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HVDC its Scope and Future Trends

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Abstract— In early days when electricity was introduced in form of low voltage DC there was no significant development in the field of converters. Due to this fact low voltage DC systems were not able to sustain themselves for a significant period and were replaced with high voltage AC systems. During last 62 years high voltage AC systems remained dominant in power transmission and distribution networks. In last two decades the developments in the field of converters have resulted in high efficiency DC-DC conversion systems. In addition to that renewable energy system which are inherently DC in nature have also stressed the use of DC networks for power transmission and distribution. All the electrical energy storage systems including capacitors, batteries etc. are also DC. In lieu of above facts the need and importance of low voltage as well as high voltage DC systems has increased. An HVDC system can be integrated with an existing high voltage AC system for asynchronous power transfer or it can be used an independent HVDC transmission and distribution network. This paper highlights the important aspects of high voltage DC, its advantages, its integration with existing HVAC systems, standalone use of HVDC network, its applications in renewable energy systems, issues, disadvantages, scope and future trends. HVDC is a promising area in future. The literature presented in this paper is particularly useful for researchers working in the field of HVDC and asynchronous power sharing over existing HVAC networks.

Index Terms— HVDC scope, efficiency of HVDC, electrical energy storage, interconnection using HVDC, Integration, DC-DC conversion, asynchronous power sharing

1. INTRODUCTION

After the invent of electricity, electrical power was initially transmitted using direct current (DC) only. The electrical energy transmission and distribution was initially started with DC in 1882 but power transmission using DC has been a poor step, so it was replaced by Alternating Current (AC) power transmission system. Since then, it had been a general perception of AC being the most efficient way for long distance electrical energy transmission. But with the increase in distance of load centers from generation, the losses in AC transmission system are beyond the tolerable limits. So, some other transmission means are required to efficiently transport the bulk power from generation to load centers [1]. Progress in power electronics lead the DC to be used for commercial purposes using HVDC. In 1954, the HVDC became more famous after the introduction of first HVDC transmission system, in Sweden, as Gotland scheme. After the development in semiconductor technology, the high-power converters and inverters promoted the idea of HVDC.

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DC as compared to AC has many advantages which has made the world to rethink about DC systems. DC lines can transmit more power per conductor, due to absence of power factor and reactive power issues. For HVDC smaller towers are required. HVDC lines have less corona, radio interference, transients, over voltages and no skin effect. Using HVDC links an asynchronous interconnection can be applied between AC systems having different frequency. This helps in power sharing between two AC systems while still maintaining their own characteristics independent of each other. Another advantage is that short circuit fault levels are also lower in DC systems and the line power is easily controllable.

There are some inherent problems associated with HVDC. The converters used with HVDC transmission links are very expensive and require a lot of reactive power for rectification and inversion. Harmonics are created due to converters and there are issues in voltage transformation and circuit breaking. In HVDC, converters cannot be overloaded for extended periods and power generation is also limited.

Generally, it is costly and difficult to build new overhead lines for HVDC systems. This is the main reason why HVDC has not became so much widely adopted all over the world. One solution to that problem is to integrate HVDC with existing HVAC systems [2]. To do that there are many topologies which can be adopted.

HVDC can also be used with conventional HVAC, already established system to improve the stability of power system by controlling HVDC power flow through same AC transmission lines [3]. During blackout it is required that generation plants are provided with cranking power. To avoid this condition, synchronous compensators are used with HVDC links at receiving end. That has high reliability and regulating capacity. Power of oceans and seas can be transmitted into oceans offshore for oil and gas exploration in the depth of oceans for far from land and to onshore grid stations. HVDC transmission systems are beneficial to transmit bulk power from offshore wind farms [4]. Since HVDC system is a highly efficient and reliable, so it will be adopted by data centers, communication building in near future [5].

As the renewable energy resources are being studied and utilized to provide clean power; its efficient transmission over long distances is an important issue. This need of the time implies finding technically and economically feasible transmission system that ensure stability and proper energy transmission [6]. Conventionally used marine cables have its limits for long distance power transfer, due to different reasons like high dielectric capacity, which requires compensating inductors every 15-20 km. On the other hand, HVDC lines have advantages like lower electric field at conductor surface causing less corona losses, less ohmic losses over long distances, small tower sizes, a smaller number of conductors required and losses in DC transmission system (Bipolar) with same current transmission capacity of 3 AC conductors are lower.

