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EVALUATION STUDY TO MITIGATE EXCESSIVE DC POWER CABLE CONGESTION AT TELECOMMUNICATION SITES, REDUCE EXCESSIVE CABLE COST ANALYSIS REPORT & PROVIDE COMPLETE OPTIMUM SOLUTION

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ABSTRACT

This paper discovers the challenges faced in all core network sites, principally the excessive use of DC cables across the entire core network. This not only acquires significant costs but puts the exchange at risk and jeopardizes the stability of the exchange. The voltage drops across DC cables is less than 1 VDC, while an increasing number of cables are being added to power telecommunication technologies worsen the situation & further compounding these issues. The DC system entirely powers up telecommunications network with a -48 VDC supply as mandated by IEEE standards, is critical for powering diverse ICT technologies. The DC power plant must maintain a minimum adjustable output voltage between -48 VDC and -54.37VDC system voltage. Telecommunication technologies ICT loads such as Transmission, IPMPLS, FTTH, and IGW equipment operate on the DC system at -48 VDC supply.
***Key worlds**: DC Bus way, DC Rectifier System, Power Distribution system, DC Cables. MDB, LDB, Inverters.*

I.INTRODUCTION

Efficient power distribution systems are critical for the operation of telecommunication facilities, particularly in multi-story exchanges where complex infrastructure supports a wide range of equipment [1-3]. One the challenges of the telecommunications industry is excess congestion of DC power cable [4-6]. These include heightened costs, spatial inefficiencies, and risks to operational stability due to voltage drops and cable congestion [7]. The International Telecommunication Union (ITU) and IEEE standards for telecommunication power systems recommend voltage drop within limits to ensure performance reliability [8, 9]. This problem not only increases the installation and maintenance costs but also affect the efficiency of operation and the reliability of the system [10-12]. With advancement in telecommunication technologies, it has become very important to have reliable, scalable and efficient DC power distribution systems [13-15].

The major issue relates to the steep voltage drops and high losses which are occasioned by lengthy and excessive cabling especially in multi-story sites [16, 17]. As a result of new standards in telecommunication where organizations require voltage drops of less than 1 VDC across the DC distribution systems, organizations are forced to install the new cables [18-20]. Although this approach helps overcome issues related to voltage drops, it raises a series of new issues, such as higher costs, spatial limitations, and increased probability of unfavorable performance [21-23].

This research seeks to address these challenges especially with a view to reducing over-concentration of DC cables. It seeks to assess current approaches, recommend efficient power distribution methods and techniques and determine alternative methods that could be best adopted in multi-story telecommunication sites. In this regard, the study aims at providing significant solutions to the two main problems of cable congestion and energy efficiency so as to enhance the development of power distribution architectures that are sustainable and scalable. Each approach is assessed for its cost-efficiency, scalability, and practical applicability in reducing cable congestion while ensuring reliable power distribution across multiple floors [24].

The importance of this study goes beyond the saving of costs. Efficient DC Power Distribution Systems are vital in improving the reliability of telecommunication networks, reducing energy losses and promoting green energy use in the industry. The conclusions made in this research may contribute to the development of further standards and guidelines of telecommunication power engineering. Additionally, modern telecommunication facilities require scalable and flexible power distribution solutions to accommodate future expansions and technological advancements [25].

II.LITERATURE REVIEW

The efficient distribution of direct current (DC) power in telecommunication facilities has been a critical focus for researchers and practitioners due to its significant impact on operational costs and infrastructure reliability [26]. As telecommunication networks expand to accommodate advancements in technologies like FTTH, IGW, and Transmission systems, the challenges associated with DC cable congestion have intensified [27]. Voltage stability remains a cornerstone of telecommunication power systems, with permissible voltage drops limited to less than 1 VDC [28]. Addressing voltage drops requires either additional cables or higher-gauge wires, both of which lead to increased costs and spatial inefficiencies in already congested facilities.

Recent studies have explored several strategies for mitigating DC cable congestion. Power Over Ethernet (PoE) has been proposed as an innovative solution, integrating power delivery with data transmission [1, 16, 29, 30]. PoE reduces the need for separate power cables, resulting in significant space savings and improved efficiency. However, its application is limited to low-power devices, leaving high-power telecommunication equipment dependent on traditional DC systems. Similarly, DC Bus Ducts have gained traction for their compact design and enhanced electrical performance [27]. DC Bus Ducts offer low impedance and improved thermal dissipation, making them suitable for high-capacity installations. Despite their benefits, their initial implementation costs remain a barrier, particularly in large-scale facilities requiring significant upfront investment [19].

Main Distribution Boards (MDBs) and Local Distribution Boards (LDBs) are commonly used in telecommunication facilities to optimize power distribution [31]. These modular solutions allow for shorter cable runs, reducing copper losses and installation complexity. MDBs and LDBs are particularly effective in multi-story exchanges, where shorter cable lengths can minimize voltage drops and enhance overall system reliability. However, the use of higher-gauge cables in these systems can pose challenges during installation, requiring additional accessories and structural modifications [13].

Decentralized power systems have also been investigated as a viable alternative to centralized architectures [18]. These systems provide shorter load DC cable runs, leading to lower copper losses and higher system efficiencies. Decentralized designs are scalable and can be tailored to meet specific load requirements. However, they demand significant structural modifications, including additional civil works, ventilation, and floor space for battery installations [18]. The reliance on dry-type sealed batteries further limits their applicability, particularly in high-capacity installations.

