Power Flow Analysis for Underground Transmission Options using HVDC Light®

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Prepared for: **Northeast Utilities**

Submitted by:

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Summary

Northeast Utilities (NU) has contracted ABB to develop HVDC Light® alternatives to the Southwest Connecticut Phase II AC system upgrades. This report presents the initial power flow analysis performed to confirm the feasibility of the HVDC Light® solution from a power flow point of view.

Based on the power flow analysis completed to date, 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.

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1 Introduction

This power flow analysis is part of the study conducted by the Electric Systems Consulting group of ABB Inc. to address the technical 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 two terminologies, HVDC Light® and VSC HVDC, have been used interchangeably in this report.

NU, with input from New England ISO and UI, has outlined 13 criteria that must be satisfied by the underground HVDC solution. Note that voltage source converters (VSC) are used in ABB's HVDC Light® technology. The following criteria for HVDC Light® feasibility relate to power flow:

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.)

3. Resolve 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.

8. The project cannot cause any new overloads on the 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 (330 MW net) capability of the Cross Sound Cable and 200 MW across the 1385 submarine cable between Norwalk Harbor and Northport, LI.

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 schematic diagrams for the three options are shown in Figure 1:

HVDC Light® Option 1, including five two-terminal DC lines, has been the primary focus of this power flow analysis.

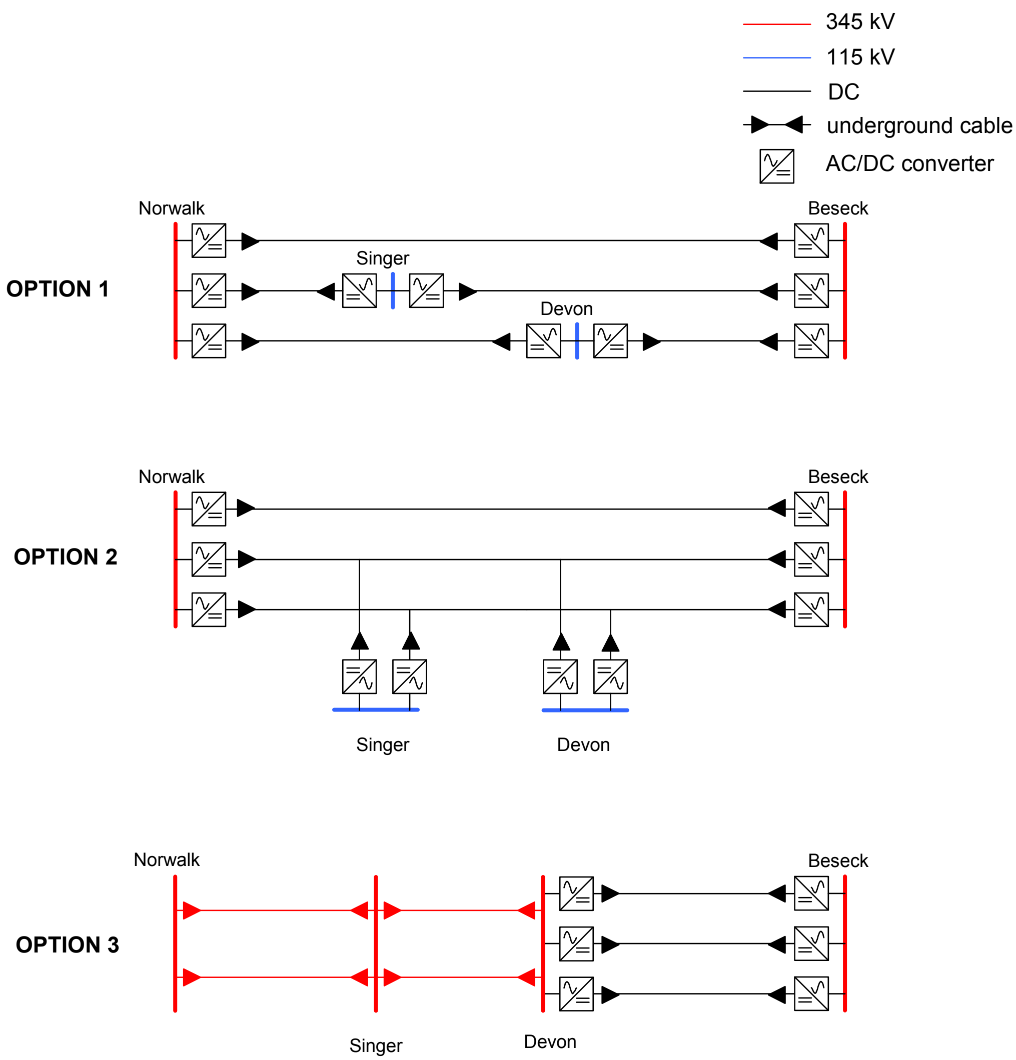

Figure 1 - Conceptual HVDC Alternatives Based on VSC Technology

This report is organized as follows. Section 2 presents the study approach and methodology. The development of the power flow system models for Phase II and a description of how the power schedules on the HVDC alternative is derived are discussed in that section. Section 3 contains the contingency analysis results. In Section 3, the performances of the HVDC alternatives with respect to the performance criteria are discussed. Section 4 presents the study conclusions. Supporting study results are provided in Appendices A - C.