(Ultra-High-Voltage Direct Current) UHVDC is one of the new key solutions to bulk power transmission over long distances. In spite of its advantages HVDC, it has some restrictions, which may limit its utilization and optimal benefits [8]. Keeping in view the possibilities and restrictions of bulk power transmission systems, UHVDC transmission with DC-voltages of ±800kV is preferred solution to transmit bulk power over several 1000 kms [9].

As we move towards increasing kVs, insulation of the system becomes the key limiting factor. The total ability of a system to produce and transmit electricity is directly related to the insulation strength of the system. HVDC transformers remain key components for the reliability of the link. Cellulose paper, pressboard and mineral oil have been used in HVDC transformers insulation systems for the last 60 years without significant changes. Porcelain has been phased out for epoxy and silicon rubber because of change from oil impregnated to resin impregnated paper for DC bushings [10].

This paper presents different aspects of HVDC like HVDC interconnection between existing HVAC asynchronous systems, HVDC transmission and its integration with renewable energy resources. Power control mechanisms and insulation issues in HVDC. In addition of that the scope of HVDC and its future aspects are also covered.

2. HVDC/ HVAC HYBRIDE SYSTEM

Nowadays power control between receiving end power transfer point is required. Nowadays core areas to be handled are offshore power transmission of renewable energy resources, self-commutation, dynamic voltage control, power sharing between weak AC system and high load centers, in feed large urban areas and DC segmented grid [11]. Worldwide due to transients black out may occur in power system. So, power restoration is very important issue which is to be handled. That’s why cranking power resources are required in black out conditions for generating stations to improve reliability and effectiveness of restoration plans [12].

HVDC is new technology applied to transmission and distribution systems due to development in power electronics HVDC systems convert AC to DC at transmission end from DC to AC at receiving end. These systems also provide Asynchronous connection and control of power through the link. Power losses and investment lost is minimized, applied for interconnected system to make power flow reliable. HVDC technology has also multi terminal interconnection ability can be utilized for long distance power transmission, submarine and asynchronous interconnections. For practical utilization of HVDC, Conversion of AC lines into DC lines can be considered as a solution to existing worldwide bottlenecks. This conversion also provides stability and control ability. These conversions can lead to formulation of HVDC super grid to combine several countries. Traditionally for modification in existing systems, HVDC systems use LCC (line commutated convertors) that control only Active Power. In LCC capacitor banks and bulky filters are used to attenuate low order harmonies and only active power is controlled. Local startup generation system is main requirement of LCC systems as they require high short circuit source. Main drawback of LCC is communication failure which can lead to black out of several cycles. As LCC and thyristor based HVDC does not supply passive grid, to ensure this facility PWM based HVDC VSC technology is applied [13]. In contrast to LCC, modern IGBT’s technology in VSC, having independent control of both active and reactive power Active and Reactive power both are controlled and no requirement of bulky filters to reduce harmonies and generating source. Also, they are free from problem of communication failure [14] and have black start capability so VSC is emergency technology and developed continuously. In already present HVDC system we use synchronous compensator that first energizes the link receiving end and then enable the link to supply part of receiving end that is being restored from black out. Compensator is used for voltage regulation purposes [15].

M. Benasla, T. Allaoui, M. Brahami andM. Denaï [73] described the characteristics related to the influence and conceivable benefit of HVDC links on the dynamic performance of the European system. The above mention paper shows that the HVDC links between North Africa and Europe can significantly increase the dynamic performance of the European system particularly in the southern regions.

M. Larruskain, et. al. suggested that tower head structure can be slightly changed for conversion of AC lines into DC. In simple services circuit AC lines feasible conversion is mono polar line while double circuit AC lines can be converted into bipolar DC lines. AC lines into DC lines can be implied by maintaining original tower structure with new modifications. Investment for this case is lower as compared to cost applied to tower structure modification. It is observed that for simple circuit AC lines tripolar DC lines is superior than modulated bipolar topology with respect to power enhancementand bipolar option create least power. For double circuit lines the most feasible conversion is one bipolar with three conductors per pole and one conductor per pole in three bipoles.

