HVDC Transmission, Part 1 - Technology

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1. Introduction

I recently posted the following two-part series:

Intermittency Compatibility Toolkit, Part 1: *A primary resource in combatting climate change is renewably produced electric power. Even though these technologies have progressed far in the last couple of decades, and it appears that this trend will continue well into the future, we are still only at the start of this journey, and we will encounter many obstacles along the way. A major barrier is the first word in the title of this paper – intermittency.*

Many states will have major problems as they attempt to reach net-zero greenhouse gas. Also as intermittent renewables scale up, some intermittence problems will be more wide-scale, effecting whole regions. How will we deal with these?

Part 1 of this series will look at the Planning Tools that will alert us to looming intermittency problems, when there is still enough time to have several options to deal with them.

https://energycentral.com/c/gr/intermittency-compatibility-toolkit-part-1

Intermittency Compatibility Toolkit, Part 2: *Part 2 will look at a tool that will enable power to flow from region to region in North America, allowing more dispatching flexibility to mitigate both intra-regional and inter-regional variability. We will also look at another tool that provides flexible dispatching for existing AC transmission lines.*

https://energycentral.com/c/gr/intermittency-compatibility-toolkit-part-2

The above was an important series, but was really just an introduction to the subjects it covered. The one part of this series that I would have really liked to spend more time on was the subject of this series – HVDC Transmission. Part 1 of this two-part series will look at the current technology that is used for HVDC Transmission, and Part 2 will look at major HVDC Transmission projects that are currently being implemented.

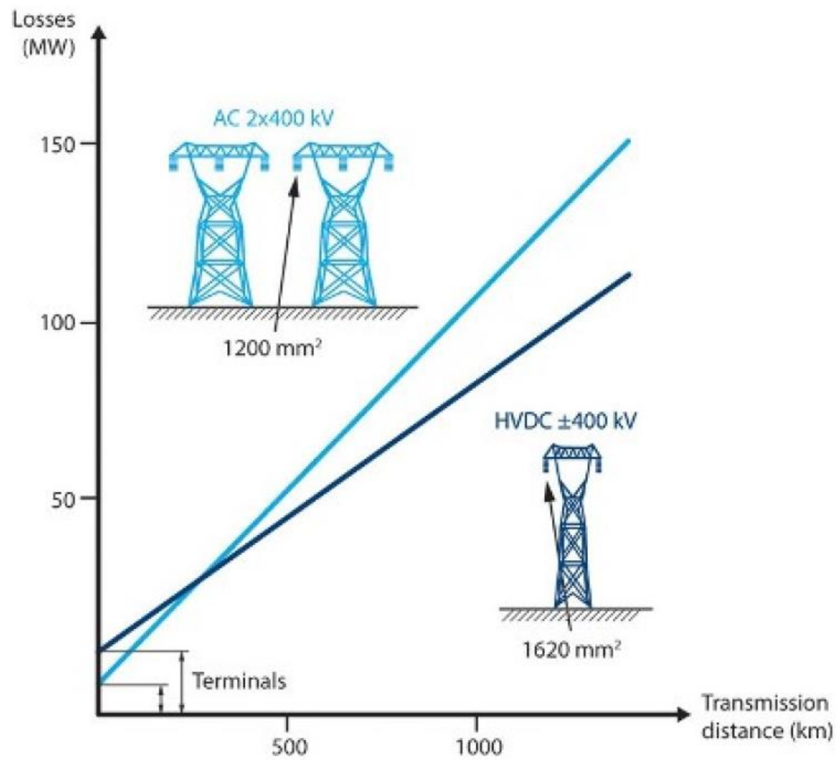
2. HVDC System Applications

In general an HVDC line tends to be used for specific critical and/or long-distance application whereas an HVAC line tends to be part of a large AC network composed of many synchronized AC lines that operate at various voltages.