2 Study Approach and Methodology

2.1 Power Flow Model Development

2.1.1 Phase II AC Model

Northeast Utilities provided 24 power flow cases for the Phase II AC solution (see Table 2-1). These cases represent three different power transfers from New England to New York (700 MW, 0 MW, and -700 MW), two options for the Kleen Energy power plant (in and out), and four different generation dispatches (numbered 2, 3, 4, and 5). This list is considered to be a representative sample of the various dispatches that the DC solution needs to handle.

Table 2-1. Power Flow Cases Provided by NU

File Name	NE-NY (MW)	Dispatch #	Kleen Plant
phase2-alt2-ne-ny-091503-2KL.SAV	700	2	IN
ph2-alt2-ne-ny-091503-2.SAV	700	2	OUT
phase2-alt2-ne-ny-091503-3KL.SAV	700	3	IN
ph2-alt2-ne-ny-091503-3.SAV	700	3	OUT
phase2-alt2-ne-ny-091503-4KL.SAV	700	4	IN
ph2-alt2-ne-ny-091503-4.SAV	700	4	OUT
phase2-alt2-ne-ny-091503-5KL.SAV	700	5	IN
ph2-alt2-ne-ny-091503-5.SAV	700	5	OUT
phase2-alt2-091503-2KL.SAV	0	2	IN
phase2-alt2-091503-2.SAV	0	2	OUT
phase2-alt2-091503-3KL.SAV	0	3	IN
phase2-alt2-091503-3.SAV	0	3	OUT
phase2-alt2-091503-4KL.SAV	0	4	IN
phase2-alt2-091503-4.SAV	0	4	OUT
phase2-alt2-091503-5KL.SAV	0	5	IN
phase2-alt2-091503-5.SAV	0	5	OUT
phase2-alt2-ny-ne-091503-2KL.SAV	-700	2	IN
ph2-alt2-ny-ne-091503-2.SAV	-700	2	OUT
phase2-alt2-ny-ne-091503-3KL.SAV	-700	3	IN
ph2-alt2-ny-ne-091503-3.SAV	-700	3	OUT
phase2-alt2-ny-ne-091503-4KL.SAV	-700	4	IN
ph2-alt2-ny-ne-091503-4.SAV	-700	4	OUT
phase2-alt2-ny-ne-091503-5KL.SAV	-700	5	IN
ph2-alt2-ny-ne-091503-5.SAV	-700	5	OUT

In an August 12, 2004 email, NU provided 115 kV system additions that are planned for the Norwalk / Glenbrook area (see Table 2-2). These lines were added to the 24 cases listed above and the new case names have the suffix "-upg" (upgrade) added.

Table 2-2. Circuit Additions Provided by NU via Email

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There will be two new circuits between 73172 (Norwalk 115) and 73168
(Glenbrook 115).  Each circuit has the following parameters on a 100 MVA
base:
R=0.00152
X=0.01969
B=0.16334
Normal/LTE/STE rating=250/369/369

