
**Preliminary Evaluation of the
System Compatibility of an HVDC
Transmission Alternative for the
Beseck - East Devon Segment of
the Middletown-Norwalk
Transmission Project**

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TABLE OF CONTENTS

EXECUTIVE SUMMARY	1
1. INTRODUCTION.....	2
2. SYSTEM STRENGTH.....	2
2.1. HVDC Short Circuit Ratio for Conventional HVDC.....	2
2.2. Short-Circuit Strength Considerations for VSC-HVDC	5
2.3. AC System Implications of Reduced Short-Circuit Strength.....	5
2.3.1. AC System Voltage Stability	5
2.3.2. Transient Stability.....	6
3. POWER FLOW RESPONSE	6
4. SYSTEM RESONANT CHARACTERISTICS	8
4.1. Approximation of System Resonance Impacts of Conventional HVDC.....	9
4.2. Approximation of System Resonance Impacts of VSC-HVDC	11
5. OTHER SYSTEM ISSUES.....	13
6. CONCLUSIONS.....	14

Executive Summary

This document is a preliminary evaluation of system compatibility issues affecting technical feasibility of HVDC alternatives for this transmission segment, with particular focus on the impact of this alternative on ac system resonances which have been previously identified as an issue for the Middletown – Norwalk transmission project.

Conventional HVDC appears technically inadvisable for providing transmission over the Beseck to East Devon segment. This transmission alternative results in ac system resonances at extremely low frequencies and weakens the ac system. The ac system weakness will contribute to performance and design issues for the conventional HVDC system.

VSC-HVDC also weakens the ac system, but the VSC-HVDC system itself does not suffer the same system weakness limitations as does conventional HVDC. The weakening of the ac system which has implications to system stability and resonant behavior. Ac system resonant frequencies are also shifted to undesirably-low frequencies with this option. While the converter could potentially be used to mitigate ac system resonance problems, this is an unprecedented solution on this scale and would involve substantial risk to employ. The substantially greater system losses of this system seem contrary to public policies promoting energy conservation. In addition to these system issues, the scale of transmission needed for this application (1200 MW power rating) is far greater than any prior application of this technology. With the available VSC-HVDC converter dc voltages, a number of dc cables would need to be routed.

Based on the system issues discussed in this report, it is concluded that HVDC options do not appear to be a technically viable alternative for providing a 1200 MW transmission path from Beseck to East Devon.

1. Introduction

Connecticut Light and Power, a Northeast Utilities subsidiary, along with the United Illuminating Company propose to construct a 345 kV ac transmission system from Middletown to Norwalk in Connecticut. It has been suggested that HVDC be considered as an alternative for the transmission segment from Beseck to East Devon, a distance of approximately 40 miles. A prior report¹, prepared by Black & Veatch has examined the feasibility of the HVDC alternative from a construction and cost standpoint. This document is a preliminary evaluation of system compatibility issues affecting technical feasibility of HVDC alternatives for this transmission segment, with particular focus on the impact of this alternative on ac system resonances which have been previously identified as an issue for the Middletown – Norwalk transmission project. This preliminary analysis is approximate, as complex ac-dc system resonant interactions have not been included in the analysis, and is not intended to be a comprehensive evaluation of the full spectrum of system compatibility issues. This report also does not repeat the background information on HVDC technologies provided in the Black & Veatch report; the reader is referred to that report for such information.

2. System Strength

In the proposed all-ac system, the dominant source of short-circuit current in the Middletown to Norwalk transmission loop is from the Middletown end, via Beseck. HVDC systems neither transmit nor source short circuit strength to the ac systems to which they are interconnected. Thus, replacing the proposed 345 kV ac transmission link between Beseck and East Devon with an HVDC system severs the remaining portion of the ac loop from its strongest source of short-circuit strength. This effect is particularly pronounced when few generation units in the southwestern Connecticut area are dispatched under light to moderate system load conditions. Most generation plants in this area are subject to environmental scrutiny and may have higher cost. With the addition of the proposed transmission reinforcement, these units are no longer forced to operate when they are uneconomic. This is in contrast with the current conditions in which they are presently required to operate more frequently due to transmission constraints. Thus, conditions of minimal local generation will be typical in the future. In this report section, some of the issues related to system weakness are described.