Jicheng Yu, LeiGu [3] proposed thatin already built HVAC systems, embedded HVDC-VSC that is based upon IGBT's can be introduced in order toenhance systemstability and power transfer capability. Interconnections employed for VSC are back to back, mono polar and bipolar Back to back scheme is used in asynchronous links. In mono polar configuration, only one conductor is used. Most widely method used is bipolar configuration due to stability issues in mono polar configuration [16].

Recently HVDC systems are applied throughout the world. Reactive power requirement and harmonic reduction are major issues of these systems. Conventional controller is controlled by thyristor by pass valves for one bridge in case of two series connected bridges. Hussein D. Al-Majali [17] explained that in modified converters GTO thyristor is applied for by pass valves. In this case turn off or firing angle is being controlled by utilizing turn off characteristics of GTO. By using GTO, during inverter and converter modes of operation there is no requirement of on load tap changer as in case of conventional thyristor. Also, harmonics reduction and reactive volt ampere absorption is superior in case of GTO based converters [17].

Traditionally HVAC is used for transmission. S. Barsali, R. Salvati , R. Zaottini [18] proposed that power can be extracted from sea currents and wave energyin the ocean in addition tooil and gas. This power can then be transmitted to offshore and onshore grid stations by HVAC and HVDC. Submarine cables have high capacitance, so they require high reactive power compensation. In case of HVDC there will be no capacitance of these cables which will result in good power control and least losses. One important factor is submarine cable cost and maintenance. HVDC cables have less losses as compared to HVAC and HVDC VSC has more losses as compared to HVDC LCC. Short circuit current of the system is maintained with in its limits in case of HVDC [19].

Wang, and MiSa Nguyen [20] proposed that Marine Current Farm (MCF) and Offshore Wind Farm (OWF) can be integrated by HVDC link. In case of multiple connections two OWFs and MCFs are used in order to create super grid by using multi terminal (MT) HVDC link. Traditional MT HVDC was based upon LCC but VSC configuration is most suitable as compared to LCC based HVDC systems. As in VSC reactive and active power control is independent so there is no commutation failure and no power reversal is needed. Power Oscillating Damping (DOP) is used to control MT HVDC link by using pole placement scheme. It was observed that as compared to VSC HVDC link and HVAC better damping characteristics are obtained and severe faults are suppressed with MT HVDC link [21-22].

Due to increase in energy demand other alternatives are required and to transmit energy to load centers is the main problem. In coming years massive development in wind energyis expected. To reduce expensive back up generation, electricity storage and to support renewable energy resources integration of power sources is required. HVDC connections take short time and are more efficient as compared to HVAC grid extension. Gerard L. Doorman, Dag Martin Froystad [23] suggested and analyzed an HVDC interconnection scheme between Great Britain and Norway for existing system. A simulation model was developed to simulate the power systems of these two countries. It was observed that interconnection will not give real financial benefits in existing situation but promising to give over all advantage in the future after ten years. For this purpose, an HVDC cable of550km and 900km is suggested. Nowadays any of interconnection is not profitable but alternatives are profitable if they are considered in future [24-25].

3. STANDLONE HVDC TRANSMISSION

HVDC interconnections, as mentioned above, is an efficient way to link multiple asynchronous high voltage AC networks but transmission over long distances using AC networks is vulnerable to high power losses. On the other hand, due to its multiple advantages, HVDC transmission is one of the power transmission systems that has captured the attention of transmission organizations for bulk power delivery over very long distances. In USA the total length of HVDC lines was about 3 percent of the entire length of the entire high voltage system in 2002. But its market share is expected to increase 44% by 2015. In a study, performed by U.S. department of energy [26] it was found that standalone long-distance HVDC transmission systems have comparatively less cost than HVAC lines when used for long-distances and operators at transmission systems can control the direction and power quantity flowing over HVDC lines more efficiently. Since DC does not depend upon frequency, the energy can be transported and recollected with ease [27]. HVDC is an efficient solution for transmission of renewable energy resources-based power. Power transmission using standalone HVDC system as compared to conventional HVAC transmission system has several advantages like it is cost effective and provide better returns over very long distances like several thousand kilometers e.g. when used to transfer power across seas and oceans [28].

Christof Humpert [29] listed following advantages of HVDC based transmission systems;

- Only ohmic losses and no eddy currents losses
- Inductance and Capacitance of transmission line in HVDC system have no impact so DC transmission lines can be used for long distances, e.g. long submarine transmission cables.
- Power flow and transfer through HVDC systems is easy, stable and controllable.