There will be one new cable between 73171 (Norwalk Harbor 115) and 73168
(Glenbrook 115).  Each circuit has the following parameters on a 100 MVA
base:
R=0.00165
X=0.02392
B=0.18754
Normal/LTE/STE rating=209/308/308
```

The additional files shown in Table 2-3 were provided by NU for performing AC contingency analysis and producing power flow drawings.

Table 2-3. Additional Power Flow Files Provided by NU

File Name	Description
contigphase2-091503.con	Contingency list for cases without Kleen Energy plant
contigphase2-091503-kleen.con	Contingency list for cases with Kleen Energy plant
contingencyadd.con	Additional contingencies for the proposed Norwalk / Glenbrook 115 kV lines
Ne345-2-ph1.drw	PSS/E drawing file for the New England 345 kV system
ph1swct-1.drw	PSS/E drawing file for the Southwest CT 115 kV system
swct0802.mon	Monitor file for AC contingency analysis
swctnew.sub	Subsystem file for AC contingency analysis

ABB created an additional PSS/E drawing that shows mainly the 345 kV system in the SWCT area. See Figure 2-1 for an example. Power flow one-line diagrams for all 24 cases are included in the Appendices.

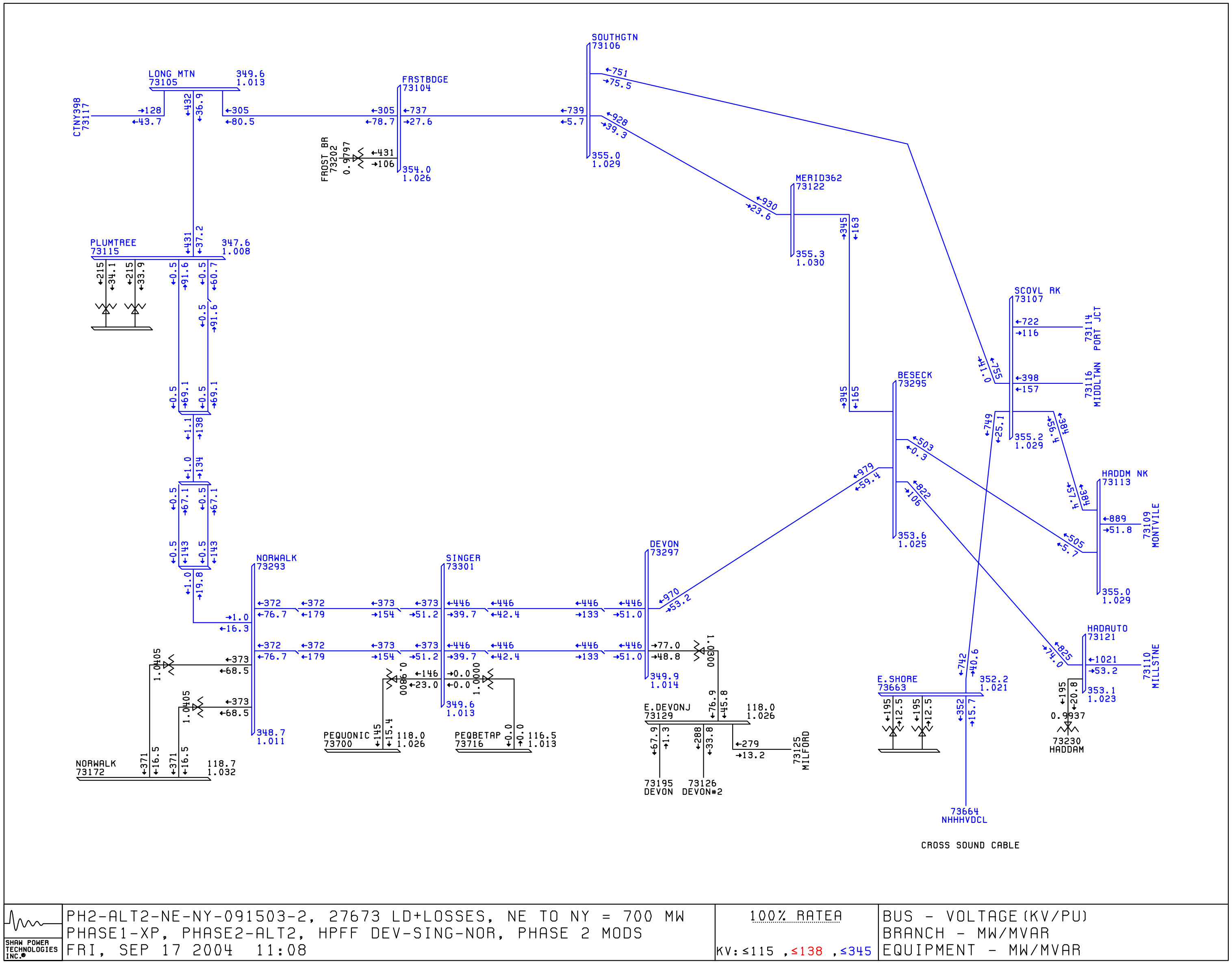

Figure 2-1. One-line Diagram of SWCT 345 kV System Including the Phase II AC Solution

2.1.2 Phase II DC Model

The primary objections to the Phase II AC solution, as understood by ABB, are:

- The overhead 345 kV line from Beseck to Devon is not desired by the Connecticut Siting Committee. The Committee prefers underground solutions.
- The underground 345 kV cables from Devon to Singer to Norwalk cause problems with system harmonic resonance and short-circuit current.

The Phase II AC solution required extensive analysis and time to develop. It successfully addresses the power flow needs of Southwest Connecticut. In addition to the 345 kV lines mentioned above, the Phase II AC solution includes numerous 115 kV upgrades as well. To take full advantage of the extensive work performed by the Connecticut utilities, ABB started with the Phase II AC solution and only the problematic equipment was removed in creating the DC solution. The Phase II 345 kV AC lines, and associated equipment, were removed, and the 115 kV upgrades were left in the case.

All 24 Phase II AC power flow cases were modified to represent the Phase II HVDC Light® solution. The following Phase II AC equipment was removed from the cases:

- Beseck – Devon 345 kV overhead transmission line
- Devon – Singer – Norwalk 345 kV underground AC cables and associated intermediate buses
- Devon and Singer 345-115 kV transformers

The following modifications were made in adding HVDC Light® Option 1 to the cases:

- A "generator" representing each converter (10 generators total) connected at the 4 utility interconnection points. These generators represent the converter injection of active and reactive power and regulation of voltage at the interconnection points.
- Close in the Bridgeport Energy – Pequonnock 115 kV line

As an initial starting point, the converter powers were set so that the total MW injections at the 4 substations approximately matched the Phase II AC cases. Based on the results of these initial loadflows, further work was done to develop for each of the 24 powerflow cases a security constrained dispatch of the HVDC links using ABB's GridView® program.

See Figure 2-2 for an example one-line diagram of the HVDC Light® Option 1. The converter symbols and DC lines are for visualization purposes only. The converter "generators" are all that is needed to represent HVDC Light® in power flow models. All one-line diagrams are included in the Appendices.

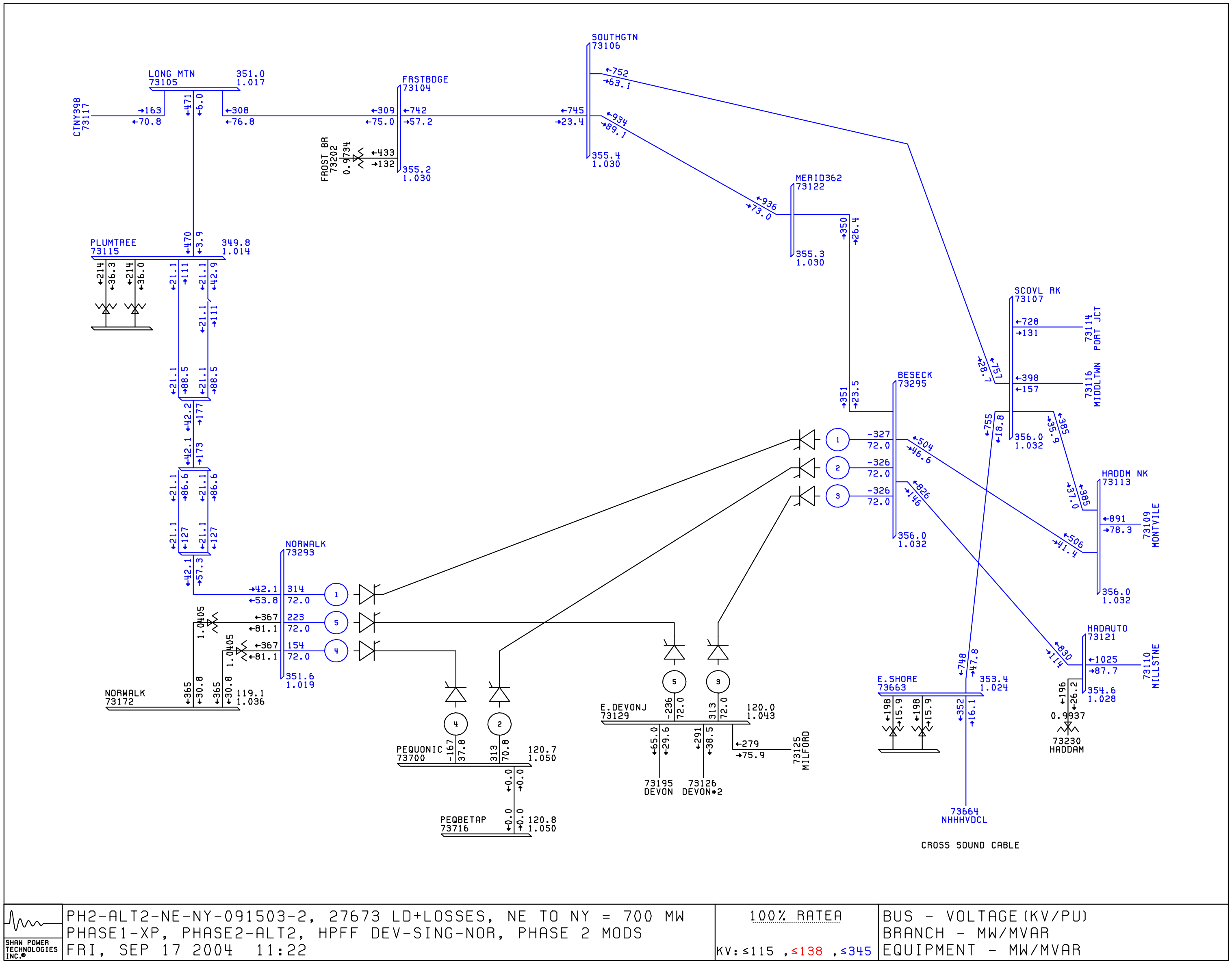

Figure 2-2. One-line Diagram of SWCT 345 kV System Including the HVDC Light® Option 1

2.1.3 Converter Power Ratings

Two different terminal power ratings are under consideration for the Phase II dc option, 370 MW and 530 MW delivered to the receiving ac network.

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.

For the purposes of the power flow analysis, the 530 MW converters were assumed. Differences in results between 370 MW converters versus 530 MW converters have not been investigated.

2.2 Contingency Analysis

2.2.1 Differences in Response of AC and DC Transmission

Before running contingency analysis to test the DC solution as compared to the AC solution, a number of known differences can be discussed and expected.

The high voltage AC transmission network consists of many lines and transformers connected together in a web or grid configuration. The primary characteristic that affects the flow of electrical power on these lines and transformers is their *impedance*. This is a measure of how the line or transformer *impedes (resists)* the flow of electrical power.

