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Medium Voltage DC Technology Developments, Applications, and Trends

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SUMMARY

Electricity has become the life blood of modern society. There is no single resource commodity that we depend upon more in our daily lives. Yet, over 100 years later, from the time when AC was proven superior over DC, we still rely on electric power equipment, networks and grids that were built up primarily during the middle of the 20th Century in most developed nations, on the premise of AC technologies. At the time, selecting AC was logical with the existing equipment of the 20th century. Today, modern advances in the transportation industry have often come through the application of electronics (electric vehicles and magnetic levitation trains, for example). These innovations utilize DC power, requiring an AC to DC conversion within the current grid infrastructure. We are living in the emerging era of the micro-grid, composed of distributed generation systems that produce DC power. Finally, solutions for integrating renewable energy with storage devices are attempting to be developed at the utility scale to deliver DC power. All of these factors combine to form an opportunity for the development and further deployment of DC technology throughout the electric grid at all levels, from transmission, through distribution, to end-use.

The purpose of this article is two-fold. First, the authors review select DC technologies and systems that were developed and used prior to the current discussions in the engineering community around DC. The topics include High Voltage DC (HVDC) technologies and operating experiences with DC on ships. Secondly, a new era of research and development on Medium Voltage DC (MVDC) is explained. Strictly, MVDC is a collection unit for many DC generation resources and loads and a power conversion problem being addressed by the team at the University of Pittsburgh. The MVDC collection system serves as an additional layer of infrastructure existing between transmission and distribution. The article is concluded with a discussion of several standards relating to DC applications, with the overall motivation to inspire discussions and further investigation amongst working professionals in this area of technological advancement.

KEYWORDS

Collection System, DC Systems, High Voltage Direct Current, Medium Voltage Direct Current, Off-shore Oil Platform, Power Electronics, Renewable Integration, Ships, Standards

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I. INTRODUCTION

At the turn of the 20th century, a fierce battle was fought over how electricity would be generated, delivered, and utilized. Of course, originally and for all the right reasons, the approaches advocated by Westinghouse and Tesla for Alternating Current (AC) ultimately won out over Edison's push for Direct Current (DC). Ever since, and certainly up through the turn of the 21st century, the electric power industry has been established and expanded across the globe predominately using AC technologies and networks. In recent years, widespread interest and a desire to integrate many forms of renewable energy resources have captured the attention of many power system equipment providers. In addition, more end-use loads have evolved that operate with the supply of low-level DC based power.

The U.S. and many parts of Europe saw the greatest development and expansions of their power grids during the 1930s to 1970s, when the vast majority of infrastructure was put in place as part of pre- and post-World War II federal programs. With strong attention and growth in the areas mentioned, future grid layouts and current installation practices may need reevaluated in the 21st century. Power electronics technology in the forms of HVDC and FACTS for utility scale applications and advancements in power conversion units (DC/DC, rectification, and inversion processes) for end-user applications are providing more options. A new arena of research that is being investigated by the authors is in the area of Medium Voltage DC (MVDC) technology development, which serves as a collection platform for many DC based processes and as an additional layer of infrastructure between the transmission and distribution sectors. Throughout this article, we will present the premise as to why engineers and scientists have begun exploring DC today, and research thrusts the authors are participating in to push technological boundaries.

II. PIONEERING DC INNOVATIONS LEADING TOWARDS MVDC DEVELOPMENT

Starting in the 1970s, developments have been made in power electronics technology to convert AC to DC and vice-versa. The conversion process from AC to DC is vital for establishing a stiff DC supply for processes downstream in the electrical apparatus. Most early-era DC systems were developed for very-long-distance transmission linking economic resources from remote locations to more densely populated load centers, and were typically several hundred miles or more in length. This still holds true today for many High Voltage Direct Current (HVDC) applications. Besides large scale power applications like HVDC systems, other uses such as naval-based ship design has considered the use of DC for a variety of reasons including space savings. Throughout this section, a snapshot of these major categories of DC solutions will be discussed.

