AEP INTERSTATE PROJECT: I-765

Technologies for 21^{st} Century Transmission

I. Abstract

American Electric Power (AEP) has committed to deploy state-of-the-art transmission technologies as part of the AEP Interstate Project, announced on January 31, 2006 [1]. The project, dubbed I-765 and targeted for service in 2014, will utilize individual phase controls and other advanced technologies to maximize power-carrying capacity and reliability that will establish the standards and benchmarks for 21^{st} century interstate transmission. These technologies, some of which were pioneered by AEP, include: (1) 765 kV AC transmission with six-conductor phase bundles, (2) phase and shield wire transposition, (3) fiber-optic shield wires, (4) wide-area monitoring and control, (5) remote station equipment diagnostics, (6) single-phase switching, (7) switchable shunt reactors, and (8) static var compensators. The highlights of these technologies are provided below.

II. Introduction

The AEP Interstate Project, proposed for construction between West Virginia and New Jersey, represents an initial step toward a transmission superhighway system -- a bold vision modeled on President Eisenhower's national interstate highway plan. This vision calls for the deployment of state-of-the-art, proven extra-high-voltage (EHV) technologies to help achieve the full potential of this new transmission project. The project, much like the 765 kilovolt (kV) system pioneered by AEP in its own service territory, will form a high-capacity, transmission "backbone" overlaying and strengthening existing regional systems, from the Midwest to the eastern seaboard.

The AEP Interstate Project consists of a 765 kV line connecting AEP's Amos 765 kV station to Allegheny Power's Doubs 500 kV station in Maryland, and terminating at Public Service Electric & Gas' Deans 500 kV station in New Jersey. The total length of the proposed line is approximately 550 miles. The project will greatly improve power transfer capability from the Midwest to Mid-Atlantic states, while enhancing the reliability of the nation's transmission grid. An increase in system transfer capability of approximately 5,000 megawatts (MW) is expected. Also, with the project in service, power losses on the transmission system will be reduced by about 280 MW at peak load conditions, equivalent to a moderately-sized generating station.

The project will leverage the considerable strengths of the existing 765 kV transmission infrastructure. It will provide effective connectivity across states and to lower-voltage transmission systems. And the system's high transfer capability will be achieved with land use efficiencies unmatched in long-distance transmission of power.

AEP has submitted the project proposal for review by PJM Interconnection LLC, a regional transmission organization operating in the Midwest and Mid-Atlantic states, of which AEP is a member. PJM expects to review the project as part of the regional transmission expansion plan (RTEP) in June 2006.

III. Evolution of 765 kV Transmission Technology

During the nearly four decades of 765 kV transmission operation by AEP, this highly successful network has grown to more than 2,000 miles of 765 kV lines and two dozen major substations, integrating key generating plants with load centers throughout the AEP System and providing interconnections with neighboring EHV systems. The network, with its demonstrable reliability, security and efficiency, is ready for a new mission -- to reliably serve the needs of the dynamic and complex electricity marketplace that has emerged during the last 10-15 years.

The 765 kV transmission technology selected for application in this project is the highest established voltage class in commercial operation in the world today. Its electrical power-carrying capacity for lines longer than 100 miles, commonly measured by power engineers using the concept of surge impedance loading (SIL) [2], is approximately three times greater than that of a 500 kV line, five times greater than that of a 345 kV line, 18 times greater than that of a 230 kV line, and more than 30 times that of a 138 kV line. The higher power-carrying capacity translates into more efficient land use. A single 200-foot wide right-of-way required for a 765 kV line is equivalent (in terms of corridor capacity) to a combined width of 750 feet at 345 kV and 1500 feet at 138 kV.

Transmission systems designed for 765 kV operation are inherently more reliable than those operating at lower voltage levels. The 765 kV lines are constructed using large/multiple conductors to obtain acceptable corona and audible noise performance. The summer normal rating of a typical 765 kV line, including terminal equipment, exceeds 4000 MVA (conductors are rated even higher), virtually eliminating the risk of thermal overloads even under severe operating conditions.

Outage statistics [3] indicate that 765 kV circuits experience, on average, 1.0 forced outages per 100 mile-years. A comparable statistic for 500 kV is 1.4 forced outages per 100 mile-years. While single-phase faults are the dominant type of failures for both voltage classes, no multi-phase faults have been recorded at 765 kV in normal operation, short of tower failure. (AEP has experienced 765 kV tower failures due to both severe icing and tornadoes.) This performance suggests a lower likelihood/severity of disruptions at 765 kV and an opportunity to apply effective mitigation measures to further improve the line (and thus system) reliability.