Electric power flows from generation (sources) to load (sinks) based on the laws of physics. Less power flows on lines with higher impedance (e.g. smaller conductors) and more power flows on lines with lower impedances (e.g. larger conductors). If one network transmission line is removed from service, then the power flows will redistribute among the remaining in-service transmission lines based on their relative impedances.

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.

In contrast, an HVDC system provides fast and automatic control of the power flow through it. When DC transmission lines are integrated into primarily AC transmission networks, the DC and AC transmission networks are connected together using AC-to-DC converters. These converters have controls that are normally set to provide a *constant* flow of power between the AC and DC systems. Unless specially designed to do so, the converter controls do not know when an AC transmission line, local or distant, has tripped off-line. When such a tripping occurs, the AC-to-DC converter in its most basic form of control will continue to maintain the requested power flow, not changing as an AC transmission line will do in response to the laws of physics. However, since the power in a HVDC system is fully controllable, supervisory controls can order a new power setting in response to certain (detectable) system conditions based on local and remote signals.

This difference between how AC and DC transmission lines respond to AC transmission outages can be both a benefit and a detriment for either type of transmission, depending on the conditions, the installed controls options, and one's viewpoint.

On the one hand, if it is desired that the AC transmission line pick up approximately the amount of power that the laws of physics require, then that can be seen as a benefit for AC. However, there is no inherent flexibility to change the flow to something else, if needed. Therefore, an ac line can become overloaded during extreme contingency conditions, possibly requiring redispatch of system generation and/or load shedding to relieve the overload. In the worst scenario, cascaded overloading and tripping of other AC lines could occur.

On the other hand, power flow in a HVDC transmission is fully controllable. HVDC transmission can move to the same power flow as the AC transmission, if appropriate controls are implemented. The largest benefit of HVDC for power flow purposes is the general ability to maintain any desired power flow within its designed capability. Operators or automatic controls can change the HVDC line flow to respond to various system problems or emergencies.

2.2.2 Dispatching DC Transmission

As discussed in the previous section, when a contingency outage occurs in the AC system, the HVDC converter in its most basic form of control will continue to maintain the requested power flow before the disturbance happens, not changing as an AC transmission line will do in response to the laws of physics. Since the power in a HVDC system is fully controllable, supervisory controls can order a new power setting in response to certain (detectable) system conditions based on local and remote signals. However, the use of remote signals has limitations. There is a practical limit to how many remote lines can be monitored and the number of signals that can be communicated back to the HVDC converters. More importantly, the use of remote signals is restricted by the ISO-NE.

As seen in Figure 2-2, HVDC Light® transmission lines are modeled as generators for power flow purposes. Just like generators, they can be dispatched to meet expected, upcoming system conditions, including the consideration of possible contingencies.

Most dispatch authorities, including ISO New England, now use Security Constrained Unit Commitment and Economic Dispatch (SCUC and SCED). This means committing and dispatching generators so that if the system loses any one critical element (N-1), all facilities will remain within their appropriate thermal ratings. Generators are not the only equipment that can be dispatched with this method. Any MW controlling device, such as a phase-shifting transformer or a DC transmission line, is subject to dispatch to ensure N-1 reliability.

The proposed HVDC Light® transmission lines would fall under the same category. It is envisioned that the power schedule on the VSC HVDC system, if put in operation, would be dispatched by ISO-NE based on economics and N-1 security (SCED).

