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Overview of DC technology - Energy conversion

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Abstract. DC transmission and distribution systems have several advantages compared to classical AC system. This paper presents a review of DC technology, doing a special mention in HVDC. It addresses some issues like HVDC converter types, DC-DC converter topologies, DC transmission and distribution topologies, transmission cables and DC circuit breakers with the main manufacturers and commercial devices.

Key words

HVDC, LVDC, DC microgrids, DC circuit breakers, DC power converters.

1. Introduction

The electrical energy demand is increasing and a possible alternative to meet these needs is the use of distributed generation (DG) [1], allowing a better use of local energy sources for local loads. The direct current (DC) transmission and distribution (T&D) system is a way to meet with the DG sources, such as photovoltaic, fuel cells or wind generators [2].

The beginning of electrical energy transmission was using DC transmission systems. It was generated by dynamos or by Volta's batteries to supply energy to arc-lighting and motors. In 1882, Thomas Alva Edison installed his low voltage DC (LVDC) system in the famous Pearl Street Station, in New York, U.S.A., to supply energy to the incandescent bulbs that he invented in 1879 [3]. In 1891, the "war of currents", starring by T.A. Edison with John Pierpont supporting DC and George Westinghouse with Nikola Tesla supporting alternating current (AC) systems, was finished concluding AC system as the winner due to less losses and less costs in transmission. This was due to an easy way to step up voltage allowing less current transmission and the use of less copper, making the system cheaper (AC costs: $399,000 vs. DC costs: $554,000) [3]–[5]. In this context, the DC system was only used in special applications.

On the other hand, power semiconductor development with high voltage and high current rates allowed the development of power converters to use in high power systems, such as high voltage DC (HVDC) [6]. These converters can control the power flow and increase the stability of transmission, and in current distribution systems are used to raise quality of the grid [7], reactive power compensation, active filters[8], etc. Distributed generators are connected to grid with power converters and are widely used in other important areas e.g.: ship propulsion and train and electric vehicle traction due to the controllability of power and breaking energy recovery possibility they offer.

Table I. – Advantages and disadvantages of DC systems

Advantages	Disadvantages
Less line loss	Expensive converter station
No skin effect	Harmonic generation
Less expensive overhead lines and cables	Difficult design of DC circuit breaker
Higher power per conductor per circuit	Difficulty of voltage transformation
Line power tie easily controlled	Reactive power compen-sation needed in converters
Only real power transmission	
Less corona loss and radio interference	
Incorporation of RES	
Higher efficiency	
Variable-speed drives (DC-bus)	

Nowadays, DC power generation is increasing due to renewable energy sources (RES) such as solar energy and wind farms. Also, DC is showing its presence in consumer load side with modern appliances such as personal computers, laptops, cell phones, LED lighting, data centres, etc. In recent times, this area has witnessed a number of research efforts and DC distribution has been compared with the AC counterpart [7]–[10].

In this article are studied the different topologies on transmission and distribution in a DC system comparing with AC T&D system, types of power converters, types of cables in DC and the problematic of DC breakers in high voltage systems, showing suppliers and commercial devices.

2. DC systems

The DC transmission system has become a major factor in the planning of the power transmission because of the development of rectifiers and inverters at high voltages and currents. These developments allow the generation in AC to convert in DC for transmission, and then back to AC for end-users. This is used in point to point HVDC systems. Also the DC system is proved to be superior to AC for low and medium voltage distribution [12]–[16], and a DC grid allows an easy integration of RES, but the DC breaker

