Middletown – Norwalk 345-kV Transmission Line

High Voltage Direct Current Transmission System Study

In order to investigate potential alternatives for the 345-kV Middletown – Norwalk Transmission Line Project, The Connecticut Light & Power and The United Illuminating Company ("the Companies"), commissioned a feasibility study of constructing a high voltage direct current (HVDC) transmission line, underground or overhead, between East Devon substation in Milford and Beseck substation in Wallingford, a distance of about 34 miles. These two substations represent the only two points along the proposed route where the substitution of an HVDC system for the proposed AC system could be made without destroying the integrity of the 345kV loop. Such an alternative was considered as a means of under grounding the 345kV line proposed for the right of way between Beseck switching station in Wallingford and East Devon Substation in Milford. At the conclusion of this study, the companies determined that HVDC transmission is not the preferred alternative for the following reasons:

- The proposed 345kV AC transmission line connects to all major AC substations in the area including Beseck in Wallingford, East Devon in Milford, Singer in Bridgeport, and Norwalk in Norwalk and thus integrates the Southwest Connecticut area into the existing 345kV transmission backbone in Connecticut and New England. For reliability reasons, the integrated 345kV system is constructed in a series of "loops", so that if an interruption occurs on one of the lines to any area served by a loop system, service can still be provided to the area from the other end of the loop. An HVDC transmission line, on the other hand, does not integrate Southwest Connecticut into the AC transmission grid in the rest of Connecticut and New England. Unlike the '345kV Loop', it does not provide an instantaneous backup source for the loss of a portion of that loop.

- An HVDC transmission system isolates the load it serves from the rest of the grid. It does not instantaneously pick up a portion of the load from an adjacent line that becomes deenergized. AC transmission lines, however, function as an integrated circuit and will instantaneously pick up a share of the load of any companion line in the event that line is deenergized.
- Electric power transmission using HVDC technology is not economical for short distances such as the ones proposed in Southwest Connecticut (34 miles). HVDC transmission systems need expensive converter stations at each end of the transmission link to convert power from AC to DC and vice versa. Economical considerations call for a certain minimum transmission distance (break-even distance) before HVDC can be considered competitive, purely on cost. Estimates for the break-even distance between HVDC and AC transmission using overhead lines are around 300 miles. There is no break-even distance between the overhead AC transmission and the underground HVDC transmission of electric power. The direct cost for an HVDC link between Beseck and East Devon would be approximately $564M for an underground option. The direct cost of the equivalent overhead AC facilities would be approximately $100M. Should the HVDC line be installed overhead, the direct cost would be approximately $400M, or 4 times as much as the equivalent AC facilities. The main reasons for the higher costs are the need for converter stations at the terminals to convert AC into DC and vice versa.
- Underground AC lines require reactive compensation and the ability to add reactive compensation must be considered when comparing underground options. HVDC only becomes viable when mid point reactive compensation is necessary

on the AC line and cannot be added. Typically, this occurs on long (24+ mile) submarine cables.

- AC/DC converters require a large amount of reactive power to operate correctly, both in rectification as well as in inversion. For a 1200 MW HVDC transmission link, reactors in the order of 480 MVAR to 660 MVAR (approximately 50% of the active HVDC link) are needed. Synchronous or static capacitors have to be installed for this purpose. The need for these reactors increases the size requirements of the AC substation to which the converter station is connected.
- AC/DC converters generate many harmonics both on the DC side and on the AC side. Unless addressed, these currents can have many negative effects on the power system, including but not limited to the malfunction of protection systems and overheating of load elements such as induction motors, etc. The DC harmonics can also interfere with neighboring communication circuits. Filters have to be installed on the AC side to mitigate the amount of harmonics transferred to the AC system. On the DC side, smoothing reactors have to be installed. These components add to the cost of the converter.
- Unlike the AC transmission system, converters have very little overload capacity. They would have to be oversized to accommodate the same emergency ratings as an equivalent AC line.
- Approximately 15 acres of land for a converter station will be required at each of the terminal stations. This requirement is in addition to the land needed for the AC portion of the substations.

Because of the above factors, the Companies determined that a high voltage DC (HVDC) transmission line is not a technically and economically practical option for the Middletown to Norwalk project and eliminated this alternative from further consideration.

HIGH VOLTAGE

DIRECT CURRENT TRANSMISSION

SYSTEM STUDY

UI

THE UNITED ILLUMINATING COMPANY

&

CL&P

THE CONNECTICUT LIGHT AND POWER COMPANY

MIDDLETOWN - NORWALK TRANSMISSION LINE PROJECT

B&V PROJECT 133193.43.1200

December 2003

Prepared By:

BLACK & VEATCH

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Appendices

Executive Summary

United Illuminating Company (UI) and the Connecticut Light and Power (CL&P), hereafter known as the Companies, have proposed to the CSC the construction of a transmission line that delivers 1200 MW transfer rating between the existing Scovill Rock Switching Station in Middletown, the proposed Beseck Switching Station in Wallingford, the proposed East Devon Substation in Milford, the proposed Singer Substation in Bridgeport, and the existing Norwalk Substation in Norwalk. One of the alternatives considered by the Companies was a high voltage direct current (HVDC) transmission line connecting the Beseck Switching Station to the East Devon Substation. Both an underground and an overhead HVDC transmission line was considered. This report examines the technical feasibility of a HVDC solution and neither recommends nor excludes an HVDC solution for the Middletown-Norwalk Project.

This report addresses the possible alternative of an HVDC Transmission System between Beseck Switching Station and East Devon Substation. The HVDC System arrangement studied is a bipolar configuration (i.e. one circuit with positive and negative conductors) with a metallic ground return conductor.

The advantage of a HVDC transmission line is that there is no restriction on the length of the line due to the build-up of capacitance. The disadvantages of an HVDC system is that it can not change current flow instantaneously in response to immediate load and source changes in the surrounding ac system. Also, the HVDC system is not commonly used in a multiple terminal configuration and the cost of HVDC transmission is higher than the ac transmission.

The estimated differential cost of an underground HVDC Transmission System between Beseck Switching Station and East Devon Substation versus an equivalent overhead ac line between the same two points is about an additional $460 million. The estimated differential cost for an overhead HVDC Transmission System versus an equivalent overhead ac line is about an additional $300 million.

1.0 Introduction

United Illuminating Company (UI) and the Connecticut Light and Power (CL&P), hereafter known as the Companies, have proposed to the CSC the construction of a transmission line that delivers 1200 MW transfer rating between the existing Scovill Rock Switching Station in Middletown, the proposed Beseck Switching Station in Wallingford, the proposed East Devon Substation in Milford, the proposed Singer Substation in Bridgeport, and the existing Norwalk Substation in Norwalk. One of the alternatives considered by the Companies was a high voltage direct current (HVDC) transmission line connecting the Beseck Switching Station to the East Devon Substation. Both an underground and an overhead HVDC transmission line was considered. Black & Veatch was asked to prepare a feasibility study for the possible application of a HVDC transmission system addressing the following issues:

- Present application of HVDC worldwide
- Pros and cons of ac and dc transmission systems
- Recommended specifications for the converter stations
- Recommended specifications for the underground transmission cables
- Recommended specifications for the overhead transmission lines
- Potential environmental impacts
- Estimated cost comparison

Black & Veatch carried out a macro level technical feasibility study based on the typical characteristics of HVDC systems, taking the requirements of the proposed system into account. While we believe that a macro analysis is sufficient at this point, a more detailed facility study, including system studies such as power flow, fault and stability studies, would be required if the HVDC option is pursued. This report examines the technical feasibility of a HVDC solution and neither recommends nor excludes an HVDC solution for the Middletown-Norwalk Project.

This report addresses the important aspects of dc transmission systems and provides technical information with respect to converter station, cable technology, and cable selection for the Beseck – East Devon section of this transmission line project. The fundamentals of dc transmission technology are also addressed in this report.

2.0 High Voltage Transmission Systems

Electric power is generated in alternating current (ac) form and transmitted to the load centers using high voltage transmission systems. High voltage transmission systems can be either ac or direct circuit (dc).

2.1 AC Transmission Technology

The first electric power transmission, which was dc transmission, was developed by Edison in 1882. However, the difficulty of converting the dc voltage from one voltage level to the other voltage level and the invention of induction motors in 1888 led the way for ac transmission.

Now, nearly the entire electrical grid in the U.S. and the world consists of ac transmission lines. The transmission lines can either be overhead lines or underground cables. However, due to the higher costs associated with UG ac cables and their effects, such as reactive power compensation on the electrical system, the overhead lines are by far the most common type.

The amount of power that can be reliably transmitted over an ac transmission line depends on the transmission voltage and the following are the typical transfer capacities:

Transmission Voltage (kV)	Power Transfer (MW)
69	50-100
115	150-350
230	300-450
345	1000-2050
500	2000-3000

The advantages of ac transmission are the following:

- The ac transmission line does not require ac/dc/ac converters.
- There is a wealth of experience available for ac lines.
- Load pickup is instantaneous for a failure in another part of the system.
- The line cost is less expensive in most of the cases except where the overhead transmission is more than 300 miles.

However, ac transmission has the following limitations:

- In the case of underground transmission, the cable charging currents are very high in magnitude and can even be equal to the load current for a transmission distance of 15-20 miles. This means that there is hardly any real power transfer possible without shunt reactor compensators.
- Long extra high voltage transmission lines require reactive power compensation and thereby increasing the overall cost.
- It is not possible to connect two asynchronous systems with ac transmission lines.

2.2 HVDC Transmission Technology

2.2.1 History of HVDC Systems

Even though the dc transmission was introduced prior to ac transmission, the alternating current became the standard in the early part of the 19^{th} century. However, the ac transmission was not practical for long underground over 25 miles and under sea transmission. With the advent of high power mercury arc valves, it was realized that high voltage dc transmission was possible.