ABB's GridView® program performs SCUC and SCED, and it was used to develop security constrained dispatches of the HVDC for the 24 power flow base case scenarios provided by NU. GridView® is normally used as an off-line planning tool for modeling the operation of electricity markets. Note that GridView® was used in this study to develop security constrained dispatch of the proposed HVDC Light® transmission for each of the 24 transfer and generation dispatch scenarios. The original transfer and generation dispatch for each of the 24 base cases were not changed. The HVDC power dispatch from GridView® was represented in the PSS/E system model and a contingency analysis was performed to determine if there were any new thermal overloads beyond those that have been identified in the Phase II AC solution contingency analysis results (see next section).

2.2.3 Phase II AC Solution Contingency Analysis

AC contingency analysis was performed on the Phase II AC cases to serve as a benchmark for measuring the performance of the DC solution. The contingency files provided by NU were used to perform AC contingency analysis on all 24 power flow base cases. The results showed a number of thermal and voltage violations, especially following NERC Category C contingencies. These results were sent to NU, and NU provided a few operating procedures that they use to resolve some of the key problems that were found.

As the Phase II AC results were intended solely as a benchmark, no further solution investigation was performed for any remaining problems. The complete AC results are included in the Appendix. Futhermore, from discussions with Northeast Utilities and United Illuminating, it was understood that the other remaining thermal overload violations will be addressed by these utilities.

2.2.4 Phase II HVDC Light® Option 1 Contingency Analysis

GridView® was used in this study to develop security constrained dispatch of the proposed HVDC Light® transmission Option 1 for each of the 24 transfer and generation dispatch scenarios. The original transfer and generation dispatch for each of the 24 base cases were not changed. The HVDC power dispatch from GridView® was represented in the PSS/E system model and a contingency analysis was performed to determine if there were any new thermal overloads beyond those that have been identified in the Phase II AC solution contingency analysis results.

3 Security-Constrained DC Dispatches

For each case, GridView® was used to find a security-constrained DC line dispatch. The resulting DC line dispatch was applied to the PSS/E case, and all contingencies were retested in PSS/E.

The final contingency results are shown in Appendix C. The final DC line dispatches are shown in Table 3-1, and comments on the results for each specific case follow Table 3-1. In the comments following Table 3-1, only the overloads attributable to the DC are discussed. Overloads of similar magnitude that occur in both the DC case and the Phase II ac case are not discussed, but can be seen in the spreadsheets if desired.

In nearly all cases, the security-constrained dispatch resolved all overloads attributable to the DC. A few minor remaining overloads were not resolved by security-constrained dispatch, but these overloads and/or the contingencies causing them are detectable from local indications at the dc converter stations. Since these few cases are detectable from local indications at the dc converter stations, they are resolvable by runbacks of the DC. The use of local indications at the converter stations to resolve these few remaining cases satisfies ISO-NE restrictions on use of remote signals.

Note that there were also numerous differences where the Phase II AC results caused overloads higher than the DC line results, but these were not investigated further. These can be seen in Appendix C. These results show that the physical response of AC network lines to contingencies is not always optimum, depending on the particular system condition and contingency.

Table 3-1. HVDC Light® Dispatches from SCUC/SCED (GridView) (positive number is westerly flow, negative is easterly)

Case Name	Case #		DC Line 1	DC Line 2	DC Line 3	DC Line 4	DC Line 5
DC-phase2-alt2-ny-ne-091503-5KL-upg.sav	0		175	135	450	-450	257
DC-phase2-alt2-091503-5KL-upg.sav	1		0	450	375	-165	175
DC-phase2-alt2-ne-ny-091503-5KL-upg.sav	2		450	450	450	450	-283
DC-ph2-alt2-ny-ne-091503-5-upg.sav	3		444	-171	450	0	82
DC-phase2-alt2-091503-5-upg.sav	4		161	108	393	450	-450
