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EHV AC and HVDC Transmission Working Together to Integrate Renewable Power

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SUMMARY

Renewable resources in North America are extensive and are expected to represent a growing share of total resources. Large hydro and geothermal resources are concentrated in fixed locations and can be readily dispatched. Wind and solar resources are more dispersed, remote from major load centers, and variable in their output. New electric transmission infrastructure is needed to access newly developed renewable resources. For optimal transmission development, it is essential to take a long term approach that reflects the characteristics of the sources being connected. The transmission system must have capacity to aggregate these diverse renewable sources, transport usable blocks of power to remote load centers and disperse the power to load serving entities in an efficient and reliable manner.

This paper outlines strengths and complementary features of extra-high-voltage alternating current (EHV AC) and high voltage direct current (HVDC) transmission systems and advocates a hybrid approach, tailored to integrating renewable resources. Variability of generation can be moderated across larger zones, losses can be reduced through higher voltage and improved grid efficiency, reliability can be strengthened with enhanced system control, and the use of resources and rights of way can be optimized with respect to the need, economics and environment.

AC systems provide flexible access to sources and loads alike. An expansive overlay of the highest practical AC voltage forms the network backbone, serving as a high capacity platform for system integration. HVDC transmission offers express, efficient delivery of large blocks of power from point to point over long distances, continuous power flow control, fault current limitation and links that can tie asynchronous AC systems. HVDC is also well suited to submarine or underground links, where AC connections are difficult or impractical. Underground HVDC can provide easier access into densely populated urban areas as a creative "off ramp" or extension of the grid.

Combining the strengths of EHV AC and HVDC technologies can focus the effectiveness of renewable energy and extend the practical range of its reliable delivery. These technologies' particular strengths can work well together in many settings. A long term view with a broader planning scope requires coordination and recognition that the ideal system is greater than a collection of disparate projects.

KEYWORDS

EHV AC, HVDC, transmission, system integration, renewable power, EHV interstate system.

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1 Introduction

The electric power grid in the United States (US) today is characterized by mature, heavily loaded transmission systems. Thermal, voltage and stability related constraints affecting regional power deliveries have been well documented on systems in the US operating at voltages through 500 kV. While various measures to mitigate these constraints have been implemented, they are commonly incremental in scope and aimed at addressing specific localized network limitations.

Expanded EHV transmission infrastructure is needed in the US to provide sufficient long term transmission capacity and accessibility to diverse generation resources, including renewables, while improving operating reliability and efficiency [1]. Such a system opens the way for abundant renewable resources to be developed and delivered effectively [2]. It also improves the ability to support increased interstate and interregional transfers in the era of open transmission access.

Overlaying AC transmission with higher EHV voltages follows a natural progression that has repeatedly proven its ability to achieve improved grid capacity, reliability, efficiency, cost and right of way utilization [3, 4]. An EHV overlay also allows selective retirement or upgrade of lower voltage facilities. HVDC can fulfill key roles in an expanded transmission grid by efficient point-to-point delivery of large blocks of power over long distances, between asynchronous networks or to points that are less practically accessible for AC connections. Its controllability can help manage power flow and mitigate congestion.

Many public debates focus on individual project comparisons and place HVDC and AC systems in opposition to one another. In fact, these technologies are complementary. It is envisioned that an expanded system is best achieved with the accessibility provided by an integrated, high capacity EHV AC grid, while leveraging HVDC's unique capabilities for special applications.

Wide-area grid design collaboration is needed to achieve long term, system-wide benefit. Standard, modular components and configurations will simplify implementation and offer savings opportunities.

2 EHV/UHV Transmission Infrastructure Development

2.1 Bulk Transmission Development Is Needed

Many factors will challenge US transmission infrastructure. Changing location and mix of generation resources looms large, driven by energy and environmental imperatives and prospective generation fleet retirements. Improving the grid to ensure reliable, unconstrained transmission capacity in the market is another. Aging transmission infrastructure will require renewal or replacement to sustain performance. Load also will continue to grow, despite energy efficiency efforts.

Public interest demands that renewable resources be tapped and made widely accessible. Wind resources are abundant in east and west coastal areas, near the Great Lakes, and across the Great Plains. Wind power could provide 20% or more of the nation's energy needs [5]. These resources generally are remote from load centers and require expanded transmission to reach distant users.

Investment in US transmission is rising but not on pace with demand [6]. The required increase in improvement projects will tax utilities' abilities to execute the work. Concurrently, global demand for goods and services will put pressure on both new asset cost and suppliers' capacity to make timely deliveries.

Reflection upon a century of electric transmission experience and observation of current global development suggest that a broader, long term national perspective is essential. A comprehensive long range transmission plan would enable the most effective use of capital, land, material, labor and time to deliver needed improvements to the system. The result would be improved transmission access, capacity, reliability, efficiency and cost that would best address society's evolving expectations.

2.2 Global EHV/UHV Transmission Development

Developing nations are rapidly expanding EHV and ultra-high voltage (UHV) transmission infrastructure (including both AC and DC) to enable economic growth. Coupling bulk power AC

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transmission with key HVDC facilities leverages the highest capacity technologies to deliver large amounts of new generation to often distant load centers. The pace of development in China and India, for example, requires broad, concerted and timely effort. Insights from such experience can benefit others' transmission development plans, including those in the US.

3 Transmission Technologies for Increased Capacity

3.1 Higher AC Transmission Voltages

AC systems came to prominence because they enabled transformation of power between generation, transmission and distribution functions to their most appropriate voltage levels. As technology advanced, transmission enabled connection of local generation and loads at successively higher voltages. This improved capacity and efficiency and enabled integration of ever larger generating plants that were built nearer to fuel and water resources and further from load centers. Energy transport expanded from pipe and rail to electric transmission lines. Delivering energy over wires became a more effective means of transport. Localized focus, however, led to different standard transmission voltages. Interconnections expanded with three separate asynchronous systems (in the US) emerging in the East, the West and ERCOT (Texas).

As technology advanced, transmission system overlays were applied that at least doubled prior transmission voltages from 115 kV to 230 kV to 500 kV, or 138 kV to 345 kV to 765 kV. In the US, the Southeast, mid-Atlantic and Pacific coastal areas arrived at 500 kV as a maximum voltage while the East Central area boasts 765 kV. Elsewhere, 345 kV remains the highest operating EHV voltage.