High Voltage DC Transmission: Solution for Transferring Bulk Power

The power grid of the future must be secure, cost-effective, and environmentally friendly, yet reliably integrated and built with intelligent solutions and innovative technologies. High Voltage Direct Current (HVDC) has proven its merit over high voltage alternating current (AC) transmission for long distance power delivery applications in many cases. HVDC advantages include reduced right-of-way clearance, improved control over power flows, power factor correction, less infrastructure, and reduced losses. HVDC also provides an asynchronous link for strong, but instability-prone AC power systems, offers advantages for renewable energy integration, and advanced HVDC systems can provide black-start capability. The cost of AC/DC conversion and DC/AC inversion terminals, for HVDC systems, has steadily decreased as the voltage ratings, current capacity, efficiency, and cost of the solid state electronics in these converters has decreased over the years, along with continued improvements in overall system design and construction [1]. HVDC interconnections have 30 to 50 percent less transmission loss than a comparable three phase AC transmission system [2]. These important factors, other attributes of HVDC technology, and the emerging applications of DC resources and supply, establishes the potential for a paradigm shift in the future development of power systems toward a larger overall DC infrastructure.

Experience with DC on Ships

The concept of an integrated power system (IPS) is familiar terminology for the Office of Naval Research and research groups within universities. The idea of IPS is to enable all the energy generated to be used by all the ship systems. Earlier IPS concepts showed that the energy within the ship propulsion system would be enough to supply traditional ship operation needs so that service generators could be eliminated, yielding significant fuel savings. Efficient use of generated energy is important, but another critical factor in ship design is space savings. Traditionally, every marine load or load circuit was interfaced with a transformer strictly for galvanic isolation. Transformers have two main functions in addition to providing galvanic isolation – impedance matching and voltage scaling. Although vital and a workhorse of past and current electric power systems, transformers rated for 60 Hz are large and heavy. The size and weight of the transformer is inversely proportional to the operating frequency. [3]

Historically, DC has had protection issues limiting DC distribution systems to a maximum rating of 1,000 V level on naval ships. Traditional electromechanical switchgear is slow and DC voltage collapse can be much faster than AC collapse. Amongst power engineering professionals, it is well known that AC circuit breakers make use of zero crossing points to clear faults, but in DC systems there are no zero crossings. Today, solid-state devices and power converters are making DC a more attractive and feasible option. Rectifier and inverter sets found in today’s modern motor drives have the capability of identifying faults in microseconds. If the technology and knowledge within the motor drives industry is mapped to future DC architectures, it is expected that the same benefits in controller performance and protection will be inherit in these systems. [3]

III. MEDIUM VOLTAGE DC MODEL DEVELOPMENT

Moving beyond the traditionally limited applications of DC power systems, the medium voltage direct current (MVDC) concept is conceived as a collection platform which will provide an additional layer of infrastructure between transmission and distribution to help integrate renewable generation (photovoltaic, wind), energy storage, and various end-use loads (industrial facilities, data centers). A general overview of the proposed MVDC architecture is shown in Figure 1. The addition of the MVDC architecture can lead to increases in efficiency via a reduction in conversion stages. For example, the MVDC architecture will aide in the reduction of conversion stages needed for integration of lower voltage renewable generation into the electric grid.

Presently, the MVDC concept has been proposed in literature but, yet to date, no complete models or simulations accounting for the entire system exist. A model of the MVDC grid has been constructed and simulated within the PSCAD/EMTDC simulation environment. To give an appreciation of the detail of the model, all machines, all switching characteristics of the power electronic converters, and the various DC loads are being simulated and captured simultaneously. To date, the MVDC grid consists of 5-MW permanent machine synchronous generators (PMSG) connected to the MVDC bus via three-level neutral point clamped (NPC) rectifiers and DC cable. 1-MW photovoltaic generation plants connected to the MVDC bus via a DC-DC converter and DC cable. Major loads include an industrial facility, electric vehicle charging station, and data center. The operation of this MVDC bus and its various sources of generation and loads are explained in greater detail within [4, 5, 6].

