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A SHARED PCB CONCEPT THAT INTEGRATES BOTH TELECOM HYBRID DC RECTIFIER (-48V) AC/DC CONVERSION AND AN INVERTER FOR DC/AC CONVERSION TECHNOLOGY.

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ABSTRACT

This paper explores the challenges associated with the traditional multiple-system approach in telecommunication exchange premises and presents opportunities for integrating both rectifier and UPS systems within a single hybrid power cabinet. With the increasing recognition of renewable energy sources, such as solar photovoltaics and wind energy—primarily generating DC power, there is a growing need to combine these with the prevalent AC systems in existing infrastructures. A hybrid approach that merges both DC and AC system designs could yield significant advantages in terms of efficiency, flexibility, and cost-effectiveness. This research focuses on the design strategies, governance approaches, and performance evaluations of systems that integrate both DC and AC components to cater to the specific requirements of telecommunication equipment, including CISCO Switches & Aggregator, OLT/FTTH, IGW, and TX DWDM Core networks equipment. The primary objective is to create a unified and streamlined power solution for both AC and DC loads within the same enclosure. The anticipated outcome of this research is the development of a combined technology rectifier (DC output) and inverter design on a single PCB board. This integrated system architecture aims to reduce energy conversion losses, improve operational efficiency, and enhance flexibility in power management. The product addresses a longstanding issue about the space problem at telecommunication exchanges; both systems can be contained within one cabinet for simultaneous power supply. Therefore, this project looks forward to an improvement of the network with a better assimilation of the data from the two systems in an efficient way.

Keywords: Renewable Energy, DC Rectifier System, Uninterruptible Power Supply, Inverter, Power Distribution Unit (PDU).

I.INTRODUCTION

The rapid evolution of the telecommunications infrastructure has increased the demand for efficient, reliable, and sustainable power solutions [1]. Telecommunication sites have unique challenges because both AC and DC power sources are used simultaneously, driven by various equipment needs. Conventional systems usually operate in isolation, leading to increased energy losses, inefficiencies, and space constraints within telecommunication exchanges [2, 3]. This fragmented approach therefore calls for the development of integrated power systems that can provide both AC and DC outputs from a single platform [4, 5].

There is a significant research gap in designing compact hybrid systems, integrating DC rectifiers and AC inverters into a single enclosure [6-8]. Normally, most applications operate on separate power systems which usually results in increased costs of operation, complex maintenance procedures, and physical space wasted [9]. Secondly, the integration of renewable energy sources, such as solar and wind energies, introduces an additional layer of complexity to these systems, requiring innovative solutions that will seamlessly integrate renewable and conventional energy sources [7, 9, 10].

This research aims to develop a hybrid power system that integrates both DC and AC components within the same PCB/cabinet. This system seeks to address the challenges of energy alteration losses, space optimization, and flexibility in power management while supporting the adoption of renewable energy sources. The proposed system will offer higher efficiency and reliability in serving diverse power needs for telecommunication equipment such as CISCO, OLT/FTTH, and TX Core network components by applying advanced design principles and control architectures.

This research is of significance because it tries to revolutionize the conventional way of managing power in telecommunication by coming up with a single, space-saving solution. The proposed system would have the potential to reduce losses associated with energy conversion, improve operational efficiency at telecommunication sites, and encourage the integration of renewable sources of energy into the system.

II.LITERATURE REVIEW

The case studies have shown that HRES improves the efficiency of energy significantly by reducing transmission, distribution, and generation losses. For instance, Furqan Asghar et al. (2024) in a case study on telecom towers in Saudi Arabia demonstrated how standalone hybrid systems optimize energy generation with a levelized cost of energy (LCOE) of $0.18/kWh [11]. Similarly, the overall efficiency improvement by advanced photovoltaic systems at the research site of NUST, Pakistan, achieved a performance ratio of 76.2% and a capacity utilization factor of 16%.