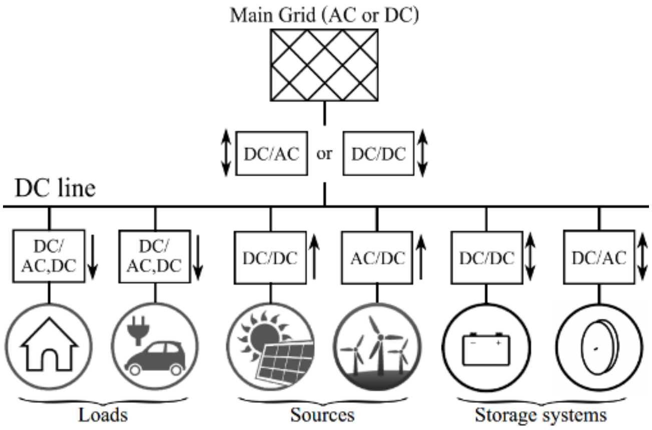

Fig. 1. DC grid

Table II
WORLDWIDE DC SYSTEM PROJECTS

Grid/System	Location	AC or DC	Main devices
CESI RICERCA DER (test)	Italy	DC	PV, diesel generator
Eletrobas	Brasil	AC and DC	PV
Ford (test)	USA	DC	Rectifier for DC loads
Green Data Center	Switzerland	DC	Rectifier for DC loads
Intel (test)	USA	DC	Rectifier for DC loads
NERSA	South Africa	AC and DC	PV
NTT Sendai Project	Japan	AC and DC	PV, MCFC, GE
Xiamen University	China	DC	PV

PV (photovoltaic), MCFC (molten carbonate fuel cell), GE (gas engine)

technology is not enough developed to use in a big scale nowadays [17].

In Figure 1 is shown a generalised DC grid system with loads, RES and storage systems. The advantages and disadvantages of using these types of systems are shown in Table I, and in Table II some of DC grid projects are exposed.

3. DC applications

Low power DC loads are widely spread in the houses, such as PCs, portable electronic devices, LED light, etc. And some low power generators, such as PV, are commonly placed above the houses. So low power DC devices are very common.

Following in a higher power level, in DC distribution field, DG could be present and it may allow a lesser number of power conversion steps in a building for DC loads and local generation comparing with the conventional AC system [2], [13], [15], [16], [18]. But further development is required in order to properly connect these new systems into the existing power system which was not designed to support active power generation at distribution level [19]. To meet RES and the grid together, a microgrid is a suitable interface [1]. The most microgrids around the world are with AC system [20], but DC microgrids are being studied and compared [21]–[25]. For example, in a photovoltaic based DC microgrid, 15% of the energy is saved comparing with AC system [11]. Hybrid microgrids are also possible [19], [26], helping both AC and DC system each other making flexible and independent control and avoiding overloads in the grid. The integration of the electric vehicle (EV) may change the grids management, due to battery storage system vehicles.

And finally, train traction, ship propulsion and HVDC are the main high power DC applications [6], [9], [10]. The HVDC transmission system is an economically suitable

Table III. – Types of DC cables

	Main characteristic	Max voltage	Other
Mass-Impregnated Cable	Oil and resin impregnated paper for insulation.	600kV	Unlimited length. Most used in HVDC. Up to 2000MW.
Oil-Filled Cable	Low viscosity oil impregnated paper for insulation. Duct to permit oil flow.	600kV	100km length limit.
XLPE	Cross-linked polyethylene as insulator.	500kV	Unsuitable with LCC. Up to 1000MW.
Lapped Thin Film Insulation	Lapped non impregnated thin PP film as insulator.	250kV	Up to 250MW capacity.
HTS Cable	Superconductor. Duct to permit liquid nitrogen flow.	275kV	Short distances (100m to 6km).

Table IV. – HVDC cable main suppliers

Manufacturer	Main location	Manufacturer	Main location
ABB	Sweeden	Brugg Cables	Switzerland
Nexans	Norway	4s Products	USA
Prysmian	Italy	General Cable	USA
Viscas	Japan	Ericsson	Sweeden
Borealis	Denmark	Siemens	Germany
KEPCO	Korea	NKT cables	Denmark
AMSC	USA	Furukawa	Japan
Europacable	Brussels	Cabelte	Portugal
LS Cable & System	Korea	BPP-Tech	UK

alternative [27] to classical HVAC system. The break-even distance for an economical advantage between AC and DC system is 50 km in cables and 800 km in overhead lines [28]. And it also solves line length limit of HVAC due to voltage stability [14], [29] and can be more efficient in offshore power applications, resource diversification and power line congestion relief [29].

A. *HVDC cables*

Underground cables for HVDC technology have been in commercial use since the 1950's. Nowadays, HVDC underground cables can carry medium and high power (100 MW up to 1 GW) over distances above 50 km, and has mainly been used in submarine applications. These cables are beginning to be used also for on-shore transmission projects. As higher power loads need to be transported over long distances across land, more and more thinking goes into creating HVDC a long distance overlay net. HVDC underground cables can safely transport high power loads over long distances with minimal losses. In addition to this transport efficiency, only a limited number of cables are required, hence allowing narrow trenches. HVDC underground cables are compatible with HVDC overhead technology and can be combined in sensitive areas. In Table III are listed the types of DC cables with main characteristics and in Table IV the main suppliers.