Centralized architectures, on the other hand, consolidate rectifiers and batteries at a single point, distributing power through a network of MDBs and LDBs [5]. This approach simplifies system management and ensures consistent power distribution across all floors. Centralized systems, equipped with advanced equalization panels, can maintain battery health and ensure operational reliability. Nevertheless, centralized systems require substantial infrastructure to accommodate high-capacity installations, making them less feasible for facilities with spatial constraints [29.

Inverter-based solutions have also been explored for reducing cable congestion. These systems offer the advantage of easy implementation and minimal cable utilization. However, they share limitations similar to decentralized systems, such as the need for higher-gauge cables and additional accessories [32]. Moreover, inverters are less suitable for large-scale telecommunication facilities due to their capacity constraints and potential weak links in the power distribution network. The trade-offs between cost, reliability, and scalability are central to the selection of an appropriate power distribution strategy. While DC Bus Ducts and MDBs offer long-term cost savings and operational efficiencies, their initial investment and installation requirements can be prohibitive [4, 14]. Decentralized and inverter-based systems provide flexibility and ease of implementation but fall short in addressing the demands of high-capacity installations. The literature underscores the importance of adopting a hybrid approach that leverages the strengths of different systems while mitigating their limitations [13, 29, 33].

Emerging technologies and innovative designs continue to shape the landscape of telecommunication power systems [26, 29].

The integration of intelligent power distribution units (PDUs) and smart monitoring solutions offers real-time insights into power usage and system health [4]. These advancements enable proactive maintenance and optimization of power distribution networks, reducing the risk of failures and enhancing overall system efficiency. Furthermore, the adoption of renewable energy sources and energy storage solutions presents opportunities for sustainable and cost-effective power distribution in telecommunication facilities [14, 34].

In conclusion, the literature highlights a range of strategies for mitigating DC cable congestion in telecommunication facilities. DC Bus Ducts and MDBs emerge as the most effective solutions for addressing the challenges of cost, reliability, and scalability. However, the selection of an optimal strategy depends on the specific requirements and constraints of the facility [35]. By leveraging the insights from existing studies and incorporating emerging technologies, telecommunication facilities can achieve efficient and sustainable power distribution, ensuring the reliability and scalability of their networks. This review provides a foundation for the present study, which seeks to evaluate and recommend the most practical and cost-effective solutions for DC power distribution in multi-story telecommunication facilities.

III.METHODOLOGY

3.1 Research Design

This research uses both technical analysis and practical evaluations to solve the problem of overcrowded DC power cables in telecommunication sites. In this regard, the research applies theoretical frameworks with empiricism to examine the existing power distribution systems and provides a way forward to counteract these structures. This comparative analysis of centralized, decentralized, and other power distribution strategies is the foundation for practical recommendations. In addition, the design also complies with IEEE Standard 946-1992 to maintain the industrial standard.

3.2 Data Collection

The study collects data from various sources including site surveys of multi-story telecommunication exchanges, vendor specifications from suppliers including GE, ABB, and Eaton, IEEE guidelines, and power supply protocols for telecommunications, and measurements and observations of the density of DC cables. The surveys as well as inspections were carried out to estimate the degree of DC power cable overcrowding. Observations included voltage drop measurements and cable density evaluations.

Technical analysis was performed using the formula:

$$\mathrm{dv} = \frac{2 \times L \times \rho \ x \ I_{max}}{A \ (mm)2}$$

Where L is the cable Run distance in meter, Imax is the Max. Current flow in Amp. & ρ is the specific resistance of copper (0.01725-resistance of copper wire at 20°C) while A is the Cable cross section Area. This formula was applied to evaluate cable performance under varying load conditions. Additionally, technical specifications of rectifiers, distribution systems, and other components were analyzed to identify optimal solutions through vendor consultations, ensuring the applicability of the proposed systems.

3.3 Data Analysis

The analysis methodology focused on cost, efficiency, and practicality, comparing various power distribution architectures under multi-story site conditions. A cost-benefit analysis was performed to evaluate the installation and operational costs of centralized, decentralized, and hybrid systems. Voltage stability, energy efficiency, and congestion mitigation were assessed across different architectures, with the primary focus on achieving a stable -48 VDC supply. Simulated scenarios analyzed the behavior of DC power distribution under varying load conditions. Models were benchmarked against IEEE standards and vendor data, as presented in Table 1. However, studies have explored several strategies for mitigating DC cable congestion (Friedman, 1995) Friedman, N. (1995). U.S. Submarines Through 1945: An Illustrated Design History. Naval Institute Press [30].

Table 1. Comparison of System Architectures: Voltage Stability, Cost Efficiency, Complexity, and Scalability

Analysis Parameter	Centralized Architecture	Decentralized Architecture	Hybrid Solutions
Voltage Stability	High	Moderate	High
Cost Efficiency	High initial, low long-term	Moderate	Balanced
Implementation Complexity	High	Low	Moderate
Scalability	High	High	Moderate

3.4 Materials and Equipment

The study utilized rectifiers that operated in parallel redundancy mode and N+1 configuration, adhering to telecommunication power standards. Modular DC distribution systems, including primary and secondary distribution cubicles, were designed for compactness and efficiency. Measurement tools such as voltage meters and modeling software were employed for power flow and performance evaluations.

3.5 Assumptions and Limitations

The study assumes that load conditions across multi-story exchanges remain consistent and that the analysis applies to -48 VDC systems, which are common in telecommunication facilities. However, structural constraints and site-specific variables may limit the applicability of certain solutions. The requirement for additional civil works, particularly for bus ducts and battery installations, may also impact project timelines and budgets.

