Connecticut Cable Transient and Harmonic Feasibility Study

Final Report
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Foreword

This document was prepared by General Electric International, Inc. (GEII) acting through its Power Systems Energy Consulting (PSEC) located in Schenectady, New York. It is submitted to Northeast Utilities (NU). Technical and commercial questions and any correspondence concerning this document should be referred to:

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Executive Summary

GE Power Systems Energy Consulting (PSEC) has conducted a transient and harmonic analysis of the Northeast Utilities (NU) 345 kV transmission system to assess the impact of a proposed cable project in southwestern Connecticut. There are two stages of the cable project (Phases I and II). Phase 1 consists of a 345 kV cable between the existing Plumtree 345kV substation and a new Norwalk 345 kV substation. Phase 2 adds the Beseck 345 kV substation between Southington and Haddam, with 345 kV cable from Beseck to Norwalk, via East Devon and Pequonnock.

The objectives of this feasibility study are

- to investigate the impact of cable switching transients on the NU transmission system, and
- to investigate the harmonic frequency response of the cable system on the NU transmission system.

The study was not intended to be a detailed facilities study, but rather a feasibility analysis to identify fatal flaws, significant impact on existing equipment or system performance, as well as the need for additional equipment. It should be noted that a long-distance EHV AC transmission cable system is unprecedented. Underground AC cables have been exclusively applied for short distances in urban environments, which characteristically have high short-circuit levels. The large amount of cable charging capacitance associated with the transmission distances involved in this project, combined with moderate short-circuit strengths relative to the cable charging currents, could represent a significant risk for transient and harmonic problems. Such problems may be a challenge to mitigate with existing technology.

The study has been performed with the Electromagnetic Transients Program (EMTP), which is recognized as the industry standard for simulating the transient performance and frequency response of electric utility systems.

Although the cable capacitance is approximately 90% compensated by the shunt reactors, the reactors do not eliminate the harmonic issues posed by the charging current. Capacitive admittance increases with frequency and inductive admittance decreases with frequency; thus the reactors do not cancel the cable charging at harmonic frequencies.

The results of the harmonic screening study indicate the potential for harmonic resonance issues. The large shunt charging capacitance of the 345 kV cable system, interacting with the system inductances, inherently results in resonances at low-order harmonic frequencies. Resonances at low-order harmonics are of particular concern because substantial harmonic currents typically exist at these orders, driven by ordinary nonlinear loads such as discharge lighting, consumer electronic equipment, and industrial drive systems. These resonances will shift around with varying system strength, greatly enhancing the probability that the system resonant frequencies will from time to time coincide with the harmonic frequencies existing in the system. Resonances coincident with a driven harmonic results in significant amplification of harmonic voltage and current distortion. Voltage distortion could propagate down to the consumer level, having a detrimental effect on power quality. Harmonic currents and voltages amplified by resonances can also adversely affect utility equipment. If NU plans to go forward with cables at 345 kV, then a more detailed harmonic study would be recommended, which would use a higher fidelity model at harmonic frequencies and would include more contingency cases and system harmonic current injection profiles.

The results of the switching transient analysis indicate the potential for severe transient and temporary overvoltages. While surge arresters can limit the magnitude of the overvoltages, it is expected that the severity of the transients may exceed the capability of normally-rated surge arresters to survive the event. (Detailed arrester duty evaluation was not in the scope of this limited feasibility assessment, but is a necessary step in the development of this project.) Increasing the voltage rating of the surge arresters will decrease arrester duty, but the diminished transient voltage protection may not adequately protect existing equipment insulation. The voltage transients caused by routine cable switching are likely to permeate to the customer level, creating potential power quality issues. The worst cases were observed when energizing the Plumtree-Norwalk cable and the Norwalk-Glenbrook cable. In these cases, a high temporary overvoltage exists, in which the voltage is elevated for a sustained period. Also, the distorted waveform has a natural frequency of low order, which would tend to propagate to the customer load.

Voltage magnification was observed in some cases at nearby 115 kV buses where other capacitor banks are located, when switching the 345 kV cables. Voltage magnification can occur when resonances form between the 345 kV cable capacitance, the 115 kV bank capacitance, and the impedance between them. The transient voltage can be amplified at the 115 kV bus, which can affect the power quality at the customer load.

