Middletown - Norwalk Transmission Project

VSC HVDC System Feasibility Study

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Prepared for Northeast Utilities

SUBMITTED BY:

Utility Consulting
ABB Inc.
940 Main Campus Drive, Suite 300
Raleigh, N C 27606

Legal Notice

Executive Summary
Middletown – Norwalk Transmission Project
VSC HVDC System Feasibility Study

This study conducted by ABB Inc., addresses the feasibility of an all-underground transmission project based on Voltage Source Converter Technology HVDC (High Voltage Direct Current) for the proposed 345-kV electric transmission line between Scovill Rock Switching Station in Middletown and Norwalk Substation in Norwalk.

The Middletown – Norwalk Project is a response to the much needed reliability improvement in Southwest Connecticut (SWCT). Due to environmental and aesthetic concerns, the project faces strict requirements to consider technically feasible options that employ an all-underground transmission line. Several studies have been conducted by NU and UI to find a technically acceptable AC underground solution with varying degrees of success. NU, UI and ISO-NE have already presented several AC alternatives to the Connecticut Siting Council (CSC). The HVDC alternative based on Voltage Source Convertor (VSC) technology had not been studied in detail.

ABB was engaged by NU, UI and ISO-NE to conduct a study to investigate if a Voltage Source Convertor based HVDC system could fulfill the technical criteria relevant for this particular application in Southwest Connecticut, and thus facilitate a technically feasible all-underground transmission option. NU, with input from New England ISO and UI, has outlined 13 criteria that must be satisfied by the underground HVDC solution. The criteria and compliance status are summarized in Table ES-1. Based on the study results presented here, column 2 of the table summarizes the ability of the HVDC Light® (VSC HVDC) technology in meeting the specified criteria. Note that voltage source converters are used in ABB's HVDC Light® technology. The two terminologies, HVDC Light® and VSC HVDC, have been used interchangeably in the reports.

Table ES-1. System Criteria for Middletown to Norwalk Project

Criteria	Comments and Discussions
1. Moving approximately 1,200 MW of power into Southwest Connecticut. Approximately 1,200 MW of power injection (800 MW incremental after Phase II, and Phases I & II give 1,400 MW; comparison of transfer capacity for both AC and DC line outages.)	Meets criterion; see Attachment B, Power Flow Study Report
2. Resolving short circuit issues at Pequonnock 115kV and Devon 115kV and Devon 115kV target of 90% of 63kA or below	Meets criterion; see Attachment C, Short Circuit Study Report
3. Resolve generation interdependencies at Pequonnock, Devon, and Norwalk Harbor	Meets criterion; see Attachment B, Power Flow Study Report
4. Improve the point of the first system resonance to 3rd harmonic or higher.	Options 1 & 2 meet criterion, Option 3 is marginal; see Attachment A, Frequency Scan Study Report

5. Provide a means of interconnecting new generation.	Meets criterion, see more discussions in Section 3.1 of this report.
6. Have the ability to add new load serving stations as required.	Similar to No. 5.
7. Must be able to operate throughout a load cycle and throughout the year with varying dispatches and line outages.	The HVDC system will be scheduled by ISO-NE over the complete load cycle in a security-constrained manner similar to how generators are being dispatched today. The automatic response function of HVDC can be utilized under contingency conditions to further improve performance for local contingencies. See Attachment B, Power Flow Study Report for detail.
8. The project cannot cause any new overloads on the system.	Complied; see Attachment B, Power Flow Study Report
9. Respect technical and physical limitations.	Complied, see Section 3.1 of this report; and also ABB Report titled "Middletown – Norwalk Transmission Project, Technical Description of VSC HVDC Converter and Cable Technology," dated October 1, 2004.
10. The project needs to result in a dynamically stable system	Complied; see Attachment D, Stability Study Report
11. The project needs to provide adequate voltage on the system.	Complied; see Attachment B, Power Flow Study Report
12. Respect existing contracts and system capabilities – cannot degrade capabilities such as the 352 MW (330 MW net) capability of the Cross Sound Cable and 200MW across the 1385 submarine cable between Norwalk Harbor and Northport, LI.	Complied; see Attachment B, Power Flow Study Report
13. Adverse Sub-synchronous Torsional Interaction (SSTI) effects should not be present – System must not act to destabilize torsional modes of nearby generators.	Refer to ABB's White Paper on SSTI - the VSC based HVDC converters have been demonstrated to be benign from a subsynchronous torsional interaction (SSTI) point of view. Note that the Cross Sound Cable HVDC cable has not caused subsynchronous torsional interaction problems for nearby generators.

ABB has developed three options for the Voltage Source Converter based HVDC system as part of the study effort. For each of the options, the converter block sizes under consideration are 370 MW or 530 MW delivered to the receiving AC Network. Note that the converter ratings can be increased somewhat with additional cooling. The final converter size for the SWCT project will be optimized in the design stage. Given the available converter sizes, it is possible to find a combination that will provide 1,200 MW capacity or more to meet the project need. The schematic diagrams for the three options are presented below in Figure ES-1:

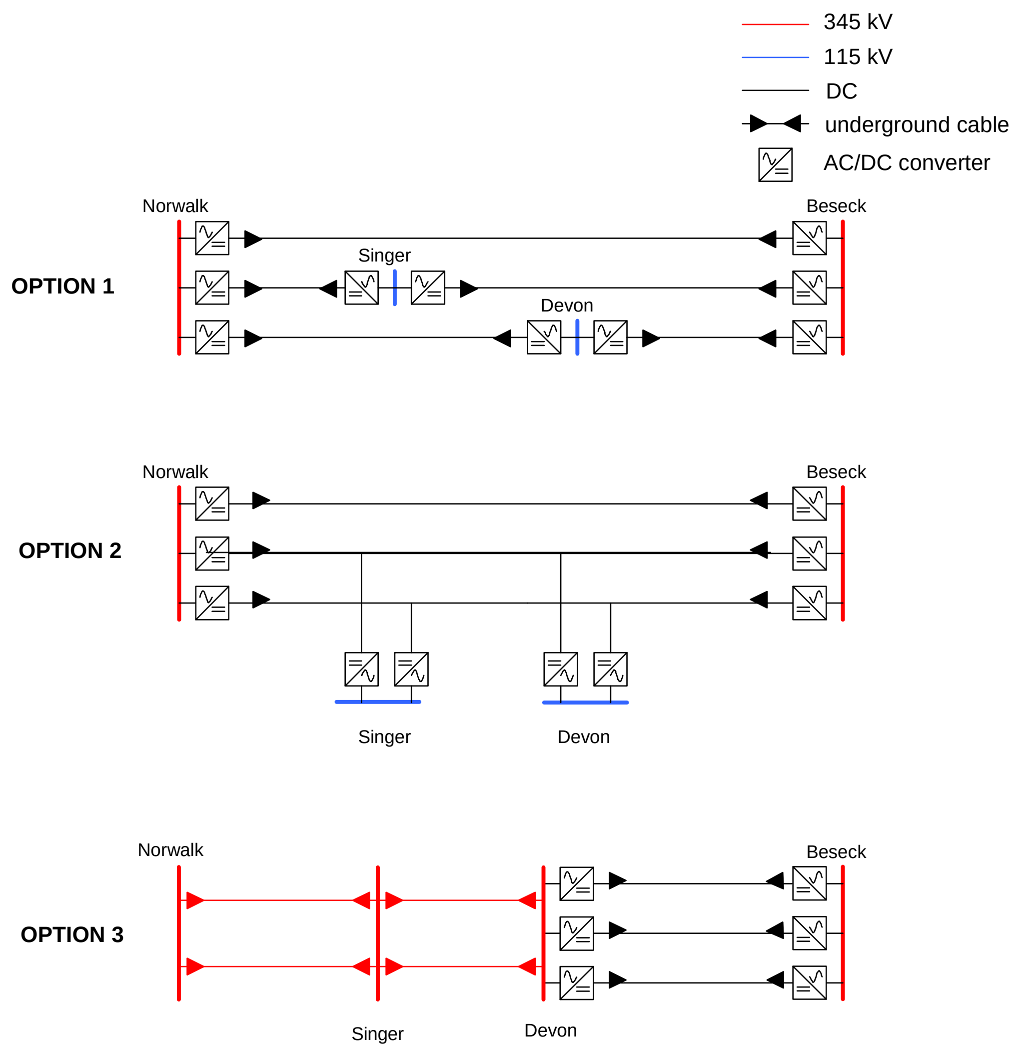

Figure ES-1. Conceptual HVDC Alternatives Based on Voltage Source Converter Technology

<u>Option 1</u> includes HVDC Light® over the full corridor from Beseck to Norwalk. It is understood that there are concerns with forced outage of the converters at Singer and/or Devon, and whether generation would need to be tripped under those conditions. For this reason, at least two converters are provided at each station.

<u>Option 2</u> is also a full HVDC Light® underground solution, using a multi-terminal configuration rather than point-to-point systems.
Less costly variants of Option 2 are possible. It is expected that the final configuration that takes into account costs, reliability, desired capacity margin and future expansion flexibility will be determined by more detailed design studies.

<u>Option 3</u> is a hybrid approach, in which 345 kV AC cables are used from Devon to Norwalk, and HVDC Light® is used only in the portion of the corridor between Devon and Beseck. This option replaces the overhead 345 kV part of the Phase II AC solution with underground DC, thus addressing the most problematic part of the Phase II AC solution.

The study conducted by ABB consisted of four major tasks:

1. System harmonic frequency analysis
2. Power flow analysis
3. Short-circuit analysis
4. Stability analysis

The results of these analyses are discussed in this report. Individual reports for each of the analyses are provided as attachments to this main report. The key finding of the study is that it is technically feasible for an HVDC solution to meet the 13 criteria shown in Table ES-1. Specifically, an all HVDC solution based on VSC technology will shift the first system resonance frequency to above the 3rd harmonic, a major concern with the AC alternative. Other considerations such as short-circuit duty, prevention of line overloads, maintaining voltage and dynamic stability were all analyzed and found to be within acceptable limits. Additional detailed studies are required to come up with an optimal system design in order to cover additional scenarios, contingency conditions, and other operational considerations.

While the first two options are technically feasible and meet the system feasibility criteria established in Table ES-1, the first resonance point of Option 3 is still under the 3rd harmonic for certain cases. This is largely due to the retention of underground AC cables from Norwalk to Devon.

The VSC HVDC technology proposed by ABB for all three options is based on existing technology. However, it is to be noted that the all-underground HVDC scheme using Voltage Source Converters proposed for Middletown – Norwalk has two unique features that were not implemented in previous installations. The two unique features are: (1) Size 530 MW versus 330 MW in Cross Sound, and (2) The multi terminal VSC HVDC, Option 2, would be the first application of multi-terminal VSC technology. In a separate report, titled "Middletown – Norwalk Transmission Project, Technical Description of VSC HVDC Converter and Cable Technology," ABB has demonstrated through previous projects that VSC HVDC systems are scalable, and the 530 MW design is currently being quoted by ABB for other applications. Also, it is anticipated that the multi-terminal VSC HVDC may not seem to be a major technological hurdle due to the fact that there exists vast experience with multi-terminal HVDC systems in operations using conventional HVDC technology. The pros and cons of each alternative are further discussed in Section 3 of this report.