The first commercial 'modern era' HVDC transmission line was an under sea route commissioned in Sweden in 1954 between the island of Gotland and the mainland. It used the high power (20 MW, $\pm$100 kV) mercury arc valves for ac/dc/ac conversion, which were the backbone of the then HVDC technology. Following the success of the Gotland project, several HVDC systems were installed using the mercury arc valve technology, including the 160 MW, ±100 kV under sea Cross Channel project between England and France and the Pacific dc Intertie between Ceililo Substation of Bonneville Power Authority (BPA) and Sylmar Substation of Los Angeles Department of Water and Power (LADWP) in the United States. The Pacific dc Intertie is one circuit of 846 miles long with a power transfer capacity of 3100 MW at ±400 kV.

The development of high voltage, high power semiconductor devices in the 1960s introduced the first commercial solid state semiconductor valve for HVDC transmission in 1970. Since then, the semiconductor thyristor (valve) technology has been improving steadily. At present, the highest dc transmission voltage is +/- 600 kV utilized in the 500 mile Itaipu HVDC System which interconnects Paraguay and Brazil with a total power rating of 6300 MW using two bipolar dc overhead transmission lines.

2.2.2 HVDC Process

The fundamental process that takes place in HVDC systems is the conversion of ac voltage to dc voltage and vice versa. Current HVDC technology can be classified into two broad categories based on the components used for the conversion:

1. **Classic HVDC systems** use high voltage, high power solid state thyristors. These systems are also generally referred to as 'Natural Commutated Converters.' Sometimes, series capacitors are added between the converters and the converter transformers. This is done if the ac system has a low short circuit level (weak system/power source), in which case the ac/dc converters are called 'Capacitor Commutated Converters.'

2. **Voltage Source Converter (VSC)** technology uses power electronic devices such as Gate Turn Off thyristors (GTO) and Insulated Gate Bipolar transistors (IGBT). Even though these devices have been in use in industrial environments for more than a decade, their application in HVDC transmission has been recognized only in the last few years. 'HVDC Light' and 'HVDC PLUS' are some of the trade names used for this kind of technology. This system provides for much better control of the ac wave shape over that of the classic HVDC system. Better control of the wave shape provides lower harmonic currents and voltages.

At present, the voltage source converters are commercially available only up to 300 MW. With the need for this system to transfer 1200 MW it would require paralleling 4-300 MW systems. Equipment vendors say this is "theoretically" feasible but presently has not been done before. The cost of paralleling 4 – 300 MW systems would be on the order of four times that of a classic HVDC system of the equivalent rating. A two-bundled conductor per pole for an overhead transmission line or eight UG cables for an underground transmission line would be required to obtain the 1200 MW. Four-300 MW HVDC converter stations would need to be integrated together at each end of the line. Because of the unproven nature of this system configuration and increased cost, voltage source converter technology is not recommended and will not be considered any further in this system study.

2.2.3 HVDC Transmission Applications

In almost all of the existing HVDC installations, dc transmission was chosen over ac transmission either due to economic reasons or due to technical considerations. The following are the main reasons for using HVDC transmission systems:

1. If bulk amounts of power need to be transported over very long distances, the overall cost of dc transmission, including the cost of converters, filters, overhead lines and losses, may be lower than the cost of overhead ac transmission. Studies have shown that for a power transfer of 1000 MW and above, an overhead dc transmission would be a more economical choice than an overhead ac

transmission line if the distance is more than 300 miles. This distance is often referred to as 'breakeven' distance.

2. For underground transmission systems of lengths greater than 15-20 miles, it may not be practical to use ac cable systems due to the presence of high charging current and the amount of shunt reactive compensation required. The dc UG cable systems are an option to be considered in this case. The 'breakeven' distance for the cable system is dependent on the amount of compensation required on the ac UG line.

3. Some ac electric power systems are not synchronized to the neighboring systems even though the physical distance between them is quite small. This situation can arise if the adjacent systems have two different frequencies (50 and 60 Hz) such as in Japan or due to stability considerations such as between the Western and Eastern electric systems of United States. In such situations, dc interconnection is the only practical solution for the overall interconnected operation.

In today's deregulated market place, dc transmission is also actively being considered to connect different control areas due to its ease of power flow control between the systems. As an example, the 54 mile dc transmission line operating at 80 kV between Queensland and New South Wales in Australia was installed to enable electricity trading between the two states.

2.2.4 Characteristics of HVDC Transmission Systems

HVDC overhead and cable transmission systems can be either point-to-point or multi-terminal type.

In the point-to-point system, electrical power is transferred from one converter station to the other without interconnecting to any other system facility or load centers. Therefore, the dc line does not require an interrupting device to isolate the line during faults because the isolation is achieved by blocking the converters. Blocking of converters using firing angle converters forces the dc voltage and current to zero.

Multi-terminal HVDC systems consist of more than two converter stations (at least three stations), thereby providing power transfer to more than one geographically separated substation. At present, there is only one multi-terminal system in operation worldwide. This system connects Hydro Quebec to New England. The line length of this line is about 930 miles and it operates at a voltage of ± 450 kV.

In HVDC systems, unlike HVAC systems, it is difficult to provide intermediate taps and stations on an existing dc line due to the unavailability of HVDC breakers. To accomplish this, additional converter stations would have to be built to operate the entire system as a multi-terminal dc system. An additional HVDC station would cost about $125 million dollars, and the system would need to be planned and configured at the beginning of any project. If not planned, the upgrade may involve replacement of controllers.

A unique characteristic of a HVDC line is the ability to control the power flow. Normally, the level of power transfer is set manually and this level is maintained irrespective of system variations such as voltage and load flow. This feature is beneficial if a scheduled power transfer is desired. However, if the dc line is connected to a load center in parallel with an ac line, the power setting has to be adjusted automatically to pick-up the deficient load if the parallel ac line is lost. Studies would have to be performed to determine the ability of the dc controllers to determine the speed of changing the power setting and the magnitude. It may well be that supplementary controllers similar to high-level controllers in the existing system have to be designed to match the performance of a pure ac system.

2.2.5 HVDC Converter Configurations

An HVDC converter is a power electronic device which converts alternating current (ac) to direct current (dc). The basic form of an HVDC converter consists of a 6-pulse bridge using thyristor valves. A thyristor valve may contain many individual thyristors assembled in series and parallel combination to provide the required voltage and current ratings. The most commonly used converter configuration is 12-pulse arrangement which is a combined unit of two 6-pulse converters.

The converters produce harmonics. The higher the converter pulse number, the fewer harmonics produced. Studies have shown that the 12–pulse is the optimal configuration for HVDC transmission based on the overall cost, including the cost of converters and the filters.

Converter stations are built using 12-pulse converters to provide either monopolar or bipolar operation. Appendix 1 illustrates typical monopolar and bipolar configurations.

In monopolar schemes, ground, sea or a metallic conductor can be used as the return path. If ground or sea return is used with monopolar operation, the resulting dc magnetic field can cause disturbances in electro-magnetic equipment in the vicinity of the dc cable. Another concern with continuous ground current is that some of the return current may flow in adjacent metallic structures such as pipelines, and intensify corrosion. For these reasons, continuous operation with ground return is not permitted in many countries.

A bipolar arrangement does not require a return path. In the case of loss of converters belonging to a pole, the unused transmission cable or conductor can be grounded and used as the return conductor for monopolar operation. During the loss of an overhead line or cable, bipolar operations again become monopolar requiring a return path. Monopolar operation with earth ground return is permitted during such emergencies. Alternatively, a metallic ground return can also be provided for continuous monopolar operation.

Bipolar arrangement is the most widely used configuration for overhead and cable transmission. Monopolar arrangement may sometimes be preferred, as in the case of back-to-back systems. Back-to-back systems are those where the converters (rectifier and inverter) are located physically at the same place without involving any overhead or underground/submarine cables.

In the case of this application, it is recommended that the HVDC transmission system between the Beseck and the East Devon substations be a bipolar configuration with a metallic ground return conductor because the return neutral current during the monopolar operation can be kept away from the earth ground and the system can operate indefinitely in this mode.

2.3 Pros & Cons of ac and dc Transmission Systems

The following summarizes the advantages of ac transmission over dc transmission:

- The cost of ac transmission system is generally lower than the dc transmission, except in cases where the overhead transmission distance is more than 300 miles.
- Almost all of the transmission systems in the world are of ac and so there is a wealth of experience available and numerous equipment vendors.
- Conventional ac transmission system equipment does not produce harmonics.
- The construction duration of ac substations is much shorter than the converter stations.
- Multiple terminal configurations are common and more easily accommodated.
- Load pickup is instantaneous for a failure in another part of the ac system.
- An ac system can respond instantaneously to immediate load and source changes. A dc system must be controlled separately.

The following summarizes the advantages of dc transmission over ac transmission:

- The cost of high voltage dc transmission system for bulk power long distance (over 300 miles) transmission is lower than the cost of high voltage ac transmission.
- The high voltage dc transmission systems improve the stability of independent ac systems connected by a dc link by isolating the ac systems from each other's disturbances.
- The systems of two different frequencies can be interconnected with a high voltage dc transmission system.
- There is no restriction on the transmission distance for underground or submarine cable dc transmission.

3.0 HVDC Underground Cable

3.1 Underground Cable Technology

The underground cables used for HVDC power transmission are mainly for submarine application, and whatever underground land installation is necessary to complete the submarine project. There are four types of power cable which are suitable for either submarine or land based HVDC applications: fluid-filled, gas pressurized, mass impregnated, and polymeric cables. Appendix 2 provides the partial list of major HVDC UG transmission projects worldwide including the length, voltage and type of cable employed.

The self-contained fluid-filled cable was the first transmission cable used in the United States, and also is one of the most commonly used cables for underground submarine transmission dc cable types. Its hollow core is completely filled with low viscosity fluid and works under static fluid pressure. The fluid pressure is fed from fluid reservoirs located at the ends of the cable or along the length of the cable route as required to maintain design pressure. Hydrostatic pressure and possible fluid system failures are major considerations when choosing a reservoir system. Often, in land cable applications, fluid reservoirs are placed among the route to sectionalize the system; this better controls the hydrostatic pressures and failure considerations. In some cases, particularly submarine cable applications, sectionalized reservoirs are not feasible. In these cases reservoirs placed at both ends maybe the only viable solution, however, cable design/cost will increase and reliability maybe compromised. Detailed design will be required to consider which system is appropriate.

