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A comprehensive review of distributed power system architecture for telecom and datacenter applications

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ABSTRACT

With the dominating utility of the internet, it becomes critical to manage the efficiency and reliability of telecom and datacenter, as the power consumption of the involved equipment also increases. Much power being wasted through the power conversion stages by converting AC voltage to DC voltage and then stepping down to lower voltages to connect to information and communication technology (ICT) equipment. 48/12 VDC is the standard DC bus architecture to serve the end utility equipment. This voltage level is further processed to multiple lower voltages to power up the internal auxiliary circuits. Power losses are involved when it is converted from higher voltage to lower voltages. Therefore, the efficiency of power conversion is lower. There is a need to increase the efficiency by minimizing the power losses which occur due to the conversion stages. Different methods are available to increase the efficiency of a system by optimizing the converter topologies, semiconductor materials and control methods. There is another possibility of increasing the efficiency by changing the architecture of a system by increasing the DC bus voltage to higher voltages to optimize the losses. This paper presents a review of available high voltage options for telecom power distribution and developments, implementations and challenges across the world.

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1. INTRODUCTION

In this digital world, the quick upgradation of network infrastructure like telecommunications and network services, optical fibers in subscriber networks, and mobile telecommunications services networks has become mandatory to satisfy the growing data needs. Subsequently, power consumed by the information and communication technology (ICT) equipment deployed in these network systems also increases every year. Total global ICT power consumption in 2015 is around 1700TWh and is expected to be 2788 to 5860TWh by 2025 [1]. In order to support the computing infrastructure, each data center requires a few MW of power, a very large data center requires 10 MW of power. It is anticipated to grow in the future to 50 MW [2], [3].

Fifty percent of the power is supplied to the ICT load in a data center, including processors, memory and other auxiliary devices. The remaining power is wasted in power conversion, power distribution and cooling [4]-[8], From Figure 1, it is understood that for each wattage of power consumed by data processing, one equivalent watt of power is being wasted in power conversion plus cooling. Therefore, ICT equipment and its cooling system consumes appreciable portion of power in datacenter. In a data center, the cooling requirement depends on the energy density of the ICT load. Therefore, energy savings within the ICT load would directly affect the loading of most support systems, such as cooling system, UPS (Uninterruptible Power Supply), and power distribution. As a result of the growing energy cost on the total cost of ownership, efficiency considerations began to influence the decisions to purchase equipment significantly. Therefore, the power supply system that feeds ICT equipment should be highly reliable and efficient [9]-[11].

As the number of power stages is more with traditional distribution system, the research has been progressing for an alternative solution to reduce the power conversion stages. It helps to increase the system efficiency and reliability by using the alternate distribution voltage [12]. Traditionally, the power distribution for the data centers is AC voltage and for the telecommunication facilities the power distribution is 48V DC [13]. Compared with low voltage DC distribution, the use of high voltage DC is an energy-efficient distribution method for both data centres and telecommunication facilities. High voltage DC distribution has been in discussion for more than a decade. Various tests [14] have also highlighted the ability of high voltage DC to increase the efficiency of distributed renewable energy generation and its lower component costs. Advantages and benefits of alternate high voltage distribution have been summarized as higher reliability, better operation and maintenance, intelligent management, reduced harmonic interface, high security, low cost and higher efficiency [14]. Various test results show that the performance, reliability and cost reduction are enhanced by implementing a high voltage DC distribution rather than a 48V DC distribution [14]. However, some challenges for implementing the high voltage DC distribution like safety [15], [16], requirement of new components to suit high voltage and implementation standards [16].

This paper focusses on the power distribution architecture of the ICT equipment deployed in datacenter and telecommunication center. An exhaustive comprehensive review of the available high voltage architectures is presented in this paper. Section 2 explains the types of power distribution used for telecom and datacenter applications. Some distribution systems are also used for other applications like automotive, residential homes and electric vehicles. As it is shown that to manage the power distribution sources that supply ICT equipment, it is necessary to understand the internal power architecture how the DC voltage is distributed to different loads.

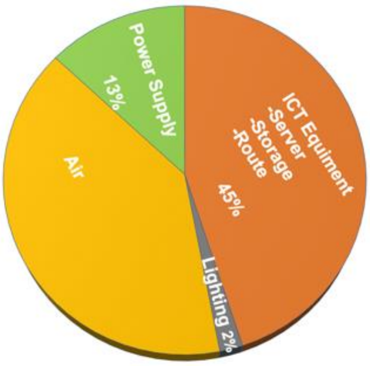


Figure 1. Data center power consumption breakdown

2. TYPES OF POWER DISTRIBUTION

The ICT equipment demands different levels of DC voltages due to the variety of electronic circuits involved. Further, these electronic devices utilize highly efficient switching devices that need low voltage and high current DC input. Therefore, a proper power distribution mechanism is critical to effectively make the voltage distribution at various levels to meet different load requirements [17]. Figure 2 shows the various power distribution systems. As discussed in Section 1, each power distribution has its own power distribution architecture which are discussed in detail.

2.1. Centralized power distribution

The name implies that the existing centralized power plants consist of charge systems, batteries, and other power distribution equipments. Figure 3 depicts the centralized power distribution system. This plant is located in a separate place from the telecommunication system. Due to the system is at a different place and distributed voltage level is low, larger bus bars or cables are required [18], [19] to connect. Centralized powering architecture is the oldest method which has advantages and disadvantages as below [19]. Advantages: a) it is simple and reliable, b) the eenergy system is outside of datacenters, c) the scaling of batteries are easy, d) the temperature on batteries is lower due to separate room installation. Disadvantages: a) energy loss is higher due to long distribution, b) less efficiency, c) higher cost due to more copper utility.

2.2. Decentralized/distributed power distribution

Distributed power is the least complicated structure to build up the required voltage levels directly at the equipment (system) chassis. The power is then distributed throughout the system [19]. Distributed power system eliminates larger busbars or cables involved with the power distribution unlike centralized power system. Figure 4 shows that the block diagram of Distributed Power System (DPS). The power is supplied from the input source to the load terminals by converting AC-to-DC and then to low voltage DC to meet specific load requirements. There are three existing power distribution architectures which can be categorised as: AC distribution, rack level DC distribution, and facility level DC distribution [20]-[28]. Decentralized powering architecture is also the oldest method which has advantages and disadvantages. Advantages: a) it requires less copper as the AC voltage is distributed to datacentre rooms, b) it is easy and flexible, c) better efficiency, d) easy maintenance. Disadvantages: a) limited space to scale the batteries, b) batteries are subjected to higher temperature, c) battery testing becomes difficult.