The applications addressed by HVDC lines tend to be those that play to HVDC strengths. For instance:

- *Superior economics for long-distance application. HVDC lines are used to evacuate power economically from large power generators located away from demand centers. This could be large hydropower plants or a collection of renewable resources in a local area. HVDC lines are more economical in* *comparison to equivalent high-voltage alternating current (HVAC) lines because of lower losses and installation costs.*[1]

- *The power-carrying capability of AC lines is affected by the reactive power component of AC power, and the "skin effect" losses, which cause a non-uniform distribution of current over the cross-sectional area of the conductor. HVDC lines are not affected by reactive power components nor do they experience any losses because of "skin effect."*
- *On average, the losses on the HVDC lines are roughly 3.5% per 1000 km, contrasted with 6.7% for comparable AC lines at similar voltage levels. HVDC lines also experience losses at the converter stations, which range between 0.6 and 1% of the power delivered. In a side-by-side comparison, the total HVDC transmission losses are still lower than AC losses for long-distance lines (lower by 30%–40%, typically).*
- *HVDC line's transmission tower configuration is also compact and has a smaller right of way requirement than a comparable AC line of similar voltage/capacity. Siemens reports that there is more than 50% reduction in right of way requirements for UHVDC lines as compared to typical HVAC lines. A bipolar HVDC requires only two cables as compared to a double circuit AC line with six conductor cables (see Figure 3). As a result, the construction costs of HVDC lines are lower when contrasted with comparable HVAC lines (see figure below).*



[1] U.S. Energy Information Administration, "Assessing HVDC Transmission for Impacts of Non-Dispatchable Generation," June 2018, https://www.eia.gov/analysis/studies/electricity/hvdctransmission/pdf/transmission.pdf

- *HVDC technology is used to interconnect asynchronous AC networks. In the case of any AC lines, the two networks must be synchronized (that is, operated at the same voltage, system frequency, and timing). Since HVDC is asynchronous, it can adapt to any rated voltage and frequency it receives. Hence, HVDC technology is used as interties between asynchronous AC networks worldwide.*
- *HVDC technology is the predominant choice for submarine cables. A cable with insulated sheets and metal outer sheath acts like a capacitor. With longer distance cable, the capacitance (of the cable increases. For long-distance AC transmission using cables, the reactive power flow resulting from the large cable capacitance will limit the maximum possible transmission distance. Hence, HVDC lines are the only viable options for long distance submarine cables. For these reasons, HVDC lines are preferred for interconnecting offshore wind plants worldwide.*
- *HVDC lines are also operated at rated peak voltage conditions at all times, unlike AC lines that on average operate at a root-mean square (RMS) value of the rated peak voltage. Since the RMS voltage ratings is only 71% of the peak, the power transmission capability when operating with HVDC is approximately 40% higher than the capability when operating with AC.*
- *HVDC lines can operate at overload capacity for a limited period (usually at 10%–15% higher than the rated capacity for less than 30 minutes). This would give sufficient time for system operators to implement mitigation measures under contingency conditions. Such extended operation of the line under overload conditions is not possible with AC lines.*
- *Since HVDC lines can operate asynchronously, they are used to ensure system stability by preventing cascading failures from propagating from one part of the grid to another. The direction and magnitude of power flow on DC lines can also be controlled by system operators. These lines could be used for power injections to balance the grid during any supply-demand imbalance.*

There also applications where HVDC do not offer the best economics:

- *HVDC lines are cost-effective only beyond a certain break-even distance for corresponding voltage and power capacity. The cost of HVDC projects are also higher due to converter stations and associated equipment. HVDC projects make economic sense only for projects exceeding a certain critical distance. As a rough rule of thumb, ABB reports this critical distance as 60 km (or 37 miles) for HVDC submarine lines and 200 km (or 124 miles) for overhead lines. For shorter distances, the investment in HVDC converter stations and related assets may be larger than comparable AC transmission lines. Also, maintaining an inventory of customized HVDC assets imposes additional costs on the system operator / transmission line owner.*
- *Limited control between terminals: In contrast to AC transmission systems, implementing a multi-terminal HVDC system is complicated and cost prohibitive. Controlling power flow between terminals remains a technical challenge.*
- *HVDC designs offer lower availability than comparable AC systems, mainly due to conversion stations and associated equipment.*

- *HVDC circuit breakers are difficult to build since some kind of mechanism needs to be developed to force the current to zero without causing arcing and contact wear. Only recently have commercial circuit breakers for HVDC applications been introduced in the market. These use a combination of power electronics and fast mechanical breakers.*

3. Types of Converter Stations

Modern converter stations are mainly dictated by the type of solid-state switches used and their architecture. Note that since my real-world exposure HVDC projects has been with Siemens, I will use their products and terminology, and reference their literature in describing HVDC Converter Stations.