Bulk power transfer capacity increased by the square of line voltage. This allowed integration of systems across a wider range of geography and capacity, especially for remote power stations. Underlying voltage systems were unloaded, providing capacity to support more localized needs. AC transmission systems became increasingly interconnected to provide desired accessibility and reliability. Interconnections between companies improved diversity of generation and loads and offered mutual system support yet, until more recently, transmission remained focused on an individual utility company footprint. Capacity margin, to withstand operating contingencies, often was considered in this local context because interconnections were limited in scope and strength.

Bulk power systems' power transfer capacity for long distance deliveries may be limited due to stability or voltage considerations rather than line thermal capacity. These concerns are largely due to system impedance and reactive support requirements, which increase directly with line length but decrease with the square of line voltage. To address these concerns, reactive compensation equipment was developed. Shunt compensation added a measure of voltage control while series compensation equipment was developed to reduce effective line impedance and increase power transfer on long lines. Using reasonable line length and applying compensation equipment, along with general strengthening of the system over time, extends transmission transfer capacity and operating range.

3.2 HVDC Development

Successive advances in high power semiconductor devices gave rise to applications of solid state DC power conversion and high power AC controllers. This enabled more reliable HVDC transmission and flexible AC transmission systems (FACTS). HVDC in the US ranges from a $\pm$150 kV, 330 MW cable to $\pm$500 kV, 3100 MW bipolar transmission.

HVDC can transfer more power over longer distances using fewer transmission lines. Transfer capacity of HVDC lines is diminished only by its losses and not by distance effects which pose reactive power and/or stability concerns in AC systems. While controllability can help relieve transmission congestion due to parallel flow issues, increased loading in the connected AC system upstream and downstream from HVDC terminals must be addressed. Existing and potential application examples include connecting remote resources such as hydroelectric developments, mine-mouth power plants or large scale wind plants. Other legacy applications include lower capacity back-to-back ties linking each of the US interconnections.

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Submarine transmission applications were developed using HVDC cable technology such that there is no specific limit to line length or power level. The controllability of HVDC circuits prevents risk of cable overload following contingencies. Extruded HVDC cables make use of long distance underground transmission applications more practical. Cable technology (both AC and DC) is commercially available through 500 kV today. Higher voltages can be developed if sufficient market demand emerges.

HVDC lines typically have two independent poles. Each pole can deliver up to one-half of the full bipolar power capacity when one circuit is out of service due to a converter outage or degradation of insulation on the opposite pole. In this respect HVDC bipolar lines can approximate a double circuit (AC) line while requiring only one-third of the number of insulated conductor sets.

HVDC is controllable. In back-to-back or transmission applications, it can interconnect asynchronous systems and buffer some disturbances between interconnected systems. In addition, HVDC does not increase short-circuit duties at the point of connection.

HVDC cannot substitute for the overall accessibility and interconnectivity of an integrated, AC grid, but it can serve as a very effective complement to the EHV transmission system, extending its reach and capabilities. Due to its special characteristics and capabilities, comprehensive system studies are needed to ensure optimal HVDC integration within the bulk AC transmission system.

There are two core converter technologies used in modern HVDC transmission [7]. These are conventional line-commutated, current-source converters (CSC) and self-commutated voltage source converters (VSC). CSC-based HVDC transmission is applied through ±600 kV and 6300 MW on double bipoles (Brazil), and soon to be applied at ±800 kV up to 6400 MW (China). VSC-based HVDC transmission is available through ±320 kV and 1100 MW for symmetric monopole configuration (overhead and underground) and up to 2200 MW at ±640 kV in a bipolar configuration.

Current Source Converter: Line-commutated converters require a relatively strong AC voltage source in order to operate properly. Therefore, the location in the AC network where they can be connected must be strong relative to their transmitted power. This requirement may hinder the application of line-commutated HVDC as high capacity transmission outlets from remotely located wind farms where strength is likely to be limited (unless or until a sufficiently strong AC grid is in place). CSCs draw reactive power from the AC network at their connection points. The reactive power demand of the converter increases with loading and is supplied by adjusting taps on converter transformers and switching AC harmonic filters and other reactive power compensation elements.

Voltage Source Converter: Self-commutated converters do not require a strong AC voltage source in order to operate properly. Therefore, they can operate almost anywhere in the AC network. VSC-based transmission can serve as the sole outlet for smaller scale wind generation using simple induction generators. VSCs do not require reactive power from the AC system and can operate at unity power factor across their entire operating range. If the AC system at any converter location requires reactive power to help support the local system voltage, the VSC station can act as a static var compensator (SVC) or STATCOM to control the AC voltage.

VSCs also lend themselves to application as DC-based “off ramps” or grid extenders from the AC bulk power grid into local networks. This is especially valuable where rights of way are congested or unavailable, or economical local voltage support is lacking. VSC-based HVDC with extruded polymer cables is suitable for underground, submarine or offshore applications.

4 Performance Characteristics

Transmission of the future must be considered as a system, greater than the sum of individual parts or singular point-to-point improvement projects. System implementation should be practically staged to maximize overall system reliability and economic benefits upon full deployment, while achieving desired performance as each stage is completed. An EHV interstate transmission overlay must provide sufficient performance and flexibility to meet evolving US needs for the long term, including FERC, NERC and regional requirements.

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Accessibility: The system must be open and accessible to integrate new generation resources and loads. There are two aspects to accessibility – the initial ability to integrate and deliver power, and the longer term flexibility for tapping into facilities to integrate additional loads and sources as they develop over time.

On ramps and off ramps for the electrical expressway are essential. Generation and delivery points may emerge at various locations over time as have the extraordinary wind resources in the middle of the country. That area cannot consume all the available capacity whereas great demand exists elsewhere. Transmission must not pose barriers to integrate this generation, to transport it, or to tap it along the route. Accessibility implies flexibility for needs that develop over the long term.

Accessibility and flexibility for tapping (at various voltages and capacities) are generally advantages of AC transmission over HVDC. AC transmission lines can be tapped more easily than HVDC to serve loads or pick up resources over moderate distances using intermediate substations. An AC tap into the HVDC system would be difficult and potentially very costly. The need to integrate the next wind plant location is one consideration; we also need a system that is flexible enough to integrate as yet unknown new communities, businesses and additional future generation. Specific studies would be needed to address requirements of such taps in the future.

In special cases, HVDC offers improved accessibility: linking asynchronous systems, high capacity underground or submarine connections, and long overhead lines not requiring intermediate substations to serve new generation or loads along its path for the foreseeable future. HVDC underground cable connections provide alternatives to overhead lines for service to urbanized areas, and to offshore or otherwise less accessible locations. HVDC cable systems provide high capacity over significant distance without reactive compensation required by long AC cable connections.

