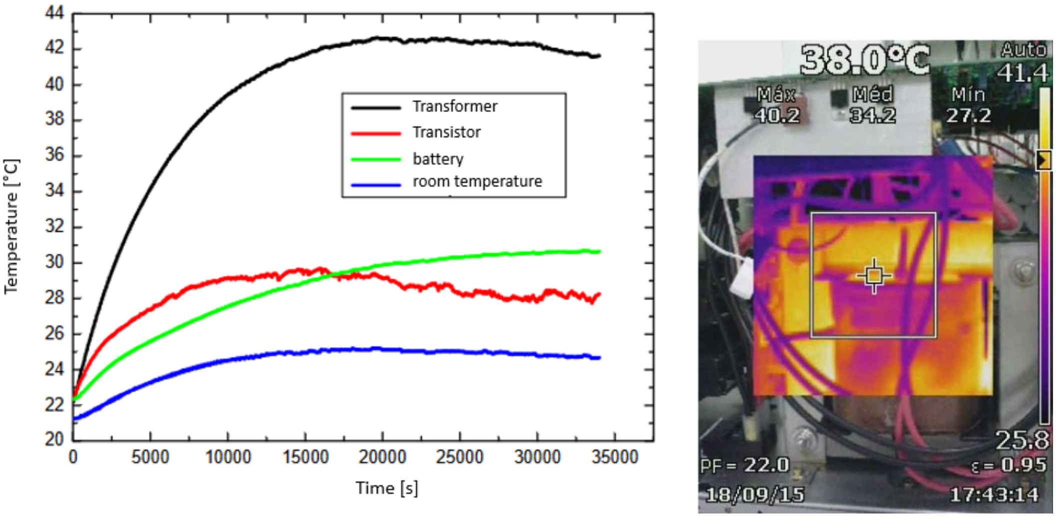

Figure 6. Experimental result of temperature variation over time and thermal image from the Transformer.

The simulation of the current UPS case will be presented next, followed by the results of simulations with modifications that were more effective in reducing component temperatures (increasing the air inlet velocity through the cooler and transformer rotation), such as certain alterations that negatively impacted the thermal performance of the UPS (replacing copper winding with aluminum and swapping the cooler with an exhaust fan).

3.3 Layout variations

3.3.1 Transformer

Rotating the transformer results in a reduction in the system's transformer temperature as observed at Table 6. This is because the airflow lines are favored by the openings provided by the copper windings, creating smoother and less directional flow, increasing turbulence, and reducing pressure losses in the system. Figure 7 it is possible to see the simulation results for the transformer at the (a) existent and in a (b) new position.

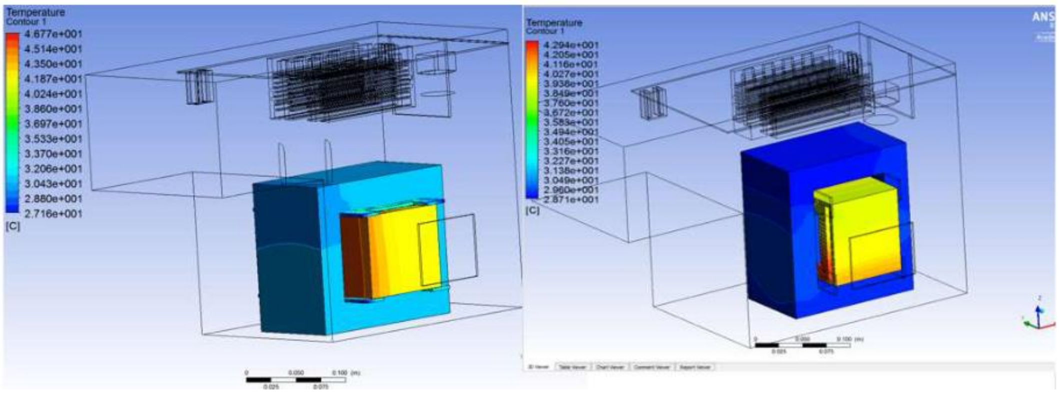

Figure 7. Simulation results for the transformer at the (a) existent and in a (b) new position.