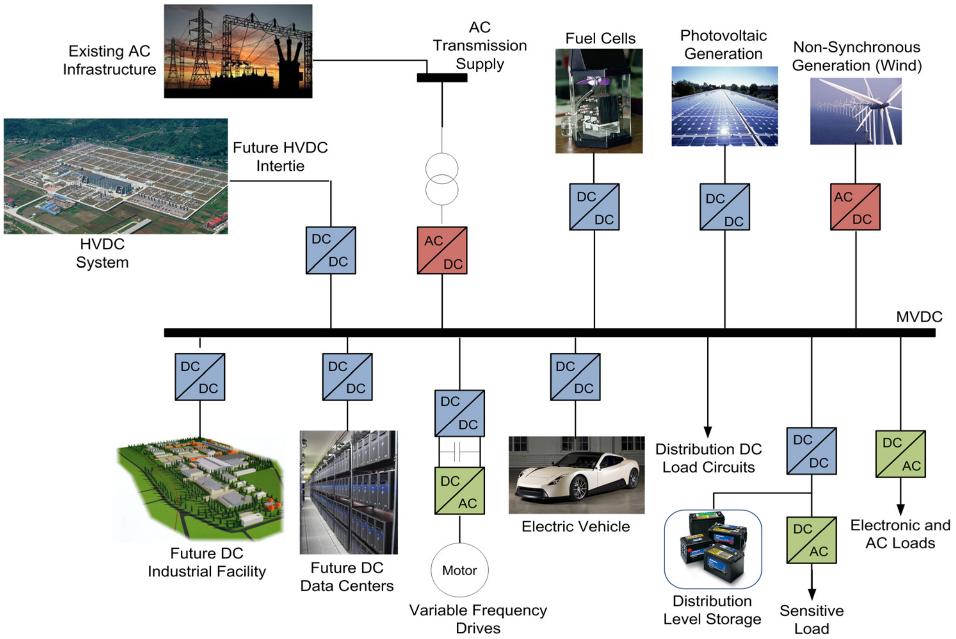

Figure 1. Medium Voltage DC (MVDC) System Architecture [4]

IV. NEW INVESTIGATIONS FOR MEDIUM VOLTAGE DC INFRASTRUCTURE

The Department of Energy (DOE), through FOA-414, has found great interest in exploring the integration of off-shore wind potential and has funded a team of diverse organizations to explore the wind speed behaviors at sea, and determine the optimal location for placing large wind turbines around the perimeter of the United States. Off-shore oil drilling operations, which are heavy industrial environments, rely primarily on AC variable frequency drives (85% of installed load) for applications such as propulsion, station keeping, drilling, and pumping product to the surface. Because the platforms are composed of large electric drive units and other machinery, operations such as those listed suffer from various power quality issues. These power quality issues arise from voltage sags, which are caused by the starting of large motors, and the energizing of magnetic components such as transformers. The power quality is compromised due to harmonic currents produced during the conversion from AC to DC for VFDs. Harmonic mitigation techniques exist, but additional equipment requires the need for more premium space at the expense of increased platform weight. [7]

With investigations being conducted by research and consulting teams, it is envisioned that large wind farm deployments will likely exist along the eastern seaboard (Atlantic Ocean). The eastern seaboards, from North Carolina through Maine, are also locations with the greatest potential for offshore oil and gas drilling. One major hurdle preventing large scale deployment of off-shore wind generation along the east coast is the lack of an electrical collection system to serve as a link between generation and transmission to shore – the MVDC architecture can serve as this link. The co-location of off-shore drilling platforms and wind generation will allow for the use of a MVDC collection system and provide both an environmentally-responsible and economical-sound solution for powering off-shore oil platforms. This innovative idea of connecting the two major themes in energy policy – off-shore wind generation and oil reserves – can potentially open up new business markets directed towards large oil companies, who take part in the drilling operations, as well as traditional power industry participants including utilities. A diagram providing a system level interconnection of local wind power generation with an off-shore oil drilling platform is provided in Figure 2.