An interesting possible application of underground HVDC would be "tunneling" into densely populated metropolitan regions. Connected to AC bulk transmission, this HVDC technology could provide improved access, bringing more economical energy to higher cost areas, and mitigating the inability to site new overhead transmission in these areas.

Reliability: The interstate system must be highly reliable, stable and robust over its long term service life. Critical system components must have low outage rates, minimal maintenance requirements, and long expected life.

Loadability: The system must be built with ample capacity to meet today's needs while building a firm foundation for the long term future. Capacity must be sufficient to overcome operating uncertainties and reasonable contingencies without congestion while taking into account transport path characteristics. Congestion bears economic and environmental consequences. When power from optimal sources is constrained, it likely leads to incremental cost and emissions from substitute generation.

Efficiency: The system must deliver energy efficiently, with minimal internal electrical loss both along the transport path and in the system overall. It must minimize property and public impact while maximizing utilization of right of way. Its design and construction must use materials and labor wisely. Ongoing operation and maintenance must be practical and economical. Its implementation must achieve all of the above in the most reasonable time frame, to avoid undesirable operational or market constraints.

Economics: The economic and environmental benefits of the system must justify its cost and environmental impact.

A Supportive Public Policy: Although not a performance characteristic of the system, governmental and regulatory policies, standards and actions must support and guide the prudent planning and development of such a system. Siting authority, as well as cost recovery and cost allocation policies must be clarified and enacted. A business environment conducive to investment also is needed to encourage those who would invest in building and owning the needed assets.

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4.1 Comparison of Transmission Technologies

For an optimal EHV bulk transmission system, individual projects must be viewed in a long term, system-wide context. Selecting the lowest cost or most efficient alternative for singular projects does not always ensure long term lower cost or better efficiency for the system. With this caveat in mind, some comparisons are drawn below to illustrate characteristics of various AC and DC alternatives.

The following sections compare alternatives to provide 6000 MW of transmission capacity point-to-point over varying distances, where AC and DC comparisons are most meaningful. This transfer requirement is chosen to get reasonable multiples of each alternative's capacity and because it is representative of recent larger projects. It is indicative of requirements for tapping those large scale renewable resources that can be practically developed from the Great Plains. Key characteristics of the desired bulk transmission interstate system are used for evaluation purposes. The subject capacity would of course not stand alone, but would be integrated into a larger grid. For illustrative purposes and to simplify the discussion, no attempt is made to fully evaluate these alternatives in the context of a complete system. Such considerations are left to detailed studies of specific projects, as progressive stages in an overall implementation of the EHV interstate system.

4.2 Assumptions

Key assumptions for comparisons are described here. A transfer capacity of 6000 MW is required over the distances from 200 to 800 miles (322 to 1287 km). AC line lengths are assumed to be 200 miles (322 km) between substations. This is not a limit but is a reasonable distance to use in order to allow for placement of reactive compensation equipment and system interconnection points. Actual line distances in practice will vary according to specific transmission plans. It is assumed that each 500 kV and 765 kV line terminal is equipped with switched shunt reactors for voltage control. Shunt capacitors are assumed for all AC lines. Surge Impedance Loading (SIL) levels of 345 kV, 500 kV and 765 kV AC lines are assumed to be 400, 900, and 2400 MW, respectively. The SIL can vary based upon specific line design, but is generally in this range.

SIL is the natural loading of an AC transmission line at which it demands or supplies no net reactive power and the voltage profile along the line is flat. Higher loadings demand net reactive power from the system and voltage profile drops along the line. At lighter loadings, there is a net surplus of reactive power and the voltage profile rises along the line. Since SIL increases with nominal voltage, loadability of an AC transmission line of given length increases markedly for higher voltage lines [8].

For this comparison loading of 345 kV and 500 kV lines will be permitted to approach twice their SIL, requiring series compensation [9]. This is not common practice in the eastern US, with its generally shorter lines, but is used more widely in the western US, where lines tend to be longer and generation is more remote. To achieve the 6000 MW transfer capacity, two 765 kV lines are assumed, operating at 1.25 times SIL, which does not require series capacitors for the 200-mile length.

Two HVDC alternatives are assumed, ±500 kV DC and ±800 kV DC, each in a bipolar configuration, without intermediate stations for the 200 mile to 800 mile (1287 km) length. Table 1 summarizes some key assumptions used for each of the following analyses.

Table 1 EHV AC and HVDC Systems for 6000 MW Delivery – Technology Comparisons

Voltage (kV)	No. of Lines	Cir-cuits per Tower	Circuit		Series Compen-sation	Shunt Reactors	Shunt Capacitors	Conductor		
			SIL (MW)	Capacity* (MW)				Type	No. in Bundle	Conductor Area kcmil (mm^2)
345 AC	4	2	400	800	Yes	No	Yes	ACSR	2	1590 (806)
500 AC	4	1	900	1800	Yes	Yes	Yes	ACSR	3	1590 (806)
765 AC	2	1	2400	3100	No	Yes	Yes	ACSR/TW	6	957 (485)
±500 DC	2	1	N/A	3000	N/A			ACSR	3	2515 (1274)
±800 DC	1	1	N/A	6000	N/A			ACSR	4	2515 (1274)

* Capacity reflects (AC) line segments of 200 miles (322 km). Series compensation of 345 kV and 500 kV AC allows loading to 2.0 of SIL. 765 kV AC requires no series compensation to achieve a capacity of 1.3 times SIL.

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4.3 Capacity and Right of Way Utilization

Several factors affect AC transmission capacity. Line thermal rating is the simplest of these factors but it is generally not most limiting for long lines. Loadability of a long EHV AC line typically reflects the steady state stability limit (net of required margin) or voltage support available at line terminals. Maximum load capability decreases as impedance increases. The impedance of a given line design is directly proportional to its length.

Figure 1, adapted from [8], shows maximum line loadability for different AC and DC voltage levels as a function of transmission distance. Transmission path loadability can be increased by raising the transmission voltage level, using shorter or multiple lines, or by reducing line impedance (e.g., by series capacitors). For a 200-mile transmission distance the number of AC lines required for 6000 MW capacity would be two 765 kV lines, six 500 kV lines and twelve 345 kV lines, respectively.

With series compensation the number of lines required for 6000 MW over a distance of 200 miles drops to four and eight, respectively, for 500 kV and 345 kV. One series compensated 765 kV line could carry 4800 MW over a 200 mile length. So the hypothetical 6000 MW capacity would still require two 765 kV lines. Even with the much heavier loading applied with series compensation, lower voltage AC systems still require up to three times the right of way, siting and ongoing maintenance of the two 765 kV lines.