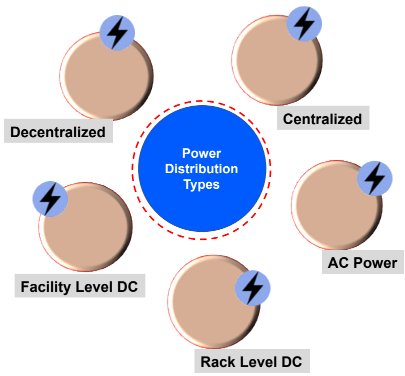


Figure 2. Power distribution types

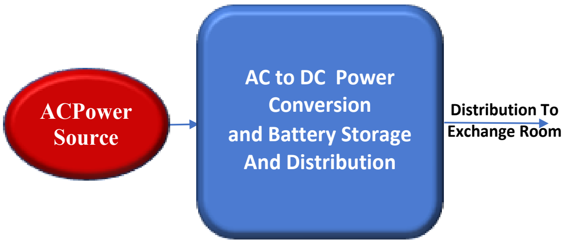


Figure 3. Centralized power supply distribution

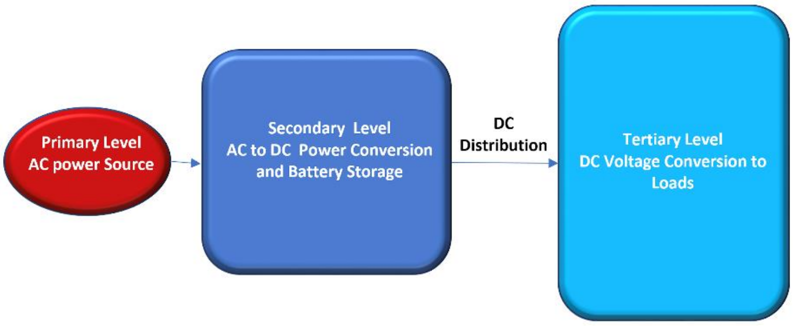


Figure 4. Decentralized power distributions system

2.3. AC power distribution

AC power distribution system consists of an UPS that regulates the given AC input voltage to a fixed output AC voltage. First it is fed to power distribution unit (PDU). Then, this regulated voltage is delivered to ICT power supply units (PSUs). These PSUs are designed to work for universal AC input voltage range. Figure 5 shows the typical architecture of AC power distribution system with four levels of power conversion from one form to another form and one level to another level. The AC distribution system consists of a battery and UPS as a backup during power outage from grid. The battery charging circuit is a part of the UPS which will control battery's charging and discharging stages.

The given AC input is converted into a DC voltage, and this DC voltage acts as internal DC bus where the battery and DC-to-AC converter are connected. The function of the DC-to-AC converter is to provide fixed AC which feeds system power supply unit. This regulated AC is converted to DC and this DC voltage is stepped down to a safe extra low voltage (SELV) with an isolated DC-to-DC converter which is 12

VDC or 48 VDC. Some loads can directly accept 12 V, while other loads need lower voltages which requires voltage regulators (VRs) to step down the voltages to meet the load requirements [29], [30]. Figure 5 shows four stages of conversion [31] in total, two stages at UPS level, 1. AC-to-DC, 2. DC to AC, and two stages with ICT Power equipment level 3. AC-to-DC and 4. DC-to-DC. So, there will be lot of power wastage in the system other than facility and cooling. Advantages: a) AC distribution is compatible with server input, b) requires few protections devices, c) yields higher efficiency if UPS is used in offline mode. Disadvantages: a) lower efficiency if UPS is used in online mode and higher power losses due to 4 stages of power conversion; b) poor battery lifetime due to high-temperature range as it is always connected to terminal voltage to avoid battery self-discharge; c) less reliability in operation as there is discontinuity of operation when there is UPS failure.

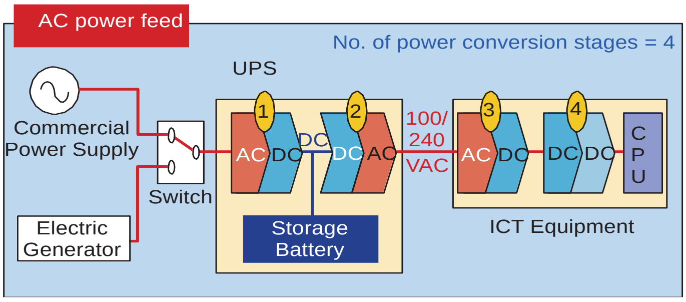


Figure 5. AC power distribution system

2.4. Rack-level DC power distribution

Few manufactures use 48 VDC equipment in their racks, which permits high power density by lowering the server's heat and power supply capacity. The output voltage is isolated by using isolated DC-to-DC converters after AC-to-DC conversion. It has the potential benefit of increasing no/light load efficiency via proper rack level management and sizing. There is also a reduction in the number of power converters needed to manage the same scale of redundancy which can reduce the initial cost of purchase. However, because the number of power conversion stages is similar to restructured AC architectures, this structure is not anticipated to enhance the efficiency. Rack level DC distribution is shown in Figure 6 [32]. The significant difference between distribution of AC power and distribution of rack level DC power is PSU configuration. ICT equipment not equipped with a power supply to convert AC-to-DC. However, the ICT equipment is equipped with DC-to-DC converter only at the front end and other on-board DC-to-DC converters to reduce DC voltage. The advantages and disadvantages are similar to AC distribution as the basic architecture is the same.

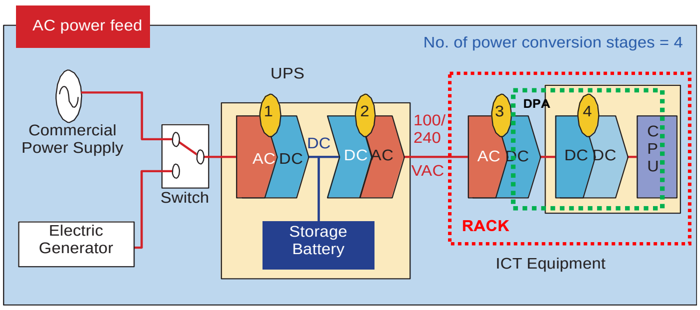


Figure 6. Rack level DC distribution to ICT equipment

2.5. Facility-level DC power distribution

Facility-level DC distribution provides higher efficiency because of the elimination of DC-to-AC conversion stage. It consists of a front-end PSU to convert AC-to-DC, PDU transformer (if applicable), and DC-to-DC converter to convert 48VDC to lower voltage to meet load requirements. DC distribution at 48

VDC is common in telecom facilities as shown in Figure 7 [32]. Although it offers higher efficiency, its use in large data and telecom centres is limited due to more power loss as the distance of cables are longer. Advantages of facility-level distribution: a) can achieve higher efficiency due to lesser number of power conversion stages, b) less cost, c) simple and easy to implement. Disadvantages of facility-level distribution a) it is not suitable for all the locations where the 48VDC bus system not available, b) application is limited due to higher currents when distributing higher current at bigger data and telecom centres.

With decreasing voltage, the amount of copper required increases and is theoretically inversely proportional to the distribution voltage square. This prompted suggestions for a high voltage DC distribution architecture to reduce copper by lowering the distributed current, as shown in Figure 8 [33]. At the current installation level, DC distributed voltage is directly fed to the PSU. The DC distributed voltage is currently limited to 48 VDC as the servers are provided with a universal AC input range or 48 VDC input. AC PSU has a bus voltage of 400 VDC, and the same 400VDC can be used as an input for the system PSU in high voltage distribution. The system PSU can be developed with minor modifications to accept 400 VDC as input as shown in Figure 8. This is an example of 400 VDC distribution system. There are different voltage ranges proposed from 270 VDC to 400 VDC but a single global standard [34]-[36] helps to choose an optimal level for the implementation.