DC-ph2-alt2-ne-ny-091503-5-upg.sav	5		450	77	144	-424	450
DC-phase2-alt2-ny-ne-091503-4KL-upg.sav	6		24	-450	450	120	297
DC-phase2-alt2-091503-4KL-upg.sav	7		0	- 1	67	450	84
DC-phase2-alt2-ne-ny-091503-4KL-upg.sav	8		235	0	108	-82	450
DC-ph2-alt2-ny-ne-091503-4-upg.sav	9		0	-114	0	121	307
DC-phase2-alt2-091503-4-upg.sav	10		0	-383	450	-5	450
DC-ph2-alt2-ne-ny-091503-4-upg.sav	11		0	-129	0	124	321
DC-phase2-alt2-ny-ne-091503-3KL-upg.sav	12		-192	0	450	189	428
DC-phase2-alt2-091503-3KL-upg.sav	13		19	-95	347	0	450
DC-phase2-alt2-ne-ny-091503-3KL-upg.sav	14		0	104	447	247	450
DC-ph2-alt2-ny-ne-091503-3-upg.sav	15		385	345	-226	500	0
DC-phase2-alt2-091503-3-upg.sav	16		450	-375	415	167	450
DC-ph2-alt2-ne-ny-091503-3-upg.sav	17		500	-290	133	-94	500
DC-phase2-alt2-ny-ne-091503-2KL-upg.sav	18		290	450	450	438	-3
DC-phase2-alt2-091503-2KL-upg.sav	19		198	450	450	14	168
DC-phase2-alt2-ne-ny-091503-2KL-upg.sav	20		450	450	450	114	112
DC-ph2-alt2-ny-ne-091503-2-upg.sav	21		450	174	450	-11	187
DC-phase2-alt2-091503-2-upg.sav	22		450	317	450	292	75
DC-ph2-alt2-ne-ny-091503-2-upg.sav	23		450	25	450	-275	389

3.1 Case Comments

Case 0 - DC-phase2-alt2-ny-ne-091503-5KL-upg.sav
The control system will monitor the flow into the Norwalk 345kV station from Plumtree. In the event of the loss of Line 321 from Long Mountain to Plumtree, the flow into Norwalk reverses (from 248 MW, -63MVAR to -87.9 MW, -75.2 MVAR in this case) and will trigger control action on the part of the HVDC to maintain the flow between Northport and Norwalk Harbor to an acceptable level.

Case 1 – DC-phase2-alt2-091503-5KL-upg.sav
There are six contingency loadings exceeding RATE B that are not seen in the ac case. However, these loadings are primarily associated with the Norwalk Harbor to Northport autotransformer and loadings or contingencies associated with the Pequonic station. The contingency loadings are summarized in the table below.

Bus 1		Bus 2			Contingency	% Loading
73166 * NORHR138	138	73171 NWLK HAR	115	1	1618-321DCT	109.4
73166 * NORHR138	138	73171 NWLK HAR	115	1	1887-321DCT	106.8
73224 * TRMB J A	115	73700 PEQUONIC	115	1	DEVON2TSTK	103.2
73166 * NORHR138	138	73171 NWLK HAR	115	1	321LINE	103.1
73166 * NORHR138	138	73171 NWLK HAR	115	1	1770-321DCT	102.3
73695 * BAIRD B	115	73713 CNGRES2B	115	1	PEQUON22TSTK	101.3

The loadings associated with lines terminating at the Pequonic station and/or associated with contingencies at the Pequonic station will be handled through local monitoring and control. The loadings of the Norwalk Harbor to Northport autotransformer are can be addressed through monitoring of the Norwalk to Plumtree flows at the Norwalk station as described in the discussion for case 0 above.

Case 2 - DC-phase2-alt2-ne-ny-091503-5KL-upg.sav
There are no potential overloads greater than or equal to 100% of RATE B for which branch overloads are not also experienced in the ac case or covered through an existing special operating procedure.

Case 3 - DC-ph2-alt2-ny-ne-091503-5-upg.sav
There are no potential overloads greater than or equal to 100% for which branch overloads are not also experienced in the ac case or for which special operating procedures do not already exist.

Case 4 - DC-phase2-alt2-091503-5-upg.sav
There are three contingency loadings greater than RATE B field in this case that do not also result in loadings greater than 100% in the ac case. These loadings are summarized in the table below.

Bus 1				Bus 2					Contingency	% Loading
73224	*	TRMB J A	115	73700		PEQUONIC	115	1	DEVON2TSTK	110.9
73166	*	NORHR138	138	73171		NWLK HAR	115	1	DC4-SIN-NOR	107.7
73166	*	NORHR138	138	73171		NWLK HAR	115	1	1618-321DCT	102.1

The contingency loading for line terminating at the Pequonic station can be addressed through local control of the HVDC Light® terminal at the Pequonic station. The contingency loadings on the Norwalk Harbor to Northport autotransformer can be addressed by monitoring the 345kV flow from Plumtree into Norwalk, as this flow reverses in the event of a loss of line 321 as discussed in Case 0.

Case 5 - DC-ph2-alt2-ne-ny-091503-5-upg.sav
There are six contingency loadings in excess of 100% of the RATE B rating that are not also seen in the ac case or addressed through special operating procedures. The contingency loadings are shown in the table below.

Bus 1				Bus 2					Contingency	% Loading
73695	*	BAIRD B	115	73713		CNGRES2B	115	1	PEQUON22TSTK	107.5
73166	*	NORHR138	138	73171		NWLK HAR	115	1	DC4-SIN-NOR	106.1
73224	*	TRMB J A	115	73700		PEQUONIC	115	1	DEVON2TSTK	102
73224	*	TRMB J A	115	73700		PEQUONIC	115	1	PEQUON22TSTK	101.3