It is also to be noted that some underlying 115 KV lines may still need to be upgraded to accommodate future load growth, after the underground VSC HVDC lines are constructed. For the purposes of this study, when simulating the VSC HVDC solution option, ABB assumed the same 115 KV reinforcements developed by NU for the Phase II AC configuration. For actual implementations the exact requirements for 115 KV reinforcements need to be re-evaluated. Also it is to be noted that 115 KV reinforcements can be accomplished with 115 KV underground AC cables.

Based on the results of this feasibility study, it is concluded that HVDC Options 1 and 2 are both feasible and capable of meeting the 13 performance criteria set forth by NU, UI and ISO-NE. The selection of the most cost-effective solution will require additional detailed studies to optimize the design, taking into account of costs, reliability, operability and flexibility.

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ATTACHMENTS

1 INTRODUCTION

This study conducted by the Electric Systems Consulting group of ABB Inc., addresses the feasibility of an underground HVDC (High Voltage Direct Current) solution based on ABB's Voltage Source Converter (VSC) Technology for Northeast Utilities' (NU) proposed 345-kV electric transmission line between Scovill Rock Switching Station in Middletown and Norwalk Substation in Norwalk.

The Middletown – Norwalk Project is a response to the much needed reliability improvement in Southwest Connecticut (SWCT). The project faces strict requirements to consider undergrounding the line as much as technically feasible. Several studies have been conducted by NU and UI to find a technically acceptable AC underground solution with varying degrees of success. NU has presented several AC alternatives to the Connecticut Siting Council (CSC). This report outlines the feasibility of an underground HVDC solution based on VSC technology that had not been studied in detail before.

The study is intended to investigate the technical feasibility of the underground VSC HVDC (HVDC Light®) alternatives and identify if there are any major fatal flaws that would eliminate the HVDC alternatives as a viable underground solution. Additional and more detailed studies will be required to optimize the design and costs of the selected VSC HVDC solution, and to address other system issues and criteria in further detail. The feasibility study consists of four major tasks:

1. System harmonic frequency analysis
2. Power flow analysis
3. Short-circuit analysis
4. Stability analysis

This report is organized as follows. Section 2 presents the study approach. The performance criteria for the study and a description of the HVDC alternatives evaluated are discussed in that section. Section 3 contains the analysis results. In Section 3, the performances of the HVDC alternatives with respect to the performance criteria are discussed. Section 3 also highlights the results of the individual studies. Section 4 presents the study conclusions. Individual study reports are provided as attachments.

Note that voltage source converters (VSC) are used in ABB's HVDC Light® technology. The two terminologies, HVDC Light® and VSC HVDC, have been used interchangeably in the reports.

2 STUDY APPROACH

2.1 Study Criteria

ABB was engaged by NU, UI and ISO-NE to conduct a study to investigate if a VSC based HVDC system could fulfill the technical criteria relevant for this particular application in Southwest Connecticut. NU with input from New England ISO and UI, has outlined 13 criteria that must be satisfied by the underground HVDC solution. These criteria are presented in Table 1 below.

Table 1. System Criteria for Middletown to Norwalk Project
1. Moving approximately 1200 MW of power into Southwest Connecticut. Approximately 1200MW of power injection (800MW incremental after Phase II, and Phases I & II give 1400MW; comparison of transfer capacity for both AC and DC line outages.)
2. Resolving short circuit issues at Pequonnock 115kV and Devon 115kV and Devon 115kV target of 90% of 63kA or below
3. Resolve generation interdependencies at Pequonnock, Devon, and Norwalk Harbor
4. Improve the point of the first system resonance to 3rd harmonic or higher.
5. Provide a means of interconnecting new generation.
6. Have the ability to add new load serving stations as required.
7. Must be able to operate throughout a load cycle and throughout the year with varying dispatches and line outages.
8. The project cannot cause any new overloads on the system.
9. Respect technical and physical limitations.
10. The project needs to result in a dynamically stable system
11. The project needs to provide adequate voltage on the system.
12. Respect existing contracts and system capabilities – cannot degrade capabilities such as the 352 MW (330MW net) capability of the Cross Sound Cable and 200MW across the 1385 submarine cable between Norwalk Harbor and Northport, LI.
13. Adverse Sub-synchronous Tortional Interaction (SSTI) effects should not be present – System must not act to destabilize torsional modes of nearby generators.

The study uses the planning and reliability criteria of ISO-NE.

2.2 Alternate HVDC Configurations

As part of this study ABB has developed and evaluated three conceptual design configurations for a HVDC fully underground solution based on the systems criteria established in Table 1. For each of the configurations, the converter block sizes under consideration are 370 MW or 530 MW delivered to the receiving AC Network. Note that converter ratings can be increased somewhat with additional cooling. The final converter size for the SWCT project will be optimized in the design stage. Given the available converter sizes, it is possible to find a combination that will provide 1,200 MW capacity or more to meet the project need. The schematic diagrams for the three options are presented in Figure 1 below:

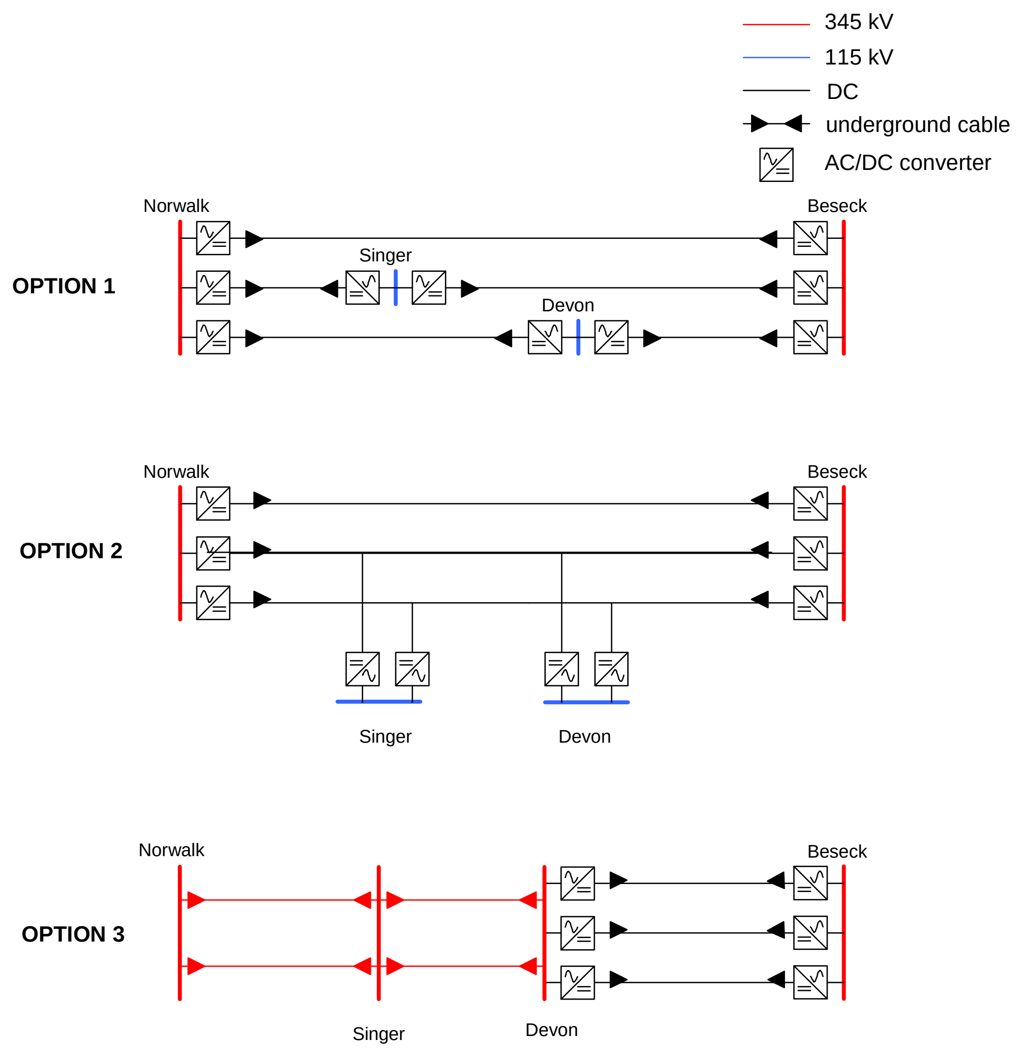


Figure 1 – Conceptual HVDC Alternatives Based on Voltage Source Converter Technology

Option 1 includes HVDC Light® over the full corridor from Beseck to Norwalk. It is understood that there are concerns with forced outage of the converters at Singer and/or Devon, and whether generation would need to be tripped under those conditions. For this reason, at least two converters are provided at each station.

Option 2 is also a full HVDC underground solution, using a multi-terminal configuration rather than point-to-point systems. Less costly variants of Option 2 are possible. It is expected that the final configuration that takes into account costs, reliability, desired capacity margin and future expansion flexibility will be determined by more detailed design studies.

Option 3 is a hybrid approach, in which 345 kV AC cables are used from Devon to Norwalk, and HVDC Light® is used only in the portion of the corridor between Devon and Beseck. This option replaces the overhead 345 kV part of the Phase II AC solution with underground DC, thus addressing the most problematic part of the Phase II AC solution.

It is to be noted that the underground HVDC scheme using Voltage Source Converters proposed for Middletown – Norwalk has never been built in the same scope in previous installations. The unique features of the proposed installations include: (1) Size 530 MW versus 330 MW in Cross Sound, and (2) Multi terminal VSC HVDC where this would be the first application of multi-terminal VSC technology (the multi-terminal design is true only of option 2). ABB has demonstrated through previous projects that VSC HVDC systems are scalable and the 530 MW design is currently being quoted by ABB for other applications.

It is also to be noted that some underlying 115 KV lines may still need to be upgraded to accommodate future load growth, after the underground VSC HVDC lines are constructed. For the purposes of this study, when simulating the VSC HVDC solution option, ABB assumed the same 115 KV reinforcements developed by NU for the Phase II AC configuration. The goal is to have no additional 115-kV reinforcements beyond what have already been identified. For actual implementations the exact requirements for 115 KV reinforcements need to be re-evaluated. Also it is to be noted that 115 KV reinforcements can be accomplished with 115 KV underground AC cables.

Although Options 1 and 2 appear to have different topologies, their performances are expected to be similar in many aspects. It should be noted that there is no models currently available to represent VSC based multi-terminal HVDC (MTDC) in the simulation tools (such as PTI's PSS/E) for power flow and stability study. Developing such models will take more time than scheduled for this feasibility study. For these reasons, Option 2 that includes MTDC configuration was not studied in the power flow and stability analyses.

Note that Option 3 was analyzed in the frequency scan study only. Since this option does not shift the first system harmonic resonance to above the 3rd harmonic frequency in some cases, a key issue and criterion for the study, it was not analyzed further.