2.1. HVDC Short Circuit Ratio for Conventional HVDC

The ratio of the ac system short-circuit capacity at each HVDC converter terminal, measured in MVA, to the rated power of an HVDC system in MW is the “short-circuit ratio” (SCR) of that HVDC terminal. An SCR less than 2.0 is considered “very low” and an SCR between 2.0 and

3.0 is defined as “low” in IEEE Standard 1204-1997². The SCR is a critical metric for conventional HVDC systems, affecting a wide range of performance issues including:

- The sensitivity of the HVDC to system disturbances; a low SCR inverter is likely to suffer commutation failure from a less severe ac system event than a high SCR inverter. Low SCR inverters have been known to suffer commutation failure from faults in nearby local distribution system, several voltage levels below the transmission system to which the inverter is connected. Commutation failure is a temporary collapse of the HVDC power transfer which has significant power quality impact, but is not usually a system security issue unless the HVDC system fails to recover.
- Ability of the HVDC system to successfully recover from faults and other system disturbances. Low SCR systems sometimes suffer commutation failures during recovery from prior commutation failures. Such repeated events may necessitate shutting down the HVDC system, which does have obvious system security implications.
- HVDC system with low SCR recover from faults more slowly than in strong system. In addition to the dynamic interactions with the ac system impedance that slow recovery, HVDC controls in weak system applications are often programmed to recover slowly to avoid commutation failure during recovery. This reduces power transfer during the critical post-fault period when generator units in the ac system, which have accelerated during the fault, must be decelerated. Reduced power transfer at this time can reduce ac system transient stability and may potentially result in voltage collapse.
- Ac voltage control is more difficult in low SCR HVDC applications. Conventional HVDC systems consume large amounts of reactive power which must be compensated by shunt capacitor banks or harmonic filter banks. Small changes in the HVDC system operating point can make substantial changes in the reactive power balance. In a low SCR system, the high ac system impedance causes these reactive changes to make large voltage changes.
- HVDC systems in low SCR applications have less control stability and inferior dynamic performance characteristics. Because of the high ac system impedance, changes in the HVDC operating point, which change the real and reactive power of the converter have a large effect on the ac voltage magnitude and phase angle presented to the converter. Changes in the ac voltage cause changes in the HVDC operating point, resulting in the closed-loop interaction between the ac and dc systems to be exaggerated. Poorly damped control performance, and even control instability can result. Ac system impedance resonances, falling at a low enough frequency such that they are within the

frequency response range of the HVDC converter controls, can further aggravate control stability problems.

- High temporary overvoltages tend to occur in ac systems with low SCR HVDC applications. If the HVDC converter operation is interrupted, the large reactive power demand of the converter is also interrupted. With the large amount of shunt capacitor compensation connected, the large reactive mismatch combined with a high ac system impedance results in large overvoltages which persist until either the capacitor banks are tripped or the HVDC system operation is resumed. These overvoltages can put utility and consumer equipment at risk.
- Ac systems with low SCR HVDC systems tend to have low-frequency resonances, due to the interaction of the converter terminal’s reactive compensation banks and the high ac system impedance. In the case of the Middletown – Norwalk 345 kV ac system, system resonances are already low due to the ac cables. HVDC further aggravates this as will be discussed in more detail later in this report.

Because HVDC performance issues are most critical following faults and other disturbances, proper evaluation of an HVDC application on an SCR basis should include post-contingency situations. Table I shows SCRs at East Devon for a 1200 MW HVDC line between Beseck and East Devon replacing the currently proposed 345 kV ac line between these points. A minimal southwest Connecticut generation dispatch is assumed.