In contrast, our study focuses on hybrid DC/AC systems for telecommunication sites, where the emphasis is on integrating renewable energy sources like solar and wind to minimize conversion losses (estimated at 4%-8%). While both the case studies and our research underscore efficiency improvements, our hybrid system aims to address the bidirectional power flow and load-sharing complexities, which are not the central focus of these external studies. Both the study by Niranjan Rao Deevela et al. (2024) on Indian telecom towers and the NUST research demonstrate the potential of hybrid systems in reducing carbon footprints. For instance, solar PV hybrid systems in India showed a reduction of 55%-58% in CO_2 emissions, even under the increased demands of 5G adoption. Similarly, the NUST photovoltaic system projected a lifetime CO_2 reduction of 75,478.60 tons, equivalent to planting 348,754 teak trees [7, 12].

Our study is in line with this finding by promoting the integration of renewable energy sources into telecommunication systems. However, it extends further by highlighting modular design approaches and comprehensive control mechanisms that can dynamically manage DC and AC loads to optimize renewable energy usage and further reduce emissions. The works of Niranjan Rao Deevela et al. and Furqan Asghar et al. also establish the primacy of solar PV as a main contributor to hybrid systems. Wind energy has also been quoted to complement this form of setup. In this regard, the study conducted by NUST stands out as an excellent application of solar resources, where the area boasts high irradiance levels, leading to a strikingly high solar fraction of 98.99%.

In comparison, this study contributes to developing further these contributions, understanding the challenges and opportunities to integrate both solar and wind energy within hybrid DC/AC systems. In this proposed design, the inclusion of bidirectional power converters with energy storage solutions ensures smooth operation with widely varying demands for loads and renewable energy. The techno-economic feasibility of hybrid systems is a key focus in the studies, with Furqan Asghar et al. highlighting an annual reduction of 37,326 kg of CO_2 emissions and operational cost savings with an LCOE of $0.18/kWh. Similarly, the NUST study projected that their PV system would achieve surplus energy generation within 12 years of installation.

Our study corroborates these insights but extends them by analyzing the cost-effectiveness of integrating DC and AC systems into a single PCB design & accordingly enclosed under single standalone enclosure. This integration reduces energy alteration losses and equipment duplication, leading to long-term operational savings while addressing space constraints in telecommunication sites. The case studies reviewed herein strengthen the potential of hybrid renewable systems in improving energy efficiency, reducing carbon footprints, and integrating renewable energy. Although these case studies provide very important benchmarks, our research contributes uniquely by addressing the specific needs of hybrid DC/AC systems in telecommunication sites. With a focus on modular design, bidirectional power flow, and enhanced control mechanisms, this study stands out as an all-encompassing solution to the evolving demands within the telecommunication industry.

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III. RESEARCH METHODOLOGY

3.1 System Design and Development

The hybrid power system was designed to integrate DC rectifiers and AC inverters within a same PCB enclosure, addressing the diverse energy requirements of telecommunication sites. The design process started with identifying power demands specific to telecommunication equipment, including CISCO Systems, OLT/FTTH modules, and TX Core networks ICT equipment. A control architecture was developed to enable bidirectional power flow, allowing seamless integration of DC and AC components. The system was also fitted with energy storage devices, such as batteries and backup generators for continuous operation during main outages. The compactness of the design was optimized given the limited space in the telecommunication exchanges.

3.2 Modeling and Simulation

MATLAB and Simulink were used to model and simulate the hybrid power system. These tools provided a detailed representation of power flow dynamics, energy conversion processes, and system behavior under varying operational conditions, including fluctuating load demands and renewable energy inputs. Simulations also allowed for the refinement of system configurations and control strategies to achieve optimal performance.

3.3 Evaluation Criteria

The system was evaluated based on the following key performance metrics provided in Table 1

Table 1Evaluation Criteria Table

Evaluation Criterion	**Description**	**Purpose**
Energy Efficiency	Analysis of energy conversion losses and overall system efficiency.	To assess how effectively the system converts and uses energy with minimal losses.
Reliability	Measurement of uptime and the system's ability to ensure continuous operation during outages.	To ensure the system can maintain uninterrupted operation under real-world conditions.
Cost-Effectiveness	Comparison of installation and operational costs against conventional AC- or DC-only systems.	To evaluate the economic viability of the hybrid system compared to traditional solutions.
Environmental Impact	Estimation of carbon footprint reduction through the integration of renewable energy sources.	To determine the system's contribution to reducing environmental impact and promoting sustainability.