For this study, sectionalizing the cable along the route was used. Sectionalizing the cable along the route requires small reservoirs for this type of cable system and can be installed in the splicing chambers along the route in order to reduce the requirement of the land. There is a significant amount of this type of cable installed worldwide, especially in Europe and Asia. The disadvantage of this cable type is there may be environmental issues because of the presence of fluid in the cable. At present, self-contained fluid-filled cable applications are slowing down due to the development of solid dielectric cable systems. However, the self-contained fluid-filled cable system is still very viable and available through manufacturers such as Pirelli in Italy, Nexans in Norway, J-Power Systems and Viscas in Japan, Taihan and LG in Korea.

The gas pressurized type cable is insulated by using paper tapes pre-impregnated with petroleum oil. In the center of the conductor, there is a hollow core which contains pressurized SF_6 gas. The gas pressurized cable should perform satisfactorily since it is 'similar' to the self-contained fluid-filled cable.

The mass impregnated cable consists of a conductor which is insulated with paper tapes impregnated with high viscosity oil. It has the advantage of eliminating the need for pressurization equipment. Also, no length limitation exists for this lapped paper insulated cable. The mass impregnated cables are dominant in submarine application. A disadvantage is that the maximum operating temperature of the cable is limited to 55° C, compared to pressurized type cable at 85° C.

The polymeric cable used in dc cable systems has been developed recently, with the introduction of VSC (Voltage Source Converter) based HVDC transmission systems. The polymeric insulation is extruded, which allows variable length. This type of cable contains no fluid. The cable splices are easier to make than the other three cable types and can be pre-manufactured and pre-tested. However, the highest dc voltage commercially applied to this type of cable is only 150 kV, with the total power transmission up to 500MW. With the need for this system to transfer 1200 MW it would require paralleling 3 cables per pole for a total of 6 cables. Cable vendors say this is feasible but presently has not been done before. It is assumed that the cost would be approximately three times that of a single bipolar cable system.

The configuration of having 3 cables in parallel would have three times the number of cable splices compared to only one cable per pole. This would reduce the reliability of the cable system, i.e., more number of failures compared to one cable per pole. However, the availability of the cable system would be higher, i.e., even if one cable failed, the two remaining cables would be available for power transfer.

Using HVDC technology and based on the information introduced above, self-contained fluid-filled cable in a duct bank would be the most feasible choice to underground a 35 mile-long cable route between the Beseck Switching Station and the East Devon Substation.

4.0 Beseck to East Devon HVDC System Technical Evaluations

4.1 HVDC System Voltage Rating

At present there is no specific guideline or national standard covering the standard transmission voltages for HVDC systems. The converter voltage ratings are usually decided based on the cost of converters and the transmission system.

Review of the existing installations show that for a power transfer of 1200 MW, the transmission voltage ratings used are between 350 kV and 500 kV.

Discussions with one of the leading manufacturers of HVDC converters regarding the dc transmission voltage between Beseck and East Devon indicated +/- 500 kV as the preferred voltage rating for the converters. This was based on their experience with previous projects of this magnitude. However, the operational experience of +/- 500 kV underground cable is much less than +/- 350 kV.

For that reason, +/- 350 kV has been considered as the dc transmission voltage for both the overhead and underground transmission lines in this feasibility study.

4.2 Converter Station Arrangement

The HVDC scheme for the present project is 'bipolar', and Appendix 3 and 4 show the converter station arrangement for Beseck Switching Station and East Devon Substation respectively.

The ac filters and the converter transformers are to be connected to the separate positions in the 345 kV substation. The arrangement would also have dc filters and a metallic ground return conductor.

4.3 Converter Transformers

The converter transformer is also an important component of the HVDC system. The converter transformer transforms the station ac voltage to a suitable voltage required for the conversion process and provides the commutation reactance.

The converter transformer is a special type of transformer which is required to withstand both the ac and dc voltages. In addition, the transformer windings are rated for both fundamental and harmonic currents.

In the case of the Companies' project, the primary ac voltage of the transformers would have to be 345 kV, however, the secondary ac voltage would be selected by the converter manufacturer depending on the converter voltage rating.

The availability of converter transformers is very critical to the overall availability of the system and so the converter station would require a spare transformer. It is recommended, based on the cost, to use three single phase converter transformers, rather than a three phase transformer, with an additional single phase transformer being kept as spare at both Beseck Switching Station and East Devon Substation.

4.4 Thyristor Valve Cooling System

The current ratings of the converters are dependant on the individual thyristors' temperature and thereby very much dependant on the cooling system. To obtain an efficient cooling system, the thyristors are cooled from both sides by means of heat sinks. A heat sink usually consists of either an air cooler or a de-ionized water cooler.

Water has about five times higher thermal capacity compared to air and so converters with water cooled thyristors are more compact than their counterpart. It is recommended to adopt water cooled thyristors for Beseck and East Devon substations to achieve a compact converter design. In fact, almost all of the new converters are provided with water cooled thyristors.

4.5 AC Harmonic Filters

Converters produce ac harmonic currents at the ac bus, which in this case is at the 345 kV substation. With the 12-pulse converter arrangement, the dominant harmonics are 11^{th}, 13^{th}, 23^{rd} and 25^{th} harmonics.

Harmonics can have many negative effects on the power system. Some of the most concerning effects are the malfunction of protection systems and overheating of load elements such as induction motors. IEEE STD 519 stipulates the amount of harmonics that can be injected into the system at the point of common coupling.

Harmonic filters are required at the converter ac busses in order to limit the amount of harmonics that would penetrate the ac system.

In the present project, it is envisioned that only 11^{th}, 13^{th}, 23^{rd} and 25^{th} harmonic filters would be required at Beseck and East Devon substations. However, system studies would have to be performed to find out whether additional filters would be required. The decision would be based on the system harmonic impedances and the harmonic voltage resonances.

Power line carrier communication (PLC) filters may also be required if these schemes are already employed on the adjacent circuits.

4.6 DC Harmonic Filters

Similar to ac harmonics, the converters also produce harmonics (ripples) at the dc side of the converter which are called dc harmonics. These dc harmonics, if allowed on the dc line, can cause interference with neighboring communication circuits. Hence, dc harmonic filters are required.

The dominant dc harmonics for the 12-pulse converters are the 12^{th} and 24^{th} harmonics.

For this project, dc harmonic filters and smoothing reactors would be required for both poles at Beseck and East Devon Substations.

4.7 Reactive Power Compensation

The converters absorb a huge amount of reactive power for their operation and typically require reactive power equal to 40% - 55% of the dc power. This means that the converters at Beseck and East Devon would require between 480 MVAR to 660 MVAR each.

Some of the reactive power can be supplied by the ac filters which typically range from 200 to 300 MVAR and the remaining would have to be supplied either from the system or by the addition of shunt capacitors.

System studies would have to be performed to calculate the amount of additional reactive power required at Beseck and East Devon, and also to determine the switching effect of the 345 kV circuits from East Devon to Norwalk.

4.8 System Protection

The protection schemes for ac side equipment are usually conventional types such as transformer differential protection for converter transformers. However, specially designed filter and capacitor bank protection schemes are required. The typical ac protection schemes are:

- transformer differential protection
- ac overcurrent protection
- ac filter overload / unbalance protection

The protection philosophy for the dc side equipment varies among the manufacturers. However, in general the following protection schemes are provided:

- Short circuit protection for converter and valve
- DC overcurrent protection
- Commutation failure protection

- DC harmonic filters protection
- Voltage stress protection
- Excessive delay angle protection
- DC differential protection
- DC maximum/minimum voltage protection
- DC line protection

4.9 Converter Station Specification

The specification for the main components of the proposed converter stations shall be as shown below:

Description	Requirement
HVDC scheme	Point to Point with a possibility to operate as a 3-terminal system
Type of transmission	Underground cable/(SCFF) or Overhead Line
Approximate Length	35 miles Underground 33.5 miles Overhead
Number of Poles	Two (i.e. one circuit of a positive and a negative pole)
Neutral Path	Metallic Ground Return
DC side switching between poles	Required
Number of converters per pole	Two converters in series per pole (12 pulse)
DC side filters and smoothing reactors	Required for 12th and 24th harmonics
AC nominal voltage	345 kV
DC nominal Voltage	+/- 350 kV
Frequency, nominal	60 Hz
Nominal Power Rating (at inverter output terminals)	1200 MW (600 MW per pole)
Minimum power for continuous operation	120 MW

Description	Requirement
Power flow required in both directions	Yes
AC side filters	Required as per IEEE 519 (less than 1.5% total harmonic voltage distortion)
3rd harmonic filter	Required as per the studies
Number of splice chambers	200
Shunt Capacitors	Required as per the studies
Communication Line between the stations	Optical fiber communication used for underground transmission line, OPGW used for overhead transmission line

4.10 Underground Cable System Specification

4.10.1 Route and Construction Requirements

The HVDC underground transmission line is assumed to be routed in public street right-of-way. The route begins at the Beseck Substation and continues south west to the Devon Substation. This route is graphically depicted in Appendix 5. The estimated total length of this route is 35 miles, all underground. The alternate UG routes in Appendix 5 were not considered for this study.

For this study, B&V recommends a land cable system of Self-Contained Fluid-Filled (SCFF) cable. The operating temperatures of SCFF is 85°C, compared to Mass Impregnated (MI) of 55°C, which allows the SCFF to operate at higher temperatures, enabling it to provide the required ampacity and transfer capability while maintaining practical cable size.

4.10.2 System Loading Requirements

The underground cable system **could** be designed to carry 1200 MW of power. The cable, splices, terminations, grounding system, and all other cable system components, shall meet the following system electrical loading requirements as follows:

Nominal Voltage	± 350 kV
Basic Impulse Level	975 kV
Continuous Ampacity Rating	1,714 A, (based on 1200 MW)
Continuous Conductor Temperature	85 degrees C for SCFF

4.10.3 Cable System Operating Environment

The following sections describe the underground environment in which the cable would be installed.