Table I
Short-Circuit Ratios at East Devon

System Condition	Short Circuit Ratio
No contingencies	4.8
Plumtree – Long Mountain 345 kV line out	2.8
Plumtree-Long Mountain 345 kV, and Norwalk-Northport 138 kV cables out	1.8

These results indicate that, while the SCR under normal system conditions is quite acceptable, a line outage brings the system into the low SCR category. Continued operation of a conventional HVDC system with the Plumtree-Long Mountain 345 kV ac line, or the Norwalk-Northport 138 kV ac cable ties out would not be acceptable because the possibility of the other of these two lines tripping, putting the East Devon HVDC terminal below an SCR of 2.0. This is in the “very low” category where extreme performance issues are a certain threat.

2.2. Short-Circuit Strength Considerations for VSC-HVDC

Voltage-source converter HVDC technology is not as sensitive to SCR limitations as conventional HVDC. It is capable, with appropriate controls, to operate with an ac system with zero short-circuit current availability. Like conventional HVDC, however, VSC-HVDC does not transmit the ac system short-circuit capacity from terminal to terminal, and is itself an insignificant contributor to short-circuit strength. This introduces ac system limitations described both in the next section, and also later in this report when system resonances are discussed.

2.3. AC System Implications of Reduced Short-Circuit Strength

In addition to the implications of ac system weakness on HVDC system operation and interactions with the ac system, increasing the ac system impedance also affects the ac system performance. Two significant areas are the impacts on voltage stability and transient stability.

2.3.1. AC System Voltage Stability

While voltage stability is a function of several system parameters, system short-circuit strength is a critical factor. By eliminating the strongest tie from the southwest Connecticut subsystem to the greater New England grid, which would have been provided by an all-ac 345 kV transmission option, the HVDC options may decrease voltage stability in the region. This is more likely the case with an outage of the northwestern feed into the system via Plumtree. In such a contingency condition, the system voltage stability may be little improved over its present-day precarious state.ⁱ This is particularly true with conventional HVDC, where the interactions between the ac and dc systems would tend to compound the complexity of the ac voltage stability problem. VSC-HVDC has the inherent capability to provide highly-controllable reactive support, acting as a virtual STATCOM in addition to the power transfer function. This capability might be used to mitigate the voltage stability impacts of weakening the southwest Connecticut (relative to the ac option) from an ac voltage stability standpoint. The ability to do so depends on the amount of reactive power support needed by the system relative to the support available from a VSC-HVDC system rated for 1200 MW real power transfer. Real power transfer can be rapidly changed with both conventional HVDC and VSC-HVDC. Reactive power in or out of VSC-HVDC converters also be changed quickly over a rather broad range. The reactive power interchange with the ac systems at one VSC-HVDC converter terminal is independent of the interchange of the converter terminal at the other end of

ⁱ The comments here on voltage stability are based on engineering judgment, and detailed studies are necessary to better define the impacts of HVDC options on voltage stability

the HVDC line. In contrast, real and reactive power interchange at conventional HVDC converters is rapidly adjustable over only a rather limited range and the fast reactive power changes at the line terminals are not independent. Over a longer time period, reactive power interchange of conventional HVDC can be independently varied over a wider range by reactive compensation bank (capacitor bank or shunt reactor bank) or transformer tap changing. These slower changes are over tens of seconds to minutes and are of limited value in mitigating voltage instability.