B. *DC power converters*

As power converters are transformers for a DC system, they are used in a widespread applications. In a DC distribution system are used to control only voltage for stability, but if in the system are some converters, this control is not a so easy tasks. These converters have been studied for ship propulsion [9], [30], International Space Station, [31], [32],

Table V. – HVDC LCC and HVDC VSC comparison

	HVDC LCC	HVDC VSC
Maturity of technology	Mature	Developing
Valves	Thyristor	IGBT
Commutation failure	Can occur	Does not occur
Minimum DC power	5% to 10% of rated power	No minimum value
Reactive power exchange with AC system	50% of active power transmitted	Independent control of active and reactive power
Reactive compensation	Required	Not required
AC harmonic filters	Switchable filters required	Less filtering required, not switchable
Converter transformers	Special design required	Conventional transformer can be used
Reversal of power flow	DC voltage polarity reversal required	Controllable in both directions, no reversal of DC voltage polarity required
Converter station foot-print (pu)	1	0.4
Converter losses (per converter end)	0.5% to 1% of transmitted power	1% to 2% of transmitted power
DC voltage	Up to 800kV available	Up to 350kV available
Power limit	Up to 8GW available	Up to 1GW available
Needed minimum transmitted power	5 to 10% of rated power	Can be zero

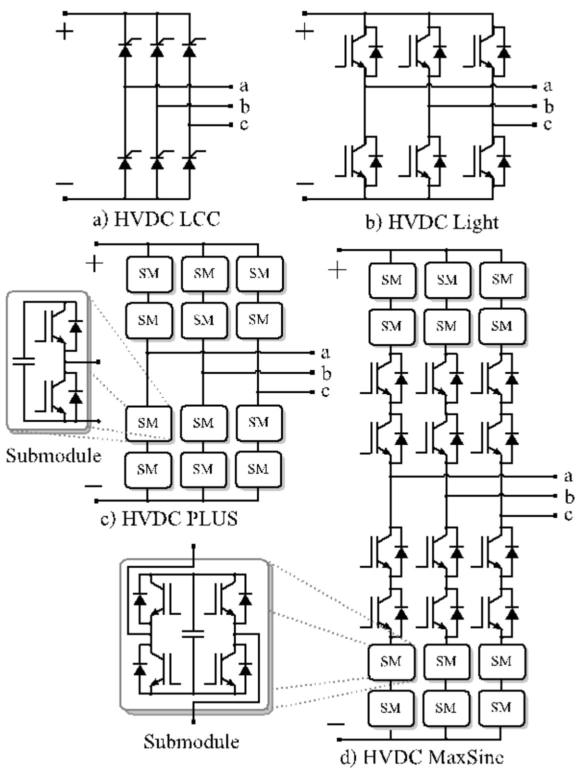

Fig. 2. HVDC converter topologies

electric vehicles, [33], [34], etc. Power converters are also used in transmission of HVDC technology, and there are two types: Line Commutated Converter (LCC) and Voltage Source Converter (VSC). These are used to convert between AC and DC. Both technologies are compared in Table V.

Converters for HVDC systems have been mainly built by using high voltage and high current rated power semiconductors, but VSC system allows other topologies due to the devices controls and these converters are not limited only for transmission: most HVDC Light installations (Figure 2b) built until 2012 use pulse width modulation for in an ultra-high-voltage motor drive, but the most recent installations, along with HVDC PLUS (Power Link Universal System) (Figure 2c) and HVDC MaxSine (Figure 2d), are based on variants of a converter called a modular multilevel converter (MMC) [35]–[37]. Main manufacturers of HVDC converters are ABB, Siemens, Alstom, Areva and TMEIC GE.

