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Cases studies

Design and construction of an electrical load simulator prototype using recycled materials

Diseño y construcción de un prototipo simulador de cargas eléctricas usando materiales reciclados

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Abstract. - *The growing need for skilled personnel within the Federal Electricity Commission (CFE) has highlighted the importance of developing innovative and resource-efficient training tools. This project aimed to design and construct a prototype electric load simulator using recycled materials to address the demand for supplementary training methods. The methodology included the selection and integration of reused components, followed by rigorous testing to validate the simulator's functionality under laboratory conditions. The scope of the project extended to the practical application of the simulator in a training session, which demonstrated its effectiveness in enhancing staff understanding of electrical load systems. The results indicate that this approach can significantly contribute to optimizing training programs within the CFE.*

Keywords: Learning and training; Mechanical design; Electrical loads; Electrical systems.

Resumen. - *La creciente necesidad de personal capacitado dentro de la Comisión Federal de Electricidad (CFE) ha puesto de manifiesto la importancia de desarrollar herramientas de capacitación innovadoras y eficientes en el uso de recursos. Este proyecto tuvo como objetivo diseñar y construir un prototipo de simulador de cargas eléctricas utilizando materiales reciclados para abordar la demanda de métodos complementarios de formación. La metodología incluyó la selección e integración de componentes reutilizados, seguida de pruebas rigurosas para validar la funcionalidad del simulador en condiciones de laboratorio. El alcance del proyecto se extendió a la aplicación práctica del simulador en una sesión de capacitación, lo que demostró su efectividad en mejorar la comprensión del personal sobre los sistemas de cargas eléctricas. Los resultados indican que este enfoque puede contribuir significativamente a optimizar los programas de capacitación dentro de la CFE.*

Palabras clave: Aprendizaje y formación; Diseño mecánico; Cargas eléctricas; Sistemas eléctricos.

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1. Introduction

The Federal Electricity Commission (CFE) plays a significant role in Mexico's social and economic development, supplying electricity to 95% of the population and employing approximately 95,000 people, including technicians, engineers, and administrative staff. Additionally, CFE is a key player in driving the country's energy transition towards cleaner energy sources and developing new energy projects [1,2]. Globally, CFE ranks 43rd out of 50 in the World Benchmarking Alliance's ranking of electrical service providers [3]. Its core mission is to deliver energy goods and services efficiently, sustainably, economically, and inclusively, aiming to establish itself as Mexico's leading energy company. To achieve this, CFE prioritizes strengthening its human capital while providing high-quality electrical energy services [4].

As part of its commitment to human resource development, CFE facilitated 11,945,954 hours of training in 2023 and 8,492,987 hours in 2024 through diverse training modalities [2]. These efforts are supported by three National Training Centers (CENAC), which offer courses and instruction nationwide [5]. However, given the size of its workforce, it is essential to complement these initiatives with additional strategies, such as localized training, peer learning, and the development of infrastructure for training and educational activities.

CFE's inventory includes numerous pieces of equipment and materials that have reached the end of their operational life [6]. These items present an opportunity for reuse, supporting the creation of training infrastructure while promoting sustainability. Similar efforts have been reported in the development of educational tools for technical training, where the reuse of materials and innovative prototypes has enhanced learning experiences while reducing costs and environmental impact [7,8]. For instance, previous works have demonstrated the effectiveness of simulators and prototypes in replicating real-world conditions for training purposes, but there is a lack of focus on using repurposed materials, especially in the energy sector.

This work addresses this gap by presenting the design and construction of a prototype electrical load simulator developed using repurposed equipment and materials. The simulator aims to provide practical, hands-on training for CFE employees, aligning with the organization's sustainability goals and the challenges set for the 2024–2030 administration [5].

The remainder of this article is organized as follows: Section 2 details the methodology used for designing and constructing the prototype. Section 3 presents the results of the simulator's laboratory testing and its application in training sessions. Finally, Section 5 concludes with the study's main contributions.