Another opportunity under study involves intermeshed DC and AC networks. The authors believe that future grids will be composed of the traditional network with pockets of DC infrastructure meshed within the existing development for better means of integrating DC based renewables like photovoltaic systems to a common DC bus which supplies DC loads. Figure 3 shows a modified IEEE 13 bus test case, which provides a representation of the latter concept. These sorts of systems will need to be analyzed using traditional methods, such as through transient and stability assessments, more earnestly to examine interactions of networks with fixed (AC) or no-frequency component (DC).

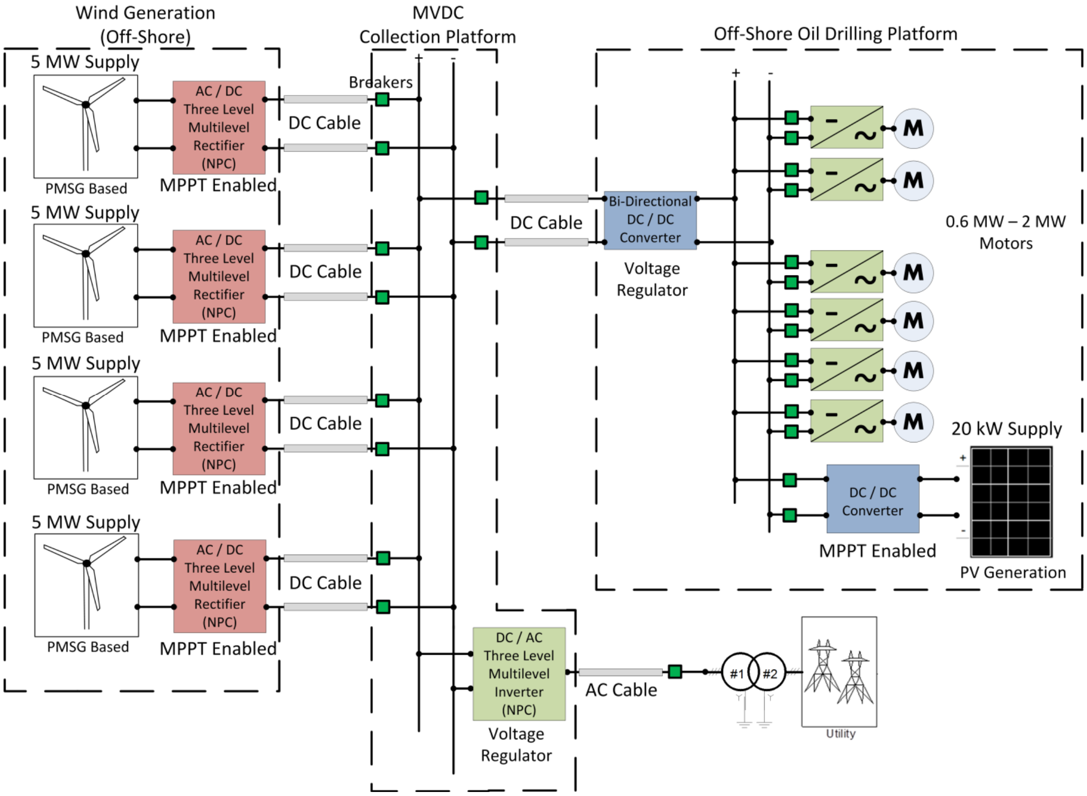

Figure 2. MVDC Architecture Utilized in an Off-shore Application

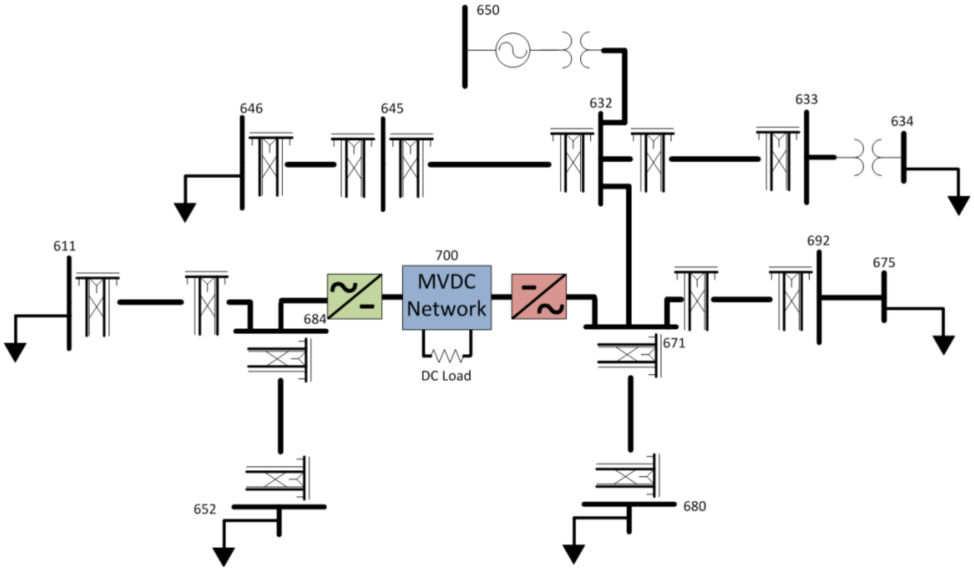

Figure 3. Meshed MVDC Network with AC System

V. STANDARDS IN MEDIUM VOLTAGE AC TECHNOLOGY AND FUTURE NEEDS FOR DC SYSTEMS

Engineers have developed concrete boundaries for classifying low and high voltage levels, and products and standards thereof. Determining the range for medium voltage tends to be difficult, and varies depending on the electrical environment being considered and the applications that are being investigated. IEEE standard 1585-2002, a guide for the functional specification of medium voltage electronic series devices used mainly for compensation of voltage fluctuation, specifies that medium voltage ranges from 1 to 35 kVac. IEEE standard 1623-2002 provides the same voltage range, a standard meant for specifying shunt connected devices to compensate for voltage fluctuation. However, NECA 600-2003, a standard for installing and maintaining medium voltage cables, sets the medium voltage range to be between 600 V to 69 kV.