Reliability of the 765 kV system is, perhaps, best illustrated by the experience of August 14, 2003. On that day, a large segment of the interconnected grid in Eastern Canada and the Northeast United States collapsed in a cascade that affected service to some 50 million people. It is notable that the cascade was effectively stopped at the “doorsteps” of AEP’s 765 kV transmission system.

IV. AC vs. DC Transmission

AC (alternating current), 60 Hz transmission technology is considered most appropriate for use in this project. AC will facilitate the future addition of intermediate station(s) -- a key advantage in populated areas, such as the Midwest-East Coast region. These stations will act as exit and entrance ramps on an interstate highway, serving local load centers and/or providing outlets for new generation that may locate along the way. The intermediate stations will help to maintain system reliability and spur economic development. Moreover, the use of AC technology will enable expansion of the project into a high-capacity transmission grid overlaying the existing systems and will facilitate its integration with those systems. By contrast, traditional DC (direct current) technology is generally limited in its application to point-to-point transmission traversing sparsely populated (or unpopulated) areas, or where the systems being connected do not operate in synchronism.

Integration of transmission systems operated at 700 kV and above with lower voltage systems has been successfully demonstrated in the U.S. and several other countries. In this project, the function will be accomplished using transformer banks of typical designs to allow future equipment interchangeability among stations. Such transformer banks have been employed by AEP in integrating its 765 kV system, stepping down to transmission voltage levels as low as 138 kV (or stepping up from generator voltages in the 24-25 kV range). These transformers are normally equipped with multiple tap positions to ensure proper voltage coordination. Also, if needed, proven technologies (e.g., series reactors) can be used at or near the point(s) of integration to ease any concerns about relative strengths of the 765 kV and local transmission systems.

V. Six-Conductor Phase Bundle

Until recently, four conductors per phase have been used in 765 kV transmission line configurations. Although the audible noise performance of such lines generally has been satisfactory, a six-conductor bundle was selected for AEP's 765 kV line now under construction in West Virginia and Virginia to further limit the noise level, particularly at higher altitudes [4]. This improved design, also to be employed as part of the proposed interstate project, offers an added benefit of reduced levels of radio and television interference.

VI. Phase and Shield Wire Transposition

At 765 kV, large physical separations between phases are utilized to ensure acceptable electrical clearances. For practical reasons, horizontal phase geometry is used to minimize the tower height. The resulting unequal phase-to-phase distances, in combination with occasionally dissimilar single-phase station equipment forming a three-phase bank, give rise to unequal phase voltages and currents across the phases. This phenomenon, known as system unbalance, has been effectively managed in the past with suitable countermeasures. Nonetheless, due to long transmission distances and high loading levels anticipated in this project, which can intensify system unbalance, plans are being formulated to transpose (i.e., rotate) phases on the new line.

Several transposition cycles will be used, in which each of the three phases will occupy every physical phase position on the tower over an equal distance along the line. This technique will help equalize the phase voltages and currents, and thus, enhance reliability of line protection, simplify implementation of single-phase switching and reduce line losses. Further reduction of line losses will be accomplished by also transposing the shield wires. The associated disadvantages of phase transposition -- added cost and complexities in line phasing and future station integration -- are considered minor and acceptable.

VII. Fiber-Optic Shield Wires

Protection of the new 765 kV line, particularly when 765/500 kV transformation is out of service at the intermediate station, will present new challenges because of the long transmission distance involved. These challenges will be met by specifying shield wires with fiber-optic cores to enable the use of so-called differential line protection -- a superior technique borrowed from transformer protection that reliably detects short circuits. Also, fiber-optic shield wires will facilitate grid monitoring with Phasor

Measuring Units (PMUs), which are basically system “stress detectors,” and aid remote control/diagnostics of the equipment.

VIII. Wide-Area Monitoring and Control

Reliable operation of a power system requires that accurate and timely system intelligence be available to transmission operators. Such intelligence, normally obtained in a discrete manner from Supervisory Control and Data Acquisition (SCADA), can be greatly enhanced with the application of continuous monitoring by means of PMUs. While still under development, the PMU network (and associated computer tools) offers a novel approach to time-synchronized, wide-area condition assessment for the management and operation of interconnected systems [5]. Plans exist to install PMU devices at the remote site(s) of this project and communicate, via the line’s optical channels, real-time data for use by system operators. These same channels also will allow the operators to switch station equipment in/out of service, as needed, to maintain system reliability.