3.1. Types of HVDC

There are basically two types of solid-state switches (a.k.a. thyristor valves) used for HVDC converters: line-commutated converters (LCCs), and voltage-source converters (VSCs). Siemens uses LCCs in their HVDC Classic line of converters:

While HVDC Classic features the lowest losses of all HVDC technologies, it's especially efficient in long-distance transmission over 600 km ... In this case, HVDC transmission typically features 30 to 50 percent lower transmission losses than comparable HVAC overhead lines. It can also carry 30 to 40 percent more power given the same right of way. In addition, the HVDC transmission link offers an overload functionality that helps to supply sufficient power in emergencies and improves grid resilience without requiring more infrastructure investments.[2]

Siemens uses VSCs in their HVDC Plus line of converters. *The Modular Multilevel Converter, introduced for HVDC by Siemens Energy more than a decade ago, is the well-established standard for high voltage, high power VSC applications today.*[3]

In Siemens Energy HVDC Plus systems, one modular multilevel converter comprises three Single-phase inverter. One converter comprises three identical phase units with two converter arms, and each converter arm contains a number of sub modules supporting the full DC voltage. Each submodule contributes only a small voltage step and is controlled individually. Practically speaking, each module within an MMC is a discrete voltage source with a local capacitor to define its voltage step without creating ripple voltage distortion across the converter's other phases. This way it is possible to achieve the required sinusoidal AC and smooth DC side output voltage waveforms without excessive harmonic distortion and high-frequency noise.

The insulated-gate bipolar transistors (IGBTs) at the heart of the submodules are fully controllable. This enables modular multilevel converters to absorb and generate reactive power independently from active power up to the converter rating. The output currents can be varied over the complete operating range in a smooth, linear way. This enables independent and very flexible control of active and reactive power, which supports the connected AC grid.

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[2] Siemens Energy, "HVDC Classic – powerful and economical high-performance power transmission," Dec 2 2021, https://assets.siemens-energy.com/siemens/assets/api/uuid:8572c795-95c7-49e8-8367-dc578b4e59a5/2021-09-27-hvdc-classic.pdf

[3] Siemens Energy, "HVDC PLUS," https://www.siemens-energy.com/global/en/offerings/power-transmission/portfolio/high-voltage-direct-current-transmission-solutions/hvdc-plus.html

3.2. Other Components in a Converter Station

Transformers at the HVDC converter station adapt the AC voltage level to the high DC voltage level. AC filters and capacitor banks are installed to limit the amount of harmonics to the level required by the network. In an HVDC conversion process, the converter consumes reactive power, which is compensated in part by filter banks and the rest by capacitor banks.[1]

3.3. HVDC Cables

For HVDC transmission, the transmission lines can be overhead lines or submarine cables. The overhead line is typically bipolar, that is, two conductors with different polarity. If one pole or line fails, half of power capacity could still be delivered. Some of the HVDC projects are also used for submarine/underground transmission. The HVDC cables are typically of two types: solid and oil-filled. The solid cables are more prevalent and economical. In this type, insulating paper impregnated with high viscosity insulating oil is used. No length or depth limitations are applicable for solid-type HVDC cables. Over the years, the oil-impregnated paper-insulated cables (MI-PPL) have been the mainstay of HVDC cables worldwide. The technology was developed in response to demand for higher voltage, larger capacity (large conductors), and longer transmission line length. This technology is not limited by converter technology. However, its limited service experience and unsuitability for land cable applications (because of its higher weight) may limit the use of this technology to just subsea/ underground projects. The oil-filled type of HVDC cable are completely filled with a low viscosity oil and work under pressure. These cables are typically used for HVDC applications for less than 60 km. In recent years, cross-linked polyethylene cables (XLPE) have also been developed for HVDC applications.

4. CAISO & the Western Energy Imbalance Market

There are a number of reasons that Western Grid has played a major role in the use of HVDC transmission in the U.S. and will continue to do so.

4.1. History

There are now two operational HVDC lines on the West Coast —Pacific Intertie with BPA and Trans Bay Cable in the San Francisco area. The Trans Bay Cable (400 MW, 200 kV) is primarily a merchant congestion relief project for delivering power to the San Francisco area. The Pacific Intertie (3800 MW, 500 kV) is the oldest and largest HVDC link in the country. It provides a generator interconnection between BPA and CAISO.