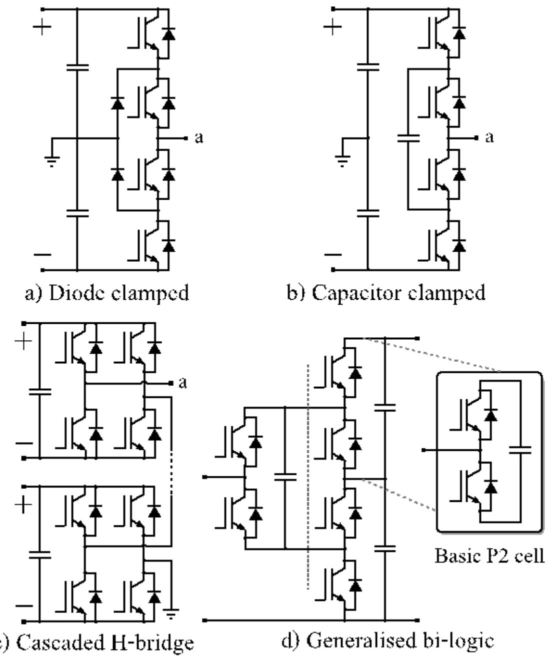

Fig. 3. Classical multilevel converter topologies

Multilevel inverters can be used to interface lower voltage DC energy storage or source devices with the grid. They consist of power modules that are stacked together to produce required high utility level voltages. One of the most versatile topologies is the cascade multilevel inverter (Figure 3c). In fact, multilevel converter technology started with the introduction of the multilevel stepped waveform concept with a series-connected H-bridge, which is also known as cascaded H-bridge converter [38]. This topology eliminates the need for single high-voltage power switches and diodes that do not exist in the utility voltage levels. They also eliminate the need for connecting lower voltage power devices and switches in series and parallel, reducing the problems and extra circuitry associated with current and voltage sharing. These converters have the advantage that they allow the harmonic filtering equipment to be reduced or eliminated altogether [39]–[41]. Classical multilevel converters are shown in Figure 3.

DC distribution voltage levels are lower than in transmission, so the devices of the power converters do not need to be so high rated in voltage or current. DC generation (photovoltaic, fuel cells) and loads (data centres, portable devices) are increasing in number, so a DC distribution system may be useful because it could avoid AC-DC conversions, increasing the whole system's efficiency [22]. So to meet voltage levels in DC systems, DC-DC converters have to be used. Mainly they are classified as isolated and non-isolated converters.

The non-isolated DC-DC converters (Figure 4) type is generally used where the voltage needs to be stepped up or down by a relatively small ratio (less than 4:1 [42]) and

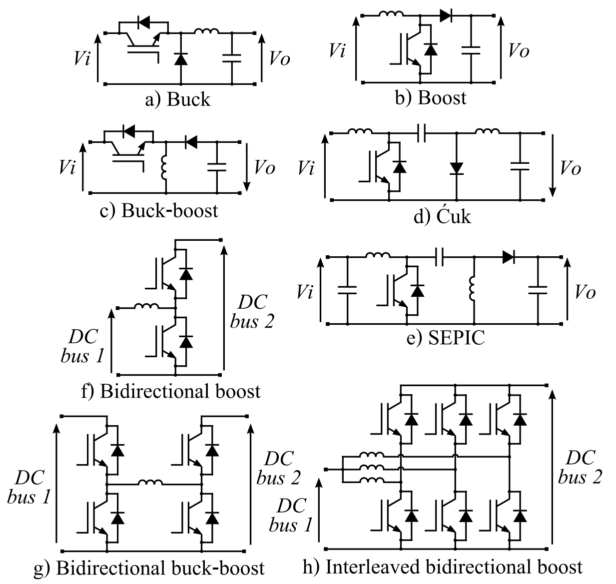

Fig. 4. Non-isolated DC-DC converters

Table VI. – High-frequency power transformer core materials: 1-Amorphous, 2-Nanocrystalline, 3-Silicon steel

Group	Series	Sat. flux (T)	Sp. losses (kW/kg)	Manufacturer
1	Microlite (2605SA1)	1.56	1.5	Metglass
	Powerlite (2605SA1)	1.56	0.6	Metglass
	Namglass	1.59	0.34	Magmet
	Vitrovac (6030F)	0.82	0.19	VAC
2	Finemet (FT-3M)	1.23	0.14	Hitachi
	Vitroperm (500F)	1.2	0.07	VAC
	Nanoperm	1.2	0.04	Magnetec
	Namglass 4	1.23	0.04	Magmet
3	Arnon 7 (3-6% Si, Fe)	1.53	1.6	Arnold
	Arnon 5 (3-6% Si, Fe)	1.48	1.06	Arnold

when there is no problem with the output and input having no dielectric isolation. These types of converters are simpler than isolated ones and can achieve better efficiency. There are five main types of converters in this non-isolated group, usually called the buck, boost, buck-boost, Ćuk and SEPIC (single ended primary inductor converter) (Figures 4a-4g). These type of converters are mainly used in low power, but to manage higher powers a multiphase current interleaving topology can be used (Figure 4h) [43].