3.6 Proposed Solutions

These are the proposed solutions to the problem of DC cable congestion; The following is a consideration of the various approaches and their strengths and weaknesses. Power over Ethernet (PoE) helps in controlling new cable installation for power limited devices by including both power and data in the same cable but is only valid for low power devices. DC Bus Ducts are compact, capable of handling higher currents, modular in construction, but expensive initially and in civil construction. ABB Group (2018) reports that DC Bus Ducts offer low impedance and improved thermal dissipation, making them suitable for high-capacity installations. Despite their benefits, their initial implementation costs remain a barrier, particularly in large-scale facilities requiring significant upfront investment. Modular Distribution Boards are easier to install and cut down cable length but may require larger cables and other add-ons.

The inverter systems are easy to install and entail least cable usage, but it has high cable gauge and extra accessories. Decentralized systems offer flexibility of scalability, short cables, and higher efficiency but consume more floor area and have ventilation issues. Centralized systems are easy to manage, highly scalable but are complex and expensive to implement, as depicted in Table 2.

Table 2. Solution Comparison: Benefits and Drawbacks

Solution	Advantages	Disadvantages
Power Over Ethernet (PoE)	Reduces cable congestion for low-power devices; integrates power and data transmission	Limited to low-power applications
DC Bus Duct/Way	Space-saving; higher current capability; modular; reduced congestion	High initial cost; requires civil works
Modular Distribution Boards	Easier integration; reduces cable runs; reliable	May require larger cables and accessories
Inverter Systems	Easy implementation; minimal cable utilization	High cable gauge requirements: additional accessories needed
Decentralized Systems	Scalable; shorter cable runs; improved efficiency	Requires additional floor space; ventilation needs
Centralized Systems	Centralized management; high scalability	High complexity; increased initial cost

3.7 Validation and Reliability

To ensure reliability, voltage drop calculations were validated using the IEEE formula, and site assessments were benchmarked against vendor specifications. Pilot testing was conducted at selected telecommunication sites to verify the practicality of the proposed solutions. Additionally, validation steps included battery equalization tests to confirm system reliability under various operational scenarios.

3.8 Ethical Considerations

No human subjects were involved in this study. Data confidentiality was strictly maintained, and proprietary vendor information was used only with prior authorization. The research aligns with ethical guidelines for technical studies.

This methodology integrates theoretical analysis, practical evaluations, and industry standards to propose effective solutions for DC cable congestion. By addressing voltage stability, cost efficiency, and implementation feasibility, the study ensures the applicability of recommendations to telecommunication power engineering challenges. The proposed MDB/LDB and DC Bus Duct solutions offer the most balanced approach, combining cost-effectiveness, reliability, and scalability for large-scale implementations.

IV.RESULTS

To address the challenges of excessive DC cable congestion at telecommunication sites, this study evaluates various solutions with their respective advantages and disadvantages.

4.1 DC Bus Duct/Way Solution

The DC Bus Duct/Way is a proposed solution designed to enhance the efficiency of DC power distribution in multi-story telecommunication facilities.

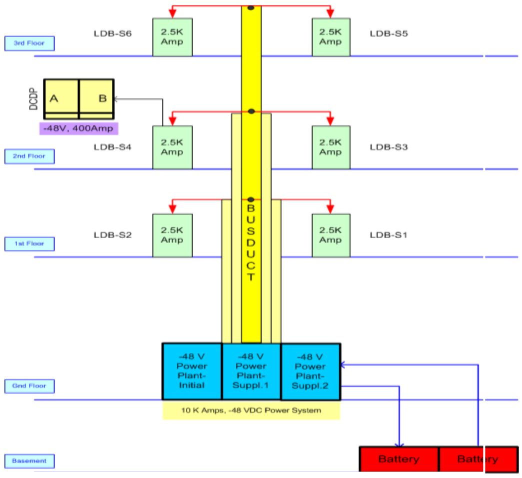

Figure.1 Conceptual design of the DC Bus Duct/Way system, highlighting its modular setup, space-saving characteristics, and integration with telecommunication site requirements.

This system leverages bus bars instead of traditional wiring to address cable congestion while delivering consistent and reliable power. Below are the detailed benefits and drawbacks of this approach:

4.1.1 Advantages

Bus bars offer numerous advantages over traditional wire harnesses. They are space-saving solutions as they require less physical space compared to wire harnesses. With a higher current-carrying capability, bus bars ensure efficient power distribution. Their design simplifies assembly processes since mounting and electrical terminals are integral parts of the bus bar, leading to faster assembly and easier repair, which in turn lowers manufacturing and field costs.

In terms of electrical performance, bus bars demonstrate improved efficiency due to their low characteristic impedance, which is achieved through high distributed capacitance and low inductance stemming from their larger surface areas and rectangular cross-sectional design. This also enhances their thermal performance, as the larger surface area facilitates better heat dissipation and improved airflow. Furthermore, the compact design enabled by bus bar construction increases long-term reliability.

Bus bars also ensure a secure -48V DC power source for all equipment on every floor at any given time, reducing cable congestion and minimizing the need for extensive cabling. This feature eliminates crowded and congested cabling environments, streamlining the overall electrical setup.

4.1.2 Disadvantages

Despite their advantages, bus bars have certain drawbacks. They are initially costly to implement, though they prove to be the most economical option in the long run. Additionally, the installation of bus bars often requires additional civil works, which can add complexity and expense to the implementation process.

4.2 MDB/LDB's Solution

The Main Distribution Board (MDB) and Local Distribution Board (LDB) solution leverages higher-gauge cables and shorter cable distances to improve power distribution efficiency in multi-story telecommunication sites. This system offers easier integration with existing setups while maintaining high reliability. Nonetheless, MDBs and LDBs effectively balance cost, efficiency, and scalability, making them suitable for facilities undergoing phased upgrades or moderate expansions (CHINT Global, 2020).