The configuration of the transformer and breaker at Glenbrook is of particular concern, since the current plan has no 345 kV circuit breaker at Glenbrook but only a 115 kV circuit breaker. This requires that the 345/115 kV transformer and 345 kV cable are energized and de-energized together. Severe overvoltages, with a growing transient oscillation, were observed when switching from Glenbrook 115 kV. There are also potential transient recovery voltage concerns when opening the breaker at Glenbrook 115 kV. A circuit breaker at 345 kV between the transformer and cable is recommended here.

Sample mitigating cases investigated breakers with controlled closing, surge arresters, and an alternate configuration of a cable with an overhead line and cable combination. Breakers with controlled closing may not provide an “automatic fix” by closing at voltage zeroes, since this condition can be worse with shunt reactor inrush. Surge arresters would help to reduce the highest transient voltage peaks, but may have to be specially rated to withstand the high overvoltage duty that would be imposed. Replacing some cable with overhead line may improve switching transient performance because of reduced capacitance, but would need further study to investigate transient issues specific to the line/cable junctions. Pre-insertion resistors could also help, but may need to be specially rated to withstand the switching duty. If an alternate arrangement of cables and overhead lines is planned, then further transient analysis would be recommended to re-evaluate switching and harmonic resonance issues and to perform a more detailed mitigation analysis.

The study results indicate that the proposed 345 kV cable project has significant harmonic resonance issues, power quality concerns, and potential challenges for equipment duty.

1. Introduction

GE Power Systems Energy Consulting (PSEC) has conducted a transient and harmonic analysis of the Northeast Utilities (NU) 345 kV transmission system to assess the impact of a proposed cable project in southwestern Connecticut. There are two stages of the cable project (Phases I and II). Phase I consists of a 345 kV cable between the existing Plumtree 345kV substation and a new Norwalk 345 kV substation. Phase II adds the Beseck 345 kV substation between Southington and Haddam, with 345 kV cable from Beseck to Norwalk, via East Devon and Pequonnock.

The objectives of this feasibility study are

- to investigate the impact of cable switching transients on the NU transmission system, and
- to investigate the harmonic frequency response of the cable system on the NU transmission system.

The study was not intended to be a detailed facilities study, but rather a feasibility analysis to identify fatal flaws, significant impact on existing equipment or system performance, as well as the need for additional equipment. It should be noted that a long-distance EHV AC transmission cable system is unprecedented. Underground AC cables have been exclusively applied for short distances in urban environments, which characteristically have high short-circuit levels. The large amount of cable charging capacitance associated with the transmission distances involved in this project, combined with moderate short-circuit strengths relative to the cable charging currents, could represent a significant risk for transient and harmonic problems. Such problems may be a challenge to mitigate with existing technology.

The study has been performed with the Electromagnetic Transients Program (EMTP), which is recognized as the industry standard for simulating the transient performance and frequency response of electric utility systems.

2. Study Approach

The study was organized into three tasks:

1. Database Development
2. Transient Analysis
3. Harmonic Analysis

Task 1. Database Development

PSEC developed a switching transient model of NU's 345 kV Connecticut transmission system, based on input data from NU. This data was used to develop a model in EMTP.

The database that was received from NU represented Phase II of the 345 kV cable project, including a cable from Norwalk to Glenbrook. This required additional modeling to represent the Glenbrook 345/115 kV transformer in detail and adjust the equivalent network in that area.

Further details regarding the system model are provided in Section 3.

Task 2. Transient Analysis

The transient analysis simulations included energization, de-energization, transformer switching, and fault clearing cases to determine switching transient overvoltages and temporary overvoltages.

Except in the limited case of some recently introduced circuit breakers with synchronous switching, the timing of circuit breaker closing is essentially random with respect to the point on voltage wave. There is also typically a variation between the closing times of the individual breaker poles (phases). Transient results are sensitive to the exact timing of switching. Because of the complexities involved, it is virtually impossible to precisely predict what breaker timing produces the most severe transient results. For this reason, detailed design studies typically use extensive Monte Carlo analysis of randomly selected breaker timings. However, for the purpose of this feasibility study, breaker timing rules-of-thumb were utilized to produce results which roughly approach the worst-case results. Energization cases were performed using fixed point-on-wave circuit breaker closing angles, e.g., closing at voltage peaks for cable energization cases, and voltage zeroes for transformer energization (to maximize inrush harmonics). Using fixed point-on-wave closing angles was sufficient to determine the switching transient issues associated with the cables. However, it should be noted that actual transient overvoltages could be higher than those presented in this report. Cases were performed without surge arresters in service to evaluate peak transient overvoltages relative to each cable. Circuit breakers were modeled without controlled closing or pre-insertion resistors. Sample mitigation cases included controlled closing, surge arresters, and an alternate overhead line/cable arrangement.