2. Material and Methods

2.1 Design Requirements

The design requirements for the electrical load simulator were based on the needs of field operations and training activities within the Federal Electricity Commission (CFE) [7].

These requirements are listed below:

1. Maximum height of 1.8 – 2 meters.
2. Opening of at least 90 degrees of rotation on its axis.
3. Panel fixed to the floor and wall.
4. Easy rotational mobility.
5. Use of reused materials.
6. Ability to simulate resistive, inductive, and capacitive loads.
7. Configurable to simulate combinations of load types.

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8. Equipped with the ability to attach measuring instruments.
9. A three-phase system with a voltage of 127 V per phase.
10. Ergonomic use for ease of operation.

2.2 Evaluation of Material for Reuse

An analysis was carried out on the available material for reuse in the construction of the simulator, focusing on the excellent condition of the electrical devices. The materials given a second life include a panel base**,** a TCS donut-type current transformer, electrical test boards, a three-phase meter, transformers, an 8x10 AWG control cable, and a socket base with 13 terminals. Figure 1 shows some examples of these materials.

Figure 1. Second use material

2.3 Design of the Load Simulator Panel

The design proposal must meet the company's requirements for an appropriate design considering the construction phase.

2.3.1 Proposal of the Single-Line Electrical Circuit

Figure 2 illustrates a three-phase, four-wire diagram (phase A, phase B, phase C, and neutral) proposed for the electrical circuit of the load simulator. This diagram shows all the equipment and elements to be used, such as the electrical loads (inductive, capacitive, and resistive), the CTs, the three-phase meter, the electrical test board with its connection, and the three phase-neutral lines. The detail section illustrates the socket base of the three-phase meter and its connection to the electrical test board. The connection includes the three phases or voltages (Va, Vb, and Vc) from the board to the meter, along with the input and output current relationships (EI-a, SI-a, EI-b, SI-b, EI-c, and SI-c) for each phase or voltage, specifying their positions on the socket base.

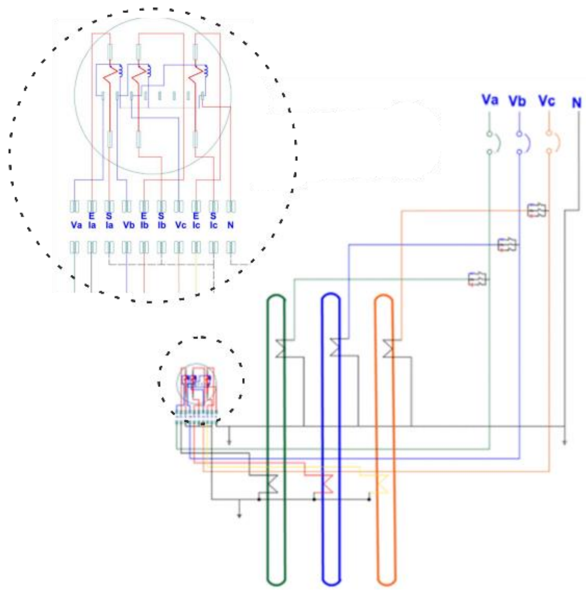

Figure 2. Three-phase, four-wire diagram (phase A, phase B, phase C, and neutral) and connection of the three-phase meter with the test board.

2.3.2 Electrical Circuit of the Load Simulator

Using the previous circuit, the electrical circuit diagram for the prototype is presented in a more illustrative way, showing each of its elements.