3.4 Data Collection and Simulation Details

Data was collected from operational telecommunication sites, focusing on power consumption patterns, renewable energy availability, and historical outage records. This data was used to replicate real-world conditions during simulations, enabling accurate performance predictions and optimization of the hybrid system's design.

3.5. System Arrangement and Mechanisms in Telecommunication Sites

3.5.1 DC Systems

The DC system, a DC power plant sourced from AC commercial power and generator, can integrate renewable energy sources like solar panels and wind turbines. It can be used in various sizes from 300A DC to 10KA DC capacity, with each rectifier module having different output capacities (25A, 50A, 110A & the max is 220A DC).

3.5.2 AC Systems

The AC output system UPS and inverter are crucial in existing electrical infrastructure, providing power for AC ICT loads. Its modular architecture, efficiency, compact size, innovative design, and comprehensive monitoring and control features offer significant benefits over current industry standards, making it a cost-effective solution for grid-connected systems.

3.5.3 *Hybrid System Design*

The hybrid system combines DC and AC subsystems, featuring inverters and converters for bidirectional current flow, and energy storage systems like batteries and generators for DC backup to prevent site outages.

3.6 System Control Design Architecture for Hybrid DC/AC Systems

3.6.1 Power Flow Control

A single module supplies DC and AC power under a single control system, ensuring optimal energy distribution to ICT loads and storage. The system tracks DC and AC output from sources like solar and wind, with load sharing based on requirements and supply. The backup energy storage is maintained by battery backups, with DC load backup durations of 4 hours, 8 hours, and 12 hours, and UPS backups of 15-30 minutes.

3.6.2 Simulation Tools

Simulation tools like MATLAB and Simulink are crucial in designing and optimizing hybrid DC/AC systems. They model performance under various conditions, load demands, and renewable energy variability, predicting load demand and adjusting power distribution strategies.

3.7 Key Performance Evaluation

The key performance approach for evaluating hybrid systems involves metrics such as energy efficiency, reliability, economic viability, and environmental impact, which evaluate system efficiency, reliability, cost-effectiveness, and carbon footprint reduction.

IV RESULTS

4.1 Key Features of the Hybrid DC/AC System

The hybrid system integrates both AC and DC capabilities, providing robust power solutions design to telecommunication site requirements. Table 2 below summarizes the key input and output specifications:

Table 2 Summary table of features of the Hybrid DC/AC System

Feature	Details
AC Input Details	- 230 VAC single-phase input - 400 VAC three-phase input - Dual source input - Single-phase and three-phase output
DC Output Details	- 48 VDC output - Maximum 75 KVA AC and greater than this output - Maximum 210 kW DC output - 1-pole AC distribution option - 2-pole AC distribution option - -48 VDC distribution option with surge protection (input & output) - Built-in transfer technology

The findings show that the hybrid system's advanced AC and DC configurations ensure flexibility in managing diverse telecommunication equipment needs while enhancing energy distribution and protection capabilities. Its built-in transfer technology further optimizes system reliability and efficiency.

4.2 Complexity in System Design

The integration of DC and AC systems presents significant challenges, including:

Compatibility Issues: Difficulties arise between DC and AC components, particularly in the bidirectional conversion of multiple power sources.

Stability Concerns: Issues during transient conditions or grid disturbances can affect overall system performance.

High Upfront Costs: Hybrid systems often require substantial initial investment, compounded by a lack of standardization.

Governing Obstacles: Integrating AC and DC systems into traditional AC supply infrastructures poses regulatory challenges.

Other multiple useful approaches: Key Considerations in Architecture selection

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4.2.1 . AC UPS – Power Conversions

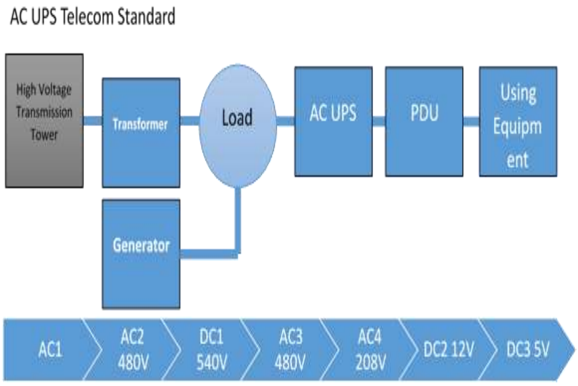

Fig. 1 AC UPS – Power Conversions

- **Description:** Traditional system converting AC to DC, storing in batteries, and inverting back to AC.
- **Key Considerations:**
  - Efficiency losses in double conversion.
  - Ideal for general-purpose AC equipment.
  - Simple but reliable architecture.