4.2. Future

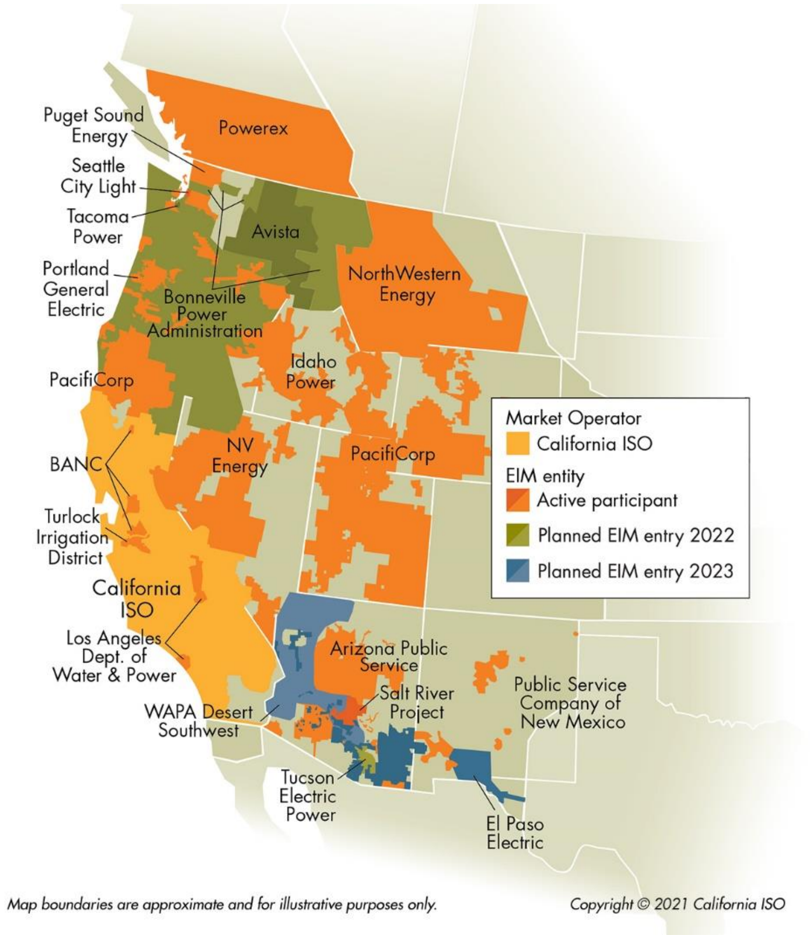
California has been leading renewable energy deployment in the United States. California's original renewable portfolio standard (RPS) target called for 33% renewables procurement by 2020. The share of intermittent renewables was about 24% in 2020.

Recently, the state increased its RPS target to 50% by 2030. This calls for a major ramp up in procurement of electricity from renewable resources in the near future. Potential HVDC projects capable of delivering renewable power to the state could help California to meet its 50% RPS target.

4.3. Western Energy Imbalance Market

CAISO defines Imbalance Energy as the "… difference between supply and demand in the Real-Time verses the Energy and Demand scheduled in the Day–Ahead Market." Also one of the main functions of the Real-Time Market was to minimize Imbalance Energy by using existing bids, and accepting new bids for the Real-Time. The CAISO Western Energy Imbalance Market is an extension of the CAISO Real-Time Market, and supports imports and exports from/to other Balancing Authority Areas.

The western EIM is a real-time bulk power trading market, the first of its kind in the western United States. EIM's advanced market systems automatically find the lowest-cost energy to serve real-time customer demand across a wide geographic area. Utilities will maintain control over their assets and remain responsible for balancing requirements while sharing in the cost benefits the market produces for participants. The map below shows current EIM participants, and those utilities that plan to join in the next few years.[4]



Since launching in 2014, the western EIM has enhanced grid reliability and generated cost savings in the $millions for its participants. EIM improves integration of renewable energy, which leads to a cleaner, greener grid. As of 2019, there have been $650 Million in benefits. See the map on the left for the membership of the western EIM.

[4] Western Energy Imbalance Market (EIM), About, https://www.westerneim.com/Pages/About/default.aspx