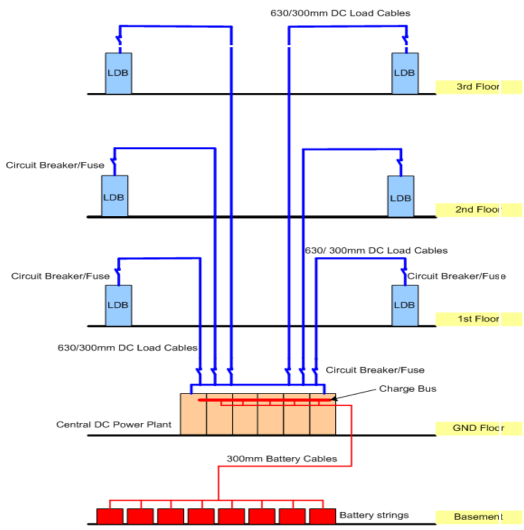

Figure 2 Simplified layout of the MDB/LDB solution demonstrating the integration of higher gauge cables and its connectivity to reduce cable runs in a multi-floor setup.

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4.2.1 Advantages

This solution offers several advantages, particularly in its ease of integration with existing setups, making it quicker and simpler to implement compared to bus duct solutions. The approach is less complex and less demanding during installation. By utilizing higher gauge cables, such as 300mm², 630mm², or even larger sizes, the system can efficiently handle higher power demands.

Another notable benefit is the use of passive components like cables and fuses/circuit breakers between the power plant and the load, enhancing the system's reliability. Furthermore, local distribution boards (LDBs) can be connected to main distribution boards (MDBs) on the same floor over shorter distances, significantly reducing the number of cables required. This streamlined design results in a more efficient and organized power distribution system.

4.2.2 Disadvantages

Despite its advantages, this solution has some drawbacks. The use of higher gauge cables can make the installation process more involved, requiring careful handling and additional effort. Moreover, accommodating larger cables might necessitate the use of additional cables and accessories, potentially increasing installation complexity and costs.

4.3 Inverter Solution

The **Inverter Solution** is a straightforward and minimally invasive approach to managing DC power distribution. It is particularly suited for securing a reliable -48V DC power source while reducing cable congestion.

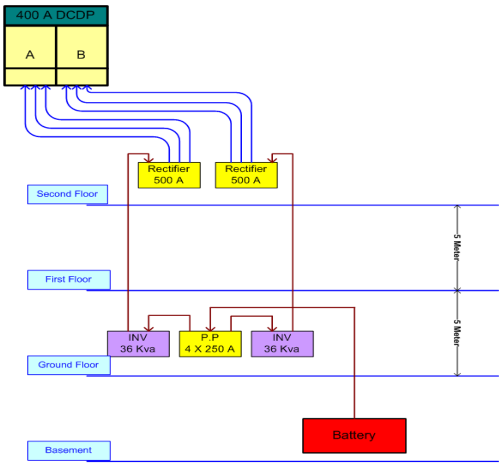

Figure 3Illustration of the Inverter Solution showcasing its minimal cable utilization and efficient footprint design for telecommunication sites.

4.3.1 Advantages

This proposal stands out for its ease of implementation, making it more straightforward than other alternatives. It provides a secure -48V DC power source at any given time, ensuring reliable power availability. Additionally, the solution reduces cable congestion by minimizing cable utilization, which also leads to a smaller footprint requirement. These features make it an efficient and space-saving option for power distribution.

4.3.2 Disadvantages

However, the use of higher gauge cables can present challenges during the installation stage, as it may require more effort and careful handling. Furthermore, accommodating these larger cables might necessitate additional cable ladders and accessories, potentially increasing installation complexity and associated costs.

4.4 De-Centralized DC power system Solution-I

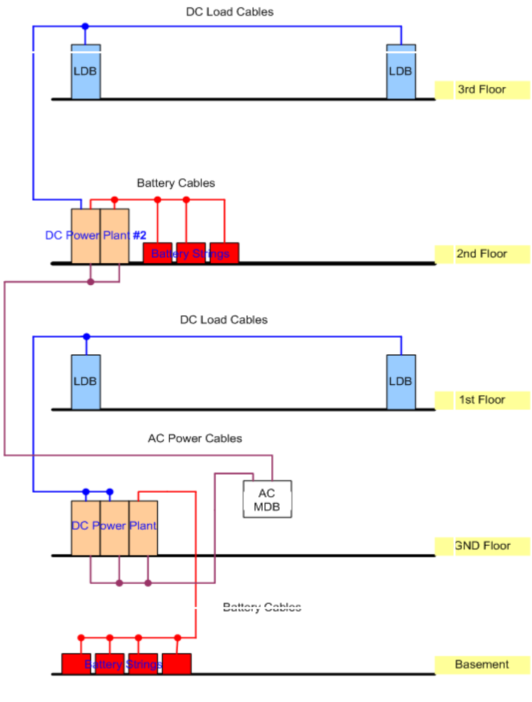

Figure 4 Diagram illustrating the De-Centralized DC Power System Solution-I, emphasizing shorter load DC cable runs, scalability, and access to telecom cabinets across multiple floors.

4.4.1Advantages

This solution offers several significant advantages. It enables shorter load DC cable runs, which result in lower copper losses and improved overall efficiency. The system is easier and quicker to implement, making it highly practical. Additionally, higher system efficiencies are achievable, primarily due to the effectiveness of the DC power system. The setup is also easily scalable, allowing seamless expansion of the power plant to meet growing demands. Moreover, future expansions are straightforward and compatible with various telecom cabinet technologies, ensuring adaptability and long-term usability.

