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DC Energy Technologies: The Key to A Sustainable Tomorrow?

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Abstract **–** Development of semiconductor technology, the introduction of computers, smart devices and many household appliances into our lives, especially in the last 20 years, the increase in interest in renewable energy sources, the density of the population in the grid and the increase in the number of electric vehicles have shaken the throne of AC, which has been in use for more than a century. DC is making a strong comeback with these developing technologies. DC-powered digital consumer devices today account for one-fifth of total power consumption. It is projected that in the next 20 years, 50 percent of our total loads will consist of DC consumption, an increase with even more accelerating momentum than expected. In addition, the importance of energy saving, is increasing day by day. Increasing number of devices that produce and use DC, there is a great opportunity to save energy. By distributing DC power to DC devices instead of converting it to AC along the way, it is possible to avoid the significant energy losses that occur each time electricity is converted. In this paper, DC from the past to the future, technologies using DC and its advantages over AC are analyzed, considering the above-mentioned developments.

Keywords – AC versus DC, Advantages of DC, DC Energy, DC Technologies, Energy Sustainability

I. Introduction

AC (Alternating Current) has been promoted as a superior option for power distribution and transmission ever since electricity was invented. Nonetheless, one of the pioneers of electricity, Thomas Edison, advocated for the usage of DC (Direct Current). There was no way to control and magnify the DC voltage at the load at the time. As a result, there was a significant degree of loss and voltage fluctuation at various load sites during the transfer of DC power from the generator to the load. To address this issue, Westinghouse suggested using AC distribution. Thanks to the alternating current system Tesla worked on with Westinghouse to amplify and transmit voltage over long distances, the hydraulic power of Niagara Falls was discovered and the electricity generated there was transmitted to the American continent and then to the whole world [1], [2].

Although the AC and DC power transmission paradigms clashed in the early days of the electric power system, one side seems to win because of its ability to convert voltage levels. The power system might be DC today if DC technology had been able to achieve this capability. Conversely, electromagnetic transformers provided AC the ability to change the voltage level, which gave AC the advantage in the conflict between currents. It became a medium for the generation, transmission, distribution and utilization of electrical energy in the form of residential loads [3].

AC continues to be the main power source in our electrical infrastructure, despite the fact that a lot has changed since the invention of electricity. Nonetheless, the advancement of power converters and DC energy sources has brought about a renewed interest in DC [4].

DC was forced to wait until High Voltage Direct Current (HVDC) transmission technology was developed before DC was once again included in the power grid. Reactive power losses and high electrical currents caused by line charging/discharging were prevented, and HVDC transmission was successful. Then, DC appeared on the generating side of the electrical system in the shape of renewable energy sources, which are power generation sources driven by both environmental and economic considerations.

Power electronic DC/DC converters can increase the voltage produced by photovoltaic cells, which provide DC power directly in solar power systems. Through the development of DC/DC converters, DC has obtained transformers in the field of power electronics. DC/DC converters are intended to modify the voltage level and enable the DC voltage to be raised and lowered, whilst DC/AC inverters and AC/DC rectifiers perform the tasks of altering the kind of electricity.

As for wind power, many wind farms provide AC power, which they then must convert to DC because of frequency fluctuations. After that, this DC is delivered back into the AC power system at a steady frequency for conversion. On the side of power generation, DC is therefore present.

DC power is in high demand on the home front due to the enormous rise in contemporary electronic loads. In addition to the typical domestic electronic loads, the contemporary notion of Light Emitting Diode (LED) lighting generates an additional DC electrical energy consumer.

In addition to this, variable speed drives used in air conditioning (heating and cooling) result in the conversion of input AC power to DC, which is subsequently converted back to AC and supplied to the compressor motor. The total demand for DC power for contemporary residential buildings may surpass the demand for AC power if these loads are regarded as loads that also require DC power. The home distribution system is the only segment of the global electric power system in which DC power is not widely used in practical applications.

A study examined the energy savings of residential buildings with in-building power distribution systems that combine AC and DC power sources. According to the findings, energy savings from DC amount to 5% of total energy consumption in the absence of battery storage in the home and 14% in the presence of storage.

