

Review

# Electric Power Network Interconnection: A Review on Current Status, Future Prospects and Research Direction

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**Abstract:** An interconnection of electric power networks enables decarbonization of the electricity system by harnessing and sharing large amounts of renewable energy. The highest potential renewable energy areas are often far from load centers, integrated through long-distance transmission interconnections. The transmission interconnection mitigates the variability of renewable energy sources by importing and exporting electricity between neighbouring regions. This paper presents an overview of regional and global energy consumption trends by use of fuel. A large power grid interconnection, including renewable energy and its integration into the utility grid, and globally existing large power grid interconnections are also presented. The technologies used for power grid interconnections include HVAC, HVDC (including LCC, VSC comprising of MMC-VSC, HVDC light), VFT, and newly proposed FASAL are discussed with their potential projects. Future trends of grid interconnection, including clean energy initiatives and developments, UHV AC and DC transmission systems, and smart grid developments, are presented in detail. A review of regional and global initiatives in the context of a sustainable future by implementing electric energy interconnections is presented. It presents the associated challenges and benefits of globally interconnected power grids and intercontinental interconnectors. Finally, in this paper, research directions in clean and sustainable energy, smart grid, UHV transmission systems that facilitate the global future grid interconnection goal are addressed.

**Keywords:** energy interconnection; renewable energy; clean energy; power transmission; interconnection technologies; HVDC; MMC-VSC; HVDC light; VFT; FASAL



**Citation:** Imdadullah; Alamri, B.; Hossain, M.A.; Asghar, M.S.J. Electric Power Network Interconnection: A Review on Current Status, Future Prospects and Research Direction. *Electronics* **2021**, *10*, 2179. <https://doi.org/10.3390/electronics10172179>

Academic Editor: Bor-Ren Lin

Received: 30 June 2021

Accepted: 30 August 2021

Published: 6 September 2021

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## 1. Introduction

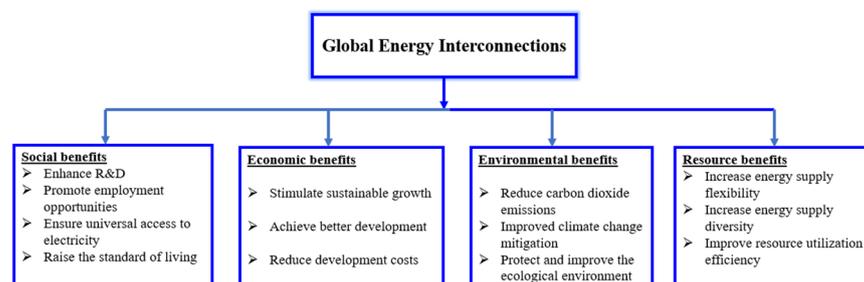
Electric power system networks are widely interconnected to deliver power to the loads economically and reliably. The improvement in reliability of the electrical power system network enhances the quality of service and reduces the power supply interruptions which include load-shedding and blackout. National economies and power transmission development mainly depend on the power grid infrastructure. In general, electrical energy generation and utilization (load centers) are far away from each other. Power grid interconnection and control of power flow are necessary to supply power to the load centers. Researches show the vast potential of renewable energy to generate electricity for the decarbonization of electricity systems [1,2]. However, the extent of reliability and practical implementation of such a system is a significant challenge due to the inherently variable nature in the development of RES based technologies such as wind turbines and solar PV systems [3–5]. A reasonable approach to tackle the variability challenge is the interconnection of adjacent power systems and export or import electricity during high

and low power generation, respectively [6]. The idea of global power grid interconnections was originated in the first half of the 20th century by Buckminster. It was considered the potential benefits of a global grid with renewable energy as a backbone. However, it was dismissed due to the limited maximum distances of power transmission (around 350 m) [7]. Later, the concept of the global grid was acknowledged by the United Nations (UN) in 1969 at the World Game Seminar [8].

Recently, at the 2015 UN sustainable development summit, Chinese president Xi Jinping said that China will take the lead on discussions about establishing a “global energy internet” to fulfill the global power demand with green and clean energy alternatives. Currently, UN secretary general considered the advantages of a global grid to be in line with UN’s commitment for sustainable development in the 2030 agenda. However, there are some arguments supporting the idea of a global grid, implementation of intercontinental interconnectors to-date have been limited to short distance subsea AC links such as the Egypt-Jordan and Morocco-Spain interconnectors, and land-based interconnectors with limited flow between central Asia and eastern Europe [8].

The detailed benefits of energy interconnection include social, economic, resource and environmental benefits as depicted in Figure 1. For this reason, many countries are increasing the large power grids and cross-border power grid interconnection. North America, Russia-Baltic Sea and Europe have large interconnected power grids [9,10]. Cross-border interconnected power grids are also developing in Gulf countries, Southern Africa, South America and other regions in the world [11,12]. Moreover, the technological benefits of large scale power network interconnections are [13]:

- Balancing mismatches in supply and demand: Connecting summer peak-demand regions with winter peak-demand regions. For example, regions of different time zones, getting large benefits by balancing seasonal and daily peak-load variability.
- Incorporating intermittent renewable power: Transmission interconnection is a tool to facilitate incorporation of variable renewable resources. The evolution of high and ultra-high voltage transmission technology opens up entirely new transportation corridors and interconnection possibilities.
- Accessing remote energy resources: Electricity utilization is concentrated in major cities having large energy demand. This large demand will not be fulfilled by the local energy resources. Even renewable energy sources such as wind, hydro, and solar are highly location-specific and these sites are often located in remote regions far away from the demand centres.



**Figure 1.** Benefits of global energy interconnection [14].

The remaining paper is organized as follows. In Section 2, a global energy consumption overview is presented. In Section 3, large power grid interconnections, including renewable energy and its integration, and global power grid interconnections are described in detail. In Section 4, the current trends in power grid interconnection technologies including HVDC (LCC and VSC-MMC, VSC-HVDC light), high-frequency AC link, VFT and FASAL are discussed in detail. Future prospects of intercontinental and international grid interconnections are presented in Section 5. In Section 6, Research directions in grid interconnections, including clean and sustainable energy, smart grid developments and UHV transmission, are presented. Finally, the paper is concluded in Section 7.

## 2. Global Energy Consumption Overview

Due to industrialization, population growth, and developments in developing and developed countries, global energy demand increases rapidly. The primary energy consumption of the world has increased from 3460 million tonnes oil equivalent (mtoe) to 13,632 mtoe in a span of 53 years (from 1965 to 2018). This growth has seen an increase of 2.9% in 2018, which is approximately double the 10 year average [15]. Figure 2 depicts global energy consumption in the last 50 years [16]. Energy evolution has gone through firewood to coal and further to oil and gas. Nowadays, more than 80% of the global energy utilization depends mainly on natural gas, coal, oil and other fossil energy resources. The global energy consumption trends and projection based upon the fuel share is depicted in Figure 3. The global power generation based on fuel mix is shifting with renewables gaining share at the expense of coal, nuclear and hydro. The percentage of natural gas share is almost constant at about 20%. In 2018, 66% of new electricity generation capacity was contributed by renewable energy sources. Their stake in the global power market is expected to be approximately 30% in the year 2040. On the other hand, a significant decline in coal consumption demonstrates a confluence with the renewables before 2040 [17]. Figure 4 depicts the global primary energy utilization structure by region in 2018. It is evident from Figure 4 that the primary fuel for power generation in North America is oil and natural gas followed by coal. In South and Central America, oil and hydro is the dominant source of energy while natural gas consumption is at third position. In Europe, oil and natural gas have a large share followed by coal. However, nuclear and renewables also have a significant role. In the Commonwealth of Independent States (CIS) and the Middle East, natural gas is dominant and accounts for more than half of the total energy consumption in both regions. In Africa, oil, natural gas and coal account for approximately 90% of the total energy consumption. In the Asia Pacific region, coal is the dominant fuel followed by oil.

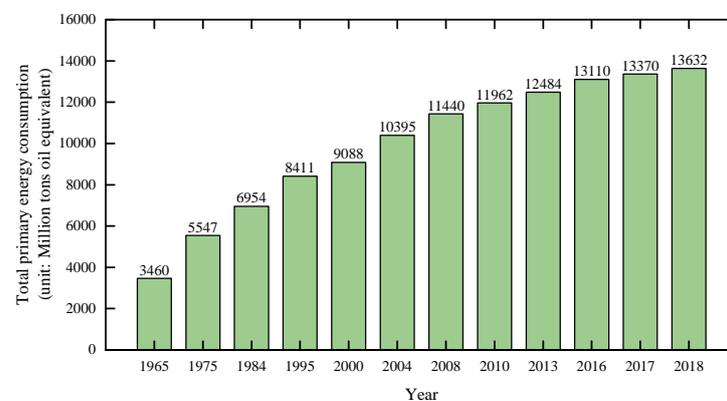


Figure 2. The global energy consumption trends in the past years (1965–2018) [15].