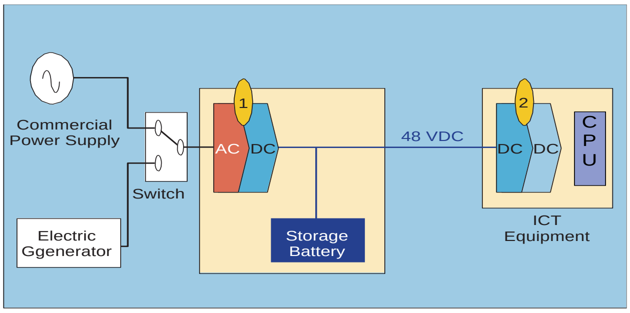


Figure 7. Facility level 48VDC power distribution system for ICT equipment

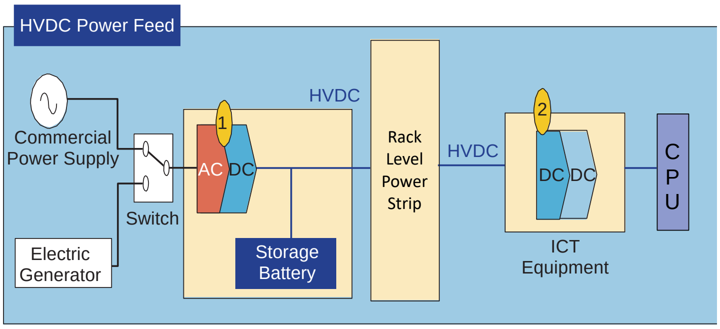


Figure 8. Facility level high voltage DC Power Distribution System

3. DISTRIBUTED POWER ARCHITECTURE

Section 2 explains the various methods of power distribution to access the power to the ICT equipment. However, there is another level of power distribution within the ICT equipment, which is being operated at different voltages for different circuitry to function correctly. For example, each ICT equipment has its purpose with microcontrollers, DSP, ASIC, sensors, and analog & digital circuitry. Each device requires different operating voltage with specific amount of current to function correctly. Therefore, the ICT system uses various architectures to distribute power at various levels. Method one is to distribute multiple voltages from a single voltage bus. Method two is stepping down one voltage level to another level then distribute from second level. Method one is called distributed power architecture (DPA) [37] and the method two is known as distributed power architecture with intermediate bus (DPA-IB). The power converters between the DPA DC bus and IB are classified as intermediate bus converters (IBC).

DPA is a popular method to distribute power for various loads. It is widely used across telecommunication and datacenter networks, Figure 9 shows that detailed architecture of DPA with various

DC buses and stages of conversion of voltages from one value to another value. Figure 10 (a) shows the distributed power architecture. In this architecture, 48V DC is main DC bus which is converted from front-end power converters. There is an intermediate bus converter to convert 48VDC to 12VDC. 12VDC bus is called the intermediate bus. 12V is used to further distribute the voltage to the other low voltage loads. The advantage of the intermediate bus stage is that it eliminates the isolated DC-to-DC converters.

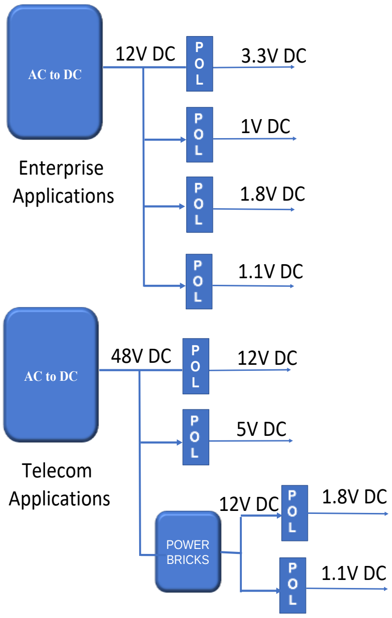
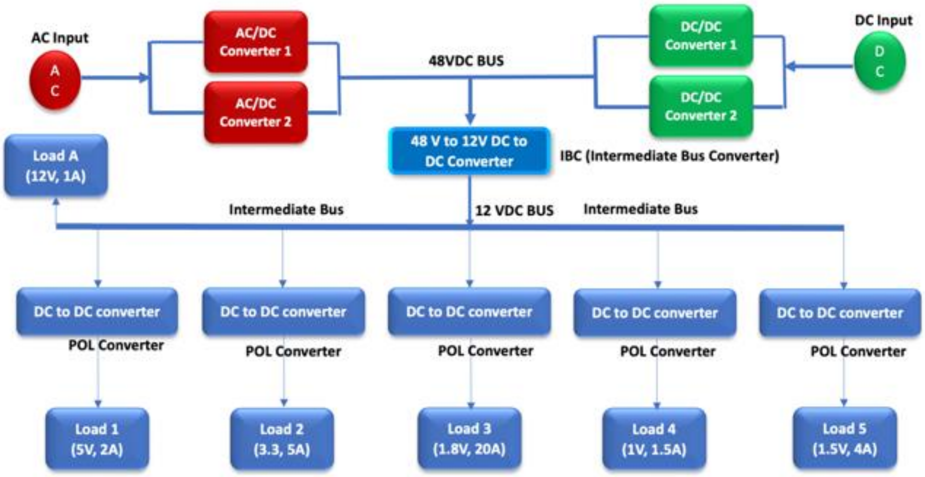


Figure 9. Block Diagram of internal power stages of DPA

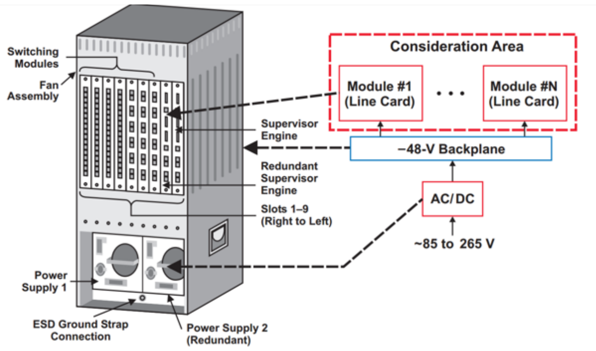
The intermediate bus is brought from the 48 VDC bus with the help of IBC. IBC is an isolated DC-to-DC converter with tight regulation [38], [39]. The converter gives higher efficiency due to regulated input voltage and fixed output voltage. IBC is followed by a set of non-isolated converters termed as point of load converters (POL). POL is a non-isolated power converter which is used to stepdown the given input voltage to the range of 3.3 VDC, 1.8 VDC, 1 VDC, 0.8 VDC. Since the IBC is tightly regulated, there is no requirement of tight regulation at the point of load converter. POL converter is used to power the low voltage devices such as microcontrollers, memory and digital I/O circuits. POL gives greater flexibility by avoiding larger current carrying requirement throughout the board as it is generally placed very near to the circuit/device.

Several methods have been proposed for IBC and POL converter developments with higher efficiency and higher power density in [40]-[44], which can be used for HV power distribution. Figure 10 (b) shows the telecom and data center centralized power supplies located at the bottom of the rack including AC-to-DC front end rectifier and charger, battery and a DC-to-DC converter. Typically, the 48VDC main bus is linked from the power supply output to the back plane. The back plane in the system chassis will have different mating connector slots for connecting to the ICT equipment. ICT devices, such as line cards, fabric cards, have IBC and POL converters internally.

Section 3 explains the internal power architectures to distribute the power to various devices with different voltage and current ratings. DPA is a popular method in various ICT equipment as it operates with reduced power losses, better signal integrity and higher adaptability. PCB trace width is greatly reduced by adopting DPA with IB method because of the presence of IBC converters and POL converters. POL converters are placed near to the low voltage and higher current loads to reduce the higher current trace length and loops.



(a)



(b)

Figure 10. (a) block diagram of intermediate bus distributed power architecture; (b) system level diagram of internal power stages of DPA with intermediate bus [45]

4. HIGH VOLTAGE DC POWER DISTRIBUTION AND ITS ARCHITECTURES

Globally, the 48 VDC system has been used in telecom, but in recent years there has been a problem with the 48VDC. According to the data reported on the change of the calorific value per rack in ICT equipment, the calorific value was approximately 2kW in 1992, the calorific value surpassed 5kW in 1998. In addition, in 2003, the calorific value exceeded 10 kW, and in 2009 the calorific value of most server routers was above 10 kW.

The power density of the ICT equipment increases dramatically year after year, resulting in increased electricity consumption per rack. As the load current increases, there is a need for many power cables to carry increased current. Figure 11 shows the power cables required in a 48 VDC system to send 100 kW of power. Other issues arise when ICT equipment power density increases, such as spacing, cooling, and overall system cost [46]. The better alternative solution is a high voltage DC distribution system that solves the problems of 48 VDC.