A comparison between AC and DC power distribution systems is provided by another study, which points out that the advancements in DC energy sources and power electronic converters have sparked a renewed interest in DC power distribution. For varying power electronic converter efficiencies and system voltage levels, different results are shown. For very high levels of power electronic converter efficiency and at a higher voltage level than AC, the reviewers demonstrate that DC becomes superior to AC [3].

II. Materials and Method

A. Differences between AC and DC

AC is a form of energy in which the electric current changes direction periodically, usually in the form of a sinusoidal wave. AC voltage also has positive and negative half-waves. Care must be taken in AC circuits as the current flows in both directions.

DC is an electrical form of energy with a constant voltage level, where the direction of the electric current is always the same. DC voltage has negative and positive poles. DC always flows in the same direction. Pure DC consists of a straight line.

The main differences between DC and AC:

- Direction: In DC voltage the direction of current is constant, whereas in AC voltage it is constantly changing.
- Waveform: DC voltage has a flat waveform, AC voltage has a sinusoidal waveform.
- Conductivity: DC has better conductivity because it is unidirectional, while AC may suffer conduction loss due to its frequency.
- Power Loss: DC causes less energy loss during power transfer because it minimizes the loss due to resistances in transmission lines.

B. Systems Using DC

A centralized power grid approach supported exponential growth in the AC electricity industry as it expanded and soon reached larger communities. Even if DC use is still common today, major AC system components including transformers, transmission lines and towers, switchgear and circuit breakers, light bulbs, motors, etc. were utilized extensively. This section focuses on structures that run on DC energy.

1) Energy Storage, Distributed Generation, and Microgrids

Power grids are becoming more decentralized, with growing pressure to integrate renewable and distributed energy sources. Many of these require power electronics interfaces to connect. Fuel cells and microgrids will likely play key roles in future systems. Several renewable sources, like solar panels, naturally produce DC power. Wind turbines can be optimized by combining some capacity with power electronics, often using a DC bus. Converting DC to AC and back to DC leads to efficiency losses that could be avoided. As the grid evolves, finding ways to efficiently integrate diverse energy sources and minimize unnecessary power conversions will be increasingly important. Fig. 1 shows the converter structure in renewable energy sources. Our current AC distribution system has almost no energy storage, but as DC energy becomes available, there will naturally be an increase in storage systems [5].

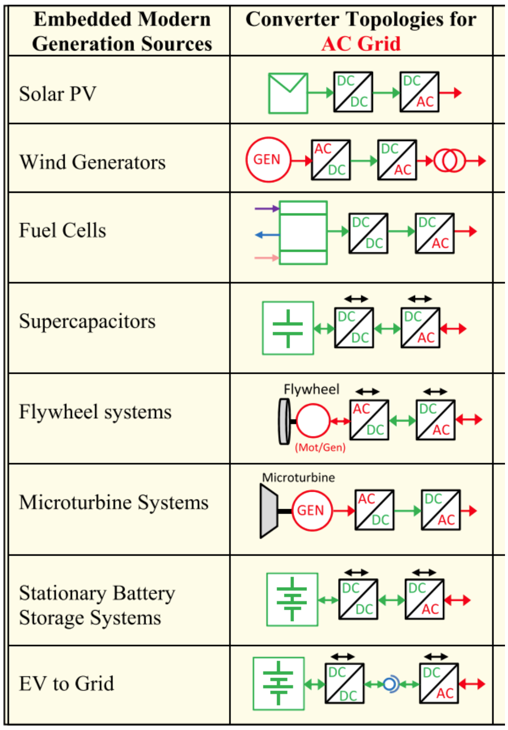

Fig. 1 Converter structure used in the connection of distributed generation plant to the AC grid

2) Electric Vehicles and Batteries

Laptops and other portable electronics are frequently used with battery chargers. This argument will also be impacted by the development of electric vehicle technology in the future. Fleets of electric vehicles not only have the potential to become substantial electricity consumers, but when these vehicles are grid-connected, their batteries can also enhance system resilience and energy storage by recharging the grid.

3) Computers, Lighting and Household Electronics

Computer servers and other electronic devices have grown to constitute substantial system loads. The way that lighting is produced is also evolving as more people pick energy-efficient substitutes for incandescent lights. A DC power supply is needed for these devices.