2.3.2. Transient Stability

The ac system short-circuit strength of an ac bus, to which a generation unit is connected, is a measure of the transmission system's ability to maintain that generating unit in synchronism during and following a system fault or other disturbance. Replacing the proposed 345 kV ac line between Beseck and East Devon with HVDC reduces this synchronization strength. Transient stability of generating units in the region, particularly those in southwest Connecticut, is likely to be negatively affected. While HVDC system power modulation schemes have been developed and successfully implemented to augment system stability, these schemes are effective primarily in adding damping (thus improving multi-swing dynamic stability) but are generally ineffective in supporting first-swing transient stability. Significant mitigation of transient stability limitations typically require a rather large increase in power transfer immediately following a fault. An HVDC system generally is not capable of meeting this objective due to reactive compensation and equipment overload considerations. Also, the HVDC power transfer is likely to collapse during the fault, due to depressed ac voltage, and will be recovering from the collapsed state in the critical post-fault period.

3. Power Flow Response

The inherent characteristic of an HVDC transmission system is to maintain constant power flow, independent of changes in the surrounding ac system. However, the HVDC power flow can also be easily and directly controlled through control action. The flow of power over an ac line is primarily a function of the difference in phase angles in the bus voltages at the line terminations. When a line is removed from the network (e.g., to clear a fault), the inherent changes in voltage phase angles cause the power previously carried by the outaged line to be shifted to other lines.

If an HVDC line is in the network, it will not automatically respond like an ac line to pick up the extra flow requirements. This shifts a disproportionate burden onto other ac lines, which could potentially result in overloads, collapsed voltages, or cascading outages. It is possible to control the HVDC line such that it responds like an ac line by sensing ac system conditions and changing HVDC power setpoints accordingly. However, this approach is constrained by the

limited overload capability of the HVDC line. Ac lines have thermal time constants on the order of tens of minutes which allow the line to carry substantial overload for a brief time until system operators can take corrective action to reduce loading to the emergency line rating, which itself is substantially greater than the normal line rating. The thermal time constants of the semiconductor devices in HVDC converters are much shorter and less tolerant of overload. Thus, the use of an HVDC line in the critical Beseck to East Devon segment increases the contingency burden on other 345 and 115 kV ac lines in the area. Because system planning and operations are constrained by contingency considerations, use of a 1200 MW HVDC tie results in less load carrying capacity for the system than if a nominally-rated 1200 MW ac tie is used for the same tie. To overcome this limitation, extra capacity would need to be designed into the HVDC line.

4. System Resonant Characteristics

Previous reports by GE Energy have clearly shown that the transmission system in southwest Connecticut resonates at an unusually low frequency with the proposed all-ac Middletown – Norwalk transmission expansion. This is due to the large amount of charging capacitance provided by underground ac cables in the proposed design. The low-frequency resonance characteristic introduces risks of overvoltage and inferior power quality. An alternative ac design for the system, which has been suggested to the utilities, was to place a significant portion (20 miles) of the Beseck – East Devon segment underground. The substantial addition of shunt charging capacitance was shown to aggravate the resonant situation, and a negative recommendation on technical grounds was offered in a previous GE Energy report³. The HVDC alternatives evaluated in this report have been suggested as another means to avoid overhead ac transmission in this segment.

There are three ways that substitution of an HVDC line for the overhead 345 kV ac line between Beseck and East Devon will affect resonant characteristics of the ac transmission system west of East Devon. These are:

1. The weakening of the ac system, as described previously, tends to drive the ac system resonance to a lower frequency. The resonant frequency of the system is roughly proportional to the square root of the ratio of the short-circuit capacity (in MVA) divided by the capacitive MVAR in the system. Thus, weakening the system has a comparable effect on resonant frequency as increasing the capacitance (i.e., adding ac cables).
2. A conventional HVDC system requires substantial reactive power at both the rectifierⁱⁱ and inverterⁱⁱⁱ terminals. Depending on system design, the reactive requirements at each end can be as much as 60% of the rated power of the HVDC system. Also, harmonic filters^{iv} are required to allow the converter to operate correctly and to avoid telecommunication interference and power quality problems. Harmonic filters inherently provide reactive power, and thus are used to partially fulfill the reactive power requirements. In a typical system, fulfillment of filtering requirements constitute charging MVAR equal to about 35% of the HVDC system power rating. Even if the ac system can supply reactive power, such as at Devon where reactive power can be

ⁱⁱ Rectifier: converter of ac power to dc.