Table 5. Maximum temperature analysis for the transformer at the existent and in a new position

Component	Existent position	New position
Transformer	46.77 ºC	42.94 ºC
Transistor	26.86 ºC	26.85 ºC
Heat sink	26.86 ºC	28.86 ºC

3.3.2 Fan velocity

Several possible changes in the cooler speed were analyzed, aiming to optimize the heat transfer of the system. Two alterations will be presented: one resulted in a significant decrease in component temperatures (considered optimal), while the other, due to flow deviation, led to a deterioration in heat transfer for some components of the UPS. Figure 8 illustrates the temperature distribution for different air inlet velocity. Increasing the air inlet velocity leads to an increase in airflow, which in turn enhances turbulence and forced convection, favoring heat exchange between the components and the air.

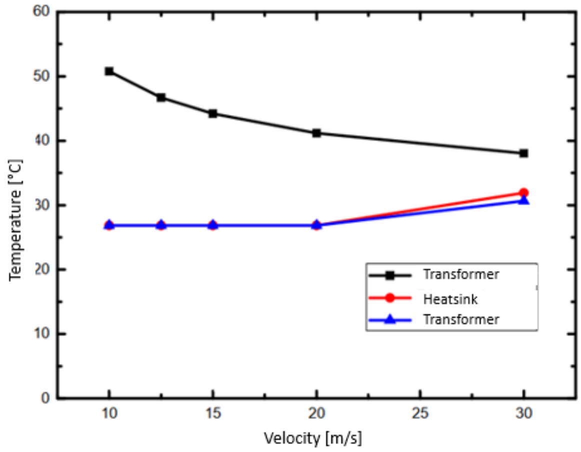

Figure 8. Temperature distribution for different air inlet velocities.

However, an analysis of the flow was conducted using the parameters employed, and as observed in Figure 9, there is a sudden deviation in the flow near the air inlet. The airflow collides with one of the dissipator walls, causing a diversion and preventing any form of forced convection from occurring in the region of the transistors.

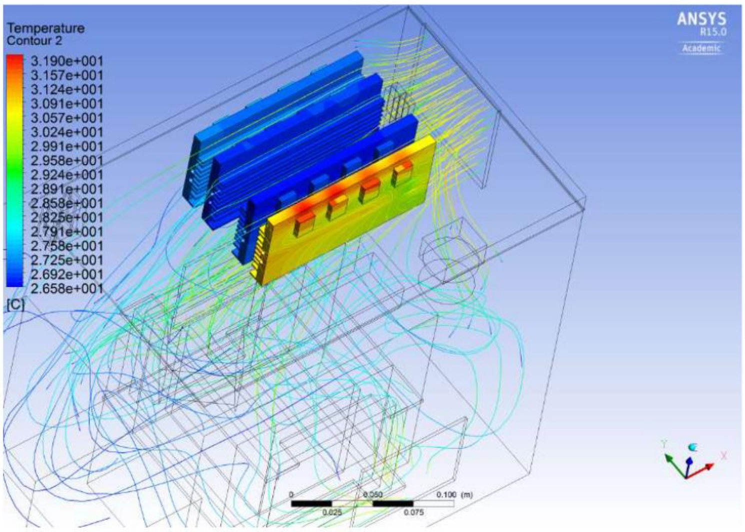

Figure 9. Flowlines being deflected when colliding with one of the sinks.

3.3.3 Fan behavior

The fan can function as a cooler, where the airflow is from the outside to the inside of the UPS, or as an exhaust fan, where the airflow is reversed, from the inside to the outside of the UPS. Based on this, we simulated this variation in the fan behavior. Figure 10 display the temperature distribution in the UPS when it is cooled by an exhaust. Replacing a cooler with an exhaust fan in the studied UPS is not feasible because it leads to a generalized increase in the temperature of all internal components due to the flow orientation. In other words, the airflow is hindered when the outlet is positioned at the top and the inlet is at the bottom (air being sucked in by the exhaust fan). Table 4 presents the maximum temperatures extracted at the different components, considering the fan as a cooler and as an exhaust.