4.10.4 General

On a worldwide application, there are three primary ways to install HVDC land cable systems; tunnel, duct bank and direct buried. European and Asian countries primarily use tunnel and direct buried applications, depending on the route of the cable system, i.e. urban or rural. The United States uses duct banks for urban areas and in some cases direct buried for rural areas. The main reason for the U.S. dominantly using duct bank systems versus tunneling is driven by the cost and necessity. The cost for tunneling is much higher than duct bank applications and the majority of city streets in the U.S. still have room for trench excavation procedures.

For this project, a duct bank system located in established streets and roads, would be the primary choice for the entire route. The cable circuit would be installed in duct bank the entire length. Where required along the route, the cable would be routed in casings used for crossings that would be installed using a horizontal drilling or jacking method.

4.10.5 Operating Environment Criteria

Underground transmission cable operating environment is as follows:

Summer Ambient Soil Temperature	25° C
Typical Duct Bank Width	3.0 feet
Thermal Resistivity	
• In Situ Soil	90° C-cm/W
• Concrete Encasement	60° C-cm/W
• Imported Select Backfill	60° C-cm/W
Minimum Burial Depth to	
• Top of Duct Bank	3.0 feet

4.10.6 Cable System Electrical Design Criteria

This section describes the major components of the 350 kV HVDC cable system. By having dc, the total losses in the cable are low, being only resistive conductor losses. The cable may transmit about two to three times as much power as that of an ac system. The estimated cable size for the project is 3,500 kcmil copper.

4.10.6.1 Underground Cable. Self-Contained Fluid-Filled (SCFF) is the cable system recommended for this project.

4.10.6.2 Splices. Regardless of dc or ac power usage, splices are typically minimized for various reasons, such as, installation and maintenance cost and reliability. Since a majority of HVDC cables world wide are submarine, tunnel and direct buried, the number of splices are less than ac cable systems which are more often installed in a duct system. Technically, splices for HVDC cable are acceptable and have been installed but because of the above reasons, dc splices are limited in number world wide. This is an important fact, due to the city-street installation requirements for this project. The maximum cable lengths for city-street shipment and installation are limited to approximately 2500' per reel.

4.10.6.3 Terminators. Type – 350 kV, 975 kV BIL. The BIL rating for the cable would be determined after system studies are performed.

4.10.6.4 Splicing Chambers. With a bipolar dc cable system, under short term emergency operations, it is possible to operate one cable at reduced power, thus enabling services to be rendered with one cable not energized. For this reason, a separate splice chamber is recommended for each cable, to ensure worker safety. A 35-mile route would require approximately 200 splice chambers. Splicing chambers are typically used in conjunction with duct bank applications for splicing and cable pulling procedures. It also allows for splice placement and pressurized reservoir placement, when using SCFF cable. Each splice chamber would be equipped with two accesses (chimneys) to facilitate cable installation and maintenance access.

Two standard splicing chambers would be required. Normal splice chambers would be 20' long by 8' wide by 8' high and would be approximately every 2000' along the route. Stop splice chambers would be 25' long by 8' wide by 8' high and would be placed throughout the route to control hydraulic head pressure and facilitate operation and maintenance of the system. The number of stop splice chambers would be determined during detail design. Each manhole would be suitable for AASHTO heavy loading H-20.

4.10.6.5 Duct Bank Conduit Duct bank materials would be in accordance with the following.

- Size - 6 to 8 inches. (depends on the size of the cable)
- Type - Schedule 40 electrical grade or nonmagnetic such as PVC.
- Couplings - Duct connections would use separate electrical long-line duct couplings.

4.10.6.6 Riser Conduit. Conduit riser materials would be in accordance with the following.

- Size - 6 to 8 inches (depends on the size of the cable)
- Type - Schedule 40 electrical grade PVC or any non-magnetic conduit.
- Couplings - Duct connections would use bell and spigot type connections.

4.10.6.7 Cable Temperature Monitoring System. A fiber optic cable system design shall be integrated in very close proximity or part of the 350 kV power cable for the purpose of temperature monitoring.

4.10.7 Cable System Installation

This section covers the duct bank and manhole installation parameters.

4.10.7.1 Trench Excavation and Restoration. After concrete encasement of the conduits, Fluidized Thermal Backfill would be used to backfill the trench. Excavated material would be regularly removed from the construction site. The controlled backfill mix shall be tested for thermal properties and strength.

Street restoration would be in accordance with applicable federal, state and local laws, ordinances and codes, but not less than one foot of pavement restoration on each side of the trench excavation.

It is estimated that 10% of the trenching may require excavation of rock along the 35-mile route. If dense rock is encountered, excavation is very difficult if not impossible using traditional trenching methods. This leaves only a few solutions. Horizontal drilling and casings are other alternatives for excavating rock. This procedure is costly, yet minimal excavation is required by comparison to trenching. Blasting, although an easy way to remove rock proficiently, is very invasive in city streets. The risk of damage to existing utilities, structures, businesses and residence is often too high, especially on well congested and historical streets.

4.10.7.2 Duct Bank. The following parameters would be utilized in the design of the duct bank.

- Minimum depth to top of the duct bank would be 3 feet.
- Conduits/ducts would be encased with reinforced concrete. The concrete would be specified to have a compressive strength of 2,000 psi. The concrete would be tested for thermal properties and strength.
- The trench (above the concrete duct bank) would be filled with a low strength Fluidized Thermal Backfill (FTB™) which consists of the same properties of the duct bank concrete with the exception of the strength. The FTB would have a strength of 250-500 psi.
- A cable marking tape directly above the duct bank and within 18 inches of grade or paved surface would be utilized for the entire underground length of each duct bank.
- At least one spare PVC duct would be provided within the duct bank for spare cable.

4.10.7.3 Casings. A steel casing or polyethylene pipe would be installed using jack and bore or horizontal drilling methods where the duct banks cross railroads, highways and rivers/canals. The diameter of this casing pipe is dependent on the cable size.

4.10.7.4 Cofferdam. Cofferdams are usually used when drilling techniques are not practical. They consist of two main techniques, wet and dry. The wet is used to remove the material at the bottom of the body of water similar to a trench. Conduits are then pulled into the body of water from one end to the other. Concrete is then placed in the trench. A dry application would typically consists of double steel sheeting with the void filled with gravel. One side of the body of water is completed first to allow for traffic to utilize the other side, then reversed. After completion of the dry cofferdam, typical trenching techniques would take place to install the duct bank.

4.10.7.5 Construction Access Requirements. The majority of construction would be limited to construction within the city-street easement. A minimum construction access width of 25 feet would be required to allow for construction of the duct bank. A minimum of 10 feet on one side from the duct bank center line and a minimum of 15 feet on the other side would be required to allow for access to the trench by conduit trailers, dump trucks and thermal backfill mixing trucks.

At each bore crossing, minimum rectangular construction access areas approximately 120'x 60' and 20' x 40' for equipment staging, would be required, on entrance and exit sides, respectively, to perform the boring.

Soil erosion and sediment control would be maintained during construction activity as required and in accordance with the applicable city and county laws, ordinances and codes.

Traffic control, work hours, and coordination with local law enforcement would be maintained as necessary throughout construction as defined by permits.

4.11 Overhead Transmission Line System Specification

4.11.1 Route and Construction Requirements

The HVDC overhead transmission line is assumed to be routed on the existing transmission line right-of-way. The route begins at the Beseck Substation and continues southwest to the East Devon Substation. The estimated total length of this all overhead route is 33.5 miles. An alternate overhead route was not considered for this study.

4.11.2 System Loading Requirements

The overhead transmission line system would be designed to carry 1200 MW power. The system shall meet the following system electrical loading requirements of:

Nominal Voltage	± 350 kV
Basic Impulse Level	975 kV
Continuous Ampacity Rating	1,714 A, (based on 1200 MW)
Maximum Conductor Temperature	140° C
Continuous Conductor Temperature	100° C

4.11.3 Transmission Line Design Criteria

This section describes the major components of the 345 kV high voltage dc overhead transmission line system.

4.11.3.1 Overhead Conductor. Two-bundle 1590 kcmil 45/7 ACSR "Lapwing" is assumed for this estimate. This is the same conductor size used for the overhead ac transmission line alternative.

4.11.3.2 Shield Wire. Two shield wires are assumed for the line; one is assumed to be 19#10 (CL&P Standard) Alumoweld and the other one is assumed to be OPGW.

4.11.3.3 Metallic Ground Return Conductor. The metallic ground return conductor assumed is two-bundle 795 kcmil 26/7 ACSR "Drake" conductor.

4.11.3.4 Structures. The structure type assumed for this alternative is a single tubular pole with a horizontal configuration. The shield wires would be supported by tubular steel davit arms located above the conductors. The metallic ground return conductor would be placed between the pole conductors. The typical structure height is 75'. The typical span is 650'. The NESC final tension is assumed at 9600 pounds for each 1590 kcmil 45/7 ACSR. The maximum sag is approximately 30 feet under the Companies' standard criteria. The structures would be designed for the Companies' standard loadings. The typical tangent structure configuration is shown in Appendix 7.

4.11.3.5 Foundations. The foundations are assumed to be drilled pier foundations. Rock is assumed along the line route for 30 percent of the foundations.

4.11.3.6 Insulators and Hardware. Insulator and hardware strength would be designed and selected for the ultimate wire loadings.

4.11.4 Transmission Line System Installation

The HVDC overhead transmission line would be built using standard transmission line construction practices. All of the construction of the overhead line would be done on existing transmission line right-of-way; therefore, no right-of-way or clearing costs are included in the cost estimates. For the 5.9 miles extending south out of Beseck, the dc line would parallel an existing 345 kV wood H-frame line. The next 1.6 miles between E. Wallingford and Wallingford Junctions has an existing 115 kV wood H-frame line that would parallel the dc line. The final 3.3 miles between Wallingford and Cook Hill Junctions has an existing 115 kV double circuit lattice tower line that would parallel the dc line.