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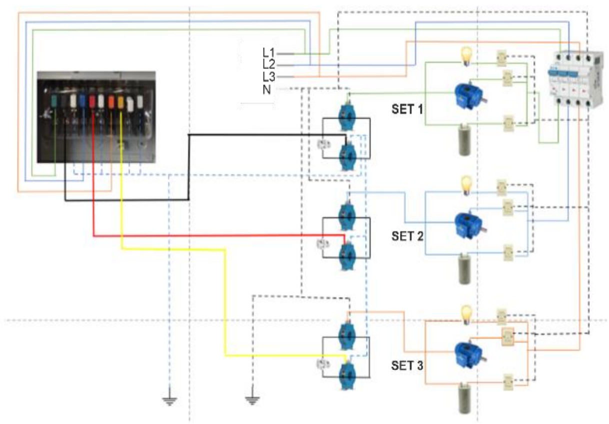

Figure 3. The electrical circuit of the simulator with its components.

With the previous proposal, design requirements 5 through 9 were met.

2.3.4 Preliminary Design Proposal

Once the electrical proposal for the load simulator is established, the mechanical design must address the manufacturing and construction requirements. Figure 4 shows the proposed model for fixing the prototype, where both the lower part (which will be fixed to the floor) and the upper part (fixed to the wall) of the simulator structure, attached to the floor and wall, respectively, can be observed.

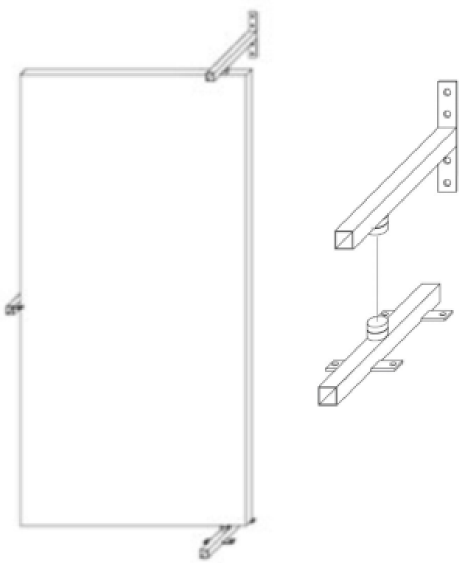

Figure 4. Model for panel mounting.

With the established fixing method, it is possible to propose the layout of the simulator components in a 3D arrangement. Figure 5 shows the top, front, and rear views of the prototype with the arrangement of its elements.

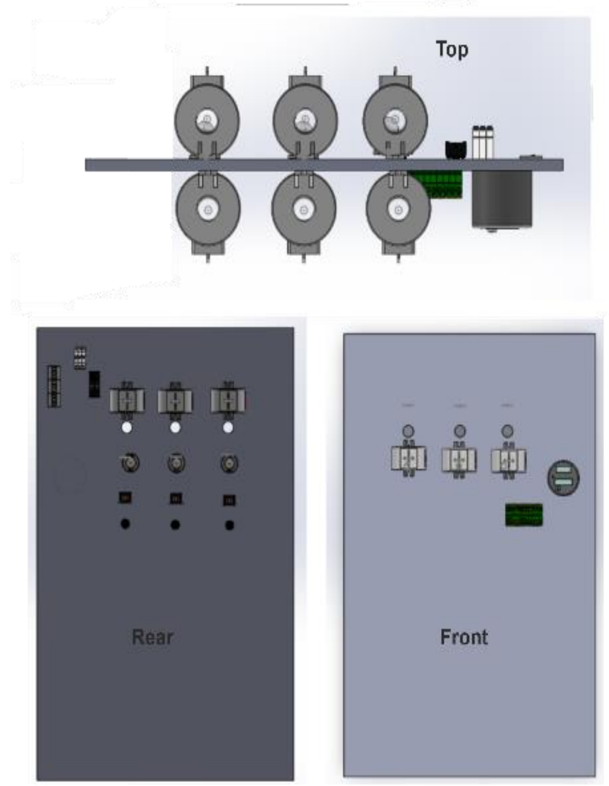

Figure 5. Views of the simulator element distribution

With the above, the remaining design requirements have been fulfilled.

2.4 Construction of the Simulator Prototype

2.4.1 Materials Used

At this stage, a broader overview of the selection of materials that were reused is provided.