4.2.2 DC UPS – Telecom Standard

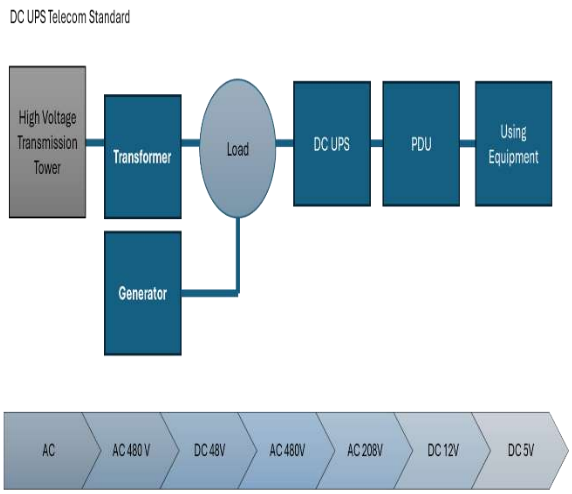

Fig. 2 DC UPS – Telecom Standard

- **Description:** Direct DC power supply architecture commonly used in telecom applications.
- **Key Considerations:**
  - Simplifies power conversion stages.
  - Reduced energy losses (no need to convert back to AC).
  - Compatibility with telecom-standard equipment (-48V DC).

4.2.3 Centralized DC UPS / Battery Plant

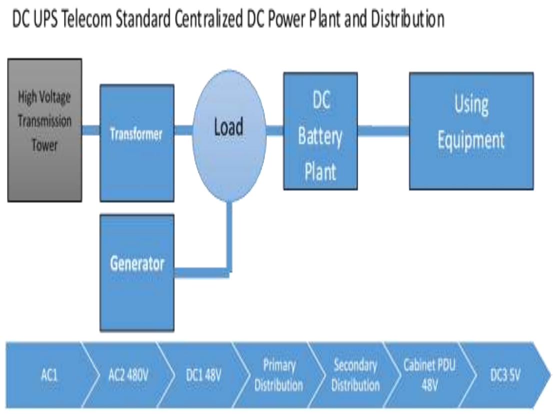

Fig. 3 Centralized DC UPS / Battery Plant

- **Description:** A single, centralized DC power system with a large battery bank supplying multiple loads.
- **Key Considerations:**
  - Centralized management and scalability.
  - Reduced redundancy.
  - Suitable for large-scale operations with uniform load requirements.

4.2.4. Integrated DC UPS

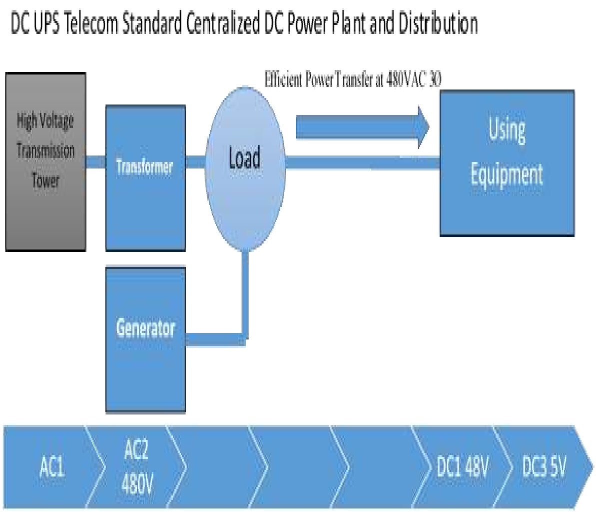

Fig. 4 Integrated DC UPS

- **Description:** Combines power conversion and distribution in a single integrated unit.
- **Key Considerations:**
  - Compact design with simplified deployment.
  - Best for smaller installations.
  - Limited flexibility for future scaling.