Figure 12 shows the benefits of high voltage DC over 48VDC low voltage. The load current of ICT equipment can be reduced while increasing the voltage of electrical supply. If the current decreases due to increased voltage, then the size of the power cable reduces, which results in reduction in the number of power cables. Figure 13 shows the cables needed for a 48 VDC and high voltage DC (400 VDC) to transfer 100 kW of power. The size of copper required for the cables used in a 400 VDC system is almost 15 times lower than the one used in the 48 VDC system. The problems associated with low voltage DC can therefore be eliminated with high voltage DC.

High voltage DC power distribution has the flexibility to use when there are multiple input sources like solar, wind, and fuel cells because the number of power stages can be reduced by arranging the system as per the application requirement. High voltage DC is more preferred for DC microgrid in Datacenters [47]. Now the pros and cons of high voltage DC are explored.

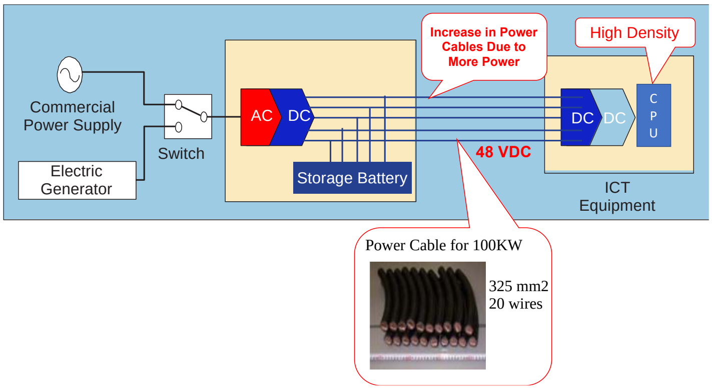


Figure 11. 48VDC wiring configuration of multiple ICT loads

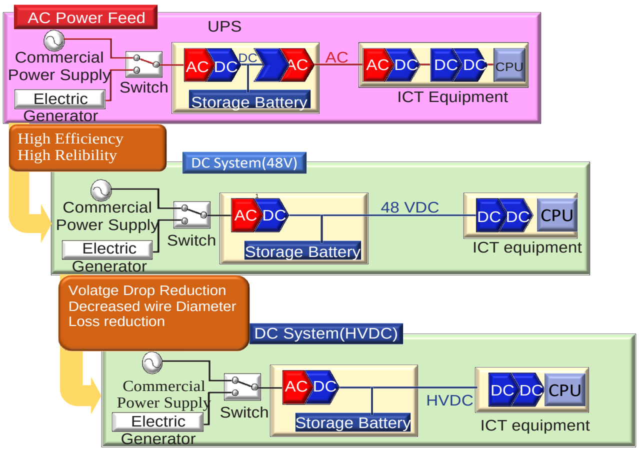


Figure 12. Comparison of AC, DC 48V and high voltage DC power distribution

Figure 13. Comparison of wire count for 48VDC and 400VDC [40]

4.1. Advantages of high voltage DC

4.1.1. Efficiency

In the ICT equipment, power conversion from AC-to-DC and DC-to-DC is necessary for supplying the components with suitable DC power. As a result, four conversion stages are required in AC power distribution. Two conversion stages in DC power distribution, two conversion stages in DC distribution is due to direct feeding of power from the rectifier and battery. In general, one conversion stage's power loss is about 10 percent of the total converted power. Thus, DC power distribution is more efficient than the distribution of AC power due to fewer conversion stages. The DC power distribution network can be more effective by raising the DC voltage from the standard 48V to a higher voltage, resulting in reducing of the supply current. Constructional costs are reduced due to reduced supply current, and flexibility is increased as power cables can be used with smaller diameters.

Figure 1 in section 1 shows an example of a breakdown of power consumption in an AC power distributed data center that is further described as Figure 14 with respect to DC power distribution. The shadowed areas in Figure 14 represent the approximate amount of power loss reduction accomplished by replacing an AC with a high voltage DC power distribution. As the number of stages and current in the high voltage DC power distribution are decreased, the loss caused by the conversion stages and the power used for the ICT equipment cooling system and the power feeding system may also be reduced. It is estimated that the total amount of power loss reduction is about 14 percent (which is shown by the striped portion in Figure. 14. Thereby increasing the overall system efficiency as the losses are reduced [6].

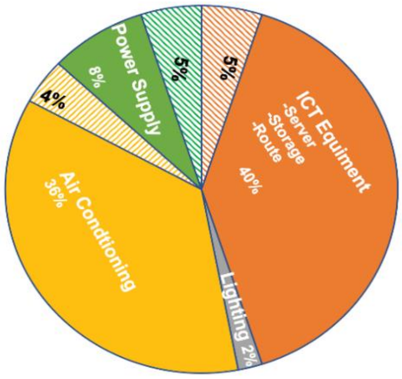


Figure 14. Data center power consumption breakdown with high voltage DC

4.1.2. Reliability

ICT service is one of today's most essential services. A large amount of economic activity is dependent on the IT networks, services include ticket booking, banking financial services, credit card services and e-commerce. Suppose ICT service system failure/breakdown occurs, in that case, this will have a more significant impact on society demanding a higher power supply reliability. Suppose a power failure occurs from the grid. In that case, the battery will start providing power to the load (ICT equipment) without interruption. In an AC distribution system, the battery DC power is converted to AC power with the help of a DC to AC converter, and the ICT equipment is fed with AC power. Conversions of DC to AC and AC-to-DC are required to provide sufficient DC power to the components. Whereas in the DC power distribution system, the battery power directly supplies the ICT equipment. A system that feeds on DC power is straightforward. So, it is ten times more reliable than an AC system [48], [49]. The high voltage DC power feeding system has the same configuration as a 48VDC system, making it highly reliable.

4.1.3. Compatibility with renewable energy

An additional benefit of 400VDC power distribution system is its suitability towards easy integration of distributed local power generation sources, particularly renewable ones. As well as more efficient to support the auxiliary loads such as LED lighting. Therefore, 400 VDC power distribution architectures act as a fundamental enabling technology for a wide range of other technologies that can lead to energy efficiency improvements in commercial buildings.

4.1.4. Lower installation cost

The installation cost of the high voltage DC power distribution is lower due to fewer power converter requirements, and reduced copper consumption. Approximate copper savings are about 15 times, so there are considerable savings in mounting cable bus bars. In the same manner, the cost savings due to the removal of two conversion stage converters. The distribution of high voltage DC power is more accessible than the distribution of AC power and the conventional distribution of DC power. Although it has more benefits, the high voltage DC has the following disadvantages below [50].

4.2. Disadvantages of high voltage DC

– Supply voltage
  When the bus voltage is increased to higher voltage range, such as 400VDC and higher, it is challenging to meet the quality and reliability with existing components. Usage of higher voltage requires the development of new components. So, the design and selection of acceptable voltage is an essential factor in high voltage DC power distribution to meet targeted reliability and quality of the system.
– System configuration

The system will be bulky while migrating from low voltage to high voltage DC due to changes in input filters and other interconnecting equipment. In addition, as the configuration is changing, the cost of the system also increases.

– System grounding and safety

Higher voltage increases the system's risk, creating problems in keeping insulation distance and space, protecting methods, retaining the safety [51], and operating and managing the system. Therefore, a more Vigilant selection of grounding scheme is discussed in.

Frank Bodi [50] conducted a survey to understand the willingness of data center and telecommunications to implement high voltage DC power options 84% of the responses showed that they are interested in high voltage DC options. In comparison, 80% of the responses show that high voltage DC options are considered for their centers.