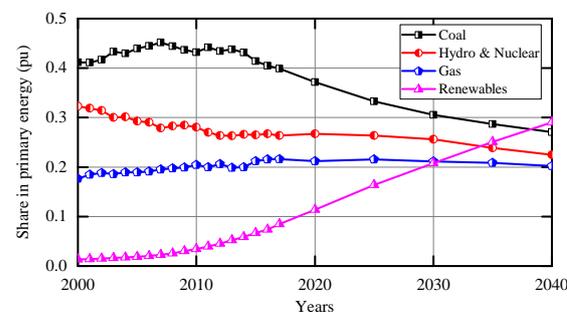
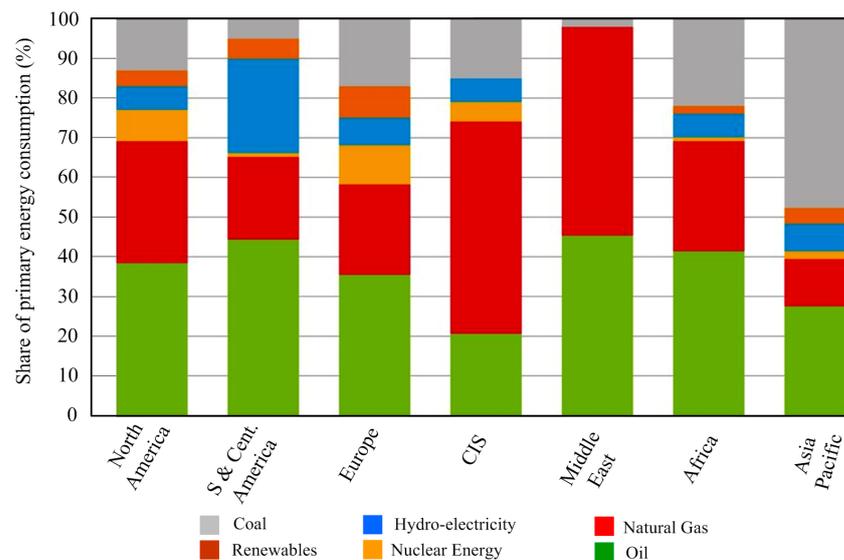


Figure 3. The global energy consumption trends and projection based on fuel share [17].



**Figure 4.** Region-wise primary energy consumption by fuel around the globe [15].

### 3. Large Power Grid Interconnections

The increase in voltage levels in the power grid and the enhancement in scale such as the transmission distance, load level, installed capacity and the allocation efficiency of power grids have been significantly improved. After the discovery of electricity, the global power grids have advanced from isolated, small and urban to large-scale interconnected power system networks. The second generation of power grids are specified by large-scale interconnection and development of the zoned and layered power grids. On this behalf, the power grids of third generation will form the power grid mode of local grids, organically combining backbone grids and microgrids [18,19].

#### 3.1. Renewable Energy and Its Integration

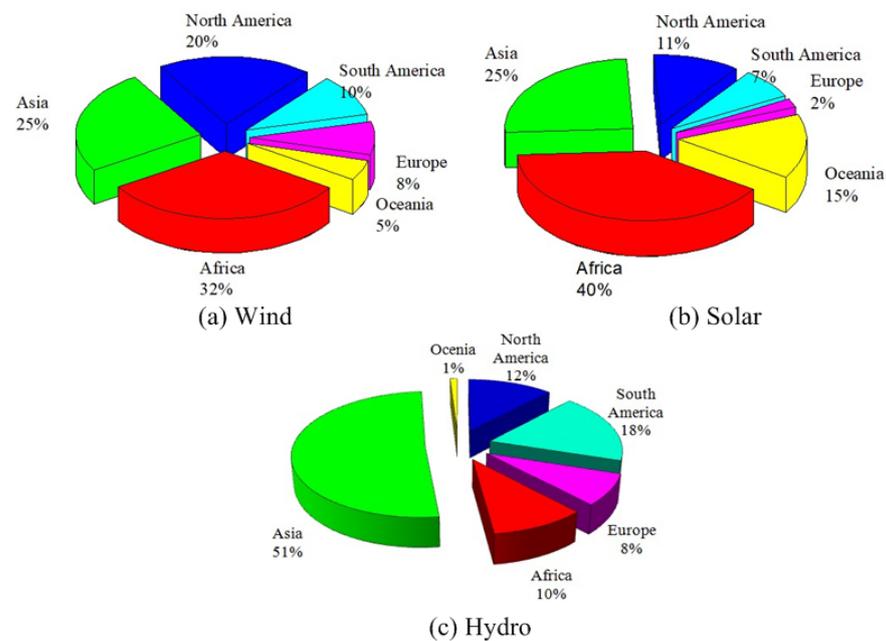
The fast development of clean energy systems leads to immediate requirements of large power grids interconnection. Rapidly developing clean energy such as wind, solar and hydro energy systems are significant part of current world energy advancement and also an excellent alternative to carbon emissions mitigation and the establishment of sustainable energy supply [20].

The total world's theoretical reserves of wind power potential is about  $2000 \times 10^3$  TWh/year. The wind energy resources are affected by the topography, atmospheric circulation, water, land and other factors and it is unevenly distributed around the globe. Figure 5a shows the global distribution of wind energy resources [21].

The total annual global solar radiation is equal to about 116 trillion tons of standard coal. The total annual global solar radiation is higher than the global fossil fuel reserves. The global solar energy resources distributions is shown in Figure 5b [21].

The gross theoretical potential of hydropower around the globe is about 41,914 TWh/year. Technically exploitable hydropower potential is about 15,778 TWh/year which is about 38% of the gross theoretical potential of the world [22]. The exploitable hydropower resources in different regions around the globe are shown in Figure 5c [22].

The power generated by the wind and the solar are random and intermittent. Due to these features of new and clean energy, the interconnection of large power grids is essential [23]. Moreover, it is necessary to control the proportion of wind and solar power in the total installed capacity. For this purpose interconnection of both high power grids as well as low power micro and smart grids are required. Due to the evolution of smart grids of different capacities, interconnection with high power grids are required at all power level.



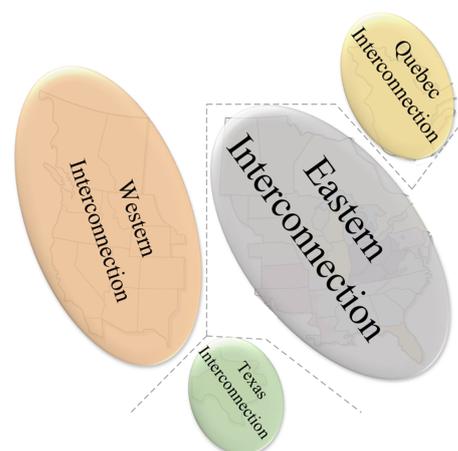
**Figure 5.** The worldwide distribution of renewable energy sources. (a) Wind energy. (b) Solar energy. (c) Hydro energy [21].

### 3.2. Global Large Power Interconnections

Interconnection of the synchronous power grids is gradually expanding in most parts of the world. In this section, different existing and future power grid interconnections around the globe are presented in detail.

#### 3.2.1. North America

In eastern North America, the total capacity of the synchronous power grids is more than 760 GW installed over  $5.2 \times 10^6$  km<sup>2</sup> of area. These synchronous power grids are the largest installed capacity globally, having 500 kV as the backbone network and consisting of few 750 kV power networks. A geographical map of North America interconnected power system networks is depicted in Figure 6. In North America, four synchronous power grids are interconnected asynchronously across the United States, Canada and Mexico, including the eastern and western, together with the Texas and Quebec interconnections [24]. The Eastern interconnection is interconnected to the Western interconnection through six HVDC lines, to the Texas interconnection through two HVDC lines, to the Quebec interconnection through four HVDC lines, and one variable frequency transformer (VFT).



**Figure 6.** Electric power grid interconnections in North America [25].

### 3.2.2. Latin America

Latin America has also taken a move in the integration of electricity markets that leads to economic liberalization, enhances energy security, and reduces generation costs. Latin America has created three main regions for the grid interconnection, which include the Southern Cone (MERCOSUR, excluding Venezuela), the Andean Community (CAN), and Central America (SIEPAC) [26]. The interconnection between Colombia and Panama is expected to start soon having 450 kV and power transmission capacity of 600 MW [27]. Moreover, Colombia and Ecuador share four transmission lines with a maximum export capacity of 535 MW [28]. Many more cross-border interconnections are expected in these regions, for example, Colombia plans a new MTDC interconnection project (Guajira-Cerrromatoso-Panama) in order to export energy [29].

### 3.2.3. Africa

An initiative called Africa Clean Energy Corridor (ACEC) meant for regional cooperation for promoting regional electricity trade and renewable energy (RE) deployment. It harnesses great RE potential existing in East and Southern African sub-regions stretching from Egypt to South Africa. The ACEC initiative, taken up by the International Renewable Energy Agency (IRENA) and recognized by Ministers from the Eastern Africa Power Pool (EAPP) countries and the Southern African Power Pool (SAPP) at the fourth IRENA Assembly in 2014. The initiative enhanced deployment in cross-border interconnection and trade of renewable power in a continuous network from Egypt to South Africa. In Eastern and Southern Africa, 80% of electricity is generated from fossil fuels (natural gas, oil, or coal). It is expected that by 2030, 50% of electricity in Eastern and Southern Africa could come from clean and cost-effective renewables [30,31]. It is proposed that a submarine cable in Africa include the East Africa–West Africa Channel and Africa–European Interconnected Channel. The total length is 4000 km, while the total capacity is 50 GW [32].

### 3.2.4. Europe

In Western Europe, the installed capacity of synchronous power grids attains 690 GW expanded over nearly  $4.5 \times 10^6$  km<sup>2</sup> of area. To fulfill the mission of clean energy development, European countries try to establish a “Europe-Mediterranean-Middle East” super-power grid by 2050. This will interconnect renewable energy power generation bases in the Middle East, North Africa, and areas along the North Sea coast in Europe [33]. A conceptual plan of a European supergrid linking renewable energy projects is shown in Figure 7 [21].

### 3.2.5. Northeast Asia

The countries of Northeast Asia (NEA) were previously poorly connected, have started to explore the possibility of constructing interstate electric ties (ISET) and interstate grids (ISG). Northeast Asia power grid consists of synchronized power grids in each country. Some of the existing interstate transmissions in the NEA region are presented in Table 1 [34,35].