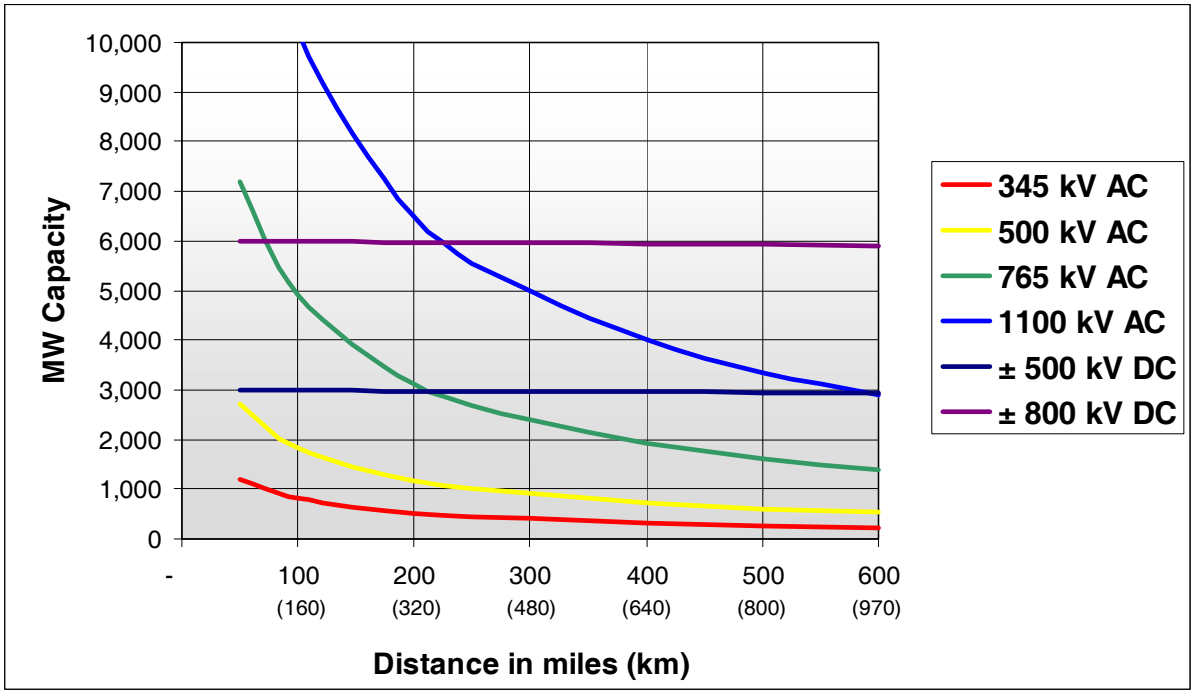

Figure 1 Line Loadability vs. Distance (No Series Compensation)

DC line capacity is virtually unaffected by length, since DC lines do not share the impedance and reactive power behavior of AC lines. Line-commutated DC converters require reactive power support from the AC grid as a function of loading, as do AC transmission lines. DC line losses reduce the delivered capacity. A single ± 800 kV bipolar transmission line is expected to deliver over 6000 MW so only one such line is required for every two ±500 kV DC or two 765 kV AC lines of the same length (with AC intermediate substations every 200 miles). Note that, from a loadability standpoint, ±500 kV DC and 765 kV AC are comparable if expressed on a consistent basis, i.e., 765 kV line to ground rms voltage is 442 kV compared to ±500 kV. ±800 kV DC corresponds to 1400 kV AC.

Each bipolar HVDC transmission line is comprised of two circuits and requires less right-of-way than a single circuit AC line of comparable voltage. For uninterrupted longer lines, ±800 kV HVDC has greater permissible capacity than the AC choices shown. This paper does not include detailed

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consideration of UHV AC, such as that recently deployed in China. For comparison, 1100 kV AC has an SIL of 5,000 MW and would deliver 6,500 MW over 200 miles without intermediate substations or series compensation.

For short distances, underground HVDC cables can use shared rights of way without causing reliability concerns, extending the use of existing rights of way. For typical line lengths on the order of 200 miles, cost and efficiency benefits favor AC overhead line solutions.

4.4 Reliability

Comprehensive reliability data, in similar formats, are not widely available for AC and DC transmission. Some basic observations are presented here, but available information is limited, and comparisons between AC and DC are difficult. For AC systems, typical outage experience for 765 kV, 500 kV and 345 kV was documented at 1.0, 1.4 and 1.6 forced outages per 100 miles per year [10], respectively. At 765 kV, outages are overwhelmingly due to single phase faults. Multi-phase 765 kV faults do not occur except in case of tower failure due to extremely rare events such as tornado damage or heavy ice storms. Single phase operation has been employed for nearly 30 years on some 765 kV and 500 kV lines to avoid three phase tripping for temporary faults [11]. This scheme interrupts and re-closes only the faulted phase while maintaining operation of the healthy phases. This cuts the incidence of three phase outages, minimizing system disturbances caused by faults and associated switching operations.

HVDC outage data (collected from existing applications through ±600 kV) indicate outage rates of under 0.5 permanent outages per 100 line miles per year. Outages are overwhelmingly confined to a single pole. Bipolar outages seldom occur except for tower failures due to tornado damage or heavy ice storms (as with 765 kV AC). Availability of modern terminal equipment is generally above 98.5% including both scheduled and forced outages. In the case of a single ±800 kV bipolar high capacity HVDC transmission link, two series-connected converters are used on each pole. Therefore, if only one converter is lost, or the line insulation is only partially degraded (but can still sustain half voltage), the line can still transmit 75% of its rated power indefinitely. This is not possible today with a single circuit AC line, although technologies that would enable limited operation with one phase out of service are being developed to allow time for operator corrective action, such as generation re-dispatch.

4.5 Energy Efficiency

Figure 2 compares losses at full load, including estimated line resistive and terminal equipment losses, for the hypothetical 6000 MW project for each of the same point-to-point transmission alternatives. Losses are calculated assuming series compensation for 345 kV and 500 kV AC lines. Line losses are proportional to the square of line currents so higher voltage systems offer significant energy efficiency advantages. For the 200-mile (322 km) line length, 765 kV saves 60 MW and 160 MW, respectively, versus the 500 kV and 345 kV AC alternatives, and 30 MW compared to the ±500 kV DC alternative. Losses of ±800 kV DC and 765 kV AC are comparable at this distance.