Studies show that the most preferred DC voltage is 380-400VDC. The less preferred voltage for high voltage DC distribution is around 250V. Reasons for considering high voltage DC are stated as reduced copper, increased efficiency, reduced floor space, simplified installation, and increased availability. The concerns raised for high voltage DC are lack of standards, power equipment technology, compatibility to ICT equipment, cost, safety, and compliance. By considering various points between low voltage and high voltage power distribution, high voltage power distribution has been concluded to be a more effective powering solution.

High voltage DC power and the importance of high voltage DC distribution for data centers and telecommunications are discussed above by considering the merits and demerits for high voltage DC distribution. There are few architectures already studied and implemented for the distribution of high voltage DC power. Each high voltage DC architecture is reviewed in this section to understand the operational and implementation benefits and challenges involved. The selection of supply voltage for a high voltage DC distribution system depends on several factors [52]:

– Different country laws, standards, and regulations
– Distributed sources of power generation (the use of solar power generation, wind generation, and fuel cells are expected to increase in future ICT systems)
– Battery architecture (number of battery cells connection)
– Verification of previous and current developments
– Rated voltages of different components in the equipment.
– The AC voltage waveform peak values

4.3. High voltage DC Architectures

4.3.1. 270 V DC power distribution system

Takashi [46], has developed a 270VDC Telecom Power supply system by considering various factors like system reliability, system cost, and human safety [46]. The primary reason for 270 VDC is to match with input AC peak voltages where the input AC is around 200 V. The operating principle of the 270 VDC system is simple by means of converting 200 VAC-to-DC and then regulating to 270 VDC by using a DC-to-DC converter. This 270 VDC voltage is supplied to telecommunication equipment (TE) through distribution cabinets. During power failures, the charged batteries supply 270 VDC. This configuration helps to eliminate another voltage compensator which is generally used in conventional 48 VDC systems [46]. Implementation of the 270 VDC bus system shows positive results in terms of efficiency, reliability, and cost.

Figure15 shows the typical architecture of 270VDC power distribution. It consists of a rectifier to convert AC-to-DC voltage and a DC-to-DC converter to convert unregulated DC voltage to regulated DC voltage. The same DC-to-DC converter is used to regulate battery voltage in the absence of AC power.

The purpose of second level DC-to-DC converter to step down regulated high voltage DC to component voltage levels. There is a separate charger to charge the battery from the source. The switch is placed to connect and disconnect the battery source based on the AC source availability. This 270 VDC architecture have the advantages which has been already mentioned, but it has disadvantages.

– The specifications of the noise filters, fuses, connectors, and onboard DC-to-DC converters are changed due to the change in DC bus voltage from lower voltage to the higher voltage. Such components may become greater in volume or worse in performance, although the diameter of the cable may be smaller.
– The fuse and connector sizes are larger to satisfy the supply voltage specifications. Each voltage would require different amounts of arcing voltage and connector pitch.
– DC-to-DC converter efficiency may decrease due to higher voltage switching losses, but this can be minimized by applying various technical advances, such as zero voltage switching and the use of wide bandgap devices.

– The system-level cost of the 270 VDC is higher for lower wattages because of filters, fuses, and connector cost, However, it is cheaper for higher wattage when compare with 48 VDC.

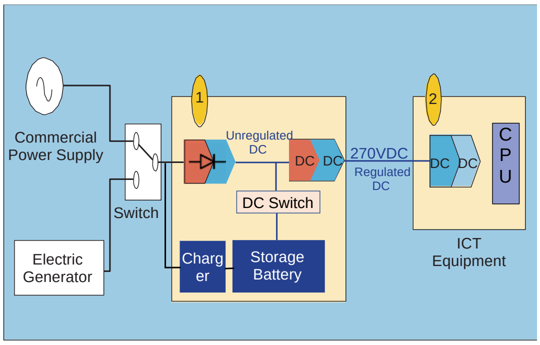


Figure 15. 270 V DC power distribution system architecture

4.3.2. 300 V DC power distribution system

The architecture of 300 VDC power distribution is the same as the 270 VDC system except for the bus voltage and battery terminal voltages. The selection of 300 VDC is based on 188 VAC to 265 VAC voltage range as the maximum peak value of input AC is 375 V. The battery voltage is also sized as per this DC bus voltage to supply during power failures. The 300 V system offers high efficiency, better reliability, and low deployment costs compared to the conventional 48 V device. The benefits of high efficiency and decreased installation costs are restricted to rated load power ranging from 3.5 kW to 60 kW.

Sizing of the batteries is an essential factor for high voltage power distribution as the battery is the combination of the series connection of multiple cells to get the required voltage level by considering each cell maximum and minimum voltages. For example, when 156 cells are connected with a maximum voltage of 2.35 V per cell, then the battery voltage is 367, which is below the peak value of 375 VDC. Similarly, the shutdown voltage of the battery, by considering each cell voltage of 1.75 V, gives a total voltage of 273 V, which is above the lower peak value of the input voltage range. Other concerns which are faced by the 270 V system apply to 300 V system as well. The only advantage of 300 V over 270V is the wide operating range at the input. 300 VDC power distribution system is shown in Figure 16.

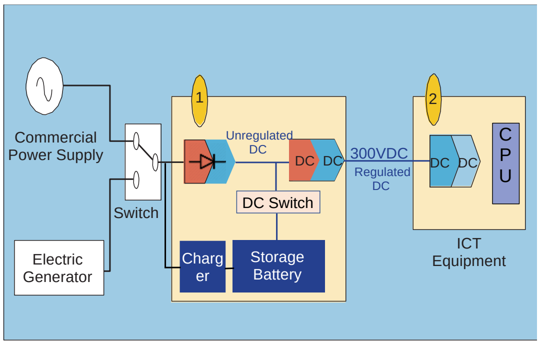


Figure 16. 300 V DC power distribution system architecture for ICT

4.3.3. 400 V DC power distribution system

There is another DC voltage level of power distribution which is 400 VDC, and this voltage is most suitable for many locations where the input voltage is 230 VAC line to neutral and universal input voltage range (90 – 270V). The working principle is almost the same as the 270 VDC system, but the DC bus is regulated to 400 VDC. The battery voltage is also matched with this DC voltage to have a common DC bus of 400 VDC. The battery is connected to the main bus through the diode and voltage compensator circuit, as shown in Figure 17. This architecture has more benefits than 270 V and 300 V in terms of reliability, efficiency, and cost. The cost reduction is due to the smaller size of cable/bus bars employed in this system

[9], [13], [34], [50]. There are two types of architecture for 400 VDC; a) wide range type, b) narrow range type.

Wide range architecture is similar to lower voltage configuration and shown in Figure 18, the primary distinction being the working voltage level relative to the lower voltage system architecture. The system has a rectifier to convert AC-to-DC voltage followed by a DC-to-DC converter to regulate the converted DC voltage to 400 V, and the same DC-to-DC converter output is connected to batteries and the ICT equipment. When there is a power failure battery supplies 400 VDC to the ICT equipment, the battery will charge when power resumes back. The range of the input voltage operation defined by the load is wide in this architecture. The DC-to-DC converter will work for the entire specified lower to the higher voltage. The protection of the battery from the lower voltage will be taken care of by a DC-to-DC converter to prevent deep discharging.

The purpose of narrow range high voltage DC is to compensate battery voltage to a specified range by the load. The narrow range architecture type is shown in Figure 17. This has a similar setup, but few differences are there in configurations as well as operation-wise. This system consists of an AC-to-DC rectifier, and a DC-to-DC converter to regulate the converted voltage, which will be fed to the ICT load, a separate battery charger to charge the battery and a voltage compensator (VC) to compensate the battery voltage. The voltage of the DC bus needs to be compensated if the load voltage operation range is narrow. VC helps to compensate for the dc bus voltage. The diodes shown in VC are to prevent the current flow from the rectifier to the battery during VC operation as the battery discharge voltage is lesser than the rectifier voltage. High voltage DC narrow range architecture has three advantages when compare with a wide range [53], [54]. a) Higher efficiency due to narrow input voltage, b) Low voltage drops, c) Flexibility to choose the battery type.