4) Air Conditioning (Cooling and Heating) Based on Variable Speed Drives

The AC power at the input is converted to DC and then converted back to AC and fed to the compressor motor.

5) Electrolysis Devices

DC power is required for chemical processes such as water electrolysis.

6) Ships

Currently, ships are using more and more power electronic converters. Motor control is incredibly accurate and energy-efficient when power electronic converters are used. But using rectifiers that are Diode Front Ends (DFEs) can cause harmonic distortion issues in the AC bus when converters are employed. There is no harmonic distortion when Active Front

Ends (AFEs) are utilized. But the price of Active Front Ends is steep. Harmonic distortion on the AC bus will be less of an issue if all power electronic converters share a single DC bus. We will just require half of the power electronics equipment. The future of shipboard electrical systems appears to be the utilization of a common DC bus to connect a small AC bus and high-power consumers. [6].

7) Telecommunications

A DC distribution system offers the convenience of plug-and-play functionality without the need for synchronization. This efficient system is commonly found in telecommunication networks and data centers, where it serves as a reliable power source at low voltage levels (48 Vdc). Similar to traditional DC distribution systems, these systems exhibit similar characteristics [7].

The standard measure of reliability in such a system is five nines (99.999%), whereas for comparison, the usual requirement for AC bulk power systems is three nines (99.9%). The permitted downtime for each is much different, at 5 minutes and 9 hours annually, respectively. The ability to link the core battery stack directly to the common bus explains how DC systems may attain such great reliability. This type of approach is common in both the consumer electronics and telecommunications sectors. [8].

8) Semiconductors

Power electronic converters (PECs) are devices that improve the performance of DC distribution networks. Their development was made possible by the emergence of the semiconductor industry in the 1960s. Semiconductor technology is constantly evolving, making PECs more compact, dependable, efficient, and economical. As a result, DC distribution systems are beginning to outperform AC distribution systems in terms of efficiency, dependability, cost, and size[7].

9) Data Centers

Data centers are the foundation of the online world. They host anywhere from a few dozen to thousands of servers, each with its own processors, hard disks and memory.

Large enterprises rely on facilities in various industries such as technology, consulting, finance and research for their operations. Despite their importance, these facilities are known for being energy intensive. One prominent example is the Lakeside Technology Center located in Chicago, which stands as one of the largest data centers globally. Its energy consumption surpasses that of the O'Hare International Airport, ranking it as the second-largest energy consumer in the region with over 100 megawatts consumed. On a national scale, these data centers account for a significant amount of electricity usage, totaling 14.6 terawatt-hours per year according to a report by Lawrence Berkeley National Laboratory (LBNL).

Systems with low voltage DC operating at 48 Vdc are made for use in places like data centers. It takes at least three conversion stages from the AC input to the load to produce this voltage level. Even while DC distribution systems' components are subjected to higher electrical voltages than those of typical AC systems, they are more dependable in data centers. The fact that these systems employ fewer conversion stages accounts for their increased reliability. Fig. 2 shows the measured fault currents for UPSs in NTT plants when AC and DC are applied. In DC the fault is zero [7] .

Fig. 2 Data on the reliability of power systems for 23,000 DC and 10,000 UPS systems (NTT Facilities)

10) AC and DC Distribution Grids

Regarding energy security and environmental effect, renewable energy technologies provide numerous advantages. The technical issue lies in integrating intermittent power sources with the system while maintaining power quality. The literature has put up a number of suggestions for enhancing power quality in AC grids.

When designed as DC distribution grids, they enable the connection of additional distributed generation (DG) and offer consumers a better quality of power than AC distribution grids. Consequently, the proposal of DC grids leads to a noteworthy decrease in issues related to power quality, losses and fault periods, and protection failures. The positive aspects of DC and AC distribution systems are contrasted in Table 1 [9]. LV and MV protection devices are available for both AC and DC lines, with respect to protection costs.

Although DC technology has advanced, AC technology is still more attractively priced.

DC voltages can pose increased safety risks as the lack of a natural current zero crossing point makes it more difficult to interrupt DC circuits, increasing the potential for electric shock and arc flash hazards. Appropriate safety measures, such as the use of specialized circuit breakers and grounding systems, are crucial to mitigate these risks in DC-based applications [9], [10], [11].