73196		GLEN JCT	115	73198	*	SOUTHGTN	115	1	8100-8200DCT	100.4
73162		WATERSDE	115	73163	*	COS COB	115	1	GLNBRKA1STK	100.2

Four of the contingency loadings are on lines terminating at Pequonic or the result of contingencies at Pequonic allowing local monitoring and control to adjust the HVDC Light® dispatch to be adjusted to mitigate the loadings in the event of these contingencies. The remaining two contingencies are less than one half of one percent above the RATE B rating and will be dealt with through minor adjustment to the security constrained economic dispatch of the HVDC.

Case 6 - DC-phase2-alt2-ny-ne-091503-4KL-upg.sav
There are no 115kV or 345kV branches with loadings greater than 100% of RATE B that are not also overloaded in the ac case.

Case 7 - DC-phase2-alt2-091503-4KL-upg.sav
There are a number of contingencies that result in overloading of the 73195* DEVON 115 - 73690 DEVON178 115 - 1 and/or 73195* DEVON 115 73691 - DEVON179 115 – 1. lines. These are the only lines for which the HVDC dispatch results in overloads not encountered in the corresponding ac case. Since the overloads are exclusively on two lines terminating at the Devon station, the overloads can be mitigated through local control of the HVDC Light® terminals at this station.

Case 8 - DC-phase2-alt2-ne-ny-091503-4KL-upg.sav

There are three potential overloads greater than or equal to 100% for which segment overloads are not experienced in the ac case. The segment contingency loadings are shown in the table below.

Bus 1			Bus 2				Contingency	% Loading
73224 *	TRMB J A	115	73700	PEQUONIC	115	1	DEVON2TSTK	119.3
73225 *	TRMB J B	115	73700	PEQUONIC	115	2	113091001DCT	100.1
73224 *	TRMB J A	115	73700	PEQUONIC	115	1	PEQUON22TSTK	100.0

Each of the contingency loadings in the above table are associated with either a line terminating at Pequonic, allowing local HVDC Light® control to adjust loading in the event of the above contingency loadings.

Case 9 - DC-ph2-alt2-ny-ne-091503-4-upg.sav

There is only one contingency overload of a 115 or 345kV branch that is not also seen in the ac case. This overload is on the 73224 * TRMB J A 115 to 73700 PEQUONIC 115 1 branch for the DEVON2TSTK contingency. The loading experienced in the event of this contingency can be mitigated through local control actions at the HVDC Light® terminals at the Pequonic or Devon stations.

Case 10 - DC-phase2-alt2-091503-4-upg.sav

There are no 115kV or 345kV branches with loadings greater than 100% that are not also overloaded in the ac case.

Case 11 - DC-ph2-alt2-ne-ny-091503-4-upg.sav

With security constrained dispatch of the DC, there are no 115kV or 345kV branches with loadings greater than 100% that are not also overloaded in the ac case.

Case 12 - DC-phase2-alt2-ny-ne-091503-3KL-upg.sav

There are no 115kV or 345kV line segments with loadings greater than 100% that are not also overloaded in the ac case or handled through special procedures.

Case 13 - DC-phase2-alt2-091503-3KL-upg.sav

There is one line for which a contingency results in loading in excess of 100% of the branch rating, however, this line terminates at the Pequonic station and therefore the overloading can be alleviated through local HVDC Light® controls. The contingency loading exceeding 10% of Rate B and the associated contingency is shown in the table below.

Bus 1			Bus 2				Contingency	% Loading
73225 *	TRMB J B	115	73700	PEQUONIC	115	2	113091001DCT	103.8

Case 14 - DC-phase2-alt2-ne-ny-091503-3KL-upg.sav
There are no 115kV or 345kV branches with loadings greater than 100% that are not also overloaded in the ac case.

Case 15 - DC-ph2-alt2-ny-ne-091503-3-upg.sav
With security constrained dispatch of the DC, there are no 115kV or 345kV branches with loadings greater than 100% that are not also overloaded in the ac case.

Case 16 - DC-phase2-alt2-091503-3-upg.sav
With security constrained dispatch of the DC, only two minor overloads occur in the dc case versus the ac case. Further, the two minor overloads are related to contingencies at the converter terminals, and can therefore easily be detected and resolved with a small runback of the DC. The first of these is a 6.4% overload of one 345/115 kV transformer at Norwalk during outage of the other 345/115 kV transformer (NORAUT contingency). This outage can be detected at Norwalk, and the DC can be run back as a mitigating measure. The other minor overload is a 7.6% overload of the Barnum A – Baird A 115 kV line for a stuck breaker contingency at Pequonnock (PEQUON42TSTK). This outage can be detected by local indications at Pequonnock, and the DC can be run back slightly.