400 VDC bus architecture power distribution system prototype has been implemented at NTT for 100 kW load center. The system has been verified with two conditions; one is the fixed input voltage of 230 VAC and second one with variable input voltage from 180 VAC to 266 VAC. As per the testing results, it has been proved that 400VDC has better efficiency (>90%) when 25% of the load is applied, and efficiency is 93% when the load is 80% with tight output regulation. Wide range power distribution system exhibits higher efficiency when compared with narrow range distribution system at maximum load condition.

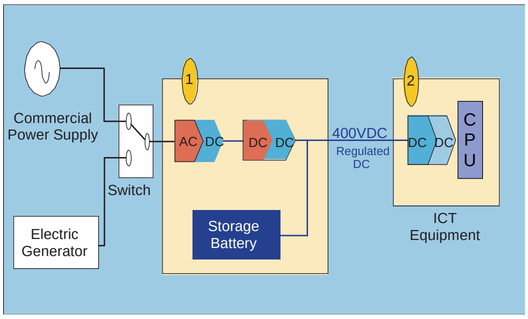


Figure 17. Wide range 400 VDC power distribution system architecture for ICT

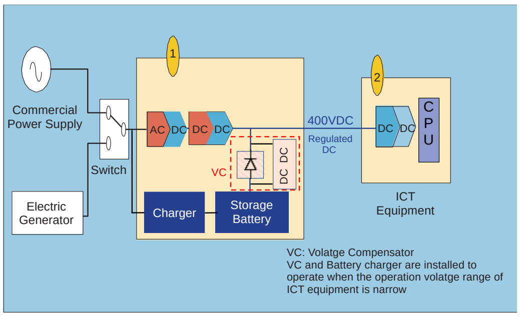


Figure 18. Narrow range 400 V DC power distribution system architecture for ICT

5. HIGH VOLTAGE DC POWER DISTRIBUTION IMPLEMENTATION CHALLENGES

It is necessary to change noise filters, connectors, fuses, and board mount DC-to-DC converters when high voltage DC is provided to an ICT equipment cabinet. This action can increase their volume or decrease in their performance, despite of the reduction in cable /bus bar size. The terminal connector size will increase with the increase in terminal pitch to meet high voltage clearance and creepage requirements. The fuse also grows larger as the cutting arc has become tougher in terms of voltage supply.

The efficiency of the onboard DC-to-DC converter could be lower due to the loss of switching (MOSFET). Advanced converter topologies like resonant switching converters and highly efficient devices Sic, GaN MOSFETs help in reducing the losses. There is another aspect to consider while using high voltage DC is the ICT equipment cabinet. The increase and decrease of these cabinets depend on supply voltage and power. Another area to consider in the design of high voltage DC is a grounding system and a human body; both end-floor methods are shown in Figure 19. The grounding system consists of inserting positive and negative current output resistance and then connecting the middle point to the earth electrode.

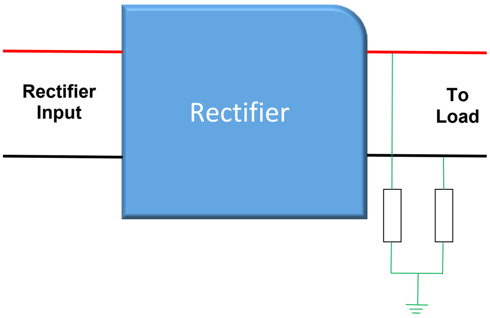


Figure 19. High voltage DC earthing at NTT [33]

Human safety may not be guaranteed by using two end grounding techniques shown in Figure 19. The voltage may increase above the 48 VDC system, which is vulnerable to electrical shock. There are two aspects that ensure the safety of the system, (i) development of power cable connection, and (ii) design of plug, socket, and outlet. Figures 20 and 21 show the connector, plug, socket, and outlet implemented for the 19-inch rack where ICT equipment is installed. Again, there will be no risk of electrical shock as the current carrying parts are not exposed.

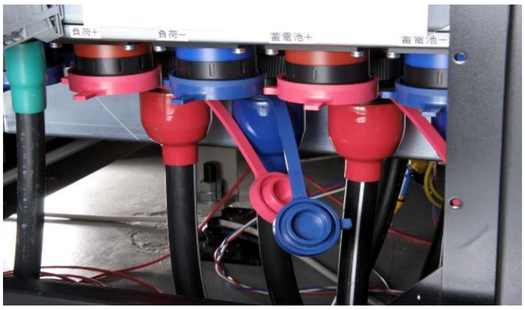


Figure 20. Connector diagrams [30]

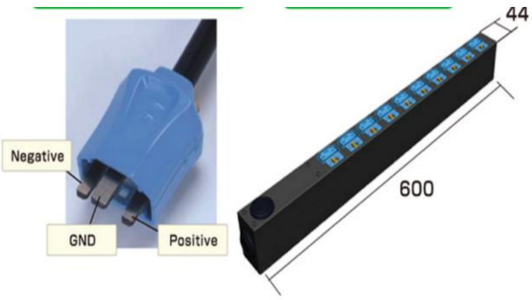


Figure 21. Connectors and socket diagrams [30]

There will be no escaping fact that the distributed architecture will completely replace centrally controlled architectures for all ICT equipment in the future at big, small, and medium sized telecom/data centers. However, many issues still need to be addressed to make the high voltage DC distributed power system architecture approach more viable and attractive for users.

The challenges of the high voltage DC power distribution system can now be identified as: packaging, onboard efficiency, noise, cost, system integration, safety.

- *Packaging:* It is necessary to develop new packaging technologies to increase the power density of power supply converters above 155W/in^3 [55]. Converter efficiency and power density can be enhanced with HV integrated technologies. Hybrid thick-film technology or similar techniques will be needed to achieve the required power density and provide appropriate thermal management.
- *On-Board Efficiency*: IBC&POL converters need higher efficiency to minimize power dissipation. Currently, onboard converters from different manufacturers can only achieve about 90 percent efficiency depending on the topology of converters and device types. Improvements are needed to increase the efficiency by optimizing the design and migrating to Sic and GaN devices [56]. Once appropriate semiconductor devices and circuit topologies are developed, the synchronous rectification method will help to increase the efficiency substantially. New converter topology technologies should be explored with lower switching losses with lower device voltage and current stresses to achieve higher efficiency. Shifting to planar magnetics will give higher efficiency for onboard converters instead of ferrite core magnetics. This will also help to meet onboard high-frequency, high-density converters challenges.
- *Noise:* Onboard converters operate with multiple kHz switching frequencies. As a result, these high frequency switching converters are placed close to other noise sensitive electronic circuits, which can cause EMI problems. Therefore, a comprehensive investigation is needed to understand the EMI problem

which in turn help in developing suitable tools and techniques for the design of noise reduction. In addition, innovative packaging and shielding strategies will be needed to minimize the EMI problem.

- *Cost:* The cost of producing onboard power modules is currently greater than [57]-[59] for central power supplies since the number of power stages in distributed power systems is higher as shown in Figure 8. In certain applications that may require DPS architecture, this may cause an economic barrier. Hovever, economic considerations are an overriding factor as there are other benefits of DPS compared to centralized power. In order to make the DPS method attractive for such applications, production costs should be reduced by adopting various techniques [4], such as streamlining DPS subsystems and making full use of surface mounting technology.
- *System Integration:* Since many things have already been done to illustrate the dynamic interactions of DPSs. Now there is a requirement of better system study integration that needs to be continued. Also, computer-aided techniques need to be developed to provide systematic design techniques, which in turn address the DPS as a whole.
- *Safety:* Safety is an important factor for high voltage DC power distribution [60]. All the primary distribution and onboard power are above SELV [61], [62]. More research is required to develop global safety standards, which will help ease of implementation of high voltage DC DPS architecture. There are few standards already developed for high voltage DC distribution [58].