3 SUMMARY OF RESULTS

The performance of the proposed HVDC alternatives with respect to the 13 criteria is discussed in Section 3.1 below. The results of the analyses performed are summarized in Section 3.2. Individual reports for each of the analyses are provided as attachments. Section 3.3 highlights the key pros and cons of each HVDC alternative.

3.1 Performance with Respect to the 13 Criteria

Criterion 1: To be capable of moving approximately 1,200 MW of power into Southwest Connecticut. Approximately 1,200 MW of power injection (800 MW incremental after Phase II, and Phases I & II give 1,400 MW; comparison of transfer capacity for both AC and DC line outages.)

In all three of the described options, sufficient converter capacity will be provided for 1,200 MW transfer into Southwest Connecticut. The HVDC converter block sizes under consideration are 370 MW and 530 MW. Combined with Phase I, each of the three alternative Phase II transmission expansion schemes gives at least 1,400 MW of net firm transfer capability into Southwest Connecticut. Each of the above Phase II options gives well over the desired 800 MW of firm incremental transfer capability into Southwest Connecticut. Note that converter ratings can be increased somewhat with additional cooling. The final converter size for the SWCT project will be optimized in the design stage. Given the available converter sizes, it is possible to find a combination that will provide 1,200 MW capacity or more to meet the project need.

Criterion 2: Resolve short circuit issues at Pequonnock 115-kV and Devon 115-kV and Devon 115-kV target of 90% of 63 kA or below

HVDC systems have no inherent fault current contribution to increase circuit breaker interrupting duty. Fault current contribution is naturally limited to maximum load current but can be reduced even further during faults by fast acting control. Further, the new added generation at Singer may be connected to the converter station through a series reactor to limit short circuit contributions. Thus, the total short circuit level at Pequonnock and Devon are lower with the HVDC Light® options as compared to the Phase II all-ac option.

The connection configuration of the converter transformers is flexible. If the configuration with a grounded wye connection on the high voltage side (ac system) and a delta connection on the dc side results in ground fault current issues, then the wye connection can be ungrounded or grounded with a resistor or reactor to limit the ground fault current. Thus, the total short circuit level at Pequonnock and Devon will meet this criterion and are lower with the HVDC options as compared to the all-ac Phase II option. (Reference: Attachment C, Short Circuit Study Report)

Criterion 3: Resolve generation interdependencies at Pequonnock, Devon, and Norwalk Harbor

The HVDC converters are fully controllable and can be dispatched to control power flow exchange of the converters with the connecting AC buses at Beseck, Devon, Singer and Norwalk. The added power flow control flexibility is expected to help resolve the interdependency issues between generation dispatch at Pequannock and Devon. The load flow study has analyzed 24 transfer and generation dispatch scenarios. The results of the contingency analysis do not show any additional system overloads or voltage problems with the all-dc solution, suggesting that generation may be independently dispatched at Devon, Pequonnock and Norwalk Harbor and that there are no generation interdependency issues. (Reference: Attachment B, Power Flow Study Report)

Criterion 4: Improve the point of the first system resonance to 3rd harmonic or higher

The ISO-New England has stated that the system resonance generally should be kept above the 3rd harmonic frequency (180 Hz) to avoid the potential adverse impact on system reliability and power quality. This is a problem with the all-ac Phase II option, even with the partial overhead transmission line from Devon to Beseck. Results of the frequency scan study conducted by ABB have shown that the proposed all-dc solution based on he VSC technology will shift the first system resonance above the 3rd harmonic frequency. (Reference: Attachment A, Frequency Scan Study Report)

Criterion 5: Provide a means of interconnecting new generation

Interconnecting new generation at Singer, Devon and/or Norwalk can be accomplished by connecting the new generators directly to the AC substations (345 kV or 115 kV) at these locations and may not require adding new converters. For interconnecting generation at new locations along the dc lines, the addition of new converters and dc cables may be required for HVDC Options 1, 2 and 3. For Options 1 and 3, this may also mean conversion to multi-terminal operation.

Criterion 6: Have the ability to add new load serving stations as required

There are several options to address the addition of new load along the corridor. With the full-HVDC options (1 and 2), new 115 kV AC cables from the Beseck, Devon, Singer or Norwalk substations can be added to serve the loads, or new HVDC converter stations could be constructed at selected locations, if the load must be connected to the HVDC lines. It is noted that the capacitance of a 115 kV underground AC cable is substantially lower than that for a 345 kV AC cable presently under consideration by NU. With HVDC Option 3, new substations can be built along and tapped into the 345-kV AC cables between Devon and Norwalk to serve new loads. New loads along the corridor between Devon and Beseck can be served by either 115 kV AC cables and/or new HVDC converter stations.

<u>Criterion 7:</u> Must be able to operate throughout a load cycle and throughout the year with varying dispatches and line outages

An HVDC system provides fast and automatic control of the power flow through it. In contrast, the control of power flow on an AC system is achieved mainly by adjusting the generation dispatch. Phase shifting transformers (PST) have been installed in many systems to control power flow. PST actions are relatively slow (typically with a response time that ranges from many seconds to minutes). Many of the PSTs in service are manually operated.

HVDC converters based on VSC technology have the added advantage of being able to respond extremely quickly to contingencies in the AC network, using local and/or remote signals. It is envisioned that the underground HVDC system will be scheduled by ISO-NE over the complete load cycle in a security-constrained manner similar to present generators dispatching, so that the system is not vulnerable to overloads and other voltage and system stability related problems in the event contingency conditions arise. Once a contingency has occurred, the voltage and stability related benefits of HVDC come into play while taking remedial action.