4.2.5. Centralized AC UPS

- **Description:** A centralized AC power system that provides backup for multiple AC loads.
- **Key Considerations:**
  - Simple deployment for environments with diverse AC equipment.
  - Larger capacity requirements for centralized units.
  - Single point of failure risk without redundancy.

4.2.6. Dual Redundant DC UPS

- **Description:** Two independent DC UPS systems for redundancy and high reliability.
- **Key Considerations:**
  - High reliability and fault tolerance.
  - Increased capital and operational costs.
  - Ideal for critical applications needing minimal downtime.

4.2.7. Edge Dual DC Power Architecture

- **Description:** Decentralized DC UPS units at the edge (closer to the load), with dual redundancy.
- **Key Considerations:**
  - Distributed architecture reduces transmission losses.
  - Enhanced reliability and localized fault tolerance.
  - Best for edge computing and distributed networks.

4.2.8. Dual Redundant AC UPS

- **Description:** Two independent AC UPS systems for redundancy.
- **Key Considerations:**
  - Supports critical AC equipment with high reliability.
  - Increased cost and space requirements.
  - Suitable for data centers and other mission-critical systems.

Double Conversion On Line Continuous supply

It ensures uninterrupted power by continuously converting AC to DC and back to AC, eliminating any fluctuations or interruptions even during power outages.

Continuous Operation:

1. AC input power is converted to DC.
2. DC is split: some charges the battery, while the rest is inverted back to AC for the load.

Power Outage Scenario:

3. The inverter draws directly from the battery (DC power) to supply AC to equipment.
4. No switching delay occurs, ensuring seamless operation.

Advantages:

5. Voltage regulation is consistent.
6. Reliable and uninterrupted power for critical systems.
7. Ideal for sensitive equipment requiring stable power.

Double Conversion Online UPS Prior to the Outage

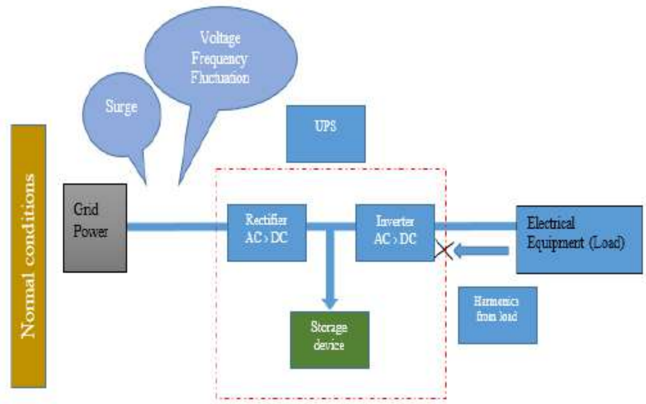

Fig. 5 Double Conversion Online UPS Prior to the Outage

Double Conversion Online UPS during an Outage

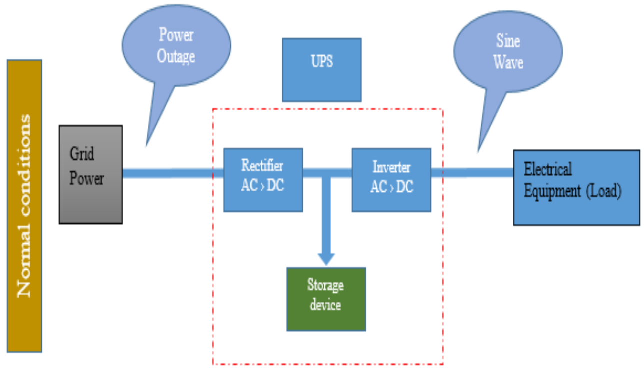

Fig. 6 Double Conversion Online UPS during an Outage

Small System Integration: Distributed architecture is ideal for small systems architecture integrated into a larger big system.