### 3.2.6. Indian Power Grids

In India the total electricity generation (including grid connected renewables) has been increased from 1110.458 BU during 2014–2015 to 1376.095 BU during 2018–2019. Among the above generation enhancement, renewables increased by 24.47% while the overall growth rate was 5.19% during the year 2018–2019. The natural resources used for electricity generation are dispersed unevenly and concerted in certain regions. To facilitate the delivery of power from the generating stations to the load centres, transmission networks and grid interconnections are essential. To consider this, a vast network of transmission lines and grid interconnections has been developed over the years. The Indian power grids are developed on a regional basis by dividing the country into five regions such as Northern, Southern, Western, Eastern and North-Eastern regions as shown in Figure 8. Moreover, these regional

grids are interconnected via HVAC and HVDC links. Some of the inter-regional grid interconnection projects operating successfully are demonstrated in Figure 8 [36]. Two UHV DC transmission projects having voltage level of  $\pm 800$  kV are incorporated in “Twelfth 5-year Plan” for grid development. One of the projects, the Biswanath Chariali–Agra, the world’s first  $\pm 800$  kV, 6000 MW, 1775 km, UHVDC multiterminal has been commissioned in September 2015 [37]. Another HVDC link, Champa-Kurukshetra,  $\pm 800$  kV, 3000 MW, bipole has been commissioned in March 2017. This is 1287 km long distance, inter-regional between WR-NR HVDC Interconnector [38]. Moreover, India has initiated working on 1200 kV UHV AC transmission system. A national test station is developed in Bina, Madhya Pradesh. It has one 400/1200 kV bay which is successfully charged, along with one 1200 kV single circuit and one 1200 kV double-circuit test transmission line [39]. According to Indian Electrical and Electronics Manufacturers Association (IEEMA), the power transfer capability of 1200 kV line is ranging from 6000 MW to 8000 MW [40].

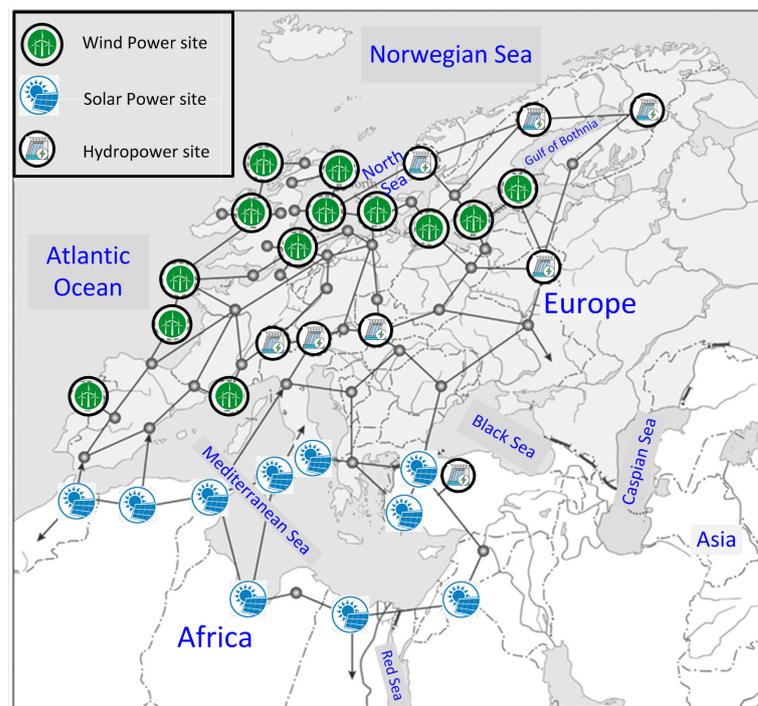


Figure 7. A conceptual plan of a European supergrid linking renewable energy projects [21].

Table 1. Existing interstate electric ties in Northeast Asia [34].

Countries	Project Name (End Points)	Voltage Rating (kV)	Power Transfer Capability (MW)	Power Exchanges (GWh/2015)
Russia-Mongolia	Gusinozersk Thermal Power Plant	220	250	283 (Mongolia’s import)/ 54 (Russia’s import)
	Chadan-Khandagayty-Ulaangom	110	90	
Russia-China	Blagoveshchenskaya-Heihe	220	95	3299 (China’s import)
	Sivaki-Shibazhan	110	90	
	Blagoveshchensk-Sirius (Aigun)	220	300	
	Amurskaya-Heihe	500	750	
Mongolia-China	Oyu Tolgoi-Inner Mongolia	220	n.a.	1200 (Mongolia’s import)

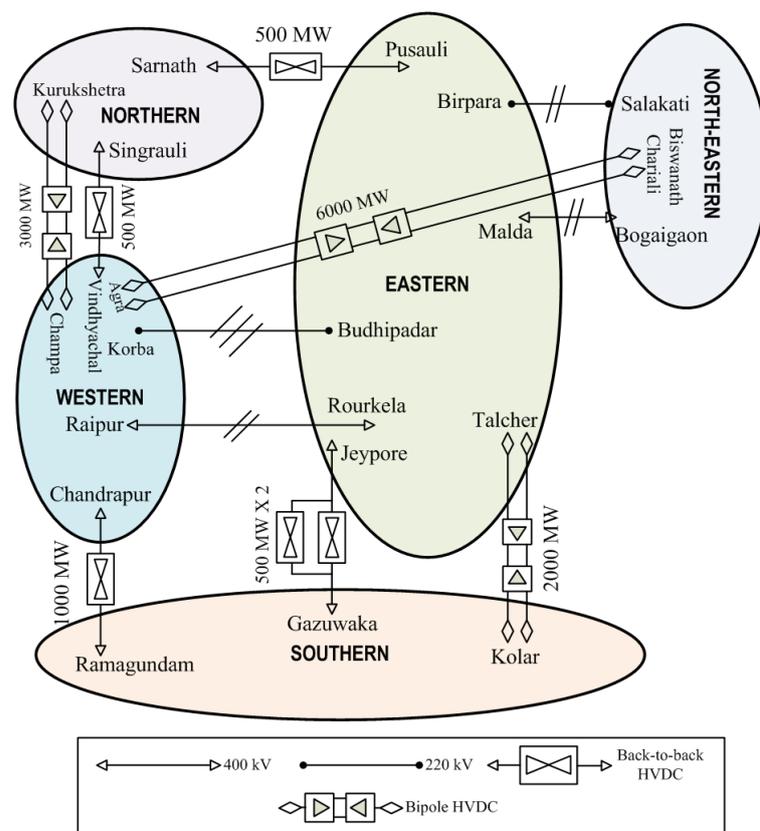


Figure 8. Some inter-regional grid interconnections in India [36].

#### 4. Current Trends of Power Grid Interconnection Technologies

Broadly, power grid interconnection may be of two types that are synchronous and asynchronous. In the synchronous interconnection, the operating frequencies of both the interconnected power grids should be the same (50 Hz or 60 Hz). In the asynchronous interconnection, the operating frequencies of both the interconnected power grids may be the same or different. The present scenario of large power grid interconnection implemented around the world includes AC synchronous interconnection, HVDC asynchronous interconnection including LCC-HVDC, VSC-HVDC light and Modular Multi-level Converter (MMC) [41,42] and Variable Frequency Transformer (VFT) based AC asynchronous interconnection. Moreover, some grid interconnection technologies are also proposed in the literature, including High-Frequency AC Link and Flexible Asynchronous AC Link (FASAL) system. Each of these technologies is discussed in detail in the following subsections.

##### 4.1. AC Synchronous Interconnections

The most widely adopted technology for the interconnection of two AC power grids is an AC link. In AC link, two independent AC power grids are interconnected through a tie-line.

- Working Principle

To control the power flow through the tie-line, regional automatic generation control (AGC) is employed. The power-angle of generators on both side of the tie line must be controlled for safe and stable operation of the interconnected system. The active power, as well as the reactive power exchange, is achieved in AC synchronous interconnection. The control of power transfer through these link lines is achieved by various power flow controlling devices, such as load tap changing transformers (LTC) [43,44], phase shifting transformers (PST) [45] and FACTS controllers [46,47].

- Benefits

It is a simple and cost-effective method of grid interconnections.

- Challenges

AC interconnection makes the operation of the power systems complicated. Moreover, it reduces the reliability and stability of the power network under severe faults conditions. If fault occurs, a short circuit current will increase on healthy side of the power network too [48].

- Existing Projects

Some of the existing projects are: (i) UHVAC project ( Weifang-Linyi-Zaozhuang-Heze-Shijiazhuang) in China, 1000 kV, length =  $2 \times 823.6$  km, started in 2020. (ii) 427 km of 1000 kV AC circuits (Kita-Iwaki power line) were developed in Japan. (iii) UHVAC project ( Mengxi-Jinzhong) in China, 1000 kV, length =  $2 \times 304$  km, started in 2020.

#### 4.2. HVDC Interconnections

In HVDC interconnection, two independent electric power networks are interconnected through high voltage direct current (HVDC) system. This HVDC system can be a LCC-HVDC system and VSC-HVDC system that can be employed in a back-to-back or point-to-point configurations depending upon the operating conditions [49,50].

The HVDC system may be monopolar and bipolar depending upon the operation and location of the converter stations. In a monopolar system, two converters are used that are connected by a single-pole line, and the ground is used as a return path. This system is conventionally used to transmit power over the sea to reduce cost. A bipolar system is a two-pole system where one conductor has a positive polarity while the other one has a negative polarity. This scheme has the advantage over monopolar. Whenever a fault occurs in one of the conductors, the other pole sustains the operation by acting as a monopolar link with the ground [51,52]. The HVDC interconnection provide isolation between the interconnected power system networks and controllability of active power transmission.

##### 4.2.1. LCC-HVDC Technology

The LCC-HVDC technology has been extensively used throughout the world for bulk power, long-distance power transmission or as back-to-back asynchronous links. It is an established and mature technology [53].