Prior to IEEE standard 1709-2010, there have been no existing standards specifically for MVDC power distribution systems above 3 kV. This standard is the first attempt at describing recommended practices for 1 kV to 35 kV DC power systems on ships. Another thorough and extensive standard with respect to electric ships is IEEE 1662-2008, a guide for the design and application of power electronics in electrical power systems on ships.

From this brief discussion on medium voltage AC and DC standards, reviewers might notice two present issues, as well as future needs. The first is that there are still some inconsistencies from standard to standard on defining the range for medium voltage AC applications. Secondly, there are a limited number of DC standards at the medium voltage DC power distribution level. Other obvious forthcoming standards include DC protection, DC switchgear, and grounding, as well as a new set of standards related to phenomena that might arise in a DC environment.

VI. CONCLUSIONS

The grid of the future will not only be operated and maintained with traditional approaches that engineers are accustomed to dealing with, but also with new methods and routines that will need to be developed as DC systems increasingly intermesh with existing AC networks. DC power equipment technology and systems have shown their merits in the case of bulk power delivery with HVDC systems, and the US Navy has spearheaded the use of DC in ship designs. Taking the lessons learned from these environments, research teams will aggressively begin to start applying this knowledge for transmission and distribution applications. Large hurdles to this paradigm shift towards a larger role for DC infrastructure in power systems are expected, and will need to overcome since most experience lies within maintaining our legacy AC system and perhaps opposition. However, an evolution in DC application is emerging, that provides tremendous opportunity for technology development, research, and new business market growth, while at the same time advancing power networks towards greater design and operational efficiencies.

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