For future deployment, the other areas to be considered are technical and operational. Technical concerns like EMC, inrush current, and maximum power levels of ICT equipment [63], are to be addressed. The functional requirements of reliability, protections, and safety must be focussed [64]. Table 1 shows the qualitative comparison between conventional low voltage distribution and high voltage distribution regarding critical parameters to be considered while designing a high voltage DC distribution system.

Table 1. Qualitative comparison of low voltage and high voltage DC distribution

Parameter	Low Voltage	High Voltage
Voltage	48 VDC is the universal applied voltage, 48 VDC is widely used for telecommunications and data center applications	Different studies show that 270, 300, 380, and 400VDC voltages are implemented. Many institutes started working to achieve optimized voltage levels.
Safety	Suitable for safety and ease of use as it is easy to manage insulation distance and space.	The use of higher voltage increases the system's risk, creating problems in keeping insulation distance and space, protecting methods, retaining safety, and operating and managing the system.
Efficiency	System efficiency is lower due to more losses and more conversion stages	System efficiency is higher due to fewer losses and less conversion stages [65]
Cable sizing	Larger cable sizes are required to carry a large amount of current [66].	Smaller sizes are required as the value of current decreases when the voltage is increased to higher values.
Battery voltage	It is not hard to adjust the battery voltage because it depends on the series and parallel connection of multiple cells depending on nominal battery and float voltage.	It is not hard to adjust the battery voltage because it depends on the series and parallel connection of multiple cells depending on nominal battery and float voltage.
Interconnect Components	No new interconnecting components need to be developed as this has been deployed for many years.	Interconnect systems such as earth connectors, plugs, sockets, and outlets are required for the development.
Compatibility with other renewable energy sources	There are no compatibility problems with other renewable sources, but to keep low voltage, it needs an additional DC-to-DC converter.	There will not be an extra converter required if the system is designed to operate within the minimum to maximum voltage range.
Global acceptance	There are already well-developed standards for using this voltage, and it is accepted globally.	There are no worldwide accepted standards for implementing high voltage DC bus systems.
Regulation	Line and load regulation well maintained	Line and load regulation well maintained
Implementation	Easy because of the simplicity in structure.	Difficult as the research is ongoing and no standards to implement.
Power density	Lower	Higher
Cost	More due to more conversion stages and cable/busbar sizes [67]	Less due to fewer conversion stages and cable/busbar sizes
Size	Depends on application	It depends on the application, but it is less compared to low voltage

6. CURRENT DEVELOPMENT STAGE OF HIGH VOLTAGE DC POWER DISTRIBUTION

Various organizations have already started using high voltage DC as their power distribution voltage. However, each has its criteria to use high voltage DC which are explained below regarding each organization's implementation status.

6.1. Nippon telegraph telephone facility

Nippon telegraph and telephone (NTT) is a Japanese telecommunications company headquartered in Tokyo that has carried out substantial research on the distribution of high voltage DC power to telecommunications and data center applications. NTT published an article in 2015 [68] on the implementation of a 100-kW system with a maximum rated voltage of 400 VDC as a distributed voltage to meet the basic requirements of ITU-T L.1201 [69] international standards.

The key specifications of the system are

– The operating voltage of the high voltage DC bus is in the range of 260 V to 400 V DC with a rated voltage of 380 VDC [70]. It is necessary to define the rated voltage of ICT equipment in order to meet this level. Thus, the ICT equipment normally works from 260 V to 400 V and will stop beyond the lower and upper limits.
– The current passing magnitude and time are specified to prevent the unintended operation of the protective circuit breaker due to inrush current.
– Safety considerations such as risk, structure, and reduction of the input power supply of ICT devices to prevent electrical shock are specified in accordance with ITU standards.

There is another advantage of high voltage DC power distribution which provides low noise and less stray current risks and the same is proved by NTT testing as the grounding is different, which is discussed above. NTT reported that ITU (international telecommunication union) technical requirements and guidance help to implement the high voltage DC system and plan an implementation strategy to reach out to its ICT vendors to extend high voltage DC-supported ICT equipment and reduce the overall system cost by 2030.

Figure 22 shows the high voltage DC roadmap of NTT; the initial plan of NTT is to implement the high voltage DC power supply network in combination with the building of new power supply systems to improve existing ones to bring in high voltage DC from the current power supply networks. At the same time, NTT develops and deploys power conversion equipment called "migration equipment" to supply power to ICT equipment that does not support high voltage DC, i.e., equipment that requires -48 VDC or 100 VAC.

Next phase, NTT extends the use of high voltage DC by adding high voltage DC supported ICT equipment while diverting any migration equipment that is no longer needed to other floors or buildings to reduce the development and maintenance cost. In order to speed up the implementation of high voltage DC, NTT is targeting to reduce the cost of high voltage DC power supply systems and encouraging various high voltage DC support systems, and implementing safety measures across the NTT Group to install high voltage DC power supply systems. The objective is to deploy 1,000 buildings by the FY2020 and all large buildings by FY2030. In fact, a variety of protective measures should be introduced.

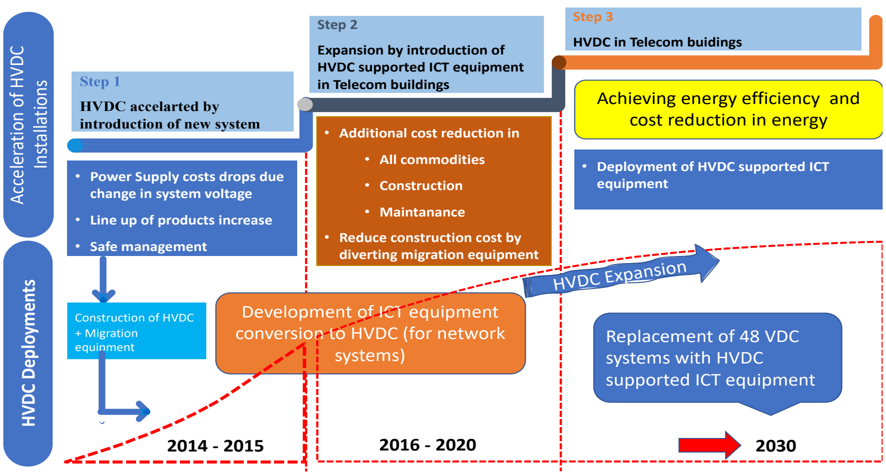


Figure 22. High voltage DC promotion Roadmap at NTT

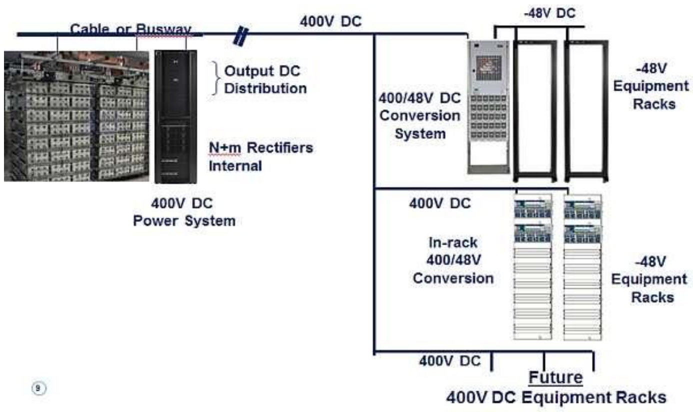
6.2. Emerson network

Emerson network power has developed many high voltage DC input products for their network products installed at various datacenters. Figure 23 shows fully functional 400V DC installation for data center and telecom environments including Emersons's power supplies and conversion systems. From the Figure 23, it is understood that the 400 VDC is used as front-end power which feeds a 48 VDC power supply to the further processing of power to lower voltages to meet ICT equipment device requirements. The advantage of making 400 VDC as the front connection is that it can be easily used for any other high voltage DC sources such as solar PV, wind, and other renewable energy.