- Working Principle

A typical LCC-HVDC system interconnecting two electric power system networks (Grid-1 and Grid-2) is shown in Figure 9. A line-commutated converter (LCC) consists of thyristors as switching devices. These converters require an AC voltage source for their operation. The term line-commutated indicates that the conversion process relies on the line voltage of the AC system to which the converter is connected to effect the commutation from one switching device to its neighboring device.

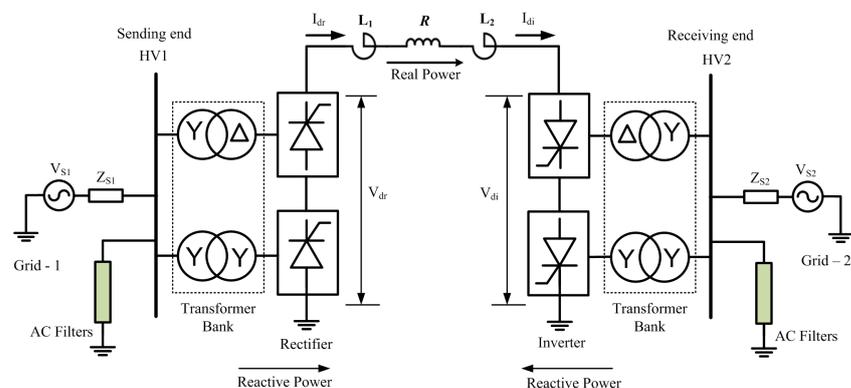


Figure 9. A LCC-HVDC system interconnecting two power grids.

A three-phase, six-pulse, full-wave bridge converter is used as a basic block for HVDC conversion. The term six-pulse is due to six commutations or switching operations per period resulting in a harmonic ripple of six times the fundamental frequency in the dc output voltage. Each six-pulse bridge consists of six controlled switching devices or thyristor valves. Each valve consists of a suitable number of series-connected thyristors to achieve the desired dc voltage rating.

- Benefits

The thyristor-based LCC-HVDC system is attractive due to low power losses, low capital cost, higher stability and higher reliability for large-scale HVDC networks [54].

- Challenges

The LCC-HVDC system suffers from drawback of commutation failure which takes place even for 10–14% of voltage dip at inverter AC bus. Moreover, it is unable to supply power to the isolated passive loads [55].

- Existing Projects

Some of the worldwide LCC-HVDC projects with their basic parameters are given in Table 2 [56–60].

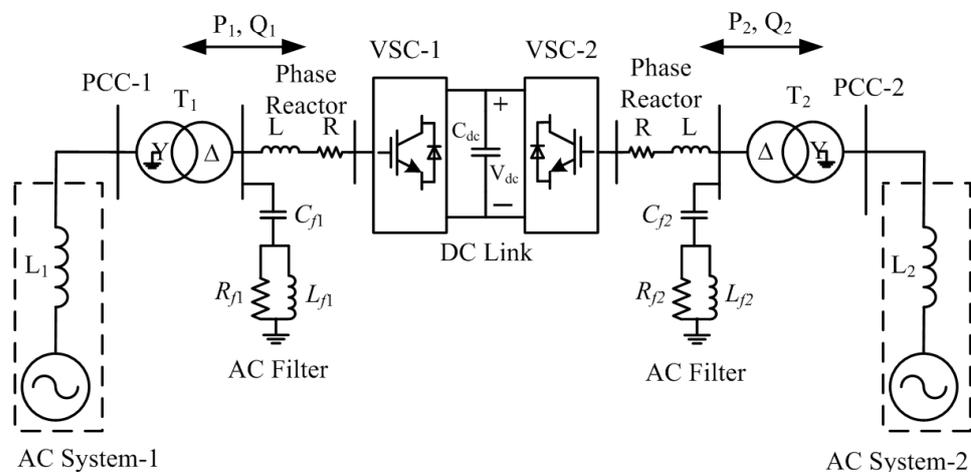
**Table 2.** Some worldwide LCC-HVDC projects and their basic parameters [56–60].

Year	Project Name	Country	Power (MW)	DC Voltage (kV)	Distance (km)
2019	Ethiopia–Kenya HVDC Interconnector	Ethiopia-Kenya	2000	500	1044
2018	Belo Monte	Brazil	4000	±800	520
2018	Nelson River, Bipole 1/2/3 (2004/1977/2018)	Canada	1000/2000/2000	±500	
2017	Western HVDC Link	UK	2200	600	422
2016	WALT	Canada	1000	500	350
2016	EALT	Canada	1000	500	500
2016	Madawaska	Canada	350	130	BTB
2016	Pacific Intertie	USA	1440	±400	1360
2016	NordBalt	Sweden–Lithuania	700	±320	400
2016	DolWin2	Germany (North Sea)	916	±320	2 × 45
2016	Quebec–New England	Canada–USA	2000	±450	1480
2015	North-East–Agra	India	6000	±800	1728
2015	Nuozhadu–Guangdong	China	5000	±800	1451
2015	Troll A 3&4	Norway	100	±60	70
2015	DolWin1	Germany	800	±320	2 × 75
2015	AL-link	Finland	100	±80	158
2015	BorWin1	Germany	400	±150	2 × 75
2015	LitPol Link	Poland–South Lithuania	500	±60	BTB
2014	Xiluodu–Guangdong	China	6400	±500	1251
2014	EstLink 2	Finland–Estonia	650	450	171
2014	Inter-Island Connector Pole 3	New Zealand	700	±350	649
2014	Oklaunion	USA	220	±31	BTB
2014	Railroad DC Tie	Mexico	300	±21	BTB
2014	Eel River	Canada	350	80	BTB
2014	Skagerrak	Norway–Denmark	700	500	140
2014	Inga–Kolwezi	Congo	560	±500	1700
2014	Mackinac	USA	200	±71	BTB
2014	INELFE	France–Spain	2 × 1000	±320	65

#### 4.2.2. VSC-HVDC Technology

The VSC-HVDC system is most suitable for multi-terminal DC grids. It is also best suited for wind integration into the utility grid [61,62]. The VSC-HVDC system consists of two voltage source converters (VSCs) connected back-to-back through a common DC link.

A Back-to-Back VSC-HVDC system interconnecting two AC power systems is shown in Figure 10 [63]. Here, both the VSCs are three-phase and six-pulse IGBT based converters.



**Figure 10.** A BTB VSC-HVDC system interconnecting two AC power systems.

However, a very high DC power exchange needs the backing of strong AC grids [64]. Moreover, AC system faults may lead to commutation failures and even unipolar or bipolar blocking [65,66]. The HVDC system has a performance issue when a low capacity AC power system network is connected on either side [67]. Moreover, the installation of a large number of high voltage switches and filter banks in the HVDC system at both sides of the tie line requires significant space [67]. The VSC-HVDC can further be classified as MMC-VSC and HVDC light which is discussed in the following subsections.

#### Modular Multi-Level Converters

Decentralized energy storages, modular structure, easy redundant submodules (SMs), and simple fault detection and clearance are Modular Multi-Level Converters (MMCs) features. These characteristics encourage MMCs to be used in high and medium-voltage/power applications.

- Working Principle

Modular Multi-Level Converters (MMC) technology's operating principle depends on replacing switching series semiconductor strings with equivalent IGBT and capacitor submodules (SM) that provide enhanced operation quality with easy scalability, high availability, fault-tolerant operation and good quality output waveform. The MMC can generate sinusoidal AC voltages with negligible harmonics by increasing the number of SMs [68]. The MMC is designed using six valves positioned in three submodules. Each valve is connected from one DC terminal to one AC terminal which is similar to the two-level converter. However, in MMC, each valve has a controllable voltage source and own storage capacitor. Every SM consists of two series connected IGBTs across the capacitor. The common point is connected to the AC voltage source [69]. A three-phase MMC is shown in Figure 11.

- Benefits

An Integrated Gate-Commutated Thyristor (IGCT) valves can be used in future implementations of the MMC that has a significant potential due to their higher ratings and reliability. However, the life cycle cost of IGCT is less as compared to IGBT for HVDC applications [70]. Hence, the Modular Multi-Level Converters provide distributed energy storage and have a modular structure that offers higher availability and fault-tolerant capability.

- Challenges

The main limitation of the MMC is that the controller is more complex and the control hardware requires a larger processing capability [71].

- Existing Projects

Some of the worldwide recent MMC-VSC projects and their basic parameters are listed in Table 3.

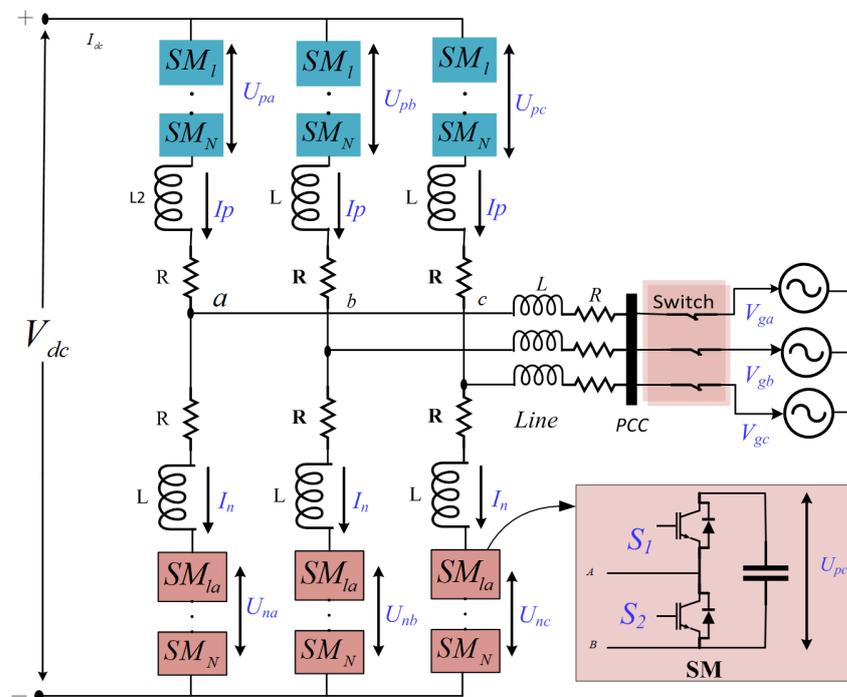


Figure 11. Three-phase Modular Multilevel Converter topology [69].