Case 17 - DC-ph2-alt2-ne-ny-091503-3-upg.sav
With security constrained dispatch of the DC, there are no 115kV or 345kV branches with loadings greater than 100% that are not also overloaded in the ac case.

The best reduction in overloading in the DC case versus the corresponding AC case is 1.6% on the Montville – Dudley T 115 kV line for the 1080LINE contingency. The AC case loading is 112.5%, and the DC case loading is 110.9%.

Case 18 - DC-phase2-alt2-ny-ne-091503-2KL-upg.sav
With security constrained dispatch of the DC, only two minor overloads occur in the dc case versus the ac case. Further, the two minor overloads are related to contingencies at the converter terminals, and can therefore easily be detected and resolved with a small runback of the DC. The first of these is a 5.1% overload of one 345/115 kV transformer at Norwalk during outage of the other 345/115 kV transformer (NORAUT contingency). This outage can be detected at Norwalk, and the DC can be run back as a mitigating measure. The other minor overload is a 1.1% overload of the Devon#2 – Trumbull 115 kV line for a stuck breaker contingency at Devon (DEVON24TSTK). This outage can be detected by local indications at Devon, and the DC can be run back slightly.

The best reduction in overloading in the DC case versus the corresponding AC case is 5.4% on the Haddam - Bokum 115 kV line for the 1620SLINE contingency. The AC case loading is 105.2%, and the DC case loading is 99.8%.

Case 19 - DC-phase2-alt2-091503-2KL-upg.sav
With security constrained dispatch of the DC, there are no 115kV or 345kV branches with loadings greater than 100% that are not also overloaded in the ac case.

The best reduction in overloading in the DC case versus the corresponding AC case is 6.3% on the Haddam - Bokum 115 kV line for the 1620SLINE contingency. The AC case loading is 107.4%, and the DC case loading is 101.1%.

Case 20 - DC-phase2-alt2-ne-ny-091503-2KL-upg.sav
With security constrained dispatch of the DC, there are no 115kV or 345kV branches with loadings greater than 100% that are not also overloaded in the ac case.

The best reduction in overloading in the DC case versus the AC case is 8.7% on the Haddam – Bokum 115 kV line for the 1620S line outage. The AC case loading is 109.2%, and the DC case loading is 100.5%.

Case 21 - DC-ph2-alt2-ny-ne-091503-2-upg.sav
With security constrained dispatch of the DC, there are no 115kV or 345kV branches with loadings greater than 100% that are not also overloaded in the ac case.

The best reduction in overloading in the DC case versus the corresponding AC case is 3.5% on the BCNFL PF – DRBY J B 115 kV line for the 1272-1721DCT contingency. The AC case loading is 129.6%, and the DC case loading is 126.1%.

Case 22 - DC-phase2-alt2-091503-2-upg.sav
With security constrained dispatch of the DC, only two very minor overloads occur in the dc case versus the ac case. Further, the two minor overloads are related to contingencies at the converter terminals, and can therefore easily be detected and resolved with a small runback of the DC. The first of these is a 2.8% overload of the Barnum – Baird 115 kV line during a stuck breaker contingency at Pequonnock (PEQUON42TSTK). This outage can be detected at Pequonnock, and the DC can be run back slightly as a mitigating measure. The other minor overload is a 0.1% overload of the Barnum – Baird 115 kV line for a contingency at Devon EDEVDEV2. This outage can be detected at Devon, and the DC can be run back slightly.

The best reduction in overloading in the DC case versus the corresponding AC case is 3.6% on the BCNFL PF – DRBY J B 115 kV line for the 1272-1721DCT contingency. The AC case loading is 129.5%, and the DC case loading is 125.9%.

Case 23 - DC-ph2-alt2-ne-ny-091503-2-upg.sav
With security constrained dispatch of the DC, there are no 115kV or 345kV branches with loadings greater than 100% that are not also overloaded in the ac case.

The best reduction in overloading in the DC case versus the corresponding AC case is 3.5% on the Grand Av. – West Riv. 115 kV line for the GRNDAV2TSTK contingency. The AC case loading is 105.2%, and the DC case loading is 101.7%.

4 Power Flow Conclusions

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 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.

Appendix A

Power Flow One Lines for Phase II AC Option

Appendix B

Power Flow One Lines for Phase II DC Option 1, Final DC Line Dispatches

Appendix C

Contingency Results with Final DC Line Dispatches (compared to AC Option results)

See included zip file containing all spreadsheets.