ⁱⁱⁱ Inverter: converter of dc power to ac.

^{iv} These harmonic filters are tuned to the characteristic harmonics of the conversion process, typically to the 11th, 13th, 23rd, and 25th harmonics. Sometimes filters are also required which are tuned to non-characteristic harmonics, such as the 3rd harmonic.

obtained from the ac cable charging, filters are still required. Thus, a conventional HVDC system adds shunt capacitance which also tends to reduce the ac system resonant frequency.

VSC-HVDC systems do not require reactive compensation and harmonic filter requirements are less.

3. An HVDC system has its own resonant characteristics which are established by the inductances of the smoothing reactor and converter transformer, and the capacitance of the overhead line or cable and dc harmonic filters. The impedances of the dc system reflect to the ac system in a complex manner; the impedance at a frequency on the dc side is seen on the ac system at a frequency plus and minus 60 Hz from the dc-side frequency. Converter controls also modify the ac-dc interaction, particularly in the case of VSC-HVDC where the controls inherently have a wide frequency response.

4.1. Approximation of System Resonance Impacts of Conventional HVDC

Frequency scan analysis of the ac driving point impedance at East Devon was performed using the ac system model previously used in the GE Energy study of the Middletown-Norwalk transmission study⁴. A generation dispatch with a minimal number of units in southwestern Connecticut was used^v, and all transmission capacitor banks were in service. The impacts of the HVDC option on ac system frequency response, exclusive of the complex interactions described in Item 3 of Section 4 above, were simulated by performing the following steps:

1. The Beseck – East Devon 345 kV ac line was removed from the model.
2. A 420 MVAR shunt capacitor was added at East Devon to represent the lower-frequency effects of harmonic filters. Filters tuned to the converter characteristic harmonics appear almost identically as simple capacitors in the critical frequency range in this study (below 3rd harmonic).
3. A 720 MVAR shunt capacitor was added at Beseck to represent harmonic filters and the shunt capacitors which would be needed to supply reactive power needs.

More detailed representation of the conventional HVDC system was judged unnecessary to obtain a preliminary estimate of the impact on ac system resonances.

^v This generation dispatch had less local generation than the previous study cited as Reference 4, thus resulting in resonance conditions different than found in that study.

Because contingency conditions are typically critical for planning and design, one line outage condition was also included. Both the original HPFF and XLPE cable options were considered. Table 2 summarizes the first resonant frequencies for the cases representing conventional HVDC, along with the ac-only case for comparison. Figures 1 and 2 show driving point impedance versus frequency plots for these cases.

Table 2
First Resonant Frequencies at East Devon 345 kV AC Bus
(multiples of 60 Hz)

Condition	HPFF AC Cable	XLPE AC Cable
Base condition, ac-only alternative	2.2	2.5
Conventional HVDC, no contingencies	1.8	2.1
Conventional HVDC, Plumtree – Long Mountain 345 kV line out	1.5	1.8