R. Sharma, T. Rasmussen, K. Jensen, and V. Akamatov [30] have reported that the HVDC transmission lines have no charging currents, skin effect and need a smaller number of conductors as compared to HVAC transmission lines. HVDC transmission systems do not require intermediate switching stations and the size and cost of circuit breaker to clear the faults in HVDC transmission systems is reduced.

CIGRE Joint Working Group B2/B4/C1.17 [31] have presented ten different configurations of HVDC lines having voltage levels of ±300kV, ±500kV, ±600kV and ±800kV for different numbers of conductor bundles. A considerable amount of research has been done on economics of HVDC transmission schemes. For example; M. L. dos Santos, et al. [28] have investigated economics of HVDC transmission system as compared to half-wave length transmission system. Their results suggest HVDC to be more economical solution for very long-distance power transmission. However, Christof Humpert [29] stated that the cost of HVDC transmission system would drastically increase if parallel conductors are used to increase the maximum power capacity of transmission system, say power up to 5 GW or above.

Suhua Lou et al., [32] have proposed a methodology for optimization of HVDC transmission capacity to maximize the transmission capacity and net profit. The results show an optimum capacity of HVDC line between limit of 3500 to 9500 MW. It was also observed that overall profit gained from an HVDC line increases rapidly when the capacity of HVDC is close to lower level limit as mentioned above. However, profit increases slowly when HVDC line is close to upper limit as mentioned above.

Although, HVDC is an economical solution for long-distance power transmission but even then, the capital cost of new HVDC overhead lines is generally very high, which is the main reason that hindered the adoption of HVDC transmission networks across the world. One solution to this bottle neck is using HVDC with existing HVAC systems. This novel idea of simultaneous ac-dc power transmission through a single circuit ac transmission line was first proposed by K. P. Basu and B. H. Khanin [33]. HVDC transmission lines can also be used in parallel with Extra High Voltage (EHV) ac lines to improve the stability issues caused by transients, by damping out the oscillations produced in power system

Q. Guo, J. Zhao, L. Niu [34] have performed a case study on faults prediction and analyzed their effects on reliability of the HVDC power transmission system. Since, HVDC power systems are mainly composed of DC transmission lines and converters, however equipment faults in different regions have their own characteristics and the impact on the DC system is different. Faults in HVDC networks can be broadly classified as “symmetrical faults” and “asymmetrical faults” as reported in [35] and simulations performed, and numerical values calculated for HVAC and HVDC transmission systems reveal the great difference between fault current magnitudes for the two systems, HVDC transmission system having considerably lower fault currents for line to ground, line to line and transmission line faults.

The demerits of HVDC transmission can be summarized into following point;

- Converters used in HVDC networks are very expensive and require a lot of reactive power for rectification and inversion.
- Line to ground voltage is limited by the danger of flashovers.
- The maximum power capacities of HVDC lines are limited due to natural limitations of insulators used in HVDC networks.
- The cost of HVDC system may increase greatly if multiple parallel conductors are needed to be used for higher power capacity.

According to Imamovic D, Kern T, Muhr M. [36]to transmit a given power HVDC would require 2.5 times more voltage than required in case of HVAC if we want to make HVDC efficient than HVAC.

4. HVDC AND RENEWABLE ENERGY RESOURCES

The excessive use of fossil fuels is the cause for severe environmental damages like the global warming, rise in the concentration of carbon dioxide and climatic changes etc. More over the fossil fuels are depleting which is a reason for fluctuation not only in their prices but also in their supply. There are compelling reasons which motivate the world to shift towards the renewable energy sources. Transmitting energy from renewable sources would require high voltage lines. For this purpose, HVDC is more suitable as compared to HVAC because most of the renewable energy sources specially wind is in offshore or remote areas. John Mac Cormacket. al., [37] presented a scheme for delivering wind power over an optimized HVDC network. The study was carried out on Jiuquan wind power base located in western China for 2015.