Table 3. List of some existing worldwide MMC-VSC projects and their basic parameters.

Project Name	Rated Power (MW)	Rated Voltage (kV)	Commiss. Year	Commiss. by	Reference
Trans Bay Cable (USA)	400	±200	2010	Siemens	[72]
Nan'ao (China)	200/100/50	±160	2013	-	[73]
Zhoushan (China)	400/300/100/100/100	±200	2014	C-EPRI	[74]
Zhangbei (China)	3000/3000/1500/1500	±500	2020	ABB	[75,76]
COBRA cable (Netherlands–Denmark)	700	±320	2019	Siemens	[77,78]
North Sea Link (Norway–Britain)	1400	±525	2021	ABB	[79]
Caithness–Moray Link (Scotland)	1200	±320	2018	ABB	[80]
BorWin3 (Germany)	900	±320	2019	Siemens	[81]
DolWin3 (Germany)	900	±320	2017	GE-Alstom	[82]
ULTRANET (Germany)	2000	±380	2019	Siemens	[83]

### HVDC Light System

An HVDC Light is based on VSC technology. It is designed for underground and underwater as well as long-distance power transmission. It offers several environmental benefits, including oil-free cables, neutral electromagnetic fields, invisible power lines and compact converter stations [84].

- Working Principle

The configuration of a bi-directional HVDC light system is depicted in Figure 12. Each converter station contains two poles, one with positive polarity and one with negative polarity, each with their neutral grounded [85].

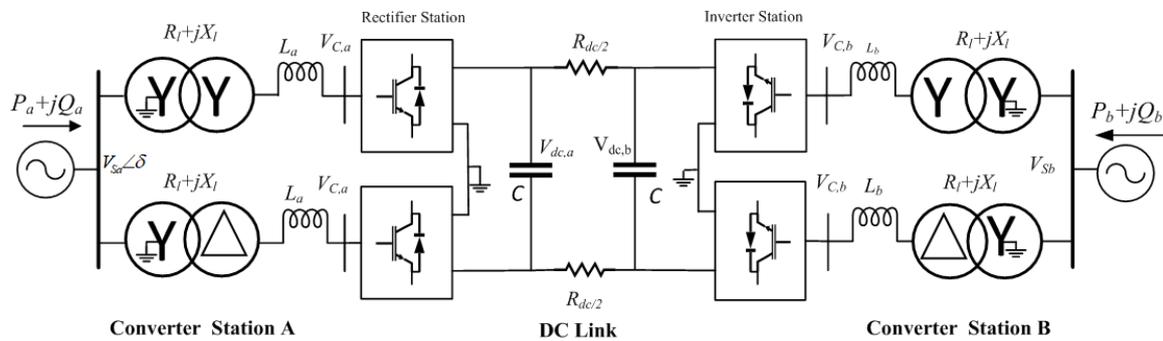


Figure 12. The HVDC light system interconnecting two power grids [85].

The proper design of controllers for both the converter stations is extremely important to take complete benefit of the HVDC light systems. There are four PI controllers at one converter station. Therefore, a bipolar bidirectional VSC-HVDC system (Figure 12) will have a total sixteen PI controllers. Some of the methods used to tune PI controllers include pole placement, bode plots, Ziegler–Nichols and PI controller tuning in cascaded loops. However, these tuning methods depends heavily on the stochastic properties and does not ensure stability [86]. Tuning sixteen PI controller is a tremendous challenge to do. Modulus optimum (MO) and symmetrical optimum (SO) methods are most often used in applications involving one considerable time constant and several small-time constants, which needs simplified models of the system. With proper tuning of PI controllers by MO and SO better respond with low overshoot and poor rejection for the disturbance [87].

- Benefits

The HVDC Light enhances the reliability of power grids. It extends the economic power transmission ranging from a few tens of Megawatts (MW) to 3000 MW and a voltage level of  $\pm 640$  kV over a distance of 2000 km. It has significant applications like integrating wind farms to utility grids, underground power links, providing shore power supplies to islands and offshore oil and gas platforms [88], connecting asynchronous grids and city center infeed [89].

- Challenges

Even though PI parameters are well documented, which rely on a particular designer's experience, the tuned PI controller does not guarantee optimal performance.

- Existing Projects

Some of the HVDC light projects are: NORDBALT (700 MW,  $\pm 300$ , 450 km, Sweden, ABB, 2015), DOLWIN2 (900 MW,  $\pm 320$ , 135 km, Germany, ABB, 2015) and MACKINAC (200 MW,  $\pm 71$ , USA, ABB, 2014) [89].

#### 4.3. High Frequency AC Link

An AC link unified power flow controller (UPFC) can also be used to control the power flow along the transmission line by injecting an ac voltage in series having controllable magnitude and phase angle without using any mechanical tap changing transformer and thyristorised phase shifters [90,91].

- Working Principle

The AC link UPFC system comprises of a shunt phase-shifting transformer (SPT), ac link capacitors (AC Link), three-throw single-pole (3T-1P) three-phase Vector Switching Converters (VeSC) and a series injection transformer (SIT) connected as shown in Figure 13.

The AC link approach is based on phase-shifting transformers with control realized by a VeSC. The VeSC uses gate turn-off switch technology and PWM operating at proper switching frequencies. It also utilizes standard three-phase transformers featuring topological modularity [92,93].

- Benefits

This system may be placed at any point throughout the transmission line. Independent control of Real (P) and reactive (Q) power through the transmission line is achieved by direct AC–AC conversion without changing the frequency and implementing the strategy of pulse width modulation (PWM) and working in conjunction with suitable configuration of the power transformers [94].

- Challenges

It uses many passive components, especially a line frequency transformer, which makes the equipment costly. Moreover, the former control theory has an issue when dealing with an unbalanced grid fault and harmonics. Thus, the theory needs enhancement to improve performance [95].

- Existing Projects

This technology is under the research and development stage. Hence, it is not been implemented so far.

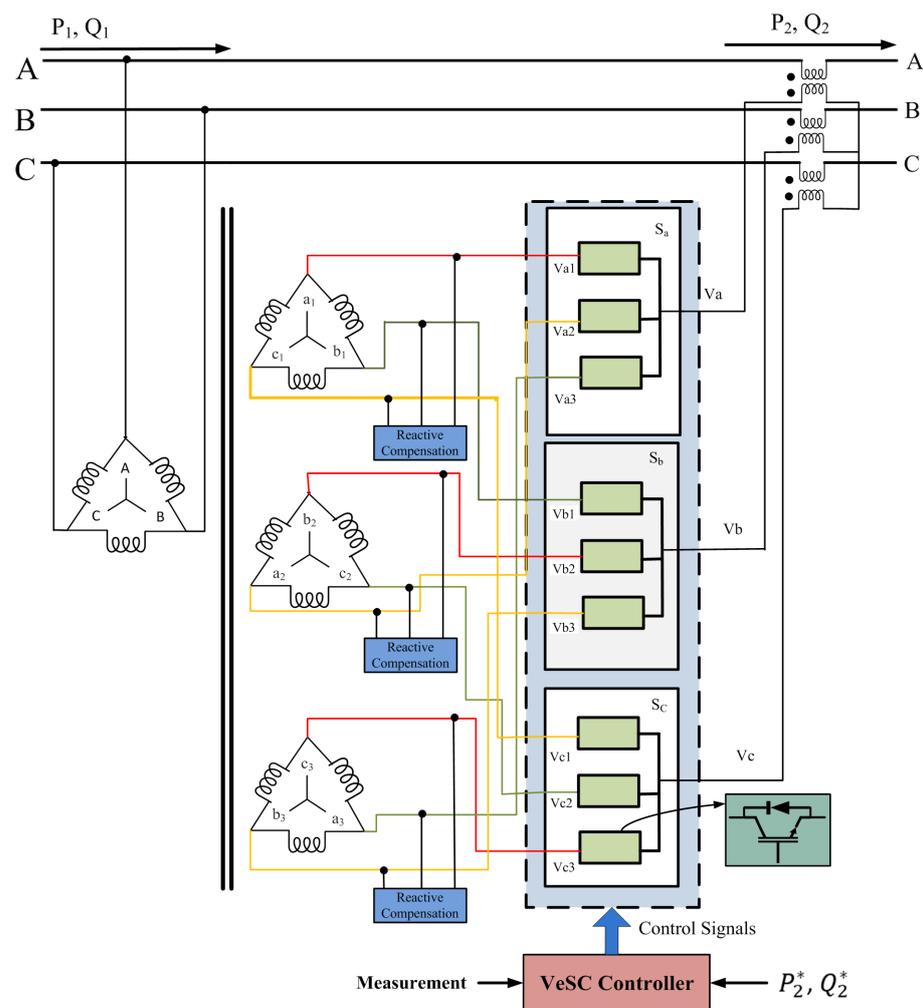


Figure 13. High Frequency AC Link using a vector switching converters [92].

#### 4.4. Variable Frequency Transformer

Alternatively, the asynchronous interconnection can also be made by the variable frequency transformer (VFT). The VFT is a controllable, bi-directional transmission device that can transfer power between asynchronous power grids [96–98].