4.4.2 Disadvantages

Despite its benefits, the solution has notable limitations. Floor loading limits pose challenges for utilizing high-capacity battery backups, and only single-layer configurations are suitable to maintain acceptable loading per square meter. This constraint leads to a significant floor space requirement for accommodating single-layer battery strings. Furthermore, the solution restricts the use of batteries to dry-type or sealed VRLA batteries OPzV, excluding the use of flooded OPzS batteries.

Additional challenges include the need for extensive civil and structural works, as well as ventilation systems, to house the battery and power plant. These adjustments often require repurposing space originally allocated for telecom equipment, which can be a logistical and financial drawback.

4.5 De-Centralized DC power system Solution-II

The **De-Centralized DC Power System Solution-II** is a distributed architecture designed to optimize power distribution by combining small systems into a larger, integrated system. This solution addresses the challenges of managing large-scale telecommunication sites by dividing the power generation and distribution across multiple locations, ensuring operational efficiency, scalability, and system reliability. Each cabinet in the system operates as an independent unit capable of sharing power with other cabinets, facilitating a flexible and modular design.

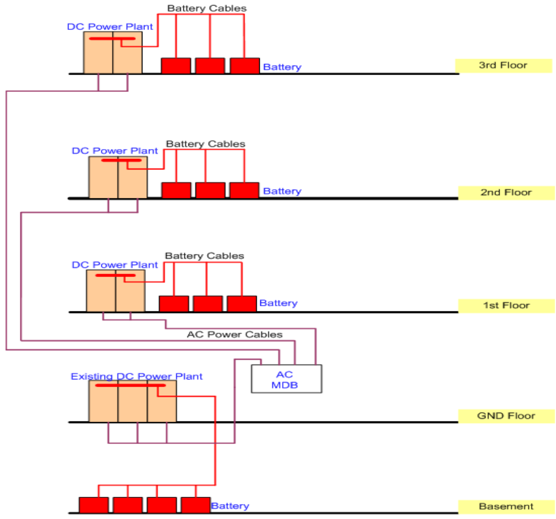

Figure 5 Layout plan for De-Centralized DC Power System Solution-II showcasing the scattered power plant architecture, including the placement of power plants, MDBs, and LDBs for each floor.

4.5.1 Scattered Power Plant Layout Plan

This section outlines two proposed designs for scattered power plant layouts, along with their respective scopes of work. The advantages and disadvantages of this approach are also discussed to provide a comprehensive understanding of its potential applications.

4.6 Off-Line Equalization Requirements in Centralized Architecture

All Big Power plant must have facilities of BB's equalization panel. Likewise other Power plants (Emerson, Delta, Eaton & Braga Moro) GE, ABB have been equipped with the optional ED83143-30 G61 Off-Line equalize Panel. The GPS Off-Line Equalizations (OLE) Panels is primarily a three-string battery connection panel with a built-in capability to disconnect a battery string and apply an equalization voltage to the disconnected battery string that has been taken "Off-Line" from the others and the system DC bus. This project integrates the new Bus Duct OLE panel, the completion of the bus-join temperature monitoring probes.

4.6.1 Equalization Process

During the equalization process the gassing rate of the batteries will be dramatically increased. Ensure that adequate ventilation is provided during this period. During the equalization process the converter status LEDs should be as follows: On/Standby LED is Green, indicating On. Alarm LED is not lit. Equalize Current LED is Yellow, indicating current >10A. As the equalization process proceeds the battery current will steadily decrease and the Equalize Current LED will go off; this is normal operation. At the end of the 12/24-hour period the converter should switch to standby mode indicating that the equalization process is complete. The equalization process will terminate automatically after a period set by the switch on the back of the converter (12/24 hours). If the battery string voltage is less than the plant float voltage (Vf) the equalization process will not start. In this situation, the converter will attempt to raise the voltage to Vf using the built-in "trickle charge" mode. In this mode, the output current of the converter is limited to approximately 3A for a period of about ten minutes. During trickle charge mode, it is normal for the Alarm LED (Red) to be lit, indicating that the output voltage is outside he acceptable range. If at the end of this 10-minute period the voltage is still lower than Vf, the converter will shut down and the On/Standby LED will alternate (Yellow/Green), indicating low battery voltage. Also, the Alarm LED (Red) will be on, indicating that the output voltage is out of the acceptable range. If during the 10-minute trickle charge period the battery voltage rises to Vf, the converter will automatically switch to normal Equalize mode and the Alarm LED will extinguish. (There may be a delay of 20-30 seconds as the battery voltage rises above 56V before the Alarm LED extinguishes.)

Summary of Findings

Table 1Table of summarized findings.

Category	Solution/Approach	Advantages	Disadvantages
1. Power Over Ethernet (PoE)	Eliminates separate DC cables for low-power devices by integrating power delivery with Ethernet.	- Reduces cable requirements. - Cost-effective for low-power devices.	- Limited to low-power devices. - Not suitable for high-capacity telecom loads.
2. DC Bus Duct/Way	Utilizes bus bars for power distribution instead of wires.	- Space-saving. - Higher current-carrying capability. - Improved thermal and electrical performance. - Long-term reliability. - Minimal cable utilization reduces congestion. - Secures -48V DC for multi-story sites.	- High initial cost. - Requires additional civil works.
3. MDB/LDB Solution	Use of Main Distribution Boards (MDBs) and Local Distribution Boards (LDBs) with higher-gauge cables.	- Easier integration with existing systems. - Shorter cable lengths reduce costs. - Reliable passive components. - Requires fewer cables with higher gauge.	- Installation challenges with higher-gauge cables. - Additional accessories may be required.
4. Inverter Solution	Centralized inverters for DC power distribution.	- Easy implementation. - Minimal cable congestion. - Secured power source.	- Installation challenges with high-gauge cables. - Requires additional ladders and accessories.
5. De-Centralized DC Power System – I	Scattered power sources and shorter cable runs.	- Reduces copper losses. - Easier implementation and scalability. - Higher system efficiency. - Suitable for future expansions.	- Floor space requirements. - Limited battery options. - Requires civil and structural work, including ventilation for battery gassing.
6. De-Centralized	Distributed	- Efficient power sharing across	- Space and ventilation