The results of the study prove that an HVDC link with an optimized transmission capacity will considerably improve quality and cost of power delivered. The unit investment of HVDC transmission line has a large impact on total power transmitted, profit and optimal schemes. In their study M. Fadaeennejad and his co-workers [38] reported that in the last decade there have been a significant increase in the installation of different renewable energy generation plants including wind (offshore and onshore), solar, hydel and ocean energy (wave and tidal). Developed countries are trying to reduce the usage of fossil fuels by accelerating energy production from renewable sources. This shift to the renewable energy has not only backed up in meeting the growing energy demands of the world, but also has reduced the environmental fears and concerns. All this requires transmission of power from remote areas for which HVDC can play a promising role. Liberti L, Carillo A, Sannino G[39] in their wave energy resource assessment state that renewable energy has also made it possible to power the remote and isolated areas on the globe. HVDC link integrated with renewable energy is the best option to transmit power to existing load centers.

According to the Global Wind Energy Council (GWEC) [40], the global wind installed capacity reached almost 194 GW at the end of 2010 with a growth rate of 22.5% per year. World's electrical energy demands have increased more than 200% of that in year 2007. During the period of 2007-2010, about 20 GW of new wind power installations were constructed which is a growth of about 27%. Neij, L. [41] reported that in the same time frame new solar power installations are about 3 GW which is an increase of 50% with respect to previously installed systems. According to Saket A, Etemad-ShahidiA [42,43] The Wind Power Plan in China is introduced and till year 2020 seven wind power bases each with an installed capacity of more than 10 GW will be completed. Till the year 2009 all over the world about 157.8 GW of energy was produced by wind out of which China has the largest share. According to Antonio [44] the wave energy has a huge power potential and methods to make use of this power are still in the stages of development. Mehlum E Tapchan [45] suggested that wave energy is much predictable source as we are aware of the high tide and low tide time. So as compared to wind power it has more utilization factor and higher power density. Wide variety of wave energy systems are under the development stage and now it's very difficult to tell which the winner will be. Usually the power generation source is at larger distance from the consumers e.g. Off shore wind power plant (100's of km away from shore), wave or tidal plants usually deep in the sea or on some remote island, a large solar power farm away from the city at some deserted area. HVDC provides economic and efficient power flow from source to grid if it's directly provided to consumer or added to existing HVAC grid [46].
M.Z. Hossain, N.A. Rahim [74] described that power DC/DC converters are extensively deliberated as the important part of renewable energy, next HVDC, automobile, medium voltage dc (MVDC) and many other systems. They have given the review about the current state of the art in power dc-dc converters (PDDC) technologies by imagining the latest influence to modulation topologies and control techniques, maximum power point tracking (MPPT) effects, constraint selection and performance optimization, and developing applications. From the above-mentioned discussion, it can obviously be remarked that PDDCs have demonstrated its level of maturity not only in commercially, but also in academic development as well. Jing Hu, Chengyong Zhao [47] suggests as the generation shifts more towards the renewable power the questions arises about how to make grids more flexible and improved so that they can accommodate discontinuous generation by the renewable sources. It means we need not only to work for the improved efficiency of the renewable, but it is also necessary that to expand and modernize the existing electrical transmission systems, so they are able to accommodate the energy generated by these renewable power sources. The answer to all these questions lies in the use of HVDC. In fact, it wouldn't be wrong to say that the generation from the renewable energy power sources has revived the use of the HVDC. Andre Bodin high lights some of the advantages which HVDC offers particularly for the case of energy from renewables [48]. HVDC transmission lines are roughly 5 percent more efficient than equivalent AC lines when moving the same amount of energy. Imagine in the case of very large power flow from a high capacity wind, solar or wave farm thousands of additional consumers can be benefitted. Lower visual impact and less space and height are requirements for DC towers as compared to AC towers. This makes them more environmentally friendly for the transmission of clean energy with minimal impact on the marine life particularly in the case of deep sea wave energy farms and off shore wind farms. When moving large amounts of electricity over distances of 500 km or more, HVDC transmission lines cost less than AC lines. Because HVDC is a more efficient way to transfer energy, transmission costs are lower, which helps renewable energy favorably compete against other power sources. HVDC lines require one-third fewer power conductors (wires) and insulators to transport energy than AC lines. This results in a narrower right-of-way and comparatively smaller footprint, minimizing effects on existing land use and lessening environmental impacts [15].

5. HVDC CONVERTERS AND CONTROLLERS

Renewable energy sources are of main importance now days. Almost all these sources are inherently DC, which in many cases need conversion to AC for general as well as specific use. When we consider HVDC and conversion into HVAC then converters, controllers, inverters and filters are the devices which should be understood and well learned to easily handle the said process. Noroozian N, et al. [49] categorizedtwo main transmission methods i.e.