AC systems have greater efficiency per “tap,” or terminal required, than HVDC. This is due to greater losses in the converter transformers, power electronics, smoothing reactors, filters and ancillary equipment comprising the DC converter stations compared to conventional AC terminal equipment. For long distance transmission, AC lines typically employ intermediate substations which provide accessibility, protection and voltage control. The intermediate AC substations add cost and some terminal equipment losses that HVDC transmission does not have.

As line length increases to 400 miles (~640 km) and beyond for a single point-to-point connection, HVDC alternatives show increasing energy efficiency compared to AC, with ±800 kV DC having greatest efficiency for longer distances, with ±500 kV DC and 765 kV AC roughly equal at 400 miles, followed by successively lower AC voltages.

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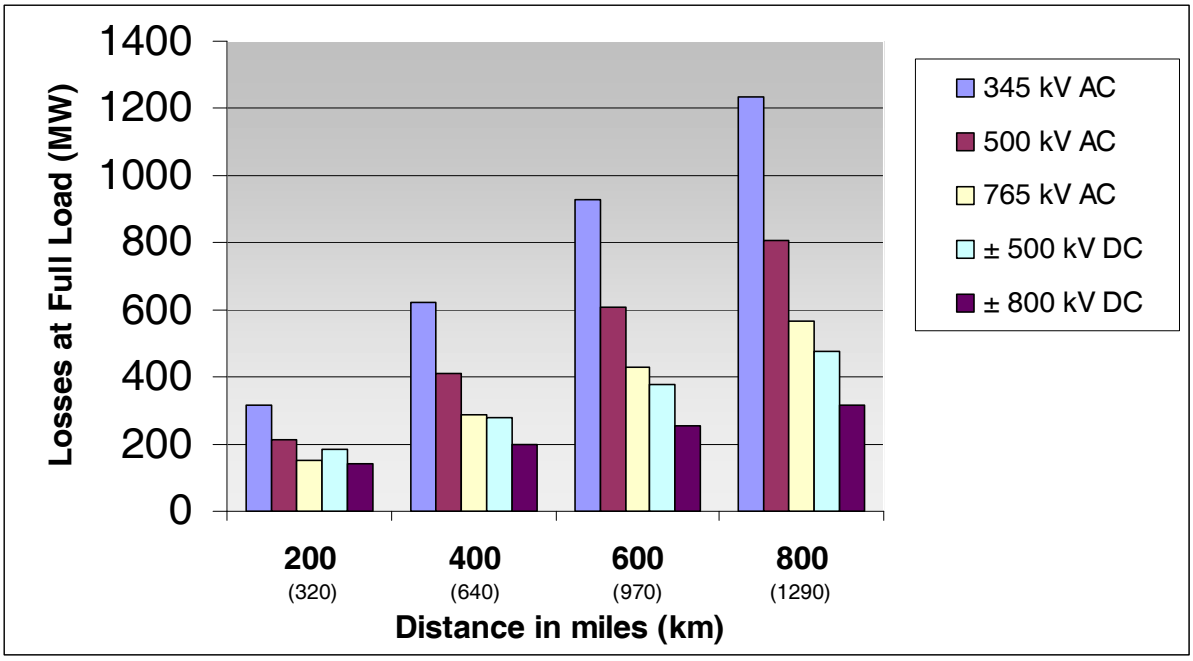

Figure 2 Loss Comparison for 6000 MW Transmission (Configurations as shown in Table 1)

For the above analysis, Table 1 summarizes assumed conductors for each voltage. For new construction, line designs and conductor selection would be project specific, and further efficiency could be realized. In fact, for future line designs, AEP is evaluating larger 765 kV conductors in order to achieve greater efficiency. While not included in the scope of our analysis, UHV AC lines could provide still greater efficiency than any of the above options.

Full-load energy efficiency of 345 kV and 500 kV AC would improve if applied without series compensation, at the expense of a greater number of lines, with increased costs and rights of way.

4.6 Cost

For an actual project, specific detailed scope and estimates must be prepared. Cost comparisons presented in Figure 3 are based on general assumptions and are conceptual estimates only. The costs include required lines, substations, reactive compensation and converter facilities. Transformer costs have been included in the AC substation costs. If this example were strictly for "point-to-point" transmission, there would be no need for system tie transformers at each intermediate substation, only for reactive compensation. Since AC accessibility for system connection has been so heavily emphasized, we have included these costs (roughly 3-5% of the total cost) in the AC examples.

The higher the AC voltage, the lower the cost per MWh delivered. For the example 200-mile transmission path carrying 6000 MW, using two 765 kV single circuit lines as the base, the cost for four 500 kV single circuit lines with series compensation is 35% greater, and the cost for four 345 kV double circuit transmission lines with series compensation is 45% greater. If 345 kV and 500 kV lines are applied without series compensation, as is more common in the Eastern Interconnection, these cost differentials become much greater because more AC lines would be required – six double circuit lines for 345 kV and six single circuit lines for 500 kV. For these shorter distances, HVDC is more costly than 765 kV, but competitive with the other AC voltages.

HVDC transmission lines cost less per mile than comparable AC lines since they require only two sets of conductors for positive and negative poles (plus any neutral return), rather than three phase (AC) energized sets per circuit. HVDC terminal cost, however, is roughly three to six times that of an equivalent number of AC terminals due to converter station equipment. For exclusively point-to-point long distance paths, HVDC requires substations and converters only at the two terminal points. AC lines typically employ intermediate switching stations. If the system plan does not require intermediate

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stations for the life of the project, HVDC enjoys a cost advantage at 400 miles and beyond. Should it become necessary to tap the DC system, it would add significant cost and challenge to do so.

It is important to note here that very long point-to-point transmission without intermediate accessibility to the line is uncommon in much of the country. However, for overabundant renewable power in remote locations or passing through sparsely populated areas, an "express lane" or bypass may be a useful complement to a well developed, accessible AC bulk transmission system. This deserves careful study to ensure that any such solutions serve long term needs of an integrated system.