The 22.5 miles of right-of-way between Cook Hill Junction in Cheshire and East Devon Substation in Milford contains 3 existing 115 kV ac transmission line circuits that would be removed for the construction of this line. Two of these circuits are on wood H-frame transmission lines. If the two H-frame lines were to remain in this section in their present configuration, there is not enough right-of-way to add the dc line. The other circuit is on a double circuit steel lattice structure. The cost to remove these existing lines is included in the cost estimate. The cost to reconstruct two of these existing 115 kV ac circuits with a new 115 kV double circuit steel tubular pole line is also included in the cost estimate.

Cost of equivalent ac system along the right-of-way from Beseck Switching Station to East Devon Substation is also shown for comparison purposes.

4.12 Estimated Construction Schedule

This section provides a brief description of the schedule required for the HVDC options. The main activities of the project schedule would be engineering, procurement, construction and commissioning.

Engineering can be divided into two parts, conceptual engineering and detail engineering. Conceptual engineering activities include system studies, line route selection, land acquisition, permitting, surveying and soils analysis. Detail engineering activities include line layout, detail design of the transmission components and creation of specifications and associated drawings for procurement and construction.

Material procurement for dc cable systems has long lead items such as underground cable and converter stations.

Construction activities for an underground line may include installation of approximately 200 splice chambers, 35-miles of duct bank installation, cable installation, cable termination, and restoration. Construction activities for an overhead line include clearing, foundation installation, structure removal and erection, hardware installation, wire stringing and restoration.

Finally, commissioning a dc system would include testing of the entire system prior to energizing the system.

The following schedule is for the dc underground cable system, with converter stations. These items are not entirely consecutive, some activities will run concurrently.

HVDC UG OPTION

Description	**Months**
Engineering	24
Procurement	12
Construction	30
Commissioning	3
Total Time	4 years

The following schedule is for the dc overhead cable system, with converter stations. These items are not entirely consecutive.

HVDC OH OPTION

Description	**Months**
Engineering	18
Procurement	12
Construction	27
Commissioning	3
Total Time	3.5 years

5.0 Environmental Issues

5.1 Area Required for Converter Stations

It is estimated that the converter stations at Beseck and East Devon would require a land area of 1250 x 575 ft (about 16.5 acres) each. No land area has been identified yet and may be difficult to acquire. This area includes vacant land area around the perimeter of the site acting as a buffer zone for noise abatement and visual shielding. This land area is in addition to the ac station land requirements at each station.

5.2 Metallic Ground Return

It is recommended that a metallic ground return conductor (neutral cable) be installed between the two converter stations. This would facilitate the monopolar operation during the outage of a single pole (i.e., either positive or negative polarity conductor) by providing a dedicated return path. The metallic ground return conductor for the underground option would be of the same construction and size as the pole conductor

(3500 kcmil) except the insulation thickness would be sized for 25 kV versus 350 kV. The metallic ground return conductor would be placed in the same duct bank as the pole conductors. The metallic ground return conductor for the overhead option would be a two-bundle 795 ACSR conductor with insulation sized for 25 kV versus 350 kV.

5.3 Electromagnetic Fields

The magnitude of steady and direct magnetic field produced by a HVDC line at the edge of right of way is about equal in magnitude as the earth's naturally occurring magnetic field. Therefore, the contribution by a HVDC line to the background geomagnetic field would be negligible.

5.4 RI, TVI and Audible Noise

The dc radio interference (RI) levels have a low nuisance value. RI levels are decreased by rain, wet snow, and other atmospheric conditions which thoroughly wet the conductor, and increased by wind.

The dc television interference (TVI) has been found to be of little concern at distances greater than 75 feet from the transmission line structure centerline.

Audible noise due to corona for dc line voltages in the range of 300 kV to 400 kV and conductor surface gradients in the range of 15 to 20 kV/cm are classified in the quiet category, and therefore should not be a concern. This noise level would be in the range of 40 dBA or less, which is below the State of Connecticut noise regulations.

5.5 Electric Fields

DC electric field strengths are typically higher than those measured beneath an ac line operating at the same voltage. However, the HVDC lines do not have capacitive charging current phenomenon similar to ac lines and hence do not have the proximity effect on any neighboring objects.

6.0 Electric System Issues

6.1 AC System Strength

Smooth operation of converters occurs when there is a strong ac system with constant voltage and frequency. The ratio between the ac system short circuit MVA (three phase) and the dc power, known as the short circuit ratio (SCR), is a measure of the strength of the ac system.

$$SCR = \frac{FaultLevel(MVA)}{DCPower(MW)}$$

If the SCR is greater than 3, it is an indication of a strong system and there should be no major problems expected in regards to the converter operation. However if the SCR is lower, the operation of the converters, especially at the inverter, would be affected by the repetitive commutation failures. In such cases special voltage regulation devices, such as Static VAR Compensators (SVC), would have to be installed for proper operation of converters.

The calculated fault currents at Beseck and East Devon 345 kV substations are 32,000A and 22,000A respectively as provided by UI.

In the case of Beseck and East Devon substations, the SCRs are calculated to be about 16 and 11, respectively as shown below:

$$\text{At Beseck , SCR} = \frac{\sqrt{3} \text{ x } 345 \text{ x } 32}{1200} = 15.9$$

$$\text{At East Devon , SCR} = \frac{\sqrt{3} \text{ x } 345 \text{ x } 22}{1200} = 10.9$$

6.2 Operation & Maintenance

Maintenance of HVDC systems can be comparable to those of high voltage ac systems. Proper maintenance scheduling and the maintenance of high voltage equipment in the converter station is executed in the same way as any other ac equipment such as transformers, circuit breakers etc.

In addition to the conventional ac high voltage equipment, some of the additional equipment which would need regular maintenance are filters, smoothing reactors, wall bushings, valve cooling equipment and thyristor valves.

In a typical HVDC installation, the normal maintenance period is about 1 week per year. In bipolar schemes, regular maintenance can be carried out on pole basis, so that the continuity of service can be maintained. Converter stations may require resident personnel for operation and maintenance.

As per CIGRE protocol 14-97, HVDC turn-key contractors shall achieve an availability of 98% for the converter stations.

7.0 Budgetary Cost Estimate

7.1 Cost Estimate

It is a common practice that the converter station equipment and the related civil work are contracted as a 'turn-key project' to the HVDC equipment manufacturers. The leading HVDC equipment manufacturers are ABB, Siemens and Alstom.

Budgetary costs for converter stations were obtained from one manufacturer. Even though this estimate was based on +/- 500 kV converters, the cost of a +/- 350 kV converter station would be about the same price. The estimated costs were compared with the unit costs published in the literature and found to be within the industry average.

The cost of HVDC underground cable was obtained from the cable manufacturers and the cost of civil work and cable installation are based on Black & Veatch's experience. Costs from the Companies have been included for the equivalent 345 kV ac system along the right-of-way from Beseck Switching Station to East Devon Substation.

The estimated differential costs for the dc underground and overhead transmission systems between Beseck and East Devon substation are shown below.

HVDC Underground Transmission Line

Item	Description	2003 cost (million $)
1	Beseck and East Devon converter stations turn-key contract (engineer, procure, construct)	228.0
2	Underground cable – material	82.5
3	Foreign Utility Relocation	2.5
4	River Crossings	6.0
5	Cable Installation (includes 10% for rock excavation)	116.0
6	Converter Station Land Costs (2 - 16.5 acre tracts)	16.5
	Subtotal	451.5
7	Sales Tax (6%)	27.1
8	Owner Engineering	3.0
9	HVDC/ac System Interface Studies	1.5
10	UG Cable Design Engineering	3.3
11	Construction Management (3.5 years)	4.0
12	Contingency (15%)	73.6
	Total DC	564.0
	Cost of equivalent AC system along ROW from Beseck Switching Station to East Devon Substation	105.0
	Differential Cost of DC System	459.0

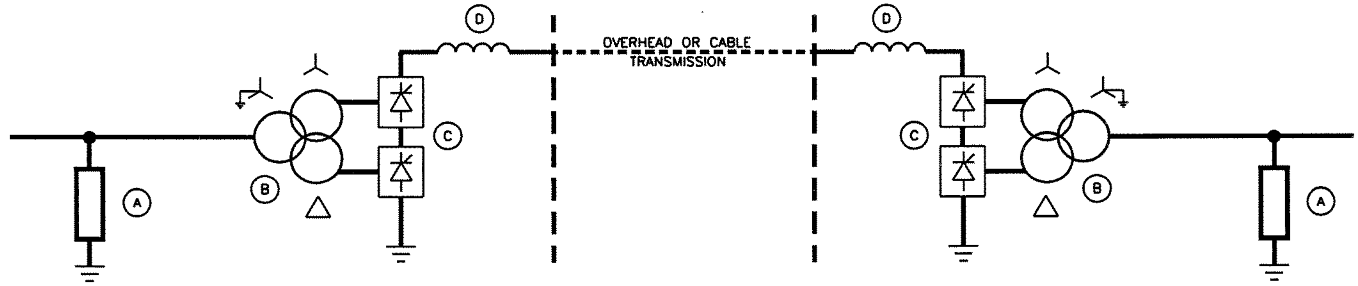
HVDC Overhead Transmission Line

Item	Description	2003 cost (million $)
1	Beseck and East Devon converter stations turn-key contract (engineer, procure, construct)	228.0
2	Overhead Transmission Line Material	12.0
3	Existing Transmission Line Removal	8.2
4	Overhead DC Transmission Line Installation	16.0
5	115 kV Line Installation	39.9
6	Converter Station Land Costs (2 - 16.5 acre tracts)	16.5
	Subtotal	320.6
7	Sales Tax (6%)	17.7
8	Owner Engineering	3.0
9	HVDC/ac System Interface Studies	1.5
10	Design Engineering	3.3
11	Construction Management (3.5 years)	4.0
12	Contingency (15%)	32.5
	Total DC	402.6
	Cost of equivalent AC system along ROW from Beseck Switching Station to East Devon Substation	105.0
	Differential Cost of DC System	297.6