The isolation of DC-DC converters is done by a transformer, so they need a variation of current flow to make them work and this is done by switching devices. These type of converters use a DC source to convert in AC to attack the transformer, followed by the rectifying step to deliver power in DC. There are many types of converters in this group. The main structures of converting DC to AC are shown in Figures 5a-5c, and to rectify the power from the transformer the structures are Figures 5d-5f. Other classical isolated converters are flyback (Figure 5g) and forward (Figure 5g). Due to the control of the AC signal generation, high frequency signals are generated to attack a high frequency transformers, because high frequency transformers are lighter, smaller and more efficient. The Figure 5i shows a dual active three-phase bridge (DAB) as an example of polyphasic converter for higher power conversion.

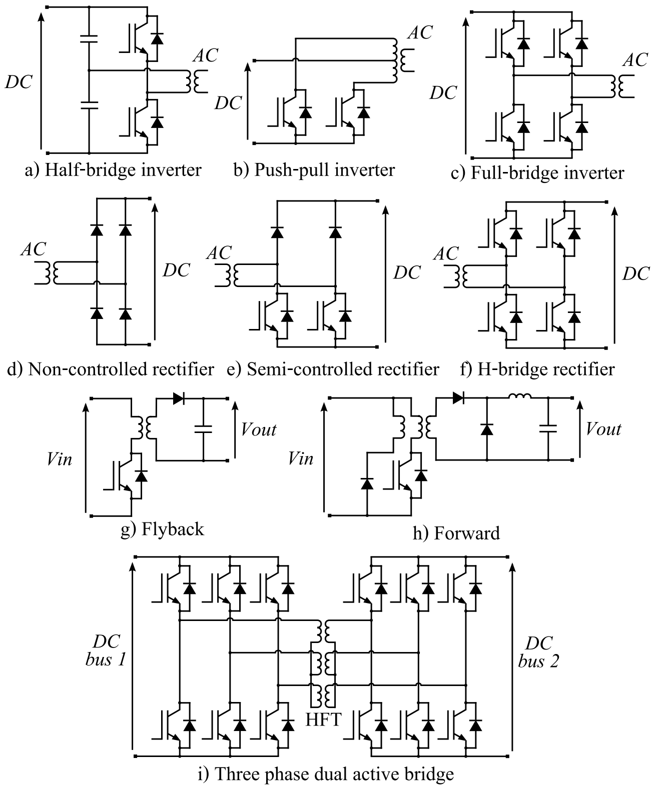

Fig. 5. Isolated DC-DC converters

High frequency transformers use magnetically soft cores (Table VI). These cores are called soft because they have low coercitivity, so they permit high variations of magnetic flux with low losses [44]–[47]. This high variation of magnetic flux is translated to a high modulation frequency with low losses, and so, a smaller volume and weight comparing to conventional 50=60 Hz transformers.

C. *DC transmission topologies*

The development of the earliest power converters, which allowed conversions between AC and DC, increased the interest of DC transmission. So some DC transmission topologies were developed [17], [29], [48]–[52], and in Figure 6 are resumed the architectures of these transmission and distribution systems.