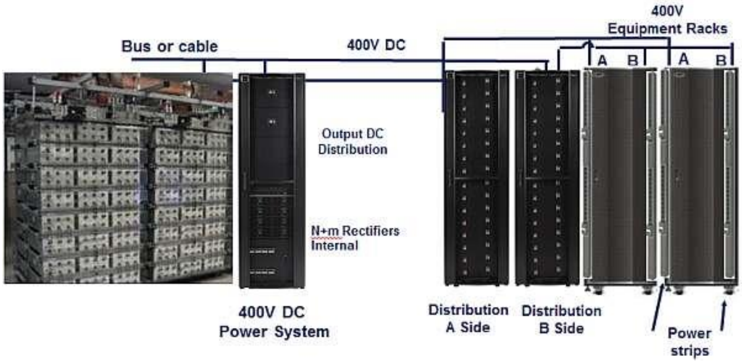
Figure 23. Emerson 400V DC product Portfolio [71]

6.3. VICOR

Salato from Vicor Corporation has presented high voltage DC to alleviate the fear of high voltage DC so that Telecom and Datacom companies would feel comfortable switching from the old standard 48 V network to a new state-of-the-art 400 V system with its many advantages. Figure 24 (a) shows that the implementation of the 400 VDC bus as a primary distribution voltage to various ICT equipment racks. This 400 VDC is further stepping down to -48VDC to process the load. Figure 24 (a) shows the future 400 VDC racks, implemented and shown in Figure 24 (b) The system looks similar to the traditional 48VDC bus system other than new interconnecting components, which is compatible with 400 VDC. From this installation, the author demonstrated the basic advantages of high voltage DC such as space-saving, cable cross-section reduction, and increase in efficiency by reducing the losses associated with higher current and conversions stages.



(a)



(b)

Figure 24. (a) power -48V DC equipment loads with 400V DC Distribution [70], (b) distributing 400V DC Power to 400V DC loads delivers maximum installation savings [72]

6.4. Intel

Intel has conducted a case study [71] to understand the cost and operational benefits in 400 VDC over traditional AC distribution for a 5.5 MW data center. Intel study has a conclusion of energy savings of 7 to 8 percent with a 15 percent capital cost savings and 33 percent space savings at the facility and the reliability improvement of 200 percent. Intel has not given any plan for high voltage DC system development and implementation. However, they have suggested its use as it is a promising technology for data centers. Intel has deployed systems with high voltage DC recently, and Intel is doing collaboration work with NTT for their microgrid project.

The majority of high voltage DC developments are seen on the front side in commercial. There are many implementations required on the primary bus as high voltage DC to replace the complete 48 V DC bus. As everyone accepts that the advantages are more with high voltage DC power distribution, industries are moving forward to implement. The deployment is slow due to lack of standards to follow. However, many standard institutes like ITU and Emerge alliance are working to make devise telecommunications and data center standards for the design and development of high voltage DC systems.

There are some other products that are released from various organizations like IBM, Plathome, NEC, HP, and Cisco. The high voltage DC product range is from 1RU storage systems to 2RU, 3RU, 4RU, Blades, and mainframe. Table 2 shows the line up of high voltage DC ICT equipment from the different organizations [70], and this high voltage DC ICT equipment is expected to be widespread in the future.

There is a need to have more work to promote high voltage DC as there is a dilemma existing with ICT equipment vendors and carrier operators. ICT equipment vendors are ready to make if the operator is ready to buy. Figure 26 shows high voltage DC development across the globe with various voltage levels of power distribution. As the whole industry is willing to migrate from low voltage DC to high voltage DC, section 6 showed the current scenario of ICT equipment deployment. The industry is still conducting research to make standards to increase the installation of high voltage DC ICT equipment by making standard products for easy implementation.

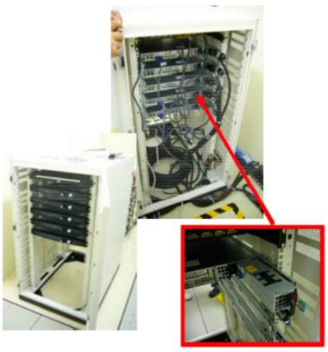


Figure 25. Intel’s high voltage DC servers at datacenters [71], [72]

Table 2. High voltage DC ICT products line [71]

Organization	Type of Product	Product Line
Plathome	Storage 2U, 3U, 4U	TrusSPS Series
NEC	Storage 1U, 2U	iStorage M series
HP	2U	DL380
	4U	Prolant
	Blades	HP:C7000
Unicom	1U, 2U	D-1000/2000
Cisco	Blade	UCS 5108
IBM	Blade	zEnterprise
NEC	Blade	Sigmablade-M

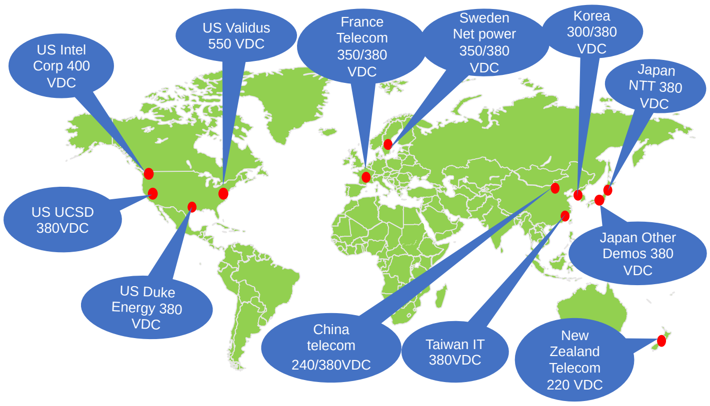


Figure 26. DC powered voltages and sites ICT across the globe [73]

7. CONCLUSION

From the studies, it has been understood that the present days' telecom and datacenter ICT equipment consumes lot of power for their data processing and communication. Almost 50% of the power is wasted for other needs while supplying power to the ICT with the existing 48 VDC distributed power architecture. The study reveals the advantages and disadvantages of exiting 48 V architecture and has shown the alternate architecture with high voltage DC distribution power system, which has more advantages.

Although high voltage DC is not cheaper, the review reveals that the high voltage DC distributed power architecture is highly reliable and efficient. Three types of high voltage DC voltage bus architectures have been implemented at the various centers to check the performance in terms of efficiency and feasibility. It has been concluded that 400 VDC bus architecture has demonstrated more advantages than 270 and 300 VDC bus.

It is understood that more research is required to select optimal DC bus voltage. The research perspective is on the distributed power architecture to meet safety, cost expectation, efficiency, and reliability. The existing high voltage DC architecture is not fully developed based on the above concerns. The studies show that the power density and sizes of the power converters need to be reduced to minimize the implementation cost by adopting new converter topologies and adding new switching devices.

The high voltage DC DPS implementation has been done by designing new components such as fuses, input connectors, and sockets for power distribution. Instead, the research is required to customize existing devices for high voltage DC to look for new interconnecting and safety devices development. As a result, high voltage DC implementation will be easier in the future.

Future research may need to focus on the industry requirement to show the better option of high voltage DC and easy replacement of exiting architecture across all telecom and datacenter applications. To adopt high voltage DC, much standardization is required from all the aspects which have been listed above so that all manufactures will follow to design and develop the power supply needs of an ICT equipment.

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