IX. Remote Station Equipment Diagnostics

Large, critical station equipment will be installed as part of this project at locations remote from the AEP System. To ensure proper functioning of the equipment, its physical status and “health” will need to be monitored on a periodic basis. Due to the long distance involved, routine inspections of station equipment normally performed on-site will not be practicable. Instead, consideration is being given to installing special remote sensors, detectors and audio/video devices -- linked via optical channels to AEP’s computers/databases – to secure the necessary equipment diagnostics.

X. Single-Phase Switching

Single-phase switching (SPS) is a concept advanced and successfully applied by AEP in the mid-1980s in conjunction with the Rockport Plant Project in southern Indiana [6-7]. The concept has allowed integration of a major generating station with the system using only two 765 kV lines. SPS takes advantage of the superior outage performance of 765 kV lines by momentarily interrupting only one of three phases to clear temporary single-phase faults. This feature, made possible by the fact that all 765 kV-connected station equipment (circuit breakers, shunt reactors, etc.) are built as single-phase units, will enhance the proposed line's availability and minimize system disturbances caused by faults and associated switching operations.

XI. Switchable Shunt Reactors

Long 765 kV transmission lines normally require that banks of shunt reactors be installed at each terminal to control high voltages. These reactor banks are commonly connected to the line via simple air-break switches, necessitating an outage of the line to disconnect/reconnect the reactors. Special circuit breakers, similar to those now in operation at selected locations on the AEP System, and/or power electronics will be used in this project to permit (de)energization of these reactors automatically or by remote supervisory action without taking the line out of service. This feature will enhance operating flexibility and enable SPS implementation.

XII. Static Var Compensators

Past research and experience indicate that the load-carrying ability of a transmission line (loadability) is highly dependent on the line length [2, 8]. This relationship, embodied in a planner's tool known as "St.

Clair Curves" (named after AEP's Harry St. Clair, who advanced the concept in the 1950s), shows that the loadability of a 550-mile-long transmission line is merely 60% of surge impedance loading. For the proposed 765 kV line, this translates to 1400-1500 MW, i.e., only about one-third of its projected thermal capacity. In order to increase the loadability of this line, a static var compensator (SVC) with an estimated control range of -500 Mvar to +1000 Mvar will be installed at the intermediate station and at the end terminal of the line. By providing the required dynamic voltage regulation and firming up the receiving systems, these SVCs will reduce the effective transmission distance to less than 300 miles, thus boosting the loadability by 80% to about 110% of SIL, or above 2600 MW.

The preliminary SVC design is similar to that of AEP's Beaver Creek SVC installation in eastern Kentucky [9], the first such application on a transmission system worldwide, scaled up from 138 kV to 765 kV. The design will be modular and will employ conventional, single-phase generator step-up (GSU) transformers arranged in a bank of four, including a spare. A "quick-connect bus" will be provided to maximize the SVC availability, and thus, retain full loadability of the new line. Furthermore, twin thyristor-controlled reactors (TCRs) and twin thyristor-switched capacitors (TSCs) comprising the SVC dynamic control range will be included in the design, along with automatic sectionalizing capability, to allow prompt isolation of any failed component in the SVC.

The SVC device at each designated location will be integrated with the 765 kV switchable shunt reactors provided for line-charging compensation. This arrangement will place the shunt reactors under the SVC control, extending the SVC's dynamic range in a cost-effective manner. Additional switched capacitors, also controlled by the SVC, will be included in the design to extend the dynamic range further and provide harmonic filtering, as required. Single-phase controls, with "ride-through" capability during fault conditions, are planned for the SVC to help maintain balanced phase voltages during normal and contingency operation.

Essentially, all technologies described herein will promote individual-phase approach to the AEP Interstate Project, unlike the vast majority of transmission lines in the nation today that operate as a three-phase unit. This approach will ensure greater system reliability and power-carrying capability for the benefit of consumers.

XIII. Glossary of Terms [10-12]

Alternating Current (AC) – Electric current that reverses (or alternates) its direction at regular intervals; two of such intervals form a cycle. AC is common in the U.S. at 60 cycles per second.

Bundled Conductor – An assembly of two or more conductors used as a phase bundle to increase its effective diameter, and thus, reduce the line's corona and audible noise effects. Spacers are employed to maintain a predetermined conductor configuration within the bundle.

Corona – A visible or audible discharge of electricity from an energized object, such as phase conductor, caused by air ionization around the object's surface.

Differential Protection – A reliable technique for protecting power equipment from internal short circuits; it functions by comparing the currents that flow at input and output terminals of the equipment.

Direct Current – A type of current that always flows in one direction; requires DC/AC converter stations to allow transformation and integration with existing AC systems.