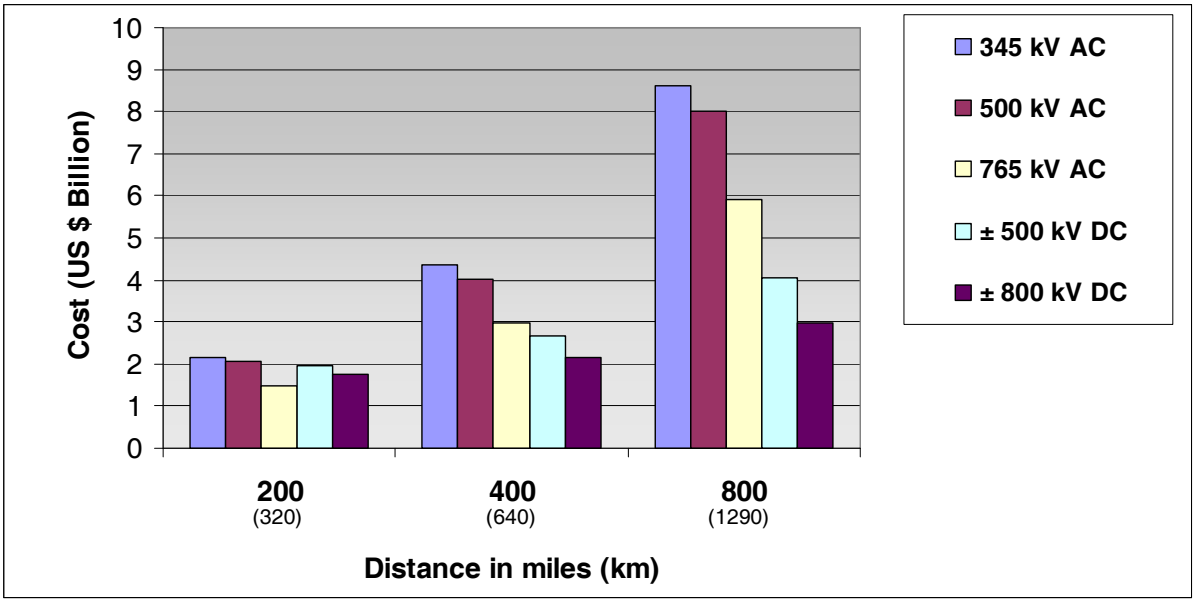

Figure 3 Project Cost for 6000 MW Capacity (Configurations as shown in Table 1)

4.7 Controllability and Congestion

Controllability and overcoming congestion have meaning in the context of the integrated system, not in the case of a point-to-point type of application, such as the 6000 MW example we have examined. Among the most important goals of the proposed interstate transmission overlay is unconstrained transmission access for generators and loads. The system must avoid congestion, either through grid design and configuration or through some means of power flow control. The value of controllability depends on the amount of time adjacent paths would otherwise be congested, causing lower cost or lower emission generation to be curtailed.

With a well designed interstate bulk transmission system, having robust capacity and minimal impedance (greatly affected by the choice of AC voltage), constraints would be much less likely than with a patchwork system of individual projects. So the issue of greatest importance is to plan and build interstate transmission as a grid with busbar-like functional characteristics.

During the implementation phases of the grid however, power flow control strategies may prove important. Power flow can be controlled by changing generation output, path impedance, line terminal voltage, or phase angle difference between terminals. Aside from generation control, flow changes can be achieved through combinations of switching reactive or phase angle compensation equipment. HVDC has the ability to control power flow to a fine degree and therefore may be able to aid in optimizing power flows.

4.8 Right of Way and Visual Impact

A key concern in siting new facilities is visual impact on the surrounding landscape. Single circuit 765 kV lines are taller than single circuit 500 kV and 345 kV AC. Figure 4 shows representative heights of typical towers. These will vary according to the demands of terrain, span length, etc. In

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order to improve capacity and ROW utilization of 500 kV and 345 kV, double circuit lines can be used. Double circuit lines have greater height and visual impact, yet provide less capacity than 765 kV single circuit lines. ±800 kV DC is taller than 765 kV AC which, in turn, is taller than 500 kV DC. All of these are significantly shorter and less visible than typical wind generators.

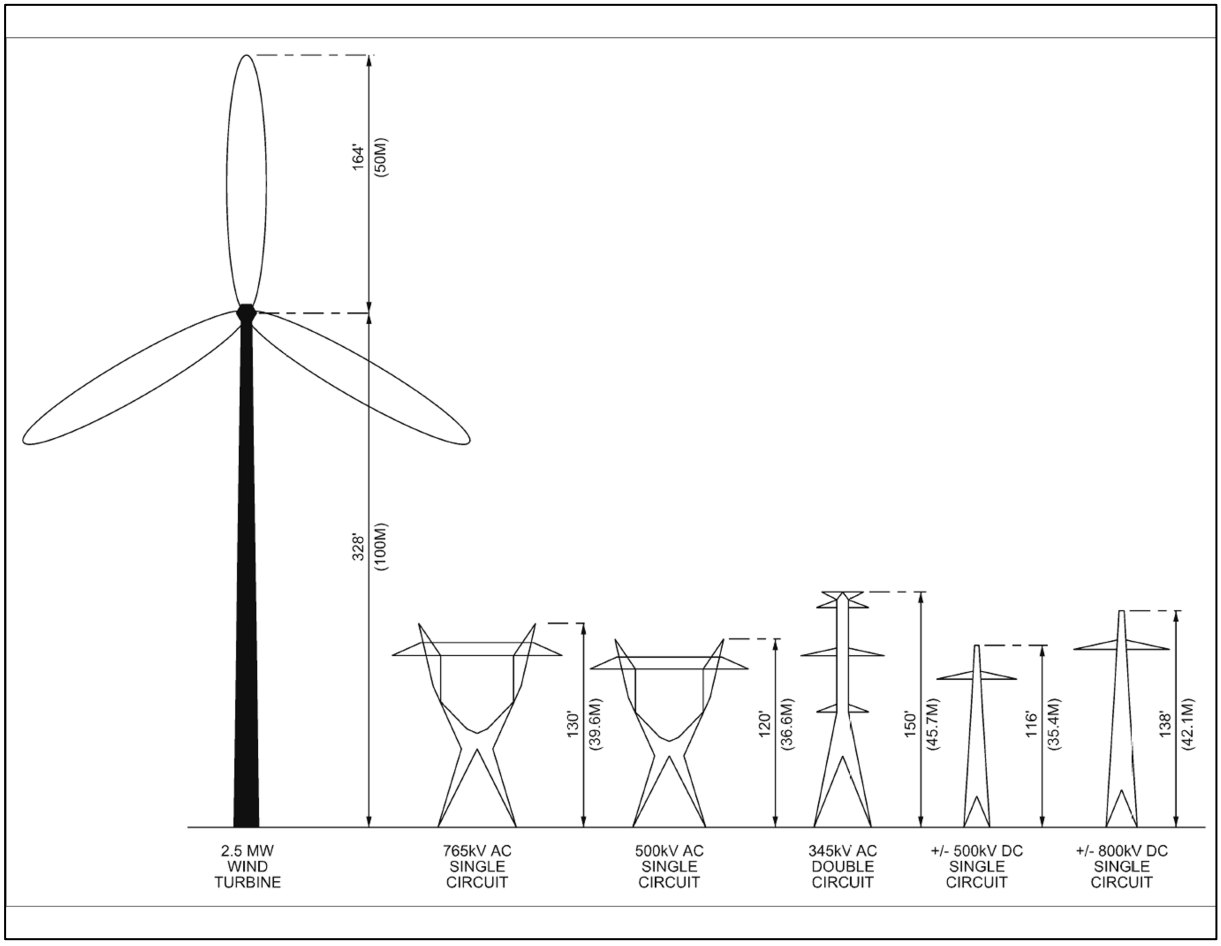

Figure 4 Tower Height Comparisons (Heights vary within a range depending on specific design needs)