- Current Source Converter High Voltage DC (CSC-HVDC) transmission technology
- Voltage Source Converter High Voltage DC (VSC-HVDC) transmission technology.

VSC-HVDC is good and will be used in near future in new energy applications**.** According to Xin Tang and Dylan Dah-ChuanLu [50], VSC-HVDC solves the problems arising due to conventional methods. This includes limitation and characteristics which are undesirable. Which includes requirement of AC network with large short-circuit ratio**.** When we go further regarding the characteristics of VSC-HVDC, then by analyzing the natural frequency characteristics of said transmission line, Song Guobing, et al. [51] described that natural frequency is related to fault location on VSC-HVDC transmission lines. In case of DC transmission, transient energy is greater than that of AC transmission.H.S. Ramadan, et al. [52] suggested Robust nonlinear control methodologies-based Sliding Model Control (SMC) for the improvement of performance and stability. In this method control signals based on SMC are formulated to control reactive and active power at specified points, thus controlling power factor close to unity for HVDC link. In addition to that DC link voltage is monitored constantly.

Geng Tang and Zheng Xu [53] suggested a hybrid HVDC topology consisting of Line commutated converter (LCC) and Modular Multilevel converter to achieve high speed fault clearing capability in bulk power transmission system. The foremost determination of a multilevel converter is achieving an output voltage or current with less harmonic distortion, low switching frequency and a balanced DC link voltage [75]. In this approach MMC is installed on inverter end combined with LCC on rectifier end to clear DC line faults. The power flow is from LCC rectifier to MMC inverter which is unidirectional. The process of starting this system consists of two phases, namely uncontrollable and Controllable. The maximum value of charging current in uncontrollable phase can be restricted at desired level by selecting suitable current limiting resistors which are inserted during charging phase. The overall results of this study governed that an HVDC system with LCC rectifier and MMC converter is better able to perform during transients.

R.K. Pandey and Arindam Ghosh [54] proposed a new methodology which depicts the design of self-tuning controllers for HVDC systems having two terminals. The beauty of the system is that rectifier gets the information of the current at inverter terminal; therefore, any change in inverter current is determined as disturbance. The rectifier then acts to mitigate this change by changing its own operating parameters. The stability of this control scheme was tested under different kinds of fluctuations.

It is expected that by 2030 25% of the cars on the road will be Plug in Hybrid Electrical Vehicles (PHEV). Das T and Aliprantis D [55] proposed a solution to use PHEV as regulators for mitigating power quality problem in grid. For this purpose, most, suitable way is to use a bidirectional DC to DC converter or DC to AC converter if the grid used is HVDC or HVAC respectively.

F. R. Islam and H. R. Pota [56] proposed a theory to design a controller and possibility of employing PHEV's as virtual active filter in HVDC network to investigate a low-cost filter solution with two different topologies.

i. Virtual active filter at rectifier end of HVDC link only.
ii. Virtual active filter for both rectifier & invertors.

Nowadays, VSC schemes utilizing hard-switched series strings of Insulated Gate Bipolar Transistor (IGBT) operated in Pulse Width Modulation (PWM) mode are easily available [57].

Feldman, R..Tomasini, M. Amankwah, E. Clare, J. C. Wheeler, D. R., & Whitehouse, R. S proposed a low loss VSC configuration for HVDC transmission. In this scheme the combination of MMC cells and soft switched H-bridge is utilized. H-bridge is made up of strings of IGBT connected in series in order to sustain higher kick back voltages as generated by R-L load during switching. Results show that this converter operates stably with varying combinations of an R-L load. Losses in this converter have been demonstrated in the range of 0.85 to 1.1%.

In many areas of the world asynchronous ac grid connections are made using LCC-HVDC for bulk power transfer. Due to low SCR of ac network it has poor voltage regulation ability. This cause commutation failure of LCC-HVDC link connected with this line. ChunyiGuo, Chengyong Zhao and Xiuyu Chen [58] proposed a scheme to enhance the immunity of LCC-HVDC link against commutation failure. Different combinations of VSC inverters, VSC rectifier and LCC inverter and rectifier were combined in hybrid approach. It is obvious from all the topologies studied that VSC when used as rectifier provides better improvement in the performance of LCC converters. This scheme also increases the immunity of LCC inverter against commutation failure. The vice versa is not a better option. The advantages of LCC HVDC links are reduction in transmission losses, lower equipment cost and possible use of higher voltages.