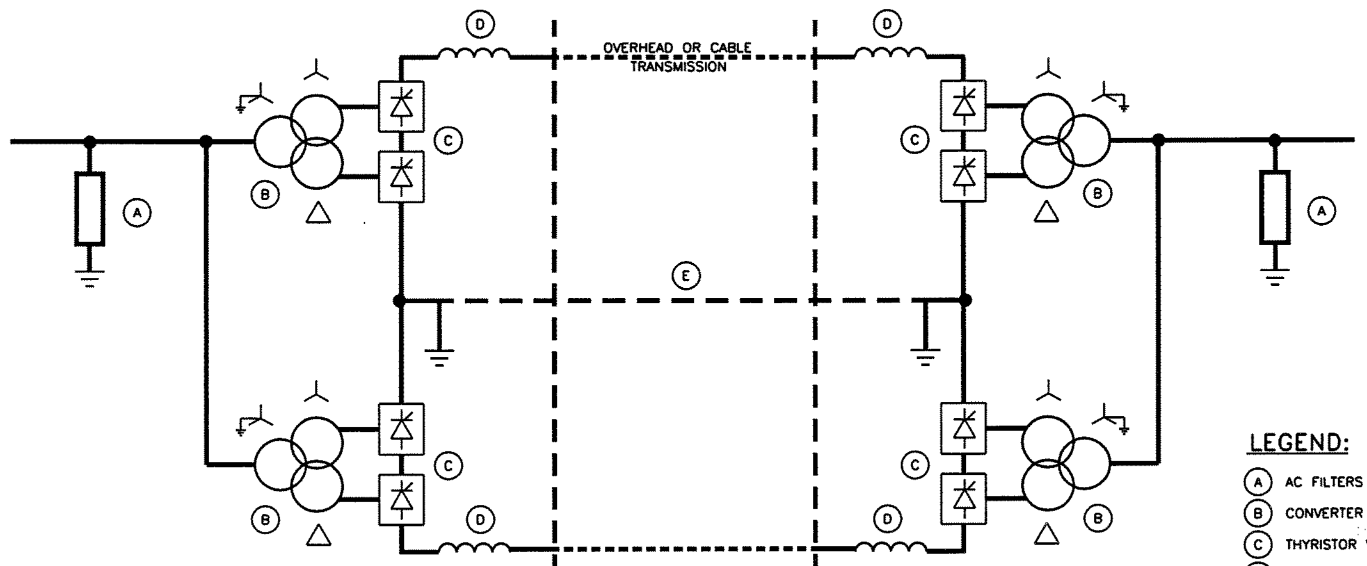
References

1. E.W. Kimbark, Direct Current Transmission, Volume 1, John Wiley & Sons, 1971.
2. J. Arrillaga, High Voltage Direct Current Transmission, Peter Peregrinus Ltd., 1983.
3. R.L. Hauth, P.J. Tatro, B.D. Railing, B.K. Johnson, J.R. Stewart and J.L. Fink, "HVDC Power Transmission Technology Assessment Report ORNL/Sub/95-SR893/1, Oak Ridge National Laboratory, April 1997.
4. Electric Power Research Institute, Underground Transmission Systems Reference Book, 1992 Edition.
5. DC± 500 kV Oil-Filled Submarine Cable Crossing Kii-Channel. Fujikura Technical Review, 2001.

APPENDIX 1
HVDC CONVERTER CONFIGURATIONS



MONOPOLAR SCHEME WITH SEA/GROUND RETURN



BIPOLAR SCHEME

LEGEND:

- (A) AC FILTERS AND SHUNT COMPENSATION
- (B) CONVERTER TRANSFORMER
- (C) THYRISTOR VALVES
- (D) DC SMOOTHING REACTOR
- (E) NEUTRAL RETURN FOR CONTINUOUS MONOPOLAR OPERATION

NOT TO BE USED
FOR CONSTRUCTION

SCHEME

APPENDIX 2

UG HVDC SYSTEMS

APPENDIX 2

HVDC Cable (Submarine & Underground Land) Application Worldwide

System/Project		Year	Power (MW)	Volt. (kV)	Circuit Length (mile)		Cable		Location
					Sub.	Land	Type	Size (kcmil)	
1	Gotland I	1954 1970	20 30	100 150	60		MI	180	Sweden
2	Cross Channel I	1961	160	±100	32	9	MI	670 1200	France-England
3	Konti-Skan I	1965	300	285	40	4	MI	1233 1578	Denmark-Sweden
4	Cook Strait I	1965	600	±250	74		GF	1026	New Zealand
5	Sardinia-Italian Mainland	1967	200	±200	75		MI	829	Italy
6	Vancouver Pole 1	1968 1969	312	300	21		MI	790	Canada
7	Kingsnorth	1974	640	±266	37	14	FF	1579	United Kingdom
8	Skagerrak I	1977	250	±250	79		MI	1579	Norway-Denmark
9	Vancouver II	1977	370	-280	21		FF	790	Canada
10	Hokkaido-Honshu	1979 1992	300	±250	27	0.6	FF	1184 1777	Japan
11	Gotland II	1983	130	150	57	0.4	MI	1579	Sweden
12	Gotland III	1987	260	±150	57	4	MI	1579	Sweden
13	Cross Channel II	1986	*2000	2X±270	29	16	MI FF	1579 1777	France-England
14	Sacoi (6)	1986	200	200	75		MI	829	Italy
15	Konti-Skan II	1988	300	285	37		MI	2369	Sweden-Denmark
16	Fenno-Skan	1989	500	400	124		MI	2369	Finland-Sweden
17	St. Lawrence	1991	625	±500	3		FF	2764	Canada
18	Konti-Skan III	1991	300	285	37		MI	2764	Sweden-Denmark

* Only two installations greater than 1,000 MW

APPENDIX 2

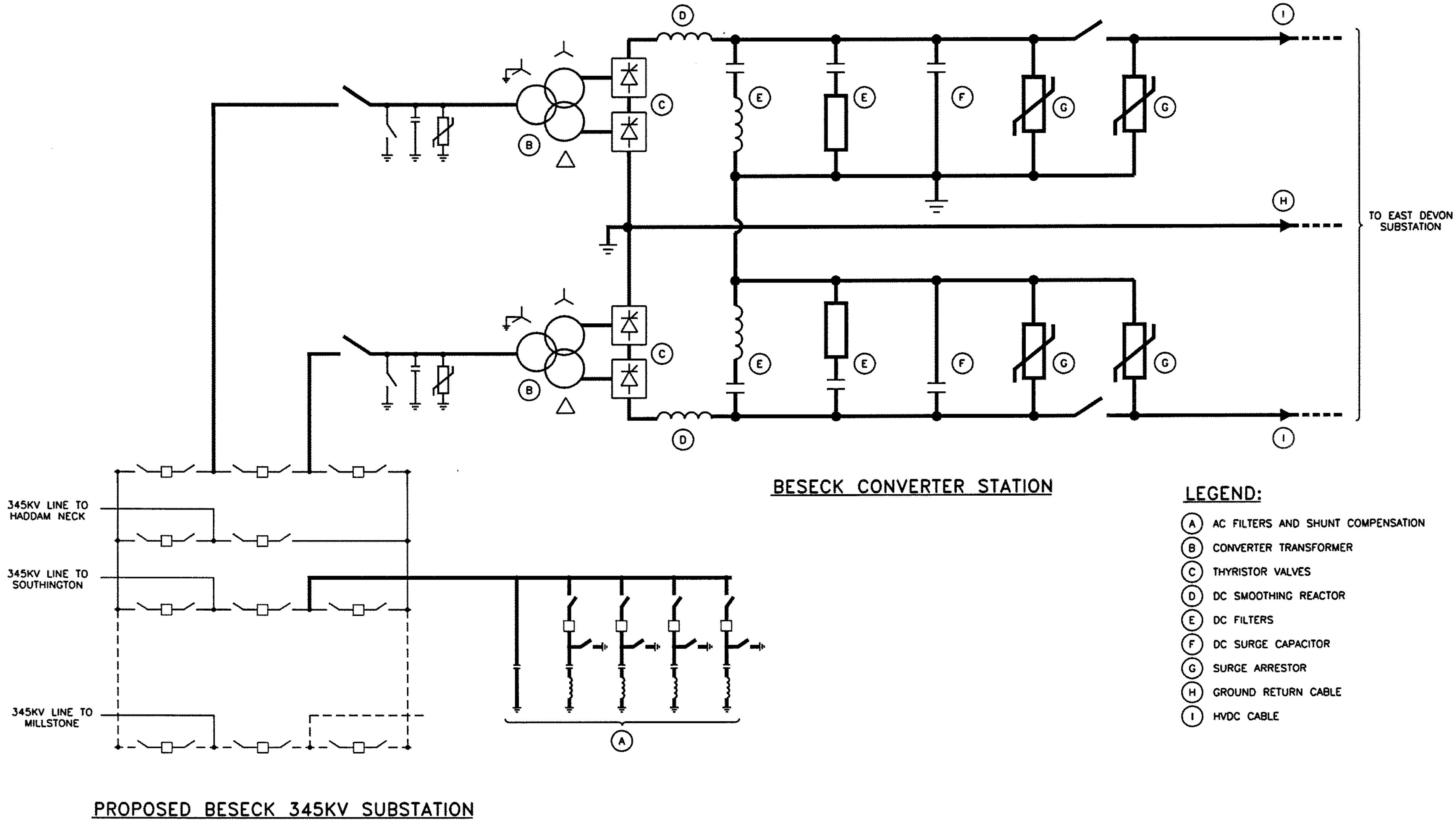
System/Project		Year	Power (MW)	Volt. (kV)	Circuit Length (mile)		Cable		Location
					Sub.	Land	Type	Size (kcmil)	
19	Skagerrak III	1993	440	±350	79		MI	2764	Norway-Denmark
20	Cook Strait II	1992	560	350	24		MI	2764	New Zealand
21	Electric Power Development Co.	1992		250	27		FF	1184	Japan
22	Cheju Island	1993	300	180	60	3	MI	1579	Korea
23	Baltic Cable Project	1994	600	450	155		MI	3158	Sweden-Germany
24	Kontek	1995	600	400	34	75	FF	1579	Demark-Germany
25	Leyte-Luzon	1996	440	±350	13		FF	1974	Philippines
26	Gotland Wind Power Evacuation	1999	50	±80		43	EP		Sweden
27	SwePol	1999	600	450	143		MI	2764	Sweden-Poland
28	KII Channel (Honshu–Shikoku)	2000	*2800	±500	30.3	1.5	FF	5922	Japan
29	Italy-Greece	2000	500	400	101	27	FF & MI	2369 3948	Italy-Greece
30	Direct Link	2000	180	±80		40	EP		Australia
31	Moyle Interconnector	2001	2 x 250	250	34	3+2	MI	1974	United Kingdom
32	Cross Sound	2001	330	±150	24		EP		U.S.A.