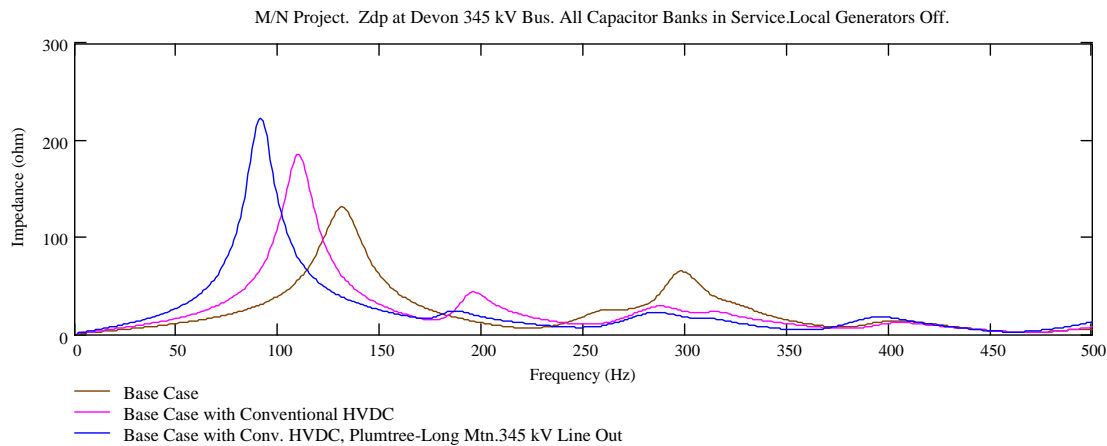


Figure 1. Driving point impedance versus frequency at the East Devon 345 kV ac bus with HPFF ac cables.

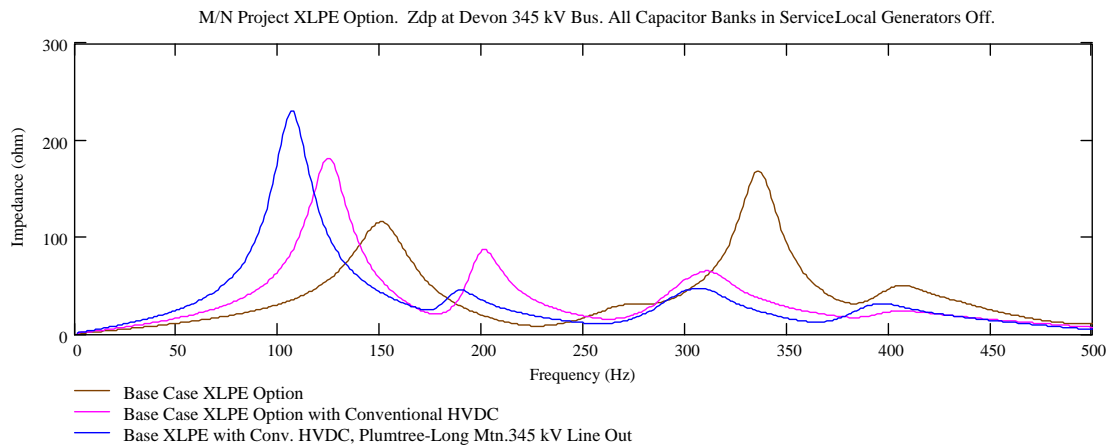


Figure 2. Driving point impedance versus frequency at the East Devon 345 kV ac bus with XLPE ac cables.

It is very clear that using conventional HVDC transmission for the Beseck –East Devon section greatly aggravates the low-frequency resonance issues. Use of XLPE for the ac cables in the transmission project does not provide significant mitigation. With only a single contingency, the system resonance drops to 90 Hz, which is extremely low.

4.2. Approximation of System Resonance Impacts of VSC-HVDC

The approximate ac system resonance impact of using a VSC-HVDC line to replace the ac line in the Beseck-East Devon segment was also analyzed. The same system model, described in Section 4.1 for conventional HVDC, was used except that the shunt capacitors at East Devon and Beseck were omitted. The requirements for filters in a VSC-HVDC system, which are much less than for a conventional HVDC system, are dependent on details of the converter design and the ac system characteristics. Therefore, the small amount of ac shunt capacitance^{vi} they might contribute to the system resonant behavior was intentionally ignored.

Table 3 provides a summary of ac system resonances. For a system to continue operation after a first contingency, it must be able to safely survive a second contingency. For this reason, a double-contingency of the Plumtree – Long Mountain 345 kV line out and the Norwalk Harbor Northport (Long Island) 138 kV cable system out was also considered^{vii}. Frequency scan plots are shown in Figures 3 and 4.

vi Typical VSC-HVDC converter ac harmonic filters might contribute MVARs equal to about 10% of the power rating, and would be on the low-voltage side of an interfacing transformer.

vii Second contingency analysis would also apply to conventional HVDC, but the severity of the first-contingency results indicated further study was unnecessary.