The power flow study conducted has demonstrated the feasibility of scheduling the power on the HVDC systems in a security constrained dispatch manner. For each of the specific generation and load conditions studied, it has been found that the HVDC converters can be dispatched in such a way that there will be no overloads for the contingencies analyzed. For most of the contingencies studied, no immediate adjustment of the power schedule is required following a contingency. For a limited number of contingencies, readjustment of the dc power schedule is required. However, the readjustment will be made automatically based on local signals. (Reference: Attachment B, Power Flow Study Report)

<u>Criterion 8</u>: No new system overloads

As expressed in the previous paragraph**,** it is envisioned that the underground HVDC system will be scheduled by NE ISO in a security-constrained manner, so that the system is not left vulnerable to overloads and other voltage and system stability related problems in the event contingency conditions arise. The load flow analysis for various transfer and generation scenarios has confirmed that using security constrained dispatch and a limited number of SPS based on local signals, there are no new system overloads. (Reference: Attachment B, Power Flow Study Report)

<u>Criterion 9:</u> Respect technical and physical limitations

The HVDC Light® converters are compact systems and do not require excessive physical space. However, they are bigger than AC substations, especially gas insulated substations (GIS). The power flow on the dc cables is controlled, therefore, unlike AC cables, there will be no overload problems with dc cables.

For additional information on physical size requirements for the converter stations and dc cable installation issues, see ABB Report, titled "Middletown – Norwalk Transmission Project, Technical Description of VSC HVDC Converter and Cable Technology," dated October 1, 2004.

<u>Criterion 10:</u> The project needs to result in a dynamically stable system

Results of the stability study for light load conditions have shown that the integrated ac/dc system is dynamically stable. (Reference: Attachment D, Stability Study Report)

<u>Criterion 11:</u> The project needs to provide adequate voltage on the system

As stated above, the HVDC Light® converters are fully controllable with respect to both active and reactive power. A VSC HVDC converter can generate or absorb reactive power independently of each other within the current ratings of the converters. In AC voltage control mode the AC voltage will be controlled to a selectable setpoint up to the maximum MVA capability similar to a conventional synchronous. It is also possible to give higher priority to the reactive power in order to support the network during low voltage conditions, thus reducing the risk of a voltage collapse in the AC system. Results of the power flow study have shown that there are no low voltage problems with the all-dc alternative.
(Reference: Attachment B, Power Flow Study Report)

<u>Criterion 12:</u> Respect existing contracts and system capabilities – cannot degrade capabilities such as the 352 MW (330 MW net) capability of the Cross Sound Cable and 200 MW across the 1385 submarine cable between Norwalk Harbor and Northport, LI.

The power flow study has analyzed 24 transfer and generation dispatch scenarios. The results of the contingency analysis do not show any additional system overloads or voltage problems with the all-dc solution, suggesting that the existing system transfer capabilities will not be degraded by the proposed HVDC systems.
(Reference: Attachment B, Power Flow Study Report)

<u>Criterion 13:</u> Adverse Sub-synchronous Torsional Interaction (SSTI) effects should not be present – System must not act to destabilize torsional modes of nearby generators

Reference is given to ABB's White Paper on SSTI with HVDC Light®. The HVDC Light® converters have been demonstrated to be benign from a subsynchronous torsional interaction (SSTI) point of view. Note that the Cross Sound HVDC cable has not caused subsynchronous torsional interaction problems for nearby generators.

3.2 Discussion of Individual Study Results

The results of the following analyses are summarized in this section:

1. System Harmonic Frequency Scan
2. Power Flow Analysis
3. Short-circuit Analysis
4. Stability Analysis

3.2.1 System Harmonic Frequency Scan

This study addresses System Criteria No. 4, Improvement of the first system resonance to the 3^{rd} harmonic or higher. Results show that the proposed all-dc solution based on the VSC technology will shift the first system resonance above the 3^{rd} harmonic frequency. Refer to frequency scan study report in Attachment A.

The ISO-New England has stated that the system resonance generally should be kept above the 3^{rd} harmonic frequency (180 Hz) to avoid the potential adverse impact on system reliability and power quality. This is a problem with the all-ac Phase II option, even with the partial overhead transmission line from Devon to Beseck. Prior studies by others of HVDC alternatives primarily based on traditional technology had concluded that the resonance frequency would be considerably lower with the introduction of an HVDC System.

Through detailed network frequency scans, it has been shown in this study that:

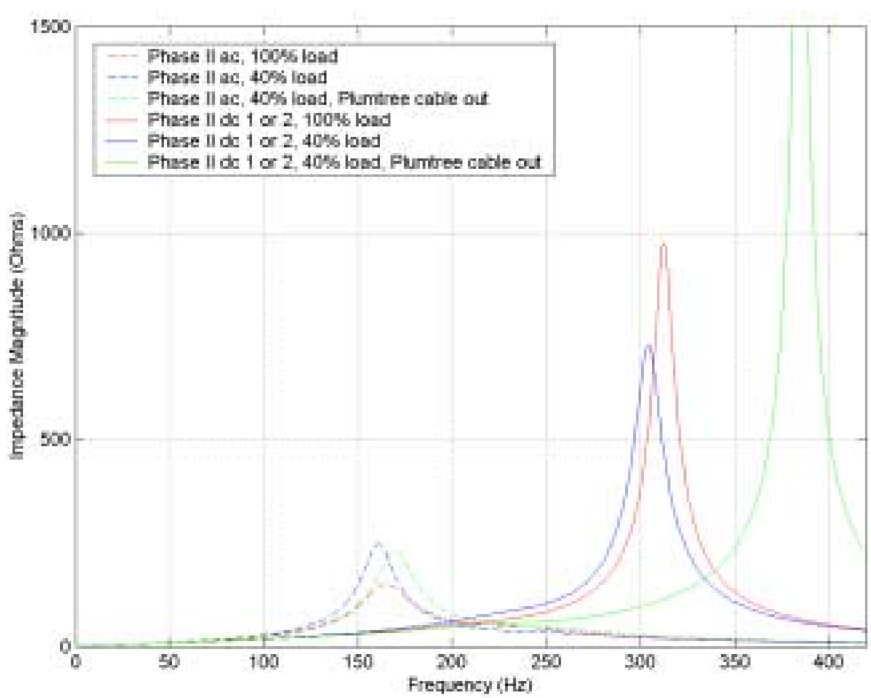
1. First, the low-order harmonic resonance does exist (under the low-generation case) for the all-ac Phase II option. The resonance is between the 2^{nd} and 3^{rd} harmonic, and it is predominantly present at the 345 kV level. The resonance occurs mainly in the region of the 345-kV corridor from Beseck to Norwalk to Plumtree. Therefore, it can be concluded that the low-order harmonic resonance is mainly caused by the capacitive charging of the Phase I and Phase II AC cables.
2. For an all-dc option using HVDC Light®, the low-order harmonic resonance on the system is eliminated, mainly because of the removal of the Phase II AC cable. The inherent low-impedance characteristic of the voltage source converters is also found to be beneficial. The first resonant frequency is now above the 3^{rd} harmonic. This satisfies the requirement of moving the network point of resonance above 3^{rd} harmonic.
3. For an alternative dc option, namely just replacing the overhead line between Devon and Beseck with dc, the inherent characteristic of the VSC helps to damp slightly and to shift up the frequency of resonance. The frequency of resonance is shifted to slightly above 3^{rd} harmonic in most cases and is a little more damped. Thus, this option only marginally meets the criteria of pushing the harmonic resonance above 3^{rd} harmonic (that is satisfies the criteria in most cases but does not in some). Further damping may also be possible through active filtering at 3^{rd} harmonic with the VSCs.

4. As stated in item 1 above, the dominating factor that results in the low-order harmonic resonance is the capacitive charging of the AC cables. Thus, by removing the AC cables with the all-dc solution a major part of the problem is eliminated. Other solutions that include AC cables are likely not as effective as an all-dc (with HVDC Light®) solution in moving the resonance above 3rd harmonic.

5. The effects of the HVDC control mode and corresponding representation of the converter have been studied, and found not to alter the overall conclusion that the all-dc Phase II system shows acceptable low-order harmonic performance.

Thus, based on the analysis presented here, from the perspective of low-order harmonic resonance the all-dc option using voltage source converter technology seems quite favorable.

An example plot from the study is shown below. This plot depicts conditions at the Norwalk 345 kV bus, with comparison of conditions with the Phase II all-ac option and the Phase II all-dc option.



It should be noted that HVDC Option 3 does not improve the first resonance frequency above the 3rd harmonic because it keeps the AC 345-kV cables of Phase II.

3.2.2 Power Flow Analysis

The power flow study analyzed 24 generation dispatch and system transfer scenarios provided by NU. Using a security constrained economic dispatch (SCED) optimal power flow to schedule the dc power levels, the study has demonstrated the feasibility of operating the proposed HVDC system throughout a load cycle and throughout the year with varying dispatches and line outages.

The power flow study report is provided in Attachment B. This report presents the power flow analysis performed to confirm the feasibility of the HVDC Light® solution from a power flow point of view. The contingency analyses performed have shown no new thermal overload or voltage violations beyond those that also occur with the Phase II all-ac solution.

Based on the power flow analysis completed, the proposed HVDC Light® Option 1 meets the required criteria as follows:

1. *To be capable of moving approximately 1,200 MW of power into Southwest Connecticut. Approximately 1,200 MW of power injection (800 MW incremental after Phase II, and Phases I & II give 1,400 MW; comparison of transfer capacity for both AC and DC line outages.)*

   Sufficient converter capacity will be provided for 1,200 MW transfer into Southwest Connecticut. The HVDC converter block sizes under consideration are 370 MW and 530 MW. Combined with Phase I, this alternative Phase II transmission expansion scheme gives at least 1,400 MW of net firm transfer capability into Southwest Connecticut. Option 1 will also give well over the desired 800 MW of firm incremental transfer capability into Southwest Connecticut. Given the available converter sizes, it is possible to find a combination that will provide 1,200 MW capacity or more to meet the project need.

3. *Resolve generation interdependencies at Pequonnock, Devon, and Norwalk Harbor.*

   The 24 power flow base cases supplied by NU and analyzed in this study represent a wide range of dispatch and operating conditions for the generation at Pequonnock, Devon, and Norwalk Harbor. The contingency analyses performed on the 24 scenarios have shown no new thermal overload or voltage violations. Hence, it is reasonable to conclude that the proposed all-dc alternative is capable of resolving generation interdependencies at Pequonnock, Devon, and Norwalk Harbor.

7. *Must be able to operate throughout a load cycle and throughout the year with varying dispatches and line outages.*

   The power flow study conducted has demonstrated the feasibility of scheduling the power on the HVDC systems in a security constrained dispatch manner. For each of the specific generation and load conditions studied, it has been found that the HVDC converters can be dispatched in such a way that there will be no overloads for the contingencies analyzed. For most of the contingencies studied, no immediate adjustment of the power schedule is required following a contingency. For a limited number of contingencies, readjustment of the dc power schedule is required. However, the readjustment will be made automatically based on local signals. Therefore, based on the results of analyzing the 24 dispatch and transfer scenarios, it seems reasonable to conclude that all-dc alternative will be able to operate throughout a load cycle and throughout the year with varying dispatches and line outages.