- Working Principle

The VFT uses a wound rotor induction machine (WRIM) as a rotary transformer which allows interconnection between the two electric power networks operating at two different frequencies. The power flow control is achieved by applying the torque by DC drive system which is coupled with the rotor shaft of the WRIM as shown in Figure 14. The direction and magnitude of power transmission depends on the direction and magnitude of the torque applied on the shaft of the rotor.

- Benefits

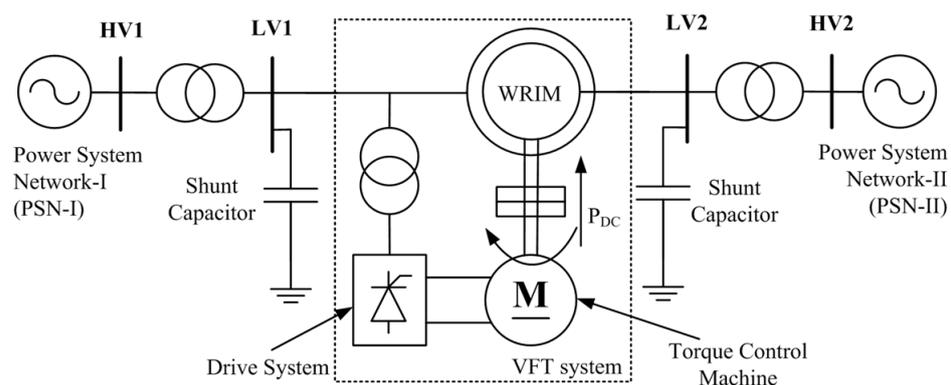
It has large rotational inertia of the machine that suppresses power oscillations. The operation is harmonics-free as no power electronic components are involved in the main path of power exchange. It has a high overloading capability due to its large thermal time constant.

- Challenges

The VFT system uses a high-power DC motor and its drive system. The use of DC motor requires frequent maintenance of carbon brushes leading to frequent shutdown. Therefore, space requirement and cost of whole system increase [99]. Moreover, rating of the VFT which is being used in the range of 100–150 MW only. Thus, at present, VFT system is not good for bulk power transfer in the range of thousands of MW between high power AC grids.

- Existing Projects

The world's first VFT was installed at Hydro-Quebec's Langlois substation in October 2003, where it used to transport 100 MW of electric power between the power grids of Quebec, Canada, and New York, USA. The second VFT was established at Laredo Substation in southwestern Texas, and its commercial operation commenced in 2007 for interconnecting Texas Power Grid with Mexico Power Grid. The third VFT was successfully inaugurated among PJM power grid and NYISO power grid in 2010 [18].



**Figure 14.** A VFT system interconnecting two power system networks.

#### 4.5. Flexible Asynchronous AC Link

In spite of a large number of technologies presently available for the interconnection of the electric power system networks, still there is a need for an efficient, reliable, fault tolerant, harmonic free and cost effective solution for the interconnection of the power system networks having controlled power flow between them. It could be used for bulk power transfer between two high power grids or low power flow between a high power grid and

a micro/smart grid. Therefore, recently, a flexible asynchronous AC link (FASAL) system has been developed [100] and reported [55] for providing asynchronous link between two electric power grids operating at same or different frequencies [101].

- Working Principle

It consists of a three-phase wound rotor induction machine (WRIM), voltage regulator and frequency converter. Two separate electric power grids are connected to the stator and rotor of WRIM, respectively. Electrical power is transmitted between the two networks by the magnetic coupling in the air gap of the WRIM. The magnitude and direction of the power transfer through the FASAL system are controlled by controlling the voltage and frequency. The FASAL system linking two power grid is shown in Figure 15.

- Benefits

The FASAL system does not inject harmonics into the power system because it is an electro-mechanical device based on generalized electric machines. It is a simple device having less number of components and also eliminates the requirement of high-power DC motor and its drive system [102,103].

- Challenges

It is an electro-mechanical device-based system. Therefore, it can not be built for a large size of the order of 1000 MW.

- Existing Projects

This technology is under the research and development stage. Hence, it is not been implemented so far.

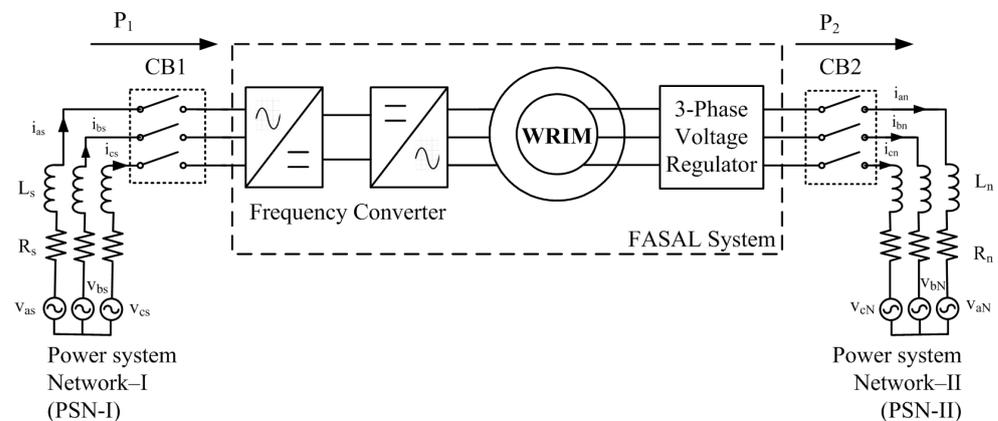


Figure 15. A FASAL system linking two power grids.

## 5. Comparative Analysis

A comparative analysis is made between the FASAL system and LCC-HVDC under various fault conditions. It is found that the FASAL system could be a better alternative to the LCC-HVDC system [104].

The FASAL system is compared with VFT for 100 MW power transfer as shown in Table 4. It is evident that in the FASAL system high-power DC motor has not been used. Moreover, an additional DC motor drive system is also required in the VFT system. Therefore, the FASAL system is more economical as it saves the cost and space requirement of 3750 HP (2.796375 MW) DC motor and its DC drive system. In the FASAL system, no DC motor has been used. Therefore, frequent shut-down due to replacement and maintenance of carbon brushes of the DC motor is also avoided. A comparative analysis of VFT and FASAL System is presented in Table 4. Moreover, comparative analysis of various grid interconnection technologies is presented in Table 5.

The economic comparison of DC and AC interconnections in terms of total installation cost and cost of losses that occur during the operation is shown in Figure 16. The total

installation cost includes station cost, including reactive compensation (M\$) and Transmission line cost (M\$/km). The comparison is made for rated power of 3000 MW and around 1200 km (750 miles) long transmission lines. Other parameters are: interest rate = 10%, power factor = 0.94, full load converter station losses are 9.75% per station, total substation losses (transformers, reactors) are 0.5% of rated power.

Table 4. Comparative analysis of VFT and FASAL System.

Variable Frequency Transformer (VFT)			FASAL System		
Components	Ratings	Quantity	Components	Ratings	Quantity
WRIM	100 MW, 17 kV	1	WRIM	100 MW, 17 kV	1
Two-winding transformers	107 MVA, 120/17 kV	2	Two-winding transformer	107 MVA, 120/17 kV	2
Two-winding transformer for Converter	>3 MVA	1	Auto-Transformer	100 MVA, 120 kV	1
DC Motor Drive System	>3 MW	1	-	-	-
DC Motor	3750 hp (2.796375 MW)	1	-	-	-

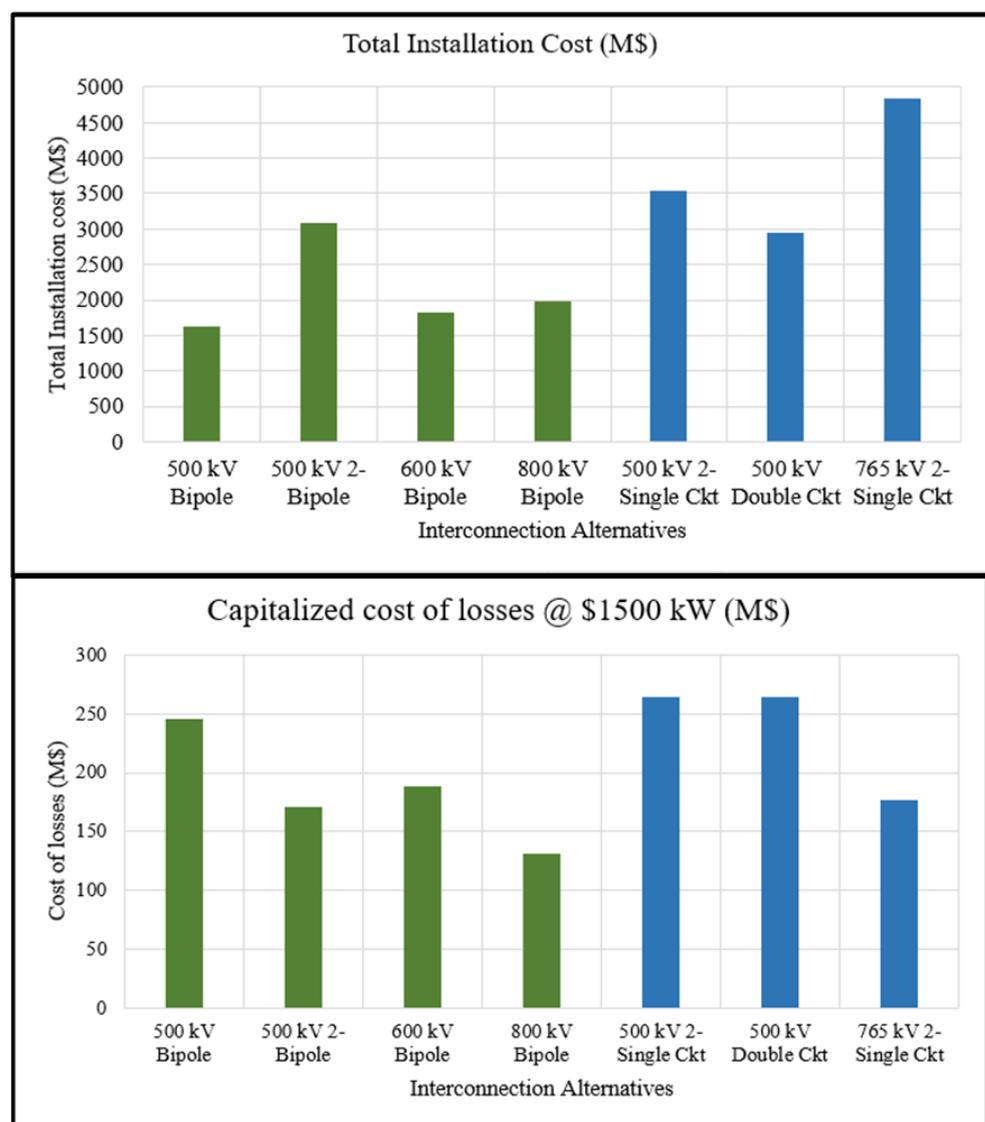


Figure 16. Costs comparison of HVDC and EHV AC transmission systems [105].