Table 3
First Resonant Frequencies at East Devon 345 kV AC Bus
(multiples of 60 Hz)

Condition	HPFF AC Cable	XLPE AC Cable
Base condition, ac-only alternative	2.2	2.5
VSC-HVDC, no contingencies	2.0	<i>(not analyzed)</i>
VSC-HVDC, Plumtree – Long Mountain 345 kV line out	1.7	2.0
Plumtree-Long Mountain 345 kV, and Norwalk-Northport 138 kV cables out	1.4	1.7

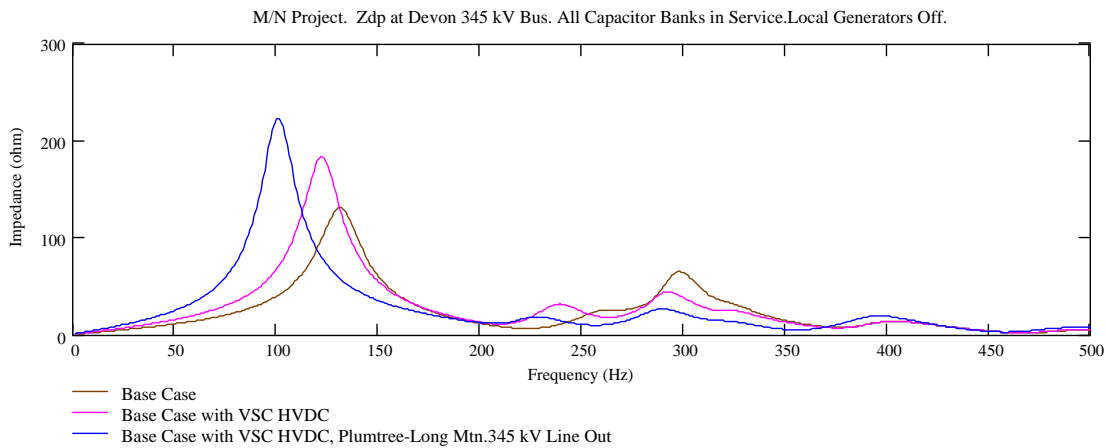


Figure 3. Driving point impedance versus frequency at the East Devon 345 kV ac bus with HPFF ac cables.

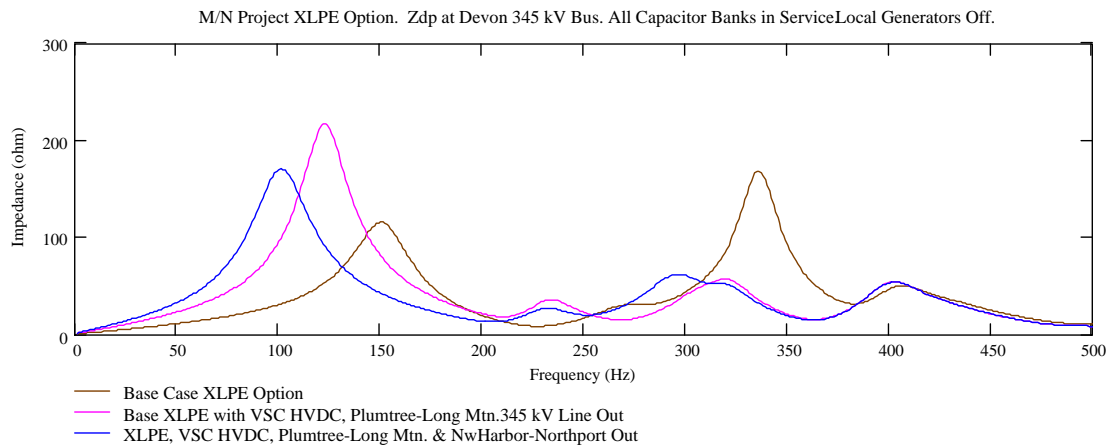


Figure 4. Driving point impedance versus frequency at the East Devon 345 kV ac bus with XLPE ac cables.