Note:
MI = mass impregnated FF = self-contained fluid-filled GF = Gas Filled EP = extruded polymer

* Only two installations greater than 1,000 MW

APPENDIX 3

BESECK CONVERTER STATION

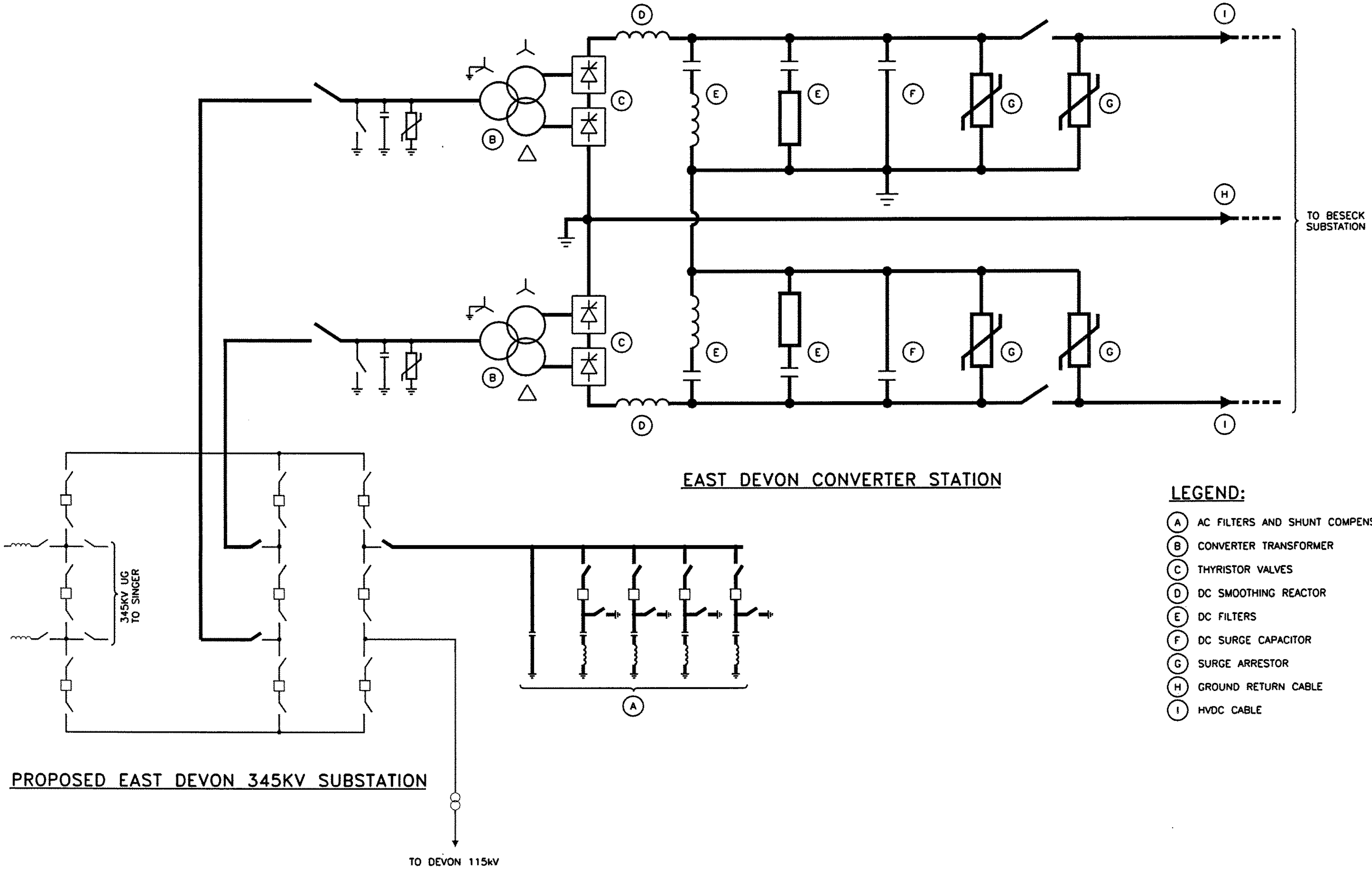


NOT TO BE USED
FOR CONSTRUCTION

BESECK

APPENDIX 4

EAST DEVON CONVERTER STATION



EAST DEVON CONVERTER STATION

PROPOSED EAST DEVON 345KV SUBSTATION

LEGEND:

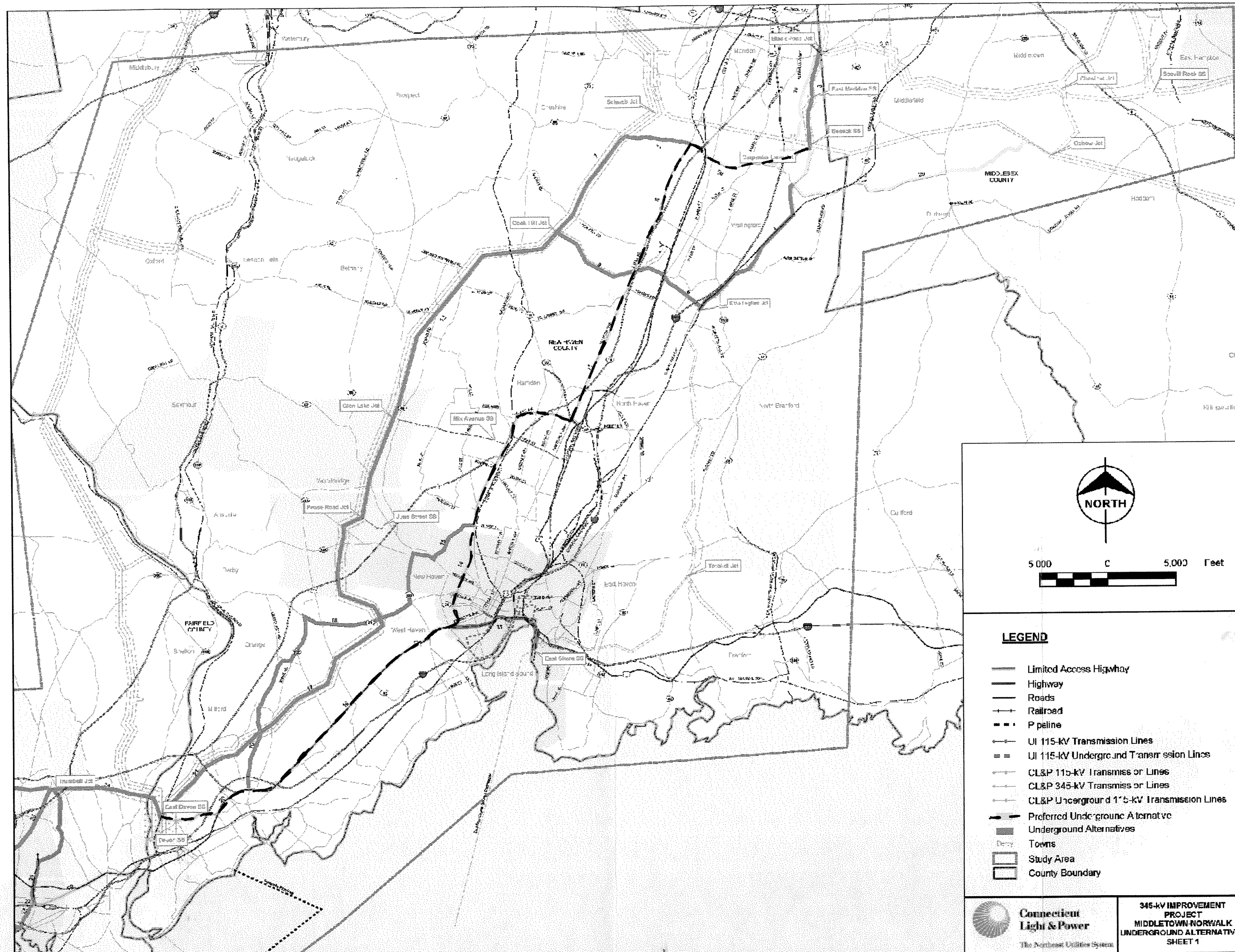
- A AC FILTERS AND SHUNT COMPENSATION
- B CONVERTER TRANSFORMER
- C THYRISTOR VALVES
- D DC SMOOTHING REACTOR
- E DC FILTERS
- F DC SURGE CAPACITOR
- G SURGE ARRESTOR
- H GROUND RETURN CABLE
- I HVDC CABLE