DC Power System – II	architecture combining small systems into larger systems.	cabinets. - Scalable. - Easily upgradable for future needs. - Suitable for smaller systems.	requirements. - Limited battery configurations. - Increased complexity for large setups.
7. Centralized Architecture	Combines rectifiers and battery backups at a single point.	- Simplifies system expansion. - Efficient backbone for the exchange. - Supports battery equalization processes.	- Requires significant central infrastructure. - High cost for initial implementation. - Maintenance challenges with large systems.

The MDB/LDB and BUS DUCT solutions are unequivocally the most suitable options identified thus far in terms of cost, reliability, and efficiency. Therefore, their implementation is strongly recommended. The MDB/LDB solution serves as a modulated or moderate variant of the BUS DUCT option, with the primary distinction being that the BUS DUCT utilizes bus bars, whereas the LDB employs cables. The LDB system is notably straightforward to implement.

Conversely, the INVERTER and decentralized power solutions for each floor present significant limitations due to their restricted capacity. The primary challenge lies in the integration of backup batteries, which cannot be deployed on a large scale as required for extensive sites. Additionally, these systems introduce potential vulnerabilities, often referred to as "weak links," which are not present in the BUS DUCT and LDB solutions. Consequently, the INVERTER and decentralized power solutions are not recommended for large-scale implementations.

4.6.2 Interpretation

The research findings highlight the critical challenges associated with excessive DC power cable usage in multi-story telecommunication facilities and provide a comprehensive evaluation of proposed mitigation strategies. The analysis focused on assessing the practicality, cost-effectiveness, and scalability of various power distribution solutions, including DC Bus Ducts, Main Distribution Boards (MDBs), Local Distribution Boards (LDBs), decentralized power systems, and inverters. The results of this study underscore the need for innovative approaches to optimize power distribution while addressing cable congestion and maintaining system reliability. The study revealed that excessive use of DC cables to power telecommunication equipment significantly increases both material costs and installation complexity. Voltage drops across long cable runs often necessitate additional cabling to meet the IEEE standard limit of less than 1 VDC, further exacerbating-congestion-issues.

Additionally, the spatial requirements of these cables place a substantial strain on facilities, often leading to operational inefficiencies and reduced scalability for future technological upgrades.

The implementation of DC Bus Ducts was identified as a promising solution due to their compact design and superior electrical performance. These systems demonstrated the ability to significantly reduce cable congestion by replacing bulky wiring harnesses with bus bar structures. Furthermore, their high current-carrying capacity and improved thermal dissipation were found to enhance system reliability. While the initial implementation costs were higher compared to other options, the long-term savings in maintenance and operational efficiency made DC Bus Ducts a cost-effective solution for large-scale telecommunication facilities. MDBs and LDBs emerged as practical and scalable solutions, particularly in multi-story facilities (Rawafid Systems, n.d.). These systems allow for shorter cable runs, reducing copper losses and minimizing voltage drops.

The modular design of MDBs and LDBs facilitates easier integration with existing infrastructure, making them a viable option for facilities undergoing upgrades. However, the study noted that the use of higher-gauge cables in these systems may require additional accessories and structural modifications during installation. Despite these challenges, MDBs and LDBs offer a balance between cost, efficiency, and scalability, making them highly recommended for immediate implementation.

Decentralized power systems were evaluated for their ability to localize power distribution and minimize long cable runs. The results showed that while decentralized systems offer higher system efficiencies and scalability, they are limited by the significant structural modifications required for battery installations [36].

Floor loading constraints and the need for enhanced ventilation further reduce the feasibility of this solution in high-capacity installations. As a result, decentralized systems are more suitable for smaller-scale facilities with less stringent spatial constraints. Inverter-based solutions were found to be relatively easy to implement, requiring minimal structural modifications. These systems also reduce cable congestion and footprint requirements. However, their capacity limitations and reliance on higher-gauge cables make them less viable for large telecommunication facilities (STMicroelectronics, n.d.). Additionally, the potential weak points in the power distribution network further diminish their suitability for long-term applications.

The comparative analysis ranked DC Bus Ducts and MDB/LDB solutions as the most effective strategies for mitigating cable congestion and optimizing power distribution. Pilot projects validated the practicality of these solutions, demonstrating significant reductions in cable congestion and improved system reliability. DC Bus Ducts excelled in addressing high-capacity requirements, while MDBs and LDBs provided a cost-effective option for facilities with moderate power demands. The cost-benefit analysis confirmed that while DC Bus Ducts involve higher upfront costs, their long-term benefits in terms of reduced maintenance and enhanced operational efficiency outweigh the initial investment. MDBs and LDBs were also found to offer considerable cost savings, particularly in scenarios where space constraints and moderate scalability are primary concerns. The results recommend prioritizing the implementation of DC Bus Ducts and MDB/LDB systems for telecommunication facilities (Sécheron SA, 2022). These solutions provide an optimal balance of cost, efficiency, and scalability, ensuring long-term reliability and adaptability for future upgrades. Decentralized systems and inverters may be considered for smaller facilities or specific applications where their limitations are not critical. In conclusion, this research highlights the importance of adopting tailored strategies to address the unique challenges of DC power distribution in telecommunication sites. By implementing the recommended solutions, facilities can achieve significant cost savings, enhance operational efficiency, and support the growing demands of modern telecommunication networks.