The absence of zero crossing current and grounding are the two main problems that arise especially for DC grid systems [5], [12].

Table 1. Advantages of DC and AC distribution system

	DC distributed power system	AC distributed power system
1	Integration of renewable energy sources	Voltage conversion
2	Reliability and uninterrupted supply	Circuit breaker protection
3	Voltage stability	Voltage stability
4	Fluorescent lighting and electronics	
5	Variable speed drives	
6	Power quality	
7	60 Hz. health concerns	
8	Lack of harmonic effect	

11) AC and DC Transmission Grids

Currently, most of the power transmission lines utilize three-phase AC technology. However, in recent years, HVDC technology has become more popular for power transmission

Table 2. Comparison between AC and DC transmission systems

	AC	DC
Transmission costs		
Investment costs		
Right of way (ROW)	High	Low
Tower	High	Simpler and cheaper
Insulators	High	Low
Conductors	High	Low
Terminal equipment	Low	High
Operating costs		
Losses	High	Low
Skin effect	Available	None
Dielectric losses	High	Low
Corona effects	High	Low
Compensation	Through reactive power	Low
Technical issues		
Control of transmitted power	Need for reactive power control	Full
Transient and dynamic stability	Bad	Good.
Fault currents	Limited	High
Power conveying capacity	Distance dependent	No distance dependency
Voltage control	Load dependent	No reactive power (Q) control
Line compensation	Available	None
Interconnection	Need for synchronization and large power oscillations	Asynchronous connection
Grounding impedance	High	Low
Reliability	Similar	Similar
Availability	Similar	Similar
Application Fields	Short distances (<50 km)	Wires that are both underwater and underground massive power transmission over large distances AC system connections made asynchronously power flow stability in an integrated power system

due to its advantages such as high-power density, controlled emergency support, no contribution to short circuit level and greater stability. Furthermore, the transmission capacity can be increased by conversion of AC lines to DC lines [9]. Table 2 shows a comparison of AC and DC networks in transmission lines.

In situations when power must be transmitted over long distances, such as through subterranean and underwater lines, DC transmission systems are more suitable over AC transmission systems. [9].

12) HVDC Transmission Lines

HVDC systems provide greater flexibility compared to AC systems, presenting notable benefits for the integration of offshore wind farms into terrestrial grid frameworks. A Voltage Source Converter (VSC) HVDC transmission system facilitates rapid and adaptable management of both active and reactive power, effectively alleviating the transmission of voltage and frequency fluctuations attributed to variations in wind energy generation. Recent technological advancements have expanded the capabilities of VSC HVDC systems, allowing for operation at elevated voltage levels and power capacities, thus rendering multi-terminal HVDC (MTDC) systems a feasible technical option [13].

Table 3 lists the HVDC grids in operation. There are some notable ones, such as Rio Madeira in Brazil, the longest HVDC installation ever built (2375 km). The Jinping-Sunan 7800 kV ultra-high voltage direct current (UHVDC) installation in China is the world's most powerful transmission line with a rated capacity of 7.2-7.6 GW. Their number is constantly increasing due to the multiple advantages that HVDC offers for power transmission over long distances (4,800 km for overhead lines and 450 km for cable systems) [9].

Fig. 3 shows the image of the 500 kV HVDC transmission line and pole. In the industry where DC grids, which are called super grids, are slowly being established, grid operators are making their plans accordingly.

Fig. 3 500 KV HVDC transmission line

When the use of HVDC is analyzed in terms of our country, there is the Black Sea HVDC transmission line between Georgia and Turkey, which has a back-to-back topology and has a transmission capacity of 350 MW. There are also 2 possible HVDC projects on the agenda. The transfer of electrical energy generated at the Akkuyu Nuclear Power Plant and an HVDC transmission line project planned to solve the electrical energy problem of Cyprus [14].