5 The Future of Electric Transmission

Support is growing for a national EHV interstate transmission grid [12]. Figure 5 illustrates one often referenced concept for such an interstate system, superimposed on a map of the existing EHV transmission system and wind resources in the US. The figure indicates an overlay of predominantly 765 kV lines. Other voltages can be chosen and applied. For UHV, fewer lines would be needed, and for voltages below 765 kV more lines would be needed. The comparisons made above have demonstrated the many advantages of 765 kV AC and it deserves due consideration in formulating plans for the interstate grid. It is understood, however, that the completion of this grid requires collaboration among stakeholders, especially transmission owners and operators. Joint studies and cooperation will be necessary to determine the final planned configurations.

Potential HVDC applications would be integrated into this EHV interstate transmission system with their placement determined by specific studies. This grid would be built upon proven high capacity transmission technology, and would open the way to integrate new power sources, including renewables as they develop. It should be noted that a new EHV grid would be a strong "integrator" of systems. (The need for back to back ties as indicated in Figure 5 would be determined.) In fact, recent proposed legislation would require transmission providers using FERC "backstop" siting

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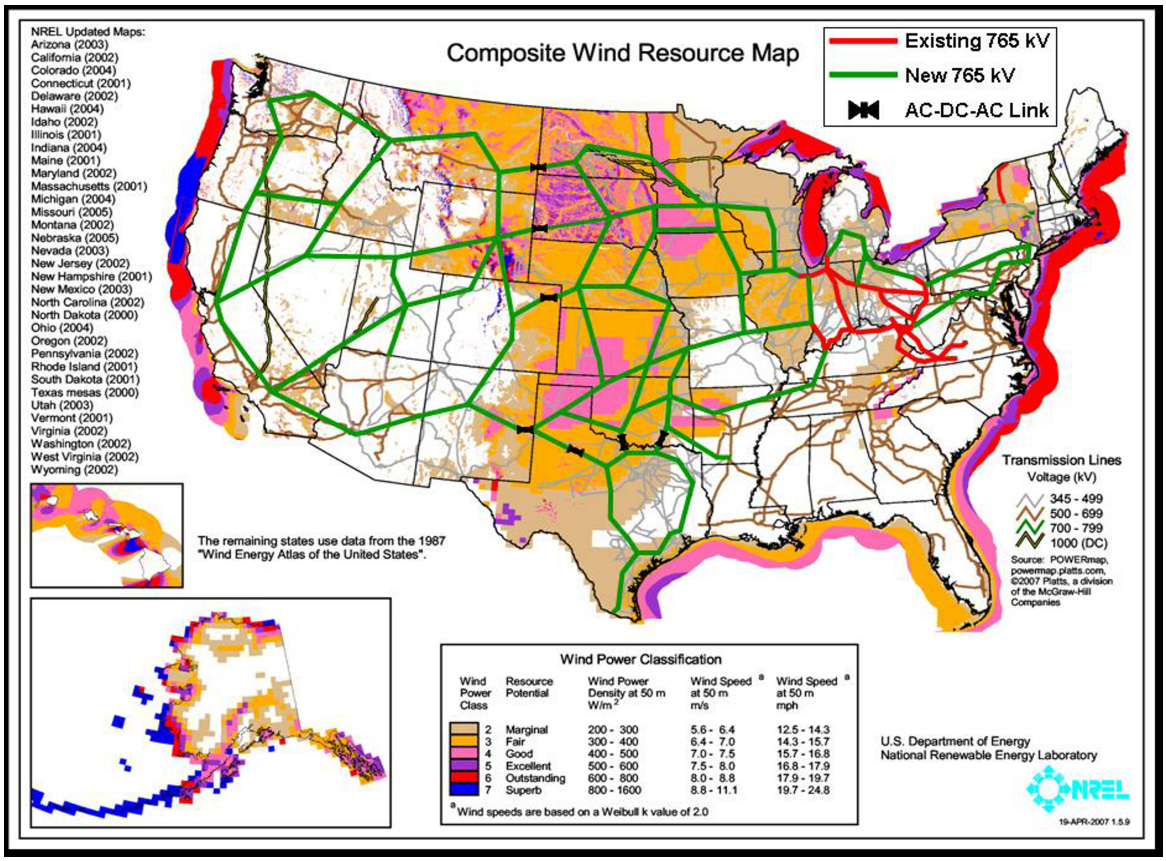

Figure 5 Conceptual Map of Interstate Grid for Wind Integration (Source: NREL)