- **Monopolar system:** one conductor with ground or metallic return path (Figures 6a and 6b)
- **Bipolar system:** two conductors with opposite polarization using a converter for each conductor. A neutral metallic return can be used, allowing a conversion of AC three phase grid into a bipolar DC system (Figures 6c and 6d)
- **Homopolar system:** two conductors with same polarization, returning through ground or a metallic path (Figure 6e). Less costs in isolation than bipolar

  Tripolar system: same as a bipolar system, but adding a bidirectional converter for the third conductor (Figure 6f). It changes the neutral conductor by an active conductor. It presents higher transmission capacity than bipolar, so it's a more efficient system to convert AC grid system to DC system. There are no tripole systems in operation yet
- **Back-to-back system:** to connect two AC systems asynchronously by a DC link. Also allows connection between different frequency AC systems (Figure 6g)
- **Multi-terminal system:** three or more converters in series, parallel or mixed (Figure 6f). Used in wind farms

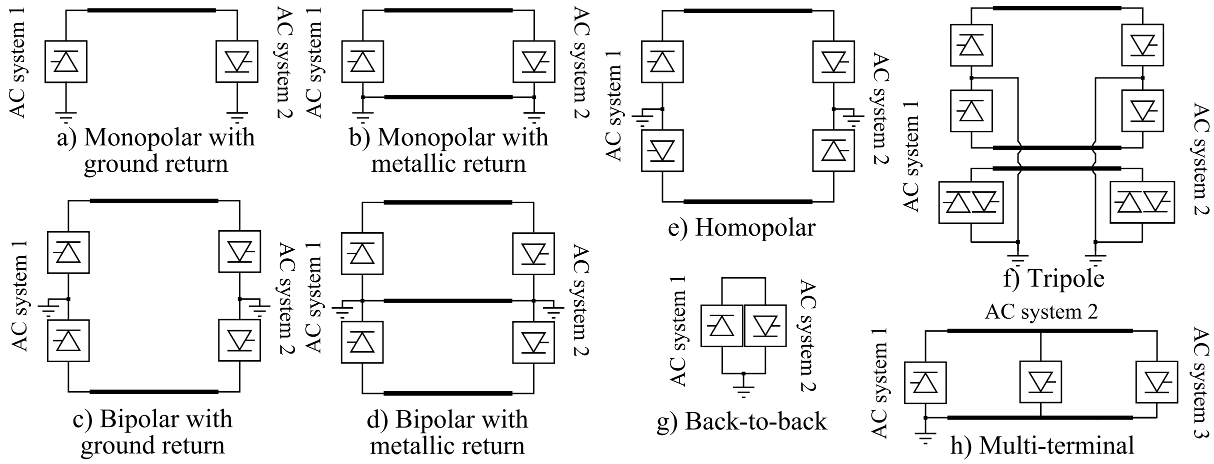

Fig. 6. DC transmission and distribution system architectures

Table VII. – Types of DC circuit breakers depending on used technology

	MRTB	Solid State Switch CB	Fast Switch	Solid State CB without auxiliary circuit
Arc/Power electronics	Arc chamber	Arc chamber+PE	PE	PE
Development needed	None	Synchronous switch, capacitor load circuit	New concept	New concept
Smallest break time	27 ms to 41 ms	27 ms	2 ms	0.1 ms
On-state losses	<1 mΩ	<1 mΩ	<100 mΩ	<1 Ω
Max breaking current	4 kA	5 kA	10 kA	10 kA
Complexity	Low	Medium	High	High

D. DC circuit breakers

The protection from damage caused by overload or short-circuit is done by circuit breakers (CB), but the main difference between requirements on AC and DC breakers is that in DC system is no natural current zero crossing, which is the main reason of the difficulty of the design of direct current CBs [53].

These circuit breakers are classified by used technology in Table VII: metallic return transfer breaker (MRTB), solid state switch circuit breaker, fast switch and solid state circuit breaker without auxiliary circuit. Main DC circuit breaker suppliers are shown in Table VIII.

Recently, ABB has developed a HVDC circuit breaker. It combines very fast mechanics with power electronics, and will be capable of interrupting power flows equivalent to the output of a large power station within 5 ms [54].

Table VIII presents the main DC circuit breaker manufacturers and the voltage and current rates of commercial breakers.

4. Conclusions

DC technology is mature in transmission, and R&D continues for different types of devices as converters and cables. But DC distribution and DC microgrids, are not so integrated in the system as HVDC transmission does. One of the most important reasons is that the protection with circuit breakers is not mature enough to protect a DC system, so for the most of DC application nowadays are locally rectified from the AC grid. The development of DC circuit breakers could be the key to continue with DC distribution and microgrid development and further installations. Meanwhile, more efficient converter topologies and control strategies are coming across in all power levels, obtaining more efficiently energy from renewable energy sources.

5. Acknowledgments

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