Table 3. HVDC grids in utilization

Country	Number of Lines	Country	Number of Lines
Africa	2	Austria	1
Brazil	2	Denmark-Germany	1
Canada	7	Denmark-Sweden	1
Canada-USA	2	Estonia-Finland	1
Paraguay	1	Finland-Sweden	1
USA	14	France- UK	1
China	6	Greece-Italy	1
India	8	Ireland-Scotland	1
Japan	3	Italy	2
Philippines	1	Norway	1
South Korea	1	Norway-Denmark	1
Thailand-Malaysia	1	Norway-Netherlands	1
Russia	2	Sweden	1
UK	1	Sweden-Germany	1
Australia	1	New Zealand	1
Australia-Tanzania	1	Turkey - Georgia	1

According to a study conducted by the Turkish National Committee of the World Energy Council, in addition to the above planned HVDC grids, it is recommended that new HVDC grids be built in Akkuyu-Istanbul, Black Sea and other regions shown in Fig. 4 in terms of energy supply and security.

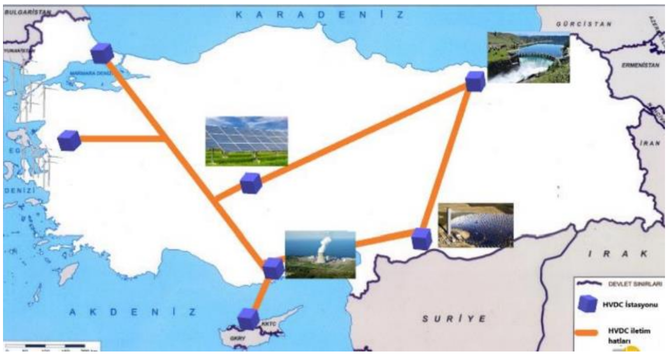

Fig. 4 HVDC grid scenario in Turkey

C. *Advantages Of Using DC*

1) Integration of Renewable Energy Sources

Integrating DC renewable energy sources into a premise DC bus is considerably simpler. They can integrate seamlessly with renewable energy sources. Doing so will save between 2.5% and 10% of the project developed each.

2) Reliability and Uninterrupted Supply

The use of DC-DC converters in renewable energy systems allows for efficient voltage regulation and power management, further increasing the efficiency and reliability of these systems.

In addition, the increasing demand for dependable information technology necessitates the implementation of uninterruptible power supplies. Each of these systems must incorporate DC battery storage capable of sustaining application operations during unforeseen AC outages.

Constant power devices, such as those found in telecommunications and industrial applications, benefit from the consistent voltage provided by DC systems because their power requirements are not affected by fluctuations in voltage. This stability ensures reliable operation and minimizes the risk of equipment damage or failure.

3) Voltage Stability

The voltage stability of DC distribution system components, especially if DC and AC distribution will coexist as they should, may exacerbate, if not alleviate, our calculations and challenges. Nevertheless, the active input stages of power supplies not only enhance the power factor but also have the capacity to inject reactive power into AC sources, thereby aiding in voltage control and ensuring voltage stability.

4) Fluorescent Lighting and Electronics

Electronic ballasts for fluorescent lights work best when powered by DC. The shift from less efficient incandescent lighting to sophisticated lighting technologies, such as compact fluorescent bulbs and eventually solid-state lighting, offers a realistic chance to deploy DC distribution systems. This approach would eliminate at least one conversion stage currently necessary in every luminaire. A parallel consideration applies to household electronic devices, all of which necessitate DC power and must convert the AC provided to them.

5) Variable Speed Drives

Both production and load scenarios benefit from variable speed drives, which facilitate the alignment of input and output power. This congruence can lead to enhanced efficiency, increased convenience, or a combination of both. Furthermore, the implementation of variable speed control is more readily attainable when utilizing a DC power source.

6) Power Quality

While power electronics are frequently perceived as contributors to inadequate power quality, power electronic converters integrated within an AC system have the capacity to comply with the majority of power quality standards and, in many cases, enhance AC power quality. Power factor correction must be incorporated into the earliest stages of DC power supplies. Furthermore, excellent design approaches and effective filtering protocols ensure that harmonic power quality remains within acceptable bounds.

It is due to the use of power electronics conversion not only to prevent poor power quality but also to improve power quality.

7) 60-Hz Health Concerns

Potential health concerns arising from human exposure to 60-Hz distribution may lead us to greater use of DC distribution systems [15].