V.DISCUSSION

The findings of this research address the pressing issue of excessive DC power cable congestion in multi-story telecommunication facilities, providing actionable insights into cost-effective and efficient power distribution strategies. The discussion focuses on the implications of each proposed solution, their feasibility in real-world scenarios, and their alignment with industry standards and operational goals [37]. The implementation of DC Bus Ducts stands out as a transformative solution for large-scale facilities, offering a compact design and high current-carrying capacity. These systems mitigate the limitations of traditional cable networks by significantly reducing cable congestion while improving electrical and thermal performance [38, 39]. Despite higher initial costs, the long-term savings in maintenance and operational efficiency position DC Bus Ducts as a sustainable and scalable choice for modern telecommunication networks. This aligns with industry demands for reliable power distribution systems capable of supporting the rapid evolution of telecommunication technologies.

Main Distribution Boards (MDBs) and Local Distribution Boards (LDBs) also emerged as highly practical solutions, particularly in scenarios where moderate scalability is required. The modular design of these systems facilitates seamless integration with existing infrastructure, minimizing installation complexity and costs. However, the requirement for higher-gauge cables presents challenges during the installation phase, necessitating additional accessories and structural modifications. Nonetheless, MDBs and LDBs effectively balance cost, efficiency, and scalability, making them suitable for facilities undergoing phased upgrades or moderate expansions (CHINT Global, 2020).

The decentralized power systems, while offering localized power distribution and shorter cable runs, are constrained by significant structural and spatial requirements. Floor loading limitations, the need for enhanced ventilation, and reliance on sealed batteries reduce their feasibility for high-capacity installations. These systems are more applicable in smaller facilities with less stringent scalability requirements. Similarly, inverter-based solutions are easy to implement and reduce cable congestion but suffer from capacity limitations and potential weak points in the power network (CHINT Global, 2020). While these solutions can address specific challenges, they lack the robustness and scalability required for large-scale telecommunication facilities (Essential Parts, 2024). A key finding of the study is the trade-off between initial investment and long-term benefits.

DC Bus Ducts, despite their high upfront costs, offer superior long-term reliability and operational efficiency, making them a preferred solution for high-capacity sites. Conversely, MDBs and LDBs, with lower initial costs and ease of implementation, serve as practical alternatives for facilities with budget constraints or moderate power demands. The validation of these solutions through pilot projects reinforces their practicality and underscores their potential to transform power distribution practices in the telecommunication industry.

This study evaluated strategies to mitigate excessive DC power cable congestion at telecommunication sites by assessing various DC power distribution systems. The key findings identified Power-over-Ethernet (PoE), DC Bus Ducts, Main Distribution Boards (MDB)/Local Distribution Boards (LDB), centralized architectures, and decentralized systems as viable solutions, each with unique benefits and drawbacks [40]. To place these findings in a broader research context, they are compared with results from recent studies on DC power distribution systems. The PoE was identified to be useful for low power devices and relieved the burden of wiring and was cheaper [41, 42]. However, it should be noted that PoE is restricted to low power applications and so cannot be used in very high-capacity telecom equipment. Vossos et al. (2021) also pointed to PoE as an energy-saving and cost-effective solution for combining power and data transfer, but also efficiency that depends on the characteristics of the components [43]. This alignment affirms the validity of using PoE in certain scenarios while highlighting its applicability in a restricted manner [44].

Finally, the study established that DC Bus Ducts provide added benefits compared to (other solutions) in terms of power and thermal management at increased initial capital costs. Vossos et al. (2021) and Chen et al. (2022) back up these findings arguing that the DC systems such as Bus Ducts lower the copper usage and increase energy efficiency. However, the capital costs still exist, for instance, in the evaluation of Chen et al. on MVDC systems, such systems are much more efficient than other DC strategies but demand high initial investments [18, 29]. MDB/LDB solution was determined to be a feasible solution with low cable usage and compatibility of higher gauge cables with other systems [45]. Similar observations were made by Darla et al. (2021) stating that high voltage DC power systems decrease the amount of copper and installation costs [32, 46]. This research also has some indication in favor of the MDB/LDB systems as more realistic solutions when the cost, and the relatively reasonable size, of the application are the major factors.

In this study, decentralized DC systems were found to be appropriate for scalable expansions but constrained by space and batteries. Similarly, Vossos et al. (2021) acknowledged that distributed DC systems are flexible, but they also found that system complexity and cost can be problematic [36]. On the other hand, centralized systems were viewed as effective backbones for telecommunication networks but had substantial underlying architecture. Chen et al. (2022) and Montoya et al. (2020) supported that the centralised DC systems would minimise energy losses and greenhouse gas emissions at the cost of implementation.

Montoya et al. (2020) stressed that the performance of DC systems in terms of energy efficiency and environmental impact is higher than that of AC systems [31]. This is in line with our study especially concerning the environmental impacts of DC Bus Ducts and central architectures. However, Waghale et al. (2022) have pointed out cases when AC systems were more efficient than DC, which proves that certain system configurations and components' choice matter. Although our work substantiates DC Bus Ducts and MDB/LDB solutions for telecom sites, other works depict opposite views. For instance, Waghale et al. (2022) established that centralized and distributed DC system are slightly lower than the conventional AC system in certain applications and called for practical confirmation of the modeled efficiency [47].