Self-Sufficiency: Each small system cabinet is self-sufficient with an entire DC power system consisting of AC input, rectifiers, battery connection modules fitted with external batteries, and DC distribution rectifier modules.
Power Sharing: The DC power developed by rectifiers and also by the batteries in a particular cabinet will be approximately equal to the DC power distributed to loads from that cabinet. The DC power of every cabinet has electrical consistency so that power can be shared appropriately with each cabinet. With this sharing, the cabinets' system can balance out the imbalances in cabinet loads.
Scalability: Growth of the system is by adding another supplemental cabinet and interconnecting it to the main cabinets.

V. DISCUSSION

The deployment of hybrid DC/AC power systems mark a paradigm shift in the pursuit of energy efficiency, carbon footprint reduction, and the integration of renewable energy sources [13, 14]. These systems address the critical energy demands of telecommunication sites, characterized by their reliance on both AC and DC power sources to meet the requirements of diverse equipment [15-17]. The integration of DC and AC systems into a single compact platform not only optimizes space utilization but also significantly minimizes energy conversion losses, a key challenge in traditional power management systems [18, 19]. The study by S. Rehman highlights the versatility and economic viability of hybrid systems combining wind, solar PV, diesel, and energy storage, underscoring their potential to improve energy access in remote areas. This finding is particularly relevant as telecommunication towers in such areas often suffer from limited grid connectivity, making hybrid systems an attractive solution [20]. While Rehman's work focuses on cost aspects with levelized costs ranging between \$0.349/kWh and \$0.458/kWh, the energy efficiency focus of the hybrid DC/AC systems in this study complements these insights by offering reduced alteration losses, which are estimated between 4% and 8% [20].

As mentioned in the survey by Kawamura et al [21], high-efficiency DC-AC power conversion technologies are a critical factor in the success of these hybrid systems. The achievement of 99.83% inverter efficiency using SiC and GaN devices is proof that advanced technologies can be applied in hybrid setups [22, 23]. This efficiency not only enhances the performance of telecommunication equipment but also aligns with the industry's broader sustainability goals by reducing energy waste. The modular design and integrated control systems further streamline power distribution, ensuring uninterrupted operation during load fluctuations or outages. The role of energy storage solutions in building resilience and adaptability is paramount, as evidenced by the hydrogen-based hybrid microgrid review by Ahmad Alzahrani et al [24] Similarly, the Hybrid system sustainability objectives become critical for renewable sources of energy such as solar and wind.

Based on the review by A. Contreras [25], the potential of rectennas in energy harvesting also suggests that there are ways to improve the efficiency of the system by converting RF signals to useful energy. Although rectennas are not built into the current hybrid system, their high conversion efficiency of up to 93% would be beneficial in supplementing the DC/AC system with power, especially in off-grid or remote areas [25]. The protection strategies and challenges of hybrid AC/DC microgrids discussed by S. Sarangi [26] provide further insight into the operation of these systems. The hybrid microgrid is theoretically very efficient, achieving over 90% efficiency, but has problems such as bidirectional power flows and grounding [26]. These challenges can be overcome by innovative control architectures and robust protection mechanisms, which are crucial for ensuring the reliability and efficiency of the hybrid DC/AC systems designed in this study [8].
These insights are useful for constructing a hybrid DC/AC system for telecommunication sites to promote sustainable energy. The integration of renewable energy sources, optimization of energy conversion, and handling of operational issues are all supported by the proposed system as it aligns with the transition to more sustainable energy solutions. The decrease in carbon footprint, along with the improvement in operational efficiency, is not only good for the environment but also for the economy, especially in areas with limited or erratic energy supply. Ultimately, the hybrid DC/AC system's compact design, efficiency, and renewable energy integration position as a pivotal innovation in the telecommunication industry, enabling a seamless transition to more sustainable and resilient energy practices.

VI. IMPLICATIONS

The key findings and insights drawn from this research in the area of hybrid DC/AC power systems for telecommunication sites raise several important implications for operational efficiency, environmental sustainability, and policy-making. These are derived from the results obtained, related literature, and emerging trends within renewable energy and telecommunication.