**Table 5.** Comparative analysis of various grid interconnection technologies.

Attributes of Technologies	Interconnection Technologies			
	FASAL	VFT	LCC-HVDC	VSC-HVDC
Efficiency	High	Low compared to FASAL	High in comparison to all (being static system)	Low compared to LCC
Complexity	Lowest as compared to VFT	Low	High	High compared to LCC
Maintenance	Lowest (DC drive absent)	Low	standard	Industry standard
Space Requirements	Small compared to VFT	Small compared to LCC	Large (to accommodate filters)	Industry standard
Black Start Capability	Capable	Capable	Not Capable	Industry standard
Control Interactions	Low	Low	High	High
Harmonic Generation	Low	Very low (no PE converter in the main path)	High	High
Impact on adjacent generators	Low	Low	High	High
Modular design	Yes	Yes	No	Yes
Integration with grid	Easy	Easy	Difficult	Industry standard
Bump-less start-up	Yes	Yes	No	Yes

## 6. Future Prospects of Intercontinental and International Grids

Network connectivity around the world has been continuously expanding over the decades. A comprehensive summary of advantage, opportunities and challenges for the global and intercontinental power grid interconnections is presented in Table 6. In 2016, international electricity power transfer totaled 765 billion kWh, and transcontinental interconnections totaled 30 billion kWh. Brancucci et al. [106] identify the potential for cost-effective exports of renewable energy based electricity (RES-E) from North Africa to the European market. The results apply to their respective scenarios as an EU primary coal and gas power system; the trend towards a more established renewable energy based electricity portfolio in continental Europe has progressed. However, the volatility of investment returns and the political instability in Northern Africa have restricted the growth of feasible interconnections.

**Table 6.** Advantages and challenges for the global and intercontinental power grid interconnections [8].

Global Grid and Intercontinental Interconnections	
Benefits and Pportunities	Risks and Challenges
1. Demand and supply are being smoothed via time-zone diversity	1. Substantial investment costs and risks
2. Latitudinal (seasonal and geographic differences) integration	2. High transmission losses
3. Enhances the diversity and security of supply	3. Risks by interconnector dependence
4. Provides versatility (lower demand for storage/reduction)	4. Regulatory concerns about industry functioning
5. Reduced operating reserves and total power generation	5. Local RES-E is more productive and should be prioritized
6. Lower market uncertainty (stable commodity prices)	6. Safeguarding the needs of residents
7. The broader market for the exchange of power	7. Technical, geographical and organizational limitations
8. Help for rising demand in developing regions	8. Balance in price difference (increase in some areas)
9. Simple exchange of energy rather than raw fuel	9. Storage the cost-effective flexibility solution always
10. Ability to circumvent low voltage grids	10. Opposition to interconnectors or convergence
11. Intercontinental RES-E will help policy goals	
12. Promotes investment and cooperation between regions	
13. Improved images from fossil to RES-E exporter	
14. Green job development and general improvement of welfare	
15. Environmental benefits due to higher RES-E incorporation	

The E-Highway 2050 project supported by the EC indicates that some (10–40) GW of transmission capacity between North Africa and Italy should be developed to help

the supply of up to 116 GW of installed solar demand centers in the European electricity market [107].

Germany and France are two major exporters in Europe; Europe's trading capacity is up to 780 billion kWh [108]. While trade potential in Russia and Central Asia has stretched 24.5 billion kWh, African countries reached 31.3 billion kWh, and 11.9 billion kWh in South Asia, 18.4 billion kWh in South East Asia, 1.1 billion kWh in East Asia. South America 46.1 billion kWh and in North America 92.7 billion kWh [34,109–111].

Italy (Villanova) operates a  $\pm 500$  kV HVDC interconnection network with an operational transmission capacity of 1 GW and a length of 375 km to Montenegro (Lastva) [112]. Cooperation on energy trade between the two countries has provided new horizons for renewable energy sources to be connected and improved. A versatile DC project between Savoy, France and Piedmont, Italy was constructed with a bipolar transmission capability of 1.2 GW [113]. The HVDC interconnectors of TalukGong, Malaysia, and Garuda Sakti, Indonesia, are rated at  $\pm 250$  kV, 600 MW, 200 km of overhead line, and 57 km of marine cable. A 400 kV AC dual circuit will be generated from Zambia via Tanzania with a transmission capacity of 0.4 GW having length of 2300 km [114].

Another project of 2 GW with a voltage level of 500 kV has been built between Ethiopia and Kenya over the last few years [115]. India has a 1 GW transmission potential for the 400 kV AC interconnector project in Nepal [116].

Iran and Armenia have a 300 MW standard interconnection line. A  $\pm 660$  kV, 4000 MW, Bipolar, HVDC transmission line project between Matiari to Lahore is built by China. Egypt and Saudi Arabia agreed in 2015 to build 1200 km of HVDC lines to connect the two countries. This project will be very relevant for grid connectivity in the Middle East, and Egypt has also begun a feasibility study on connections in the Nile Basin with African countries [114].

Similarly, as a multinational project for economic power, the transmission is carried out between China–South Korea–Japan [117]. China and Kyrgyzstan plan the start of an 8 GW HVDC  $\pm 800$  kV power line. The project will link the hydro and gas power of Central Asian countries with Xingjiang, China's rich wind power resources. India and Bhutan plan to build two 400 kV HVAC lines with transmission distances of 198 and 64 km to link Bhutan [118].

Several studies have shown the possible feasibility of Australian (South–East) Asian interconnectors [8,119,120]. A planned LCOE of US \$0.18–0.25/kWh can now be supplied with solar power from Pilbara, Australia, to Java. Compared to the existing Solar Electricity Feed-in tariff of Australian \$0.193/kWh in Java, the study's authors argued that this interconnector business case could be economically feasible within 5 to 10 years if existing cost reduction trends continue. Blakers et al. [119] argue that Australia's midday supply of high solar PV absorbs the importance of electricity storage; a factor of four will reduce the power needed to connect to South East Asia, smooth out peak generation, and flow throughout the day. The cost of transmitting low-cost solar and wind power from Australia is very high compared to South East Asia's regional generation and storage alternative [121].

Cova et al. [122] argued in the early part of the century that the financial viability of Trans-Mediterranean connectors depended heavily on factors such as construction costs and sales rates for electricity. Nearly two decades later, based on the above analyses, the same conclusion still holds for each intercontinental interconnection project. While the advantages of the integration of the intercontinental energy system are evident, the assessments show that real feasibility is heavily dependent, among other things, on the alleged capital costs, the projected cost reduction for improvements in future scenarios due to the technical learning curve and the contextual strategies in which projects are evaluated. There is a need for more comprehensive power system modeling, including sensitivity analysis, with high temporal, technological and spatial resolution [122].

## 7. Research Directions in Power Grid Interconnections

In this section, major research area and directions in the field of power grid interconnection are presented in detail. There is minimal current support for combining renewable energy with low inertial power converters for reactive power support, frequency deviations, fault rides, harmonics and phase angle hopping. The converter technology's simulated synchronicity needs to be enhanced to tackle voltage fluctuations, low damping problems and symmetric and asymmetric faults. As a consequence, resource assessment and power prediction are the main research topics. It is possible to develop metrological data and complex weather prediction analysis such that wind and solar radiance are expected ahead of the day. Another contributing factor in managing variability that can assist with frequency variability and peak shaving is creating a long service life and a high capacity, low cost and sensitive large-scale renewable energy storage system. The following research questions for GEIs need to be addressed by the interconnected grid, such as entry, testing and inspection of grid connection; power forecasting in complex metrological data; renewable energy congestion management; synchronization on broad clean energy bases; support for active/reactive power and synchronous virtual generators; storage system for electrochemical/physical/hydrogen.

### 7.1. Clean and Sustainable Energy

Environmentally sustainable and low-carbon renewable energy (RE) offers enormous potential for global energy interconnection (GEI) development. In the future, acceleration in renewable energy growth is required to increase world energy generation [123]. High-efficiency generation of low-cost conversion and plug-in forms is needed to create energy bases, especially in the North Pole and Equator regions. Hydropower is the primary source of renewable energy against intermittent grid fluctuations [124]. It offers a comfortable start/stop operation, high capacity and performance, and flexible load setting. However, large sources of hydropower can be further improved in an environmentally sustainable manner [125]. The 2030 sustainable development program was planned by the UN which enhances clean energy-share, affordability, reliability and development among the 17 sustainable development goals [126]. In 2015, India set up a clean energy development goal, and renewable energy share will increase from 30% to 40% by 2030.