NOT TO BE USED FOR CONSTRUCTION

EAST DEVON

APPENDIX 5

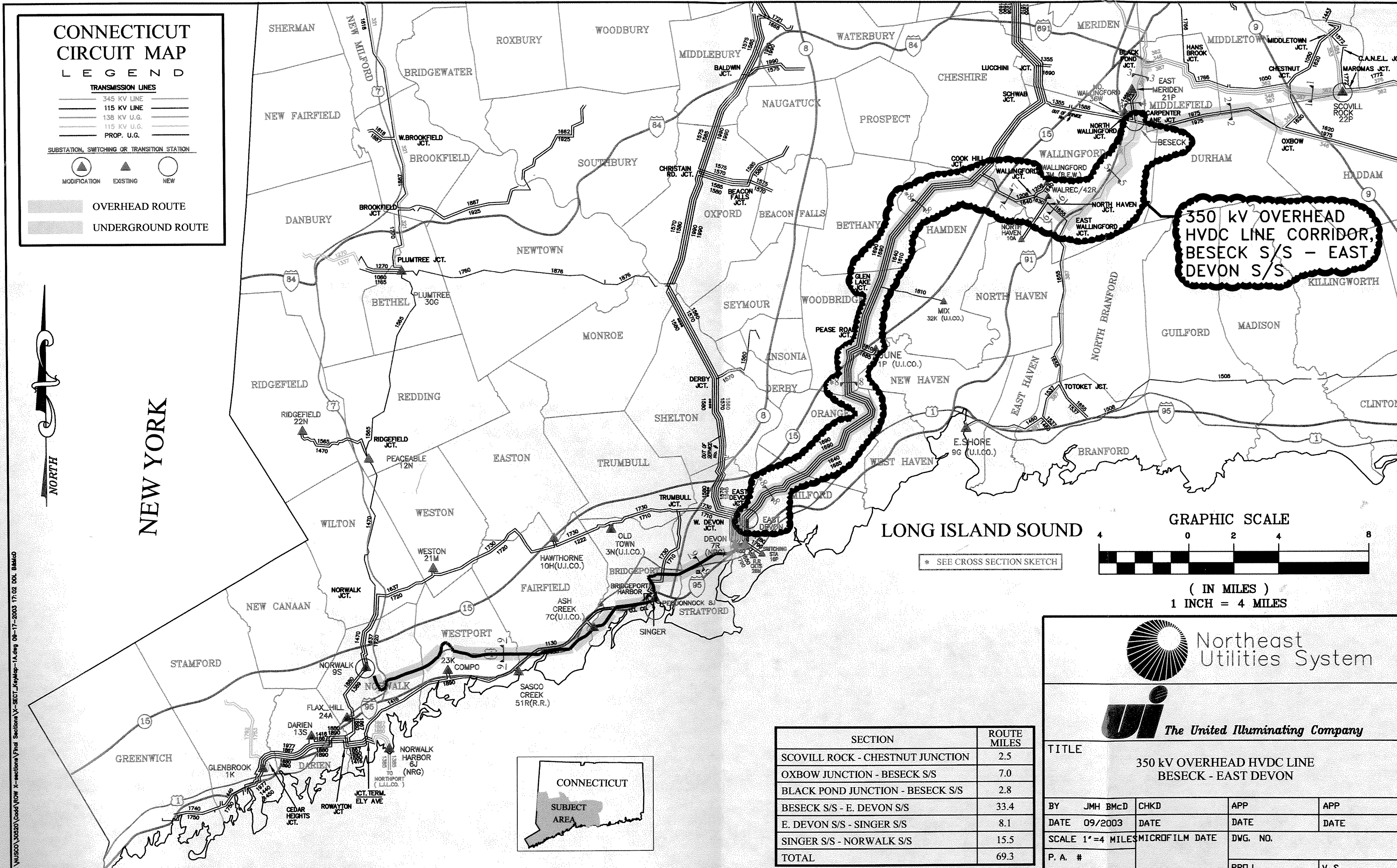
UNDERGROUND TRANSMISSION LINE ROUTE MAP



Waterbury
Middlebury
Prospect
Cheshire
Meriden
Middletown
East Hampton
Middlefield
Naugatuck
Wallingford
Durham
Haddam
MIDDLESEX COUNTY
Oxford
Beacon Falls
Bethany
NEW HAVEN COUNTY
Hamden
North Haven
North Branford
Seymour
Woodbridge
Ansonia
Derby
New Haven
East Haven
Guilford
West Haven
Orange
FAIRFIELD COUNTY
Shelton
Milford
Branford
Long Island Sound
Killingworth
Cheshire Jct
Scovill Rock SS
East Meriden SS
Beseck SS
Oxbow Jct
Cook Hill Jct
Glen Lake Jct
Mix Avenue SS
Pease Road Jct
June Street SS
East Shore SS
Totoket Jct
Trumbull Jct
East Devon SS
Devon SS
NORTH
5,000
0
5,000
Feet
LEGEND
Limited Access Higwhay
Highway
Roads
Railroad
Pipeline
UI 115-kV Transmission Lines
UI 115-kV Underground Transmission Lines
CL&P 115-kV Transmission Lines
CL&P 345-kV Transmission Lines
CL&P Underground 115-kV Transmission Lines
Preferred Underground Alternative
Underground Alternatives
Towns
Study Area
County Boundary
Connecticut Light & Power
The Northeast Utilities System
345-kV IMPROVEMENT PROJECT
MIDDLETOWN-NORWALK
UNDERGROUND ALTERNATIVES
SHEET 1

APPENDIX 6

OVERHEAD TRANSMISSION LINE ROUTE MAP



SECTION	ROUTE MILES
SCOVILL ROCK - CHESTNUT JUNCTION	2.5
OXBOW JUNCTION - BESECK S/S	7.0
BLACK POND JUNCTION - BESECK S/S	2.8
BESECK S/S - E. DEVON S/S	33.4
E. DEVON S/S - SINGER S/S	8.1
SINGER S/S - NORWALK S/S	15.5
TOTAL	69.3

Northeast Utilities System

The United Illuminating Company

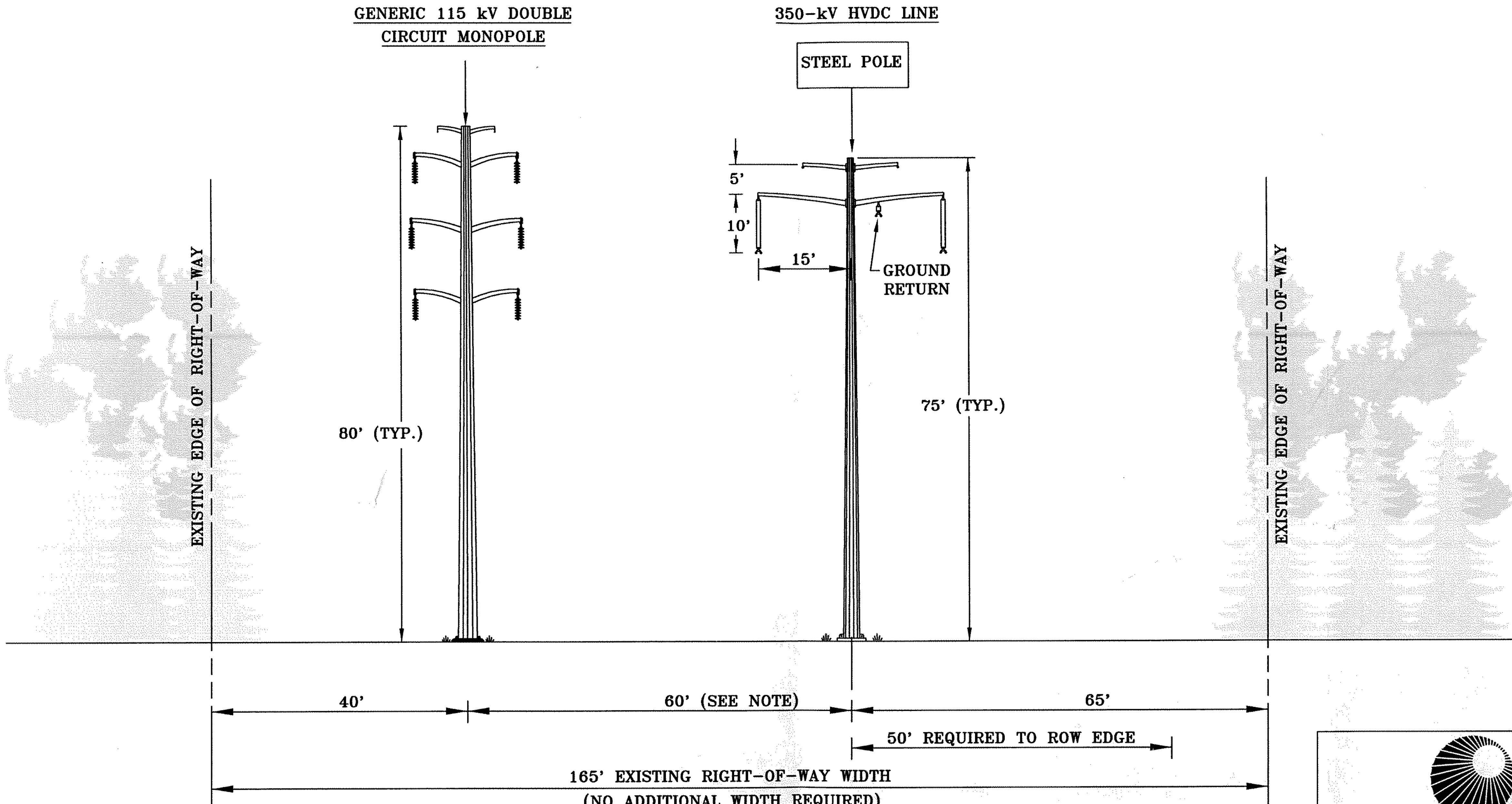
TITLE

350 kV OVERHEAD HVDC LINE
BESECK - EAST DEVON

BY JMH BMcD	CHKD	APP	APP
DATE 09/2003	DATE	DATE	DATE
SCALE 1"=4 MILES	MICROFILM DATE	DWG. NO.	
P. A. #		PROJ.	V. S.

APPENDIX 7

TYPICAL OVERHEAD TRANSMISSION LINE STRUCTURE



NOTE: ALLOWS FOR THE PLACEMENT OF ADJACENT STRUCTURES CLOSER TOGETHER BUT LIMITS THE AMOUNT OF STAGGER THAT CAN OCCUR.

Northeast Utilities System

The United Illuminating Company

TITLE GENERIC CROSS SECTION
350-kV HVDC TRANSMISSION LINE
ON OCCUPIED ROW

BY B&V	CHKD	APP	APP
DATE 10/2003	DATE	DATE	DATE
SCALE N.T.S.	MICROFILM DATE	DWG. NO.	
P.A. #		MISC./DETAILS/DETAILS /SECTION_8A_REV1	