6.1 *6.1 Operational and Technical Implications*

The hybrid DC/AC system contributes directly to reduced operational costs for telecommunication infrastructure by minimizing energy conversion losses (4-8%) and improving energy distribution efficiency. This becomes particularly important in cases of remote or off-grid sites with limited power availability. Thanks to the use of advanced control mechanisms and renewable sources of energy solar and wind systems secure consistent power supply during outages or fluctuating grid availability. This reliability is critical for telecommunication operations, which demand uninterrupted power to support high-tech equipment. Compact integration of AC and DC systems within a single enclosure reduces the spatial footprint of power systems in telecommunication sites, enabling better utilization of physical infrastructure. The modular design allows seamless incorporation of additional renewable energy sources and storage solutions, such as hydrogen-based systems or batteries, aligning with site-specific energy demands.

6.2 *6.2 Environmental Implications*

Apart from this, the high-efficiency inverters and optimally managed power reduce CO2 emissions by an amount that makes it a contributor toward the global climate objectives. This is concurrent with findings by Niranjan Rao Deevela et al., **[1]** which indicated that the emission reductions from hybrid systems can go up to 58%. Hybrid systems, therefore, designed to integrate solar, wind and other renewable sources will be important in the development of greener and more sustainable energy solutions for the telecommunications sector.

6.3 *6.3 Policy Implications*

Policymakers should consider incentives such as subsidies and tax breaks to encourage investment in hybrid renewable energy systems for telecommunication. It would help bridge the gap financially, and their acceptance would be quite fast, particularly in low-resource regions where a reliable source of energy is still scarce.

Hybrid systems can also be developed and implemented more quickly by promoting collaborative relationships between governments, renewable energy companies, and telecommunication service providers. They can share resources, knowledge, and experiences to implement renewable energy solutions more efficiently and effectively within this sector.

In addition, guidelines for the integration of hybrid DC/AC systems into existing telecommunication infrastructure should be established to overcome regulatory barriers and streamline the deployment process. This will make it easier to transition to hybrid systems that are compatible with current technologies and practices [4].

Finally, increasing funding for research and development in hybrid renewable energy technologies is crucial to addressing challenges related to energy storage, system optimization, and seamless power management, as emphasized by J. Lorincz et al.[27]. Enhanced investment in R&D can lead to innovative solutions that improve the efficiency and reliability of hybrid systems, promoting their wider adoption in telecommunications and beyond [27].

VII.LIMITATIONS

Hybrid energy systems face many critical challenges: applicability, effectiveness, and implementation. Geographical constraints limit the applicability of these systems, based on the recommended areas where there is significant solar and wind energy availability. Moreover, hybrid energy systems have a complex nature, which creates a need for delicate control architectures and accurate power management. These aspects increase the costs of the initial investment and impose technical obstacles upon implementation. Energy storage solutions also present significant challenges, as the system's efficiency heavily relies on their performance, making them a bottleneck in renewable energy applications. Furthermore, issues related to scalability and standardization arise when integrating hybrid DC/AC systems into diverse telecommunication infrastructures, complicating compatibility with existing systems.

VIII.CONCLUSION

This study explores the potential of hybrid DC/AC power systems in the telecommunications sector, focusing on energy efficiency, operational reliability, and environmental sustainability. The system integrates AC and DC components, minimizing energy conversion losses and optimizing space utilization. It supports diverse power needs and incorporates renewable energy sources like solar and wind, reducing carbon emissions and supporting global climate goals. The research provides a framework for implementing hybrid systems, allowing them to adapt to varying load demands while maintaining high efficiency.

Collaboration among stakeholders, including policymakers, telecommunication providers, andrenewable energy companies, is crucial for broader adoption. The study's findings advance the understanding of hybrid power solutions and pave the way for sustainable energy practices in the telecommunications industry.

CONFLICTS OF INTEREST

The author declares no conflicts of interest regarding the publication of this paper. Due to non-financial interest membership of organizations and scientific societies that undertake advocacy work.

AUTHOR CONTRIBUTION STATEMENT

My Role: Direct involvement in dimensions, conceptualization, and outline creation.

I measured all the current system architecture (DC Rectifier, Inverter, UPS & Converter) system utilization across the network using real-time monitoring tools, collecting data at various points to assess the possibility of this integration.

Facilitators: Provided support through resources, oversight, and strategic input to allow me visits to Multiple World well-known R&D (Delta, GE, Schneider Electric, ABB, Eaton System)

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