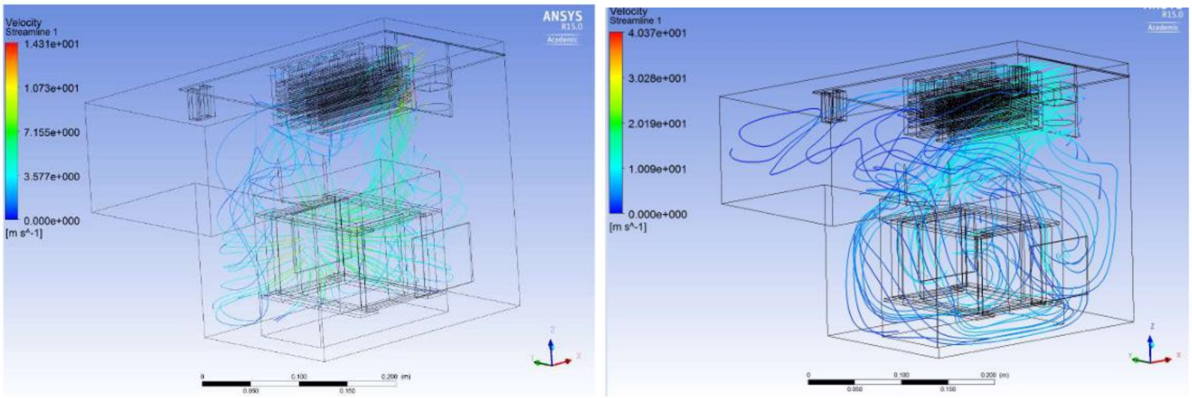

Figure 10. Air flow lines resulting from the use of an (a) exhaust fan and a (b) cooler.

Table 6. Maximum temperatures obtained for cooler and exhaust fan configuration.

Component	Cooler	Exhaust
Transformer	46.77 ºC	54.95 ºC
Transistor	26.86 ºC	28.15 ºC
Heat sink	26.86 ºC	28.07 ºC

3.3.4 Transformer windings analysis

The considered windings were made of copper, following the transformer manufacturing standards. However, recent research has shown that the use of aluminum cable for the primary and secondary windings of the transformer results in reduced losses and weight. As a result, we conducted some simulations considering this variation in the winding material of the transformer. Table 8 display the maximum temperatures for each component of the UPS with iron and aluminum windings. As observed, the replacement with aluminum windings leads to a slight increase in the operating temperature of the transformer; however, the other components have not been affected. Despite this adverse temperature variation, aluminum still offers significant advantages such as reduced weight and cost, which can offset the temperature rise.

Table 7. Maximum temperatures obtained for copper and aluminum windings.

Component	Copper	Aluminum
Transformer	46.77 ºC	47.26 ºC
Transistor	26.86 ºC	26.85 ºC
Heat sink	26.86 ºC	26.86 ºC

4. CONCLUSIONS

In conclusion, this scientific study aimed to investigate and improve the heat efficiency of an Uninterruptible Power Supply (UPS). Through the utilization of the Ansys simulator, the UPS was fully transferred to a virtual environment to compare the actual temperature measurements with those obtained from the simulator. By conducting this analysis, we were able to identify areas of improvement and propose modifications to the UPS design that can effectively reduce temperatures and enhance operational security.

The findings from this research indicate that the use of simulation tools such as Ansys can provide valuable insights into the thermal behavior of UPS systems. By accurately modeling and simulating the UPS, we can gain a deeper understanding of the heat distribution and identify potential hotspots within the system. This knowledge enables us to develop targeted design modifications to optimize heat dissipation and enhance overall efficiency.

The proposed modifications include measures such as improving airflow circulation, optimizing heat sink design, and considering alternative cooling mechanisms. These changes aim to minimize heat buildup, thereby reducing the risk of thermal failures and improving the UPS's operational reliability.

Overall, this study contributes to the ongoing efforts in UPS design and thermal management by highlighting the benefits of utilizing simulation tools for analysis and optimization. By implementing the proposed modifications, it is expected that the heat efficiency of UPS systems can be significantly enhanced, leading to improved performance, increased operational security, and extended lifespan of the equipment. Further research and practical implementation of these modifications are recommended to validate their effectiveness in real-world UPS applications.

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