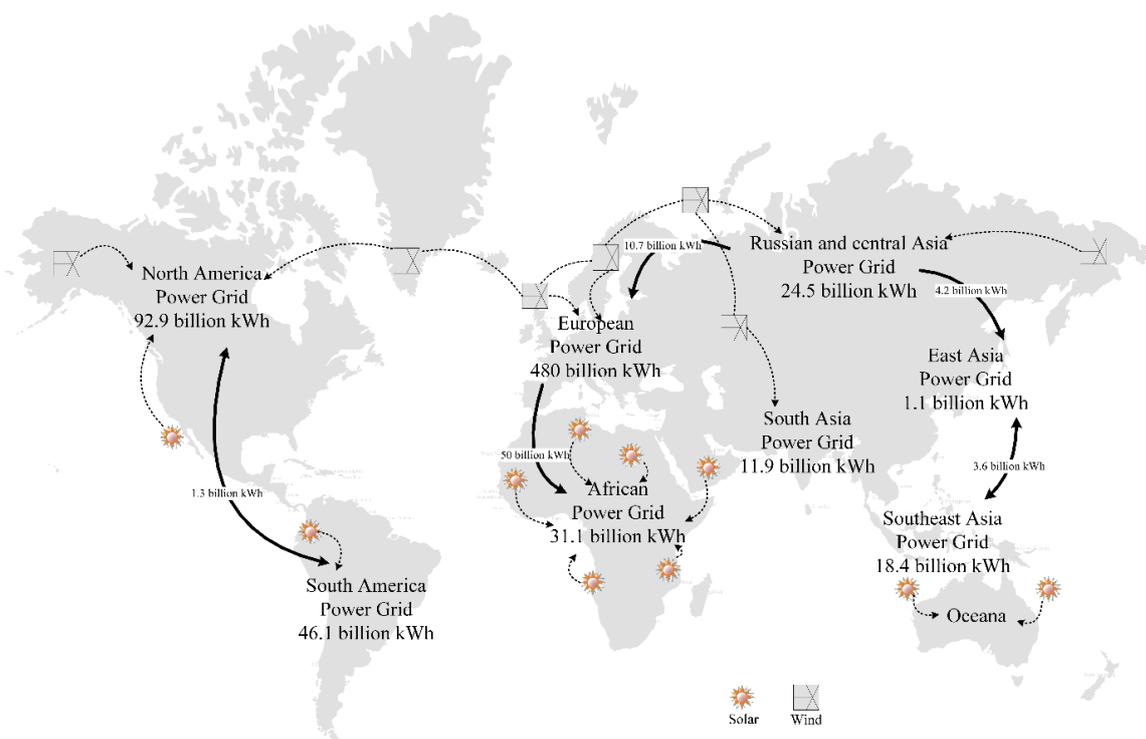
Marine and polar wind energy are ripening, such as large-scale offshore farms, extreme climate adaptation, remote activity, and maintenance. The latest research directions are the superconducting turbine and the generation of high-altitude wind power [127,128]. Research on solar photovoltaic (SPV) systems requires developing highly efficient conversion modules [129,130]; flexible expansion capabilities such as plug and play converter interaction with grid, low maintenance and simple operation. Similarly, to develop photothermal storage devices for high efficiency [131], high density and high temperatures, it is also vital to improve monitoring control accuracy. Developments in ocean energy research (tide, temperature and salt variation, wave energy) are steadily going forward in almost 30 coastal countries worldwide [132,133]; efficient energy capture devices, mitigating drastic climate change, and system maintenance are crucial issues to be tackled in the future [134].

### 7.2. Smart Grid Developments

To build a potential electric power grid, the need for technical research and development is essential. Smart substations for the future grid are made to be productive and to cope with severe weather conditions. A smart grid is realized by Defence Ministry of South Korea in order to make energy independence Island. A microgrid at Gaza Island in South Korea is developed in 2015 having SPV (314 kW), wind (100 kW) and ESS (3 MWh). The surplus energy is stored in the energy storage system (ESS) and utilized for various applications.

Global energy interconnection will be the final stage in the natural evolution of electricity grids for ever-greater interconnection. A global power grid allowed by the

smart grid infrastructure uses UHV technology to transmit power over long distances. Present renewable energy networks and high-capacity sites are located far from actual power stations. An interconnecting network will handle instability for safe and secure operation once wind and PV sources have been incorporated into the grid. Therefore, the net incorporation of high-proportion renewable energy is one of the key challenges facing the GEI sector in the future. The state and future of interconnected power-sharing grids are depicted in Figure 17.



**Figure 17.** The state and future of interconnected power-sharing grids around the globe [18].

Some of the leading research areas in the field of smart grids include intelligent information interacting in subcontracting stations and security, intelligent high-voltage transmission system and equipment, transmission state monitoring, state-of-the-art, self-healing feature, intelligent active distribution network, energy management system, versatile distribution optimization, ultra-wideband and low-power wide-area communication [135–137], development of Internet of things (IoT) for the power grids [138–141], data management and analysis using machine learning, cloud computing analysis [142,143].

### 7.3. Development of UHV Transmission Systems

Development of an ultra-high voltage (UHV) AC and DC technology is essential for the implementation and deployment of global power grid interconnection. The following properties must be in UHV transmission networks: long-distances, high capacity, flexible configuration, secure, stable and resilient to severe fault conditions. The world's first ultra-high voltage direct current (UHVDC) transmission line from Zhundong to Wannan is installed in China having 24 GW power, voltage of  $\pm 1100$  kV with a line length of 3324 km [144].

An ultra-high voltage alternating current (UHVAC) transmission project commissioned in 2016 by China, Ximeng-Beijing-Jinan having a voltage level of 1000 kV, and the project cost were 2.72 billion dollars [145]. India has built world's first UHV multiterminal DC (UHVMTDC) transmission project from Assam to Agra, 1728 km long, voltage level of  $\pm 800$  kV and power capacity of 6 GW. Many more UHVDC and UHVAC projects are

already commissioned or under construction worldwide, which will help connect future clean energy hubs to the utility grid.

The main fields of research in UHV transmission for the global electric grid interconnections are: UHV AC/DC substations and circuit design [146,147]; electromagnetically controlled environmental systems [148]; project management, construction and handling guidelines of tests on UHV equipments [149,150]; development of standard for testing of equipments; gas insulated transmission lines [151,152]; unmanned aerial and robot inspecting vehicles [153]; HVDC power grid protection and control [154–156]; performance and design evaluation of wireless, super-conductive and pipe power transmission technology [157–161].

## 8. Conclusions

This paper presents a comprehensive evaluation of the current literature associated with the idea of a globally interconnected power grid. It reviews the current status, future prospects and research direction related to global and intercontinental power grid interconnections. There is significant potential to utilize the enormous amount of efficient renewable energy-based electricity worldwide to decarbonize the electricity system. There is scope to smoothen demand and supply through time-zone diversity and area enlargement. The discrepancy between load centers, areas of high renewable electricity potential, and existing grid infrastructure leads to the intercontinental exchange of electricity and power grid interconnection towards a global power grid. A detailed evaluation of the literature shows the possible benefits, opportunities and challenges of global and intercontinental power grid interconnections. The main development trends associated with the global power grid concept reduces the costs of long-distance transmission technologies. Especially in subsea HVDC and land-based, they are partly driven by China, India, and other Asian countries as consequences of their growing economies and consequential power demand. A detailed and comprehensive review is presented on various power grid interconnection technologies with their merits and limitations. These technologies include AC interconnection, HVDC including LCC, VSC comprising MMC and HVDC light, high-frequency AC link, VFT and FASAL. Moreover, few recent projects based on LCC-HVDC, MMC-HVDC and HVDC light are listed with their essential characteristics. Benefits and challenges of power grid interconnection, including intercontinental and international grids, are also highlighted. Finally, this paper addresses the research directions in clean and sustainable energy, smart grid, UHV transmission systems that facilitate the global future grid interconnection goal.

**Author Contributions:** Conceptualization, I.; data curation, I.; writing—original draft preparation, I.; writing—review and editing, B.A., M.A.H. and M.S.J.A.; supervision, M.S.J.A.; project administration, I. and M.S.J.A.; funding acquisition, B.A. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the Taif University Researchers Supporting Project, Taif University, Taif, Saudi Arabia, under Grant TURSP-2020/278.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

3T-1P	Three-Throw Single-Pole
AC	Alternating Current
AGC	Automatic Generation Control
CIS	Commonwealth of Independent States
DC	Direct Current

EC	European Commission
ESS	Energy Storage System
EU	European Union
FACTS	Flexible AC Transmission System
FASAL	Flexible Asynchronous AC Link
GEI	Global Energy Interconnection
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistors
IGCT	Integrated Gate-Commutated Thyristor
IoT	Internet of Things
LCC	Line Commutated Converter
LCOE	Levelized Cost of Electricity
LTC	Load Tap-Changers
MMC	Modular Multi-level Converter
MO	Modulus Optimum
MTDC	Multi-Terminal DC
MTOE	Million Tonnes Oil Equivalent
P	Real Power
PI	Proportional Integral
PST	Phase Shifting Transformer
PV	Photo-Voltaic
PWM	Pulse Width Modulation
Q	Reactive Power
RE	Renewable Energy
RES	Renewable Energy Source
RES-E	Renewable Energy based Electricity
SIT	Series Injection Transformer
SM	Sub-Modules
SO	Symmetrical Optimum
SPT	Shunt Phase Shifting Transformer
SPV	Solar Photo-Voltaic
UHV	Ultra High Voltage
UN	United Nations
UPFC	Unified Power Flow Controller
VeSC	Vector Switching Converters
VFT	Variable Frequency Transformer
VSC	Voltage Source Converter
WRIM	Wound Rotor Induction Machine

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