Moreover, this study has several important implications for the telecommunication industry when it comes to issues of DC power distribution in multi-story telecommunication sites [48]. These implications span economic, technical, environmental and operational perspectives and provide answers to some of the fundamental questions facing the future of power systems. One of the most important practical consequences of the research is the possibility of achieving significant cost optimization. DC Bus Ducts and Modular Distribution Boards (MDB/LDB) offer a cost effective solution and is far from the complicated cable filled solutions[27]. These solutions eliminate additional cabling material cost, time required for installation as well as the additional maintenance cost.

For telecommunications operators this means better usage of capital expenditure which can be directed towards other areas including network improvements and technology [28].

Besides, simplified installation of compact and modular solutions contribute to the decrease of project durations and, therefore, the costs of project management [49]. Although the installation of DC Bus Ducts is initially costly than the conventional methods, the long-run benefits include low operation costs due to low energy loss and frequent breakdowns caused by low reliability of the system. These economic benefits explain why the proposed solutions are especially valuable for large-scale telecommunication facilities experiencing rapid growth [50]. From a technical viewpoint the study emphasizes the need for implementing new power distribution solutions to provide sufficient power supply for the new telecommunication networks [26]. As highlighted in the study, solutions such as the DC Bus Ducts and the Modular Distribution Bus/Load Bus Distribution systems are more appropriate for meeting power demands of the modern technologies like the 5G, IoT and edge computing devices [51].

These solutions allow power systems to be flexible in order to accommodate future technologies because the systems themselves are scalable and modular [52]. Such flexibility minimizes the likelihood of obsolescence and allows telecommunications operators to plan for the future. In addition, the findings of the study suggest that voltage control as well as minimizing losses in the distribution of direct current systems is critical to fulfilling power distribution needs and improving customer satisfaction [53]. The optimality of the DC power distribution systems has numerous impacts on the environment (54). Whenever the usage of copper is decreased in cabling and energy losses are minimized, the solutions are more sustainable. This means less greenhouse gas emissions which are useful in combating climate change, in accordance to the international standards [55]. Secondly, compact and efficient power distribution systems are still small size facilities in terms of the physical space they occupy on the earth and thus may help reduce the impacts of large telecommunication facilities [56].

The study also supports green energy compatible solutions, for instance integration of renewable energy into DC power system. The implications embraced in the findings support the principles of energy efficiency and sustainability as well as the global approach to minimizing the carbon footprint of manufacturing processes [21, 26]. At the operational level, the study offers a roadmap on how power systems in telecommunication can be made more reliable and efficient. In the reduction of cable congestion, the proposed solutions help to minimize chances of system failures due to heat, impact or improper cabling [16]. This leads to more uptime and less service disruption, which is important for consumers and their trust in a company's services.

The solutions are also easily modular and scalable, making it easy to maintain and repair the equipment. For example, the option of working with particular components without affecting the general system makes the process of identifying and solving problems much faster [14, 28]. This operation efficiency will also increase the reliability of telecom networks as a whole. The implications of the research are significant to the telecommunications industry more broadly in setting new standards for electrical distribution networks. The solutions that have been adopted in this area can therefore be used as a reference for other sectors of similar power management issues for instance data centers and industrial manufacturing [27, 31].

VI.CONCLUSION

This research provides a comprehensive evaluation of strategies to mitigate DC power cable congestion in multi-story telecommunication facilities, addressing critical challenges such as cost, spatial constraints, and operational reliability. The study emphasizes the importance of adopting innovative solutions that align with industry standards while ensuring scalability for future technological advancements. The results highlight **DC Bus Ducts** as the most effective solution for facilities requiring high-capacity power distribution. Their compact design, superior electrical performance, and long-term cost savings make them a sustainable choice for large-scale implementations. MDBs and LDBs, on the other hand, offer a balanced approach for facilities with moderate demands, providing a cost-effective and scalable solution that integrates well with existing infrastructure.

While decentralized **power and** inverter-based solutions have specific advantages, their limitations in capacity, structural requirements, and scalability make them less suitable for large-scale applications. These solutions may still find relevance in smaller facilities or niche applications where their unique benefits outweigh their drawbacks.

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The study underscores the importance of a tailored approach in selecting power distribution strategies, considering factors such as facility size, power demand, budget, and future scalability. By implementing the recommended solutions, telecommunication facilities can achieve significant reductions in cable congestion, enhance system reliability, and optimize operational efficiency. The findings also highlight the need for continued innovation and collaboration within the industry to develop next-generation power distribution systems that address evolving challenges. In conclusion, this research provides industry stakeholders with actionable insights and a roadmap for optimizing DC power distribution in telecommunication facilities. The adoption of the recommended strategies will not only address current challenges but also support the industry's broader goals of cost efficiency, sustainability, and technological advancement. Future research could explore the integration of renewable energy sources and intelligent power management systems to further enhance the efficiency and sustainability of telecommunication power networks.

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

I personally conducted the measurements & studies of many Cores multiple floor exchanges, developed the core theoretical ideas, and created the proof of outline, drawing. Over two decades of experience in the telecommunication industry, I observed the significant challenges the telecom industry facing with the high cost of adding DC power cables, which can run into the millions, especially when compared to the cost of the cabinets themselves. Here, facilitators and higher management played a role in supporting the concepts and overseeing the work, the management team was principally involved in reviewing the data and performing the analysis. The task of presenting potential solutions, as well as drafting and designing the various options, was entirely carried out by me.

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