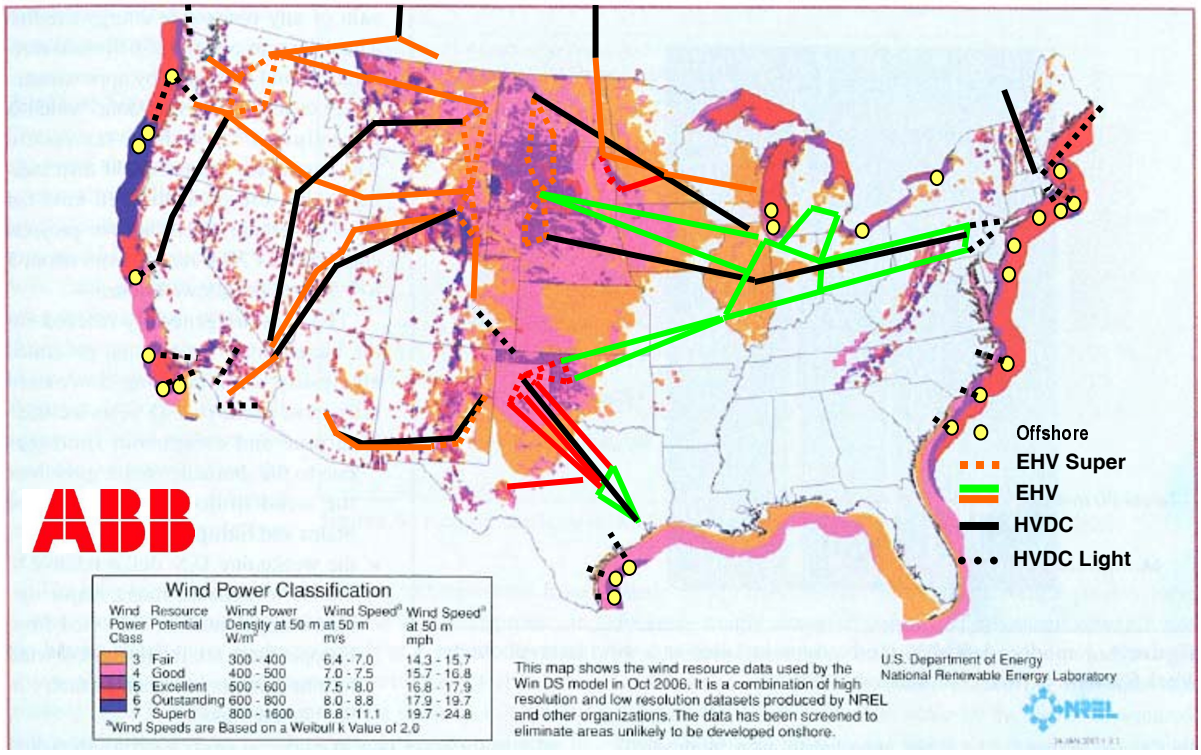

Figure 6 "Supercollector" Hybrid Transmission Concept (Source: ABB annotation of NREL Wind Map)

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authority to provide benefits to states through which their lines pass, either by offering interconnections to load serving entities seeking renewable power supplies or to renewable generators seeking access to the grid.

Figure 6 illustrates another concept of interstate transmission based primarily on HVDC application. Either concept could improve off-shore wind generation. Since wind resources along the coast lines are often close to major load centers, VSC-based HVDC transmission can provide access to high power wind plants at considerable distance off-shore. Such systems are being introduced in Europe.

An EHV interstate grid removes access barriers to suppliers and users alike, supports efficient markets and improves reliability. Higher voltage EHV systems provide environmental benefits since they offer renewable sources greater access to the energy market, are more energy efficient and reduce land requirements for transmission lines rights of way by reducing the number of lines required.

The inspiration for the EHV interstate grid is President Eisenhower's vision for a US interstate highway system. The interstate highway system is a nationwide overlay that eclipsed an old, locally focused patchwork of roads. It was a long term vision rather than a series of disjointed "just in time" projects involving small segments of the system. Some underlying routes were upgraded to better serve local needs while other obsolete routes were retired. Commerce flourished, national security and safety were enhanced and parts of the country became better connected and "closer" than ever before.

One result was that railroads became focused on complementary long-distance heavy transport rather than local access. Just as the EHV AC transmission system overlay can be viewed analogous to the interstate highway system, the HVDC may be compared to heavy haul rail lines.

5.1 Hybrid Transmission

EHV AC transmission can be used to readily pick up resources or feed loads either of which may be located along the transmission route. In fact, the very presence of EHV AC transmission can spur nearby economic development, much like the interstate highway system did in years past.

HVDC transmission can be used for long distance export of significant excess power from or through sparsely populated remote areas, linking asynchronous systems, "tunneling" into otherwise inaccessible locations or providing greater controllability of power flow. The Pacific AC and DC interties are an example of such a hybrid approach. Complementing a higher capacity, lower impedance, and lower loss EHV network by integrating targeted applications of HVDC could provide greater flexibility for system operators and for accessing diverse resources.

The EHV interstate system with any complementary HVDC links would provide superior long term grid performance at optimal overall cost. Individual projects must be judged in this context, rather than in isolation. Project purpose and long term system benefit must drive project work scopes. Isolated project and area considerations by separate parties over time led to the patchwork transmission grid we have today. Collaboration and coordination among the many stakeholders is important to achieve the best overall design for the interstate grid of the future.

5.2 EHV Interstate Transmission System – The New "Integrator"

The EHV interstate transmission system approach continues a natural progression to successively overlay higher transmission voltages in order to leverage available technologies and most effectively transport power. Underlying systems are reinforced for improved overall operational performance. Existing lines are unloaded to better serve their originally intended function of local and regional support. This progression of transmission overlays in the past has repeatedly proven its effectiveness and value.

Today's disparate voltages, configurations and equipment ratings came about as the system evolved, due to localized focus. The current grid would have been built differently if present conditions had been envisioned from the outset. Going forward, standardization and modularity can be applied, simplifying interfaces between transmission providers and improving overall system efficiency. A standard "building block" approach for equipment and systems would ease implementation and

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promote efficiency in planning, design, materials, equipment and construction. Implementation cost and time would be significantly reduced.

The US has a grand opportunity to create an advanced transmission system that fulfills its greatest potential to integrate a sustainable generation portfolio and improve transmission performance. Based upon lessons learned over a century of transmission experience and the technology comparisons above, it is evident that choosing the appropriate transmission voltages and technologies will largely define how economically, efficiently and reliably the transmission grid performs for the foreseeable future. Leveraging strengths of modern EHV AC, FACTS and HVDC technologies ensures a highly performing grid. Continuing to advance and apply transmission technologies will ensure sustained progress in system capability and performance.

The advanced interstate transmission grid would also facilitate much greater opportunity to apply advanced monitoring and diagnostics for a "smarter" transmission grid. Since there would be substantially fewer facilities to monitor in such a grid, the costs of advanced diagnostic monitoring and decision support systems are much less than would be required otherwise. This also allows a more sophisticated level of monitoring to be supported.

5.3 A System Approach to Transmission Planning

To implement the grid that is required for the future, collaborative planning is needed using a long term, system perspective. We know where the wind is, and we know where the loads are. Jointly, we can identify strategic broad-based interstate system plans to harvest renewable resources before the individual projects develop. Rather than project by project, piecemeal solutions, we must develop and justify an integrated system. In order to capture the full scale of benefits that high capacity technologies such as 765-kV and HVDC provide, the system must be examined on an interregional scale that matches the reach of those benefits.

Some keys to success include: adoption of interconnection wide planning criteria and assumptions focusing on broad system solutions; proper balance in evaluating EHV plans to ensure long term system benefits; and development of planning criteria and assumptions for the "feeder" connections to renewable (or other) resources. Naturally such "technical planning" approaches cannot occur without the requisite regulatory and cost support for the required EHV system.

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