EHV – Extra high voltage. This term is applied to system voltage levels higher than 230 kV.

Forced Outage – An unplanned failure or other system condition that requires disconnection of the failed facility (or portion of the system) to maintain operational integrity of the remaining system and to limit damage to the failed facility.

Kilovolt (kV) – 1,000 volts.

Line Charging – Reactive power "generated" by an energized transmission line due to its distributed shunt capacitance between phase conductors and ground plane; expressed in units of Mvar; varies quadratically with line voltage.

Loadability – Load-carrying ability of a transmission line operating under a specified set of performance criteria; commonly expressed in terms of surge impedance loading.

Megawatt (MW) – 1,000,000 watts; unit of active (or real) power that does useful work.

MVA – 1,000,000 volt-amperes; unit of apparent power (root-mean-square of MW and Mvar).

Mvar – 1,000,000 volt-amperes-reactive; unit of reactive power that affects system voltage.

Normal Rating – Electrical loading of a facility, as specified by its owner, that the facility can support without significant loss of life.

Peak Load – Maximum electrical demand (instantaneous or average) in a stated period of time.

Phasor Measuring Unit (PMU) – A device used for measuring magnitude and phase angle (together, a phasor) of power system voltages and currents. PMUs are installed at multiple system locations and are synchronized with Global Positioning System (GPS) time signals to allow high-precision assessment of dynamic system conditions, i.e., a system's stress.

Quick-Connect Bus – A special bus connection designed to facilitate electrical reconfiguration of single-phase station equipment without physical relocation; commonly used at critical stations to allow prompt removal from service of an inoperable phase and its replacement with a spare unit.

Reactor – An inductance coil with iron or air core that can operate in series with another power element (series reactor) or between an energized point and ground potential (shunt reactor). Series reactor is used to limit current flow to a predetermined level during either normal or short-circuit condition. Shunt reactor is used to reduce voltage by absorbing reactive power (Mvar) from the system.

Reliability – Electric system reliability is comprised of two basic and functional aspects, adequacy and security. Adequacy is the ability of a system to supply aggregate electrical demand and energy requirements of the customers at all times, taking into account forced and scheduled outages of system facilities. Security is a system's ability to withstand sudden disturbances such as electric short circuits or unanticipated loss of system facilities.

SCADA – Supervisory control and data acquisition; in a centralized remote control system, SCADA collects and transmits data and alarms from selected stations to a control center for use in system operation and off-line system studies.

Shield Wire – A grounded wire placed near phase conductors of a power line to protect the conductors from direct lightning strokes. Shield (or ground) wires also provide a path for residual currents that accompany system unbalance during normal or abnormal operation.

Single Phase – Any one phase which, in a balanced three-phase power system, carries current separated by 120 electrical degrees from those in the companion phases. All station facilities (e.g., circuit breakers, shunt reactors) operated at 765 kilovolts are built as single-phase units due to their large physical size and, therefore, can be switched individually. This feature offers unique operating flexibility generally not available at lower voltage levels.

Static Var Compensator (SVC) – A thyristor-based device for variable, continuous control of voltage and power factor on transmission lines by rapidly inserting reactive or capacitive compensation in precise amounts required by the power system.

Surge Impedance Loading (SIL) – A natural property of a transmission line; used as a convenient “yardstick” for measuring relative loadabilities of lines operating at different nominal voltages. A line loaded to its SIL is characterized by reactive self-sufficiency (no reactive power into or out of the line) and a uniform voltage profile along its length.

System Unbalance – An electrical phenomenon in three-phase power systems manifested by unequal phase voltages and/or currents across the phases.

Three Phase – A term applied to lines or equipment carrying three currents 120 electrical degrees apart, used in utility, industrial and commercial applications. Three-phase equipment is switched in its entirety because all three phases are physically located in one enclosure.

Thyristor – A solid-state switch that can open/close circuits rapidly and repeatedly without the use of moving mechanical parts; a basic component of power electronics devices.

Tower – A steel structure along transmission lines that supports conductors.

Transfer Capability – A measure of the ability of interconnected electric systems to move power in a reliable manner from one area to another over all transmission lines (or paths) between those areas under specified system conditions.

Transformer – A static electrical device that changes AC voltage by electromagnetic induction to facilitate power transfer from a generator, via transmission and distribution, to a customer’s load. A step-up transformer increases, while a step-down transformer decreases, the voltage.

Transposition – Interchange of a transmission line’s phase conductor (and possibly overhead shield wire) positions at selected intervals along the line to compensate for inductive effects.

XIV. References

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