8. *The project cannot cause any new overloads on the system.*

   The contingency analyses performed have shown no new thermal overload violations beyond those that also occur with the Phase II all-ac solution.

11. *The project needs to provide adequate voltage on the system.*

   Unlike the proposed Phase II AC solution, the HVDC Light® converters provide fully controllable reactive power injection or absorption to maintain the desired voltage. The contingency analyses performed have shown no new voltage violations beyond those that also occur with the Phase II all-ac solution.

12. *Respect existing contracts and system capabilities – cannot degrade capabilities such as the 352 MW (330 MW net) capability of the Cross Sound Cable and 200 MW across the 1385 submarine cable between Norwalk Harbor and Northport, LI.*

   These transfer conditions are represented in some of the 24 base cases provided by NU. Again, no road blocks have been found, as the contingency analyses performed have shown no new thermal overload or voltage violations beyond those that also occur with the Phase II all-ac solution.

Besides meeting the required power flow criteria, HVDC Light® provides a level of control that AC transmission cannot. If odd, unexamined system operating conditions arise in the future, the flexibility of being able to redispatch the HVDC, manually or with tools like SCUC / SCED, will prove invaluable to the system operator for reliably serving its transmission customers.

3.2.3 Short Circuit Analysis

This study addresses System Criteria No. 2, Resolve short circuit issues at Pequonnock 115 kV and Devon 115 kV and Devon 115 kV target of 90% of 63 kA or below. Study results show that this criterion can be met with the all-dc alternative analyzed.

Refer to short-circuit study report in Attachment C.

3.2.4 Stability Analysis

This study addresses System Criteria No. 10, "The project needs to result in a dynamically stable system." For the base case (light load conditions) and faults modeled in the stability analysis, no stability problems were found with Phase II HVDC Light® Option 1. The system stability performance is as good or better with HVDC Light® as compared to the Phase II AC solution. Additional analysis is recommended to confirm this conclusion. Additional power flow base case conditions and additional fault cases should be studied in the future.

The stability study report is provided as Attachment D. This report presents the stability analysis performed to verify the feasibility of the HVDC Light® solution from a stability point of view. A single base case condition was analyzed for this report, as provided by NU. This base case models light load conditions and zero transfer of power between New England and New York. Light load is considered by NU to be the most crucial load level for stability analysis in the ISO-NE region. Only HVDC Light® Option 1 was modeled for this report. In the stability study, Option 1 replaces all Phase II AC 345 kV lines and cables with five two-terminal HVDC Light® lines.

The analysis performed to date indicates no stability limitations to the implementation of HVDC Light® in the Southwest Connecticut electric transmission system. This is not surprising because HVDC Light® provides high-speed voltage control, including reactive power injection if needed, at both ends of the DC lines.

Additional base case conditions and fault scenarios may need to be studied to provide assurance of stability of the HVDC Light® options

3.3 <u>Pros and Cons of HVDC Alternatives</u>

Option 1 HVDC Light® over the full corridor from Beseck to Norwalk.

<u>Pros:</u>

- Fully underground HVDC solution shifts the first system harmonic resonant frequency to above the 3rd harmonic order.
- Minimum contributions to short-circuit current levels
- Provides multiple independent links between Beseck and Norwalk
- Provides redundant two-terminal links at Singer and Devon
- Addresses plans for new generation at Singer, Devon and Norwalk

<u>Cons:</u>

- First application with HVDC systems connected in series, and 5 systems in total.
- Slightly reduced flexibility during converter contingencies as compared to multi-terminal solution
- 530-MW HVDC system with VSC technology yet to be built
- Interconnection of new generation at new locations will require new converters.

Option 2 Full HVDC Light® underground solution, using a multi-terminal configuration rather than point-to-point systems.

Pros:

- Fully underground HVDC solution shifts the first system harmonic resonant frequency to above the 3rd harmonic order.
- Minimum contributions to short-circuit current levels
- Provides multiple independent circuits between Beseck and Norwalk
- Provides two HVDC circuits each at Singer and Devon
- Addresses plans for new generation at Singer, Devon and Norwalk
- Optimum usage of remaining converters during converter contingencies
- Multiterminal HVDC Light has been studied extensively, and the operating characteristics are fully understood

Cons:

- Multiterminal HVDC Light® systems have not yet been built
- 530-MW HVDC line with VSC technology yet to be built
- Interconnection of new generation at new locations will require new converters.

Option 3 Hybrid approach, in which 345 kV AC cables are used from Devon to Norwalk, and HVDC Light® is used only in the portion of the corridor between Devon and Beseck.

Pros:

- Minimum number of converters for a fully underground corridor solution
- Conceptually simplest design
- Addresses plans for new generation
- Provides three circuits between Beseck and Devon
- Interconnection of new generation does not require new converters.

Cons:

- Highest total capacitance due to 345 kV AC cables
- First system resonance frequency below the 3rd harmonic order in some cases
- Requires shunt reactors during light load condition to control the voltage profile of the AC cable portion of corridor
- 530-MWHVDC line with VSC technology yet to be built

4 CONCLUSIONS

Based on the results of this feasibility, it is concluded that HVDC Options 1and 2 are both feasible and capable of meeting the 13 performance criteria set forth by NU, UI and

ISO-NE. Option 3 meets all performance criteria except the one on moving the first system resonance point to above the 3rd harmonic frequency.

The selection of the most cost-effective solution will require additional detailed studies to optimize the design, taking into account of reliability, operability and flexibility.

ATTACHMENT A

Frequency Scan Study Report

ATTACHMENT B

Power Flow Study Report

ATTACHMENT C

Short Circuit Study Report

ATTACHMENT D

Stability Study Report