Soledad Bernal-Perez, et al.[59**]** have technically examined the feasibility on the use of a hybrid diode rectifier and VSC inverter HVDC link for the connection of large offshore wind farm. For onshore inverter Point of Common Coupling (PCC) short circuit if brake resistor and surge arresters are used additionally then this proposed methodology can keep the voltage link below 1.15 p.u.

Jun Zhu, et al. [60] proposed a new dynamic mathematical model of VSC-HVDC. This model is resultant of Park's transformation which uses an orthogonal transformation matrix and calculates the stability and performance of VSC converter by introducing three types of controller's namely inner current controller, outer controller, and supplementary controller. This design shows an increase in the damping ability of power system having VSC HVDC using controllers which spread the disturbances on a wide area, thereby suppressing it immediately

6. HVDC INSULATION

To improve transmission capacity, the operating voltage of High voltage direct current (HVDC) links is being increased from a maximum of 500-600kV in past to 800kV nowadays. It is expected to be 1100kV or more in near future. According to R. N. Nayaket. al. [61], the design of the oil/paper insulation system of the HVDC converters is one of the biggest challenges in 1000kV or higher systems. Especially, barriers and cables, connecting windings to bushings are the critical point because their insulation is subjected to a combination of AC voltage and switching surges.

The electrical conductivity of insulating materials, particularly that of insulating oil determines the behavior of DC insulation systems. Therefore, the conductivity of oil is an important parameter to be considered condition assessment and design of oil-filled HVDC insulation systems. Insulating oil has a nonlinear conductivity characteristic which vary with field strength, temperature, water content and contaminants generated during aging. The conductivity of oil also depends upon the time since it has been in-service. This is because of charge carrier drift processes. The conductivity of a liquid is also dependent on other factors like recombination of ions, mobility of ions and energy of activation, dissociation in oil, diffusion of charges and charge injection at electrode. According to M. Liebschner [62], in liquids, the ion drift methods can help better to describe the conduction activity. In summary, it is very difficult to present a comprehensive technique governing all aspects of conductivity. This is still a future research avenue to find a simple and fast technique that gives enough information about properties relevant to integrity of oil. CIGRÉ Joint Working Group A2/D1.41 (HVDC transformer insulation – Oil conductivity) is working on this issue.

The oil-paper/pressboard insulation system is the main insulation in HVDC converters. The common problem in this insulation system is space charge accumulation. According to X. Wu et. al. [63], there is distortion in electric field pattern of the dielectric material due to the presence of space charge. This results in accelerated aging or even failure of insulation. Previous literature in this area is focuses mainly on either thin impregnated paper or multilayer paper [64]. It was observed by M. Huang et. al. [65], that the dynamics of charge accumulation depends upon on the applied voltage, sample status and environmental conditions. In addition to that, the junction between layers of paper can reduce the amount of charge flow and mobility. Despite that still the real converters widely use the pressboard. Hence the investigation on the interface between pressboard and oil is the need of hour. Boundary between two different insulation materials in an insulation system is considered the vulnerable point.

The pulsed electroacoustic (PEA) technique is used to examine the behavior of space charge in the oil-impregnated paper insulation [66]. In these studies, the primary focus was on the thin Kraft paper because of its large acoustic attenuation in oil-paper insulation. R. Liu and A. Jaksts [67] used pressure wave propagation (PWP) technique to study the space charge dynamics in the 1mm thick impregnated pressboard. The compatibility of oil, with mixture of aramid cellulose papers for use in insulation, was investigated. The results were not satisfactory at that time due to the resolution limits of experiment equipment.

The oil-paper insulation life is strongly affected by moisture because it lowers the electrical breakdown strength and thermal endurance of the insulation [68]. According to I. Fofana, H. Borsi and E. Gockenbach [69] moisture is known as the "enemy number one" after the temperature for oil-paper insulations. During the normal operation of HVDC converter, the presence of moisture is unavoidable. Moisture in the insulation can increase in several ways due normal ageing and exposure to the atmosphere etc. [70]. The probability of breakdown of the paper insulation increases due to high moisture content. In addition to that, the increase in moisture causes the insulation to degrade prematurely, causing threat to safety of equipment [71]. So investigation of the effect of moisture on distribution of charge in multi-layer oil-paper insulation system is still a potential avenue for research.