Although use of VSC-HVDC does not aggravate the ac system resonance condition as severely as does conventional HVDC, resonant frequencies are decreased substantially compared to the all-ac option. Because a second contingency leads to an extremely low-frequency resonant condition, it might be necessary to curtail operation of the HVDC line in the event of certain system outages such as a Long Mountain – Plumtree line outage. It seems that requiring the Beseck to East Devon line to shut down or limit operation in response to loss of the other main feed into southwest Connecticut would be contrary to good transmission planning.

Because the controllability of a VSC-HVDC converter extends to the frequency range of the ac system resonances, it is theoretically possible for the converter to mitigate the ac system resonance problems. In fact, the converter used for the HVDC application is structurally similar to voltage-source converters used as active harmonic filters. However, the combination of HVDC transmission and harmonic resonance mitigation applications has not been reported in the literature. Thus, attempting such an approach for this project entails the significant technical risks of any research and development venture.

5. Other System Issues

This report is not intended to cover all the system issues related to integration of HVDC transmission into an ac system. These other issues include harmonics, insulation coordination, power quality, etc. One additional issue of significant note is transmission system losses. While conventional HVDC has less per-mile transmission losses, the conversion losses are not insignificant. The net result is that total losses for this line would substantially exceed losses for the ac alternative. VSC-HVDC has far greater converter losses. Also, because presently-available VSC-HVDC systems operate at only up to ± 150 kV, the transmission voltage is below

optimal for the power to be transmitted, causing per-mile line losses to exceed those of a 345 kV ac line.

Using available industry information and engineering estimates of line characteristics, Table 5 summarizes approximate line and conversion losses for the ac and two HVDC options. The incremental line losses for the VSC-HVDC option, relative to the ac option, equal 64 MW, or the output of a moderate-sized gas turbine powerplant unit.

Table 5
Approximate Transmission Losses for the Beseck – East Devon Line
(% of 1200 MW Rating)

Alternative	Conversion Losses	Line Losses	Total Losses
AC	0.0%	1.2%	1.2%
Conventional HVDC	1.4%	0.5%	1.9%
VSC-HVDC	5.0%	1.5%	6.5%

6. Conclusions

Conventional HVDC appears technically inadvisable for providing transmission over the Beseck to East Devon segment. First of all, ac system resonances are driven to very low frequencies. This is an application space outside of industry experience. Second, the system short-circuit ratio at East Devon falls to undesirably low values for outage of both the Plumtree - Long Mountain 345 kV line^{viii} and the Norwalk Harbor 138 kV cable tie. Thus, outage of one of these two ties would require curtailment of the HVDC operation to ensure that the system is secure in the event the other tie should be lost. This is unacceptable from a transmission planning standpoint.

VSC-HVDC does not suffer the same short-circuit ratio limitations. However, there is significant weakening of the ac system which has implications to system stability and resonant behavior. Ac system resonant frequencies are also shifted to undesirably-low frequencies with this option. While the converter could potentially be used to mitigate ac system resonance

^{viii} Outage of the Plumtree – Norwalk Phase 1 line and cable system would produce a similar effect on short-circuit ratio.

problems, this is an unprecedented solution on this scale and would involve substantial risk to employ. The substantially greater system losses of this option seem contrary to public policies promoting energy conservation. In addition to these system issues, the scale of transmission needed for this application (1200 MW) is far greater than any prior application of this technology. With the available converter dc voltages, a number of dc cables would need to be routed.

Based on the system issues discussed in this report, it is concluded that HVDC options do not appear to be a technically viable alternative for providing a 1200 MW transmission path from Beseck to East Devon.

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