The materials used are as follows:

- 13-terminal socket base.
- CTs (Current Transformers) with a current ratio of 400/5 Amps.
- Bare and insulated terminals.

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- Wiring: A 1/0 aluminum cable was used for the connection between CTs. Additionally, an 8x10 AWG control cable was used for most of the prototype. Finally, a 3x12 AWG CU heavy-duty cable connected the switches and the electrical loads.
- Thermomagnetic circuit breaker.
- Switches.
- Bulbs: 60-watt incandescent bulbs.
- Transformers.
- Capacitors: 20 microfarads.

2.4.2 Construction of the Electrical Load Simulator

A wooden sheet, previously used to mount electric power meters, was repurposed for constructing the load simulator. It was modified to meet the specific design requirements of the project. Figure 6 illustrates the process of attaching the simulator panel. To ensure both rotation and stability, a metal plate was secured to the floor, serving as the base for assembling the panel.

Figure 6. Views of the simulator element distribution

After fixing the panel, the larger surface area equipment was installed, including the CTs, the electrical test board, and, of course, the three-phase meter, as shown in Figure 7

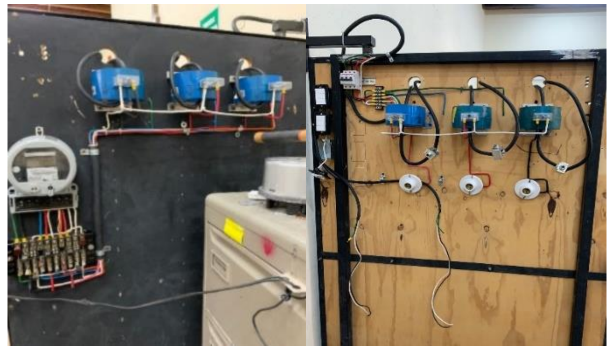

Figure 7. Connection of the front and rear part of the simulator

Finally, the connection of the power supply (three phases and a neutral), the installation of the switches, the CTs, and the connection of the electrical loads were carried out.

3. Results

Figure 8 shows the final prototype designed and built based on the company's requirements.

Figure 8. The final prototype was designed and built

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The operation of the components and the prototype was verified using a toolbox meter and an instantaneous test system with the following instruments: KLEIN TOOLS CL900 digital hook multimeter, METREL MD9240 clamp multimeter, and a conventional stopwatch.

Several load conditions were proposed for the prototype using Figure 3 as a reference. Eight configurations were proposed for the types of loads, of which only four results will be presented: resistive load, capacitive load, inductive-resistive, and finally, resistive-inductive-capacitive. The modifications to the sets are shown in the following figure.

	Configuration of the load type											
SET	Resistive			Capacitive			Resistive-Inductive			Resistive-Inductive-Capacitive		
SET 1	C⊗	R✓	Ind⊗	C✓	R⊗	Ind⊗	C⊗	R✓	Ind ✓	C✓	R✓	Ind ✓
SET 2	C⊗	R✓	Ind⊗	C✓	R⊗	Ind⊗	C⊗	R✓	Ind ✓	C✓	R✓	Ind ✓
SET 3	C⊗	R✓	Ind⊗	C✓	R⊗	Ind⊗	C⊗	R✓	Ind ✓	C✓	R✓	Ind ✓

Figure 9. Prototype Testing Conditions

The company's internal format, shown in Figure 10, was used to record the data obtained from the load cases evaluated. This format collects the data measured with conventional instruments and those obtained through the meter's ToolBox.