Temperature and Moisture have a severe effect on oil-paper insulation life. Together they reduce the dielectric strength and thermal durability. This increases the probability of breakdown of dielectric. To minimize the effect of moisture and temperature on the oil-paper insulation for the safe operation and increased life of the insulation system, multiple layers of insulation of oil-paper are commonly used in practical converters [72].

7. CONCLUSION

Nowadays for distance less than 500 km most economical option is HVAC. HVDC is considered a best option for power transmission in near future. Construction of new HVDC power lines is difficult due to social or political reasons so conversion of AC lines into DC lines is highly remarkable. One of the economic modes to make this conversion possible is modifications in tower structure. Due to high investment cost this concept is most feasible for distribution lines instead of transmission lines. For conversion of AC lines into DC lines VSC technology is most versatile for convertor stations as compare to LCC due to startup complexities. HVDC super grid can be made possible after this conversion.

Embedded HVDC has more benefits as compare to classical HVDC. Embedded HVDC shows superior applications in offshore wind farms, power sharing between weak AC system and high load centers, in feed large urban areas and DC segmented grid. Embedded HVDC uses applications of semiconductor devices. Due to low cost of semi-conductor devices in future, HVDC power transmission system will become more feasible.

HVDC link used with a synchronous compensator can provide proper mechanical inertia. So, it is a cheaper solution and powerful tool for performance improvement. Offshore wind farms are considered as huge power sources and can be integrated with other sources of energy to meet increased energy requirement. An example of such a system is HVDC interconnection between Norway and Great Britain.

As far as transmission of bulk power over long distances is concerned, HVAC has its limits which supports the concept of standalone HVDC transmission systems. Some limitations of HVAC transmission systems, like connecting asynchronous systems, can be addressed with HVDC interconnections. But transferring bulk power using HVAC lines over long distance remains a problem due to capacitance/inductance of overhead lines, which limit the transmission capacity. Standalone HVDC transmission systems however, have no such limitations. In case of HVDC the reactive components do not limit the transmission capacity of line. Also, there is no skin effect in

DC lines due to which the conductor cross section can be fully exploited, and digitally controlled systems can have more control over power flow. The towers needed for HVDC transmission lines are also smaller in size as compared to HVAC, hence less costly. There are different schemes of HVDC transmission capable of transferring bulk power from several hundred to thousand MW (like in bipolar HVDC systems) over long distance which can be adapted according the requirements of power systems.

To meet the growing energy needs of the world there is a wandering shift to generate power from renewables. With the increased renewable energy generation, the grids need to be suppler and must be capable of handling the irregular power delivery from the renewable. HVDC is the only ideal option to meet these requirements. It would not be wrong to say that HVDC got its revival due to increased production of energy by renewables. HVDC permits variable sources to be connected to the DC grids. Due to the increased efficiency long distance transmission from off shore sources to on shore grids using HVDC is the only cost-effective option. It allows HVAC to relate to renewable sources with improved power quality, stability and reliability. With the use of HVDC power operators can immediately change the direction of power flow making it possible to transmit renewable energy between countries.

When we are concerned with the conversion of DC to AC, Sliding Model Control (SMC) is a control technology used to control active and reactive power and power factor for HVDC link in case of VSC-HVDC. During transient's better performance is obtained in HVDC system with LCC rectifier and MMC converter. Current Regulator designed at rectifier end can minimize current oscillations at inverter terminal. Power quality problem in grid can be mitigated by using PHEV as regulators. In hybrid approach which combines different combinations of VSC and LCC inverter/rectifier, immunity of LCC-HVDC link to commutation failure can be enhanced.

The understanding of HVDC insulation systems and their reliability is hot area of research and needs more exploration. Characterization and aging of insulating materials used in HVDC transformers as a function of dielectric stress, temperature and moisture needs a lot of investigation. For example, development of new solid insulating materials like WEPRI board, with better conductivity that matches with oil. The monitoring of oil conductivity throughout the life of HVDC converter must be adopted in order to ensure its reliability. Research and analysis on insulation systems behavior under combined DC and AC stress is also needed. The main reason for this is that HVDC transformers are tested separately with AC and DC voltages, however during operation, they are subject to both type of voltages at the same time.

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