8) Reactive Losses

A DC system has only active power. There are no heavy electrical currents and/or losses due to reactive power losses [3].

9) High Energy Transmission Capacity

DC voltages can be efficiently transmitted over long distances with minimal power loss, making them well suited for applications where power needs to be distributed over large geographical areas. The absence of the need for frequency conversion also simplifies the design and implementation of power transmission systems, reducing complexity and increasing overall efficiency. More power is transmitted with a conductor of the same cross-section.

10) Better Voltage Regulation and Control Capability

DC transmission can be better controlled.

11) Asynchronous Connection Opportunity

It enables asynchronous connection, which is not possible in AC systems [3].

III. Results

If local DC generation is accessible, such as through solar photovoltaics, it can provide energy directly to DC loads without necessitating conversion to AC. This approach yields cost savings by eliminating additional conversion losses and related equipment. The conversion from DC to AC is not always efficient, leading to energy losses ranging from 5 to 20 percent as heat.

When comparing energy savings in residential buildings utilizing a combination of AC and DC within in-building power distribution systems, findings indicate that energy savings through DC reach 5% of total energy consumption in homes without battery storage and increase to 14% in homes equipped with storage [3].

DC transmission systems are more economically advantageous than AC systems for long-distance applications, effectively addressing several drawbacks associated with AC transmission, including the necessity for synchronization, the requirement for line compensation, and the challenges posed by high ground impedance [9].

In a 2004 study on DC distribution efficiency in data centers, Lawrence Berkeley National Laboratory (LBNL) reported that DC distribution consumes 28% less power than a typical AC distribution in data centers [7].

The Electric Power Research Institute (EPRI) found in their research that in the data center space, this means that the UPS used go through AC to DC to AC conversions, the AC electricity supplied by the backup system is subsequently transformed back into DC within the servers. This conversion process produces heat, necessitating the implementation of energy-intensive cooling systems in server rooms. Notably, the energy required to operate the air conditioning is approximately twice that needed to power the servers themselves.

At NTT Facilities in Tokyo, four DC-powered data centers eliminated AC-DC converters in their battery backup systems (fed directly from DC), reducing power consumption by 15 percent compared to traditional AC configurations. Intel estimated the annual power savings for a mid-sized data center in the US at $1.2 million.

IV. DISCUSSION

DC distribution systems possess several key advantages over AC distribution. These include enhanced efficiency and reliability, simpler integration of renewable energy sources and energy storage systems, and reduced costs. Additionally, DC systems do not encounter issues related to reactive power and frequency stabilization, leading to decreased copper losses.

Many loads necessitate DC power, including consumer electronics, LED lighting systems, and devices utilizing variable speed motor drives. DC distribution systems are currently used mostly in telecommunications systems, data centers, DC buildings, and microgrids. Because of its multiple benefits, new plants are being established around the world using DC distribution. A voltage level of 380 Vdc has gained acceptance among organizations implementing DC distributed plants, due to its high efficiency, reliability, and reduced copper costs. The enhanced efficiency of DC distribution primarily results from fewer power conversion stages. Furthermore, the radial bus structure is particularly advantageous for residential buildings, as it offers lower costs and meets minimal reliability requirements [7].

V. CONCLUSION

DC energy is important for energy efficiency, reliability and special applications. However, the advantages and disadvantages of AC and DC should be evaluated depending on the requirements of the project.

The use of DC energy becomes more economical with lower energy loss, lower maintenance costs and better voltage control. Energy savings due to less power loss will enable more economical delivery of electrification services to remote areas. Connecting more renewable energy sources will reduce carbon greenhouse gases, increase the use of green energy and create employment opportunities.

An escalating number of DC consuming devices, including computers, televisions, and monitors, are being integrated into contemporary buildings. The power provided to these devices requires conversion from AC back to DC. Transitioning to a DC infrastructure would mitigate additional losses and simplify the overall power system.

Furthermore, emerging Silicon Carbide technology has the potential to improve the efficiency of power electronic converters used in DC systems. With the development of DC/DC converters, AC is more efficient compared to electromagnetic transformers.

Considering these developments in the DC field, we can say that the second war of currents has already begun, or we have entered another process where both currents can be used with hybrid structures [16].

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