		Test Type:			
Transformer Testing					
Phase	I Primary	I Secondary	Ratio: Prim/Sec	Voltage	Real KVA
A					
B					
C					
Meter ToolBox					
Phase A		Phase B		Phase C	
VAN°		VBN°		VCN°	
VAN		VBN		VCN	
IA°		IB°		IC°	
IA		IB		IC	
Δ°A		Δ°B		Δ°C	
FP A		FP B		FP C	
kWT		kWT		kWT	
		Real KVA			
Efficiency%		Vector diagram (V-I)			
Error%					

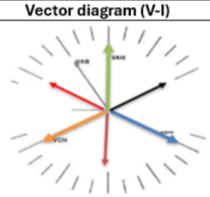

Figure 10. The internal format of the data recording system

The results obtained from the tests conducted manually and using the Toolbox for each evaluated case are presented in Table 1. The case with the highest percentage of discrepancy or error is the capacitive load, with 2.55%, while the other cases show errors below 0.1%. Capacitive loads are prone to higher measurement errors in three-phase systems due to their intrinsic characteristics. This is attributed to various factors, including the reactive nature of these loads, harmonic distortion, system impedance, and variations in load conditions

Table 1. Results of the cases evaluated.

Test: **Resistive load**		
	Measurements	
	Conventional	ToolBox
Real kVA	**21369.13**	**21360**
Measurement error %	0.0427	
Test: Capacitive load		
	Measurements	
	Conventional	ToolBox
Real kVA	**17721.6**	**17280**
Measurement error %	2.55	
Test: **Resistive - Inductive load**		
	Measurements	
	Conventional	ToolBox
Real kVA	**21202.50**	**21200**
Measurement error %	0.0117	
Test: **Resistive- Inductive-Capacitive load**		
	Measurements	
	Conventional	ToolBox
Real kVA	**28466.36**	**28400**
Measurement error %	0.0233	

The prototype demonstrated satisfactory performance across the evaluated load cases. Additionally, the results were confirmed through two separate measurement techniques, ensuring accuracy with minimal errors.

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3.1. Training developed

Once the load simulator prototype's operation was verified, it was used to support the training of the company's personnel, both new and active workers. Figure 11 shows evidence of the personnel being trained.

Figure 11. Training of company personnel.

3.2. Economic, ecological, and technical evaluation

The use of recycled materials significantly reduced the project costs compared to using new materials. For instance, repurposing a wooden sheet previously used to mount electric power meters, along with other recycled components, allowed the prototype to be built without requiring financial investment, relying solely on the labor provided by the company's employees. This demonstrates that similar projects can be developed economically without compromising functionality.

Additionally, the project promoted environmental sustainability by reusing materials that would otherwise have been discarded as waste. The company possesses a large inventory of materials and equipment that can be repurposed, reducing solid waste generation and CO_2 emissions associated with the production and transportation of new materials. This approach underscores the feasibility of integrating circular economy principles into the design of training equipment.

From a technical perspective, the prototype met the functional requirements established during the design phase. Laboratory tests confirmed its mechanical stability, capacity to support rotation, and ease of use, exceeding the expected quality standards. Furthermore, its application during a training session proved effective in simulating electrical loads and enhancing personnel understanding of electrical systems. This comprehensive analysis highlights the relevance of the project not only from a technical standpoint but also as an economic and sustainable model that can be replicated in similar contexts.

4. Conclusions

In this project, a prototype electrical load simulator in board format was designed and built using recycled materials. The prototype facilitates training on connecting, handling, and measuring various electrical loads. It also provides instruction in measurement systems, safety protocols, and fault identification, contributing to improved performance in the work field. The tests performed allowed verifying the prototype's operation by obtaining favorable results. Two different measurement techniques were used, with a maximum error of 2%. The project is expected to benefit CFE personnel by enabling more efficient training and execution of their activities. Additionally, the prototype's construction marks the beginning of a program focused on repurposing discarded

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materials and developing specialized training initiatives.

5. Authorship acknowledgment

José Francisco Castillo Martínez and Pedro Cruz Alcantar: Conceptualization, *José Francisco Castillo Martínez:* Project administration, *Pedro Cruz Alcantar:* Methodology, Review and Editing, Supervisión. *Hector Arturo Álvarez Macias, Isaac Compeán Martinez:* Review and Editing.

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