Cable energization creates transient oscillations which can potentially be magnified at buses with capacitor banks in the lower voltage systems interconnected with the cable transmission project. Voltage magnification can occur when resonances form between the 345 kV cable capacitance, the 115 kV bank capacitance, and the impedance between them. Voltages at nearby capacitor installations were monitored during cable switching simulations to screen for such magnification. This issue may require extensive analysis in any future design study.

A total of 30 cases were performed to complete this part of the study. The results of the transient analysis are provided in Section 5.

Task 3. Harmonic Analysis

The large shunt charging capacitance of cables can significantly affect the harmonic frequency response of the system. Resonances in the low-order harmonic range can be expected. There is an ambient level of harmonic distortion in any power system, due to nonlinear loads and power electronic equipment distributed throughout the system. The resonances formed by the cable charging can potentially amplify the ambient distortion to unacceptable levels. Harmonic currents may also add to the heating of the cable, and potentially constrain cable loadability. Harmonic resonance concerns were addressed by performing harmonic screening simulations. Frequency-domain simulations were performed using the EMTP model to calculate the positive-sequence driving-point impedance versus frequency at Plumtree, Norwalk, Beseck, East Devon, and Bridgeport. Comparison cases were performed with and without the new transmission cable circuit additions. Also, additional comparison cases were performed without the 115 kV capacitor banks elsewhere in the nearby system.

The impact of the cable system on ambient harmonic distortion levels was approximated by superimposing a voltage distortion component on the each of the equivalent sources in the model. The distortion spectrum was a typical combination of odd-order harmonics which were at the magnitude limits specified in IEEE 519. The distortion voltage sources represented the ambient distortion which may be present without the cable system. Using the system model, including the cable system, voltage distortion at 345 kV and 115 kV buses in the model was calculated to identify the potential impact of the system additions on ambient voltage distortion. Also, harmonic current flow on the cable circuits was measured to determine if there is any significant thermal impact on the cable system.

A total of 15 cases were performed to calculate the positive-sequence driving-point impedance, and 24 additional cases were performed to evaluate the impact of the cables on ambient harmonic distortion levels. The results of the harmonic analysis are provided in Section 4.

3. System Model

The NU system was modeled with the Electro-Magnetic Transients Program (EMTP). The extent of the model included the Phase II 345 kV cables and 345 kV transmission lines, with system equivalents located at nearby 115 kV buses and more distant 345 kV buses. A one-line diagram of the system model is shown in Figure 3-1, with the cable mileage noted. The circuit breakers shown on the diagram are representative of the switching locations in the study.

The majority of the positive- and zero-sequence data for the model was provided by NU via an ASPEN file. A text report of this data is included in Appendix A. The database that was received from NU represented Phase II of the 345 kV cable project, including a cable from Norwalk to Glenbrook. This required additional modeling to represent the Glenbrook 345/115 kV transformer in detail and adjust the equivalent network in that area, since the database had an equivalent at Glenbrook 345 kV. Table 3-1 shows the revised equivalent data.

Additional data was provided separately from NU, including charging data for the 345 kV cables and overhead lines, transformer MVA, shunt reactive compensation, and shunt capacitor data at 115 kV buses. The cable capacitance is compensated by approximately 90% with shunt reactors at the ends. Tables 3-2 through 3-6 show the additional data used in the system model.

Table 3-1. Glenbrook Equivalent Data Revision

Equivalent Location	**Z1 (pu)**	**Z0 (pu)**
Glenbrook 115 kV Driving-Point Impedance	0.003 + j0.024	0.006 + j0.023
Glenbrook – Norwalk 115 kV Transfer Impedance	0.011 + j0.225	0.07 + j0.376
Glenbrook – Pequonnock 115 kV Transfer Impedance	0.044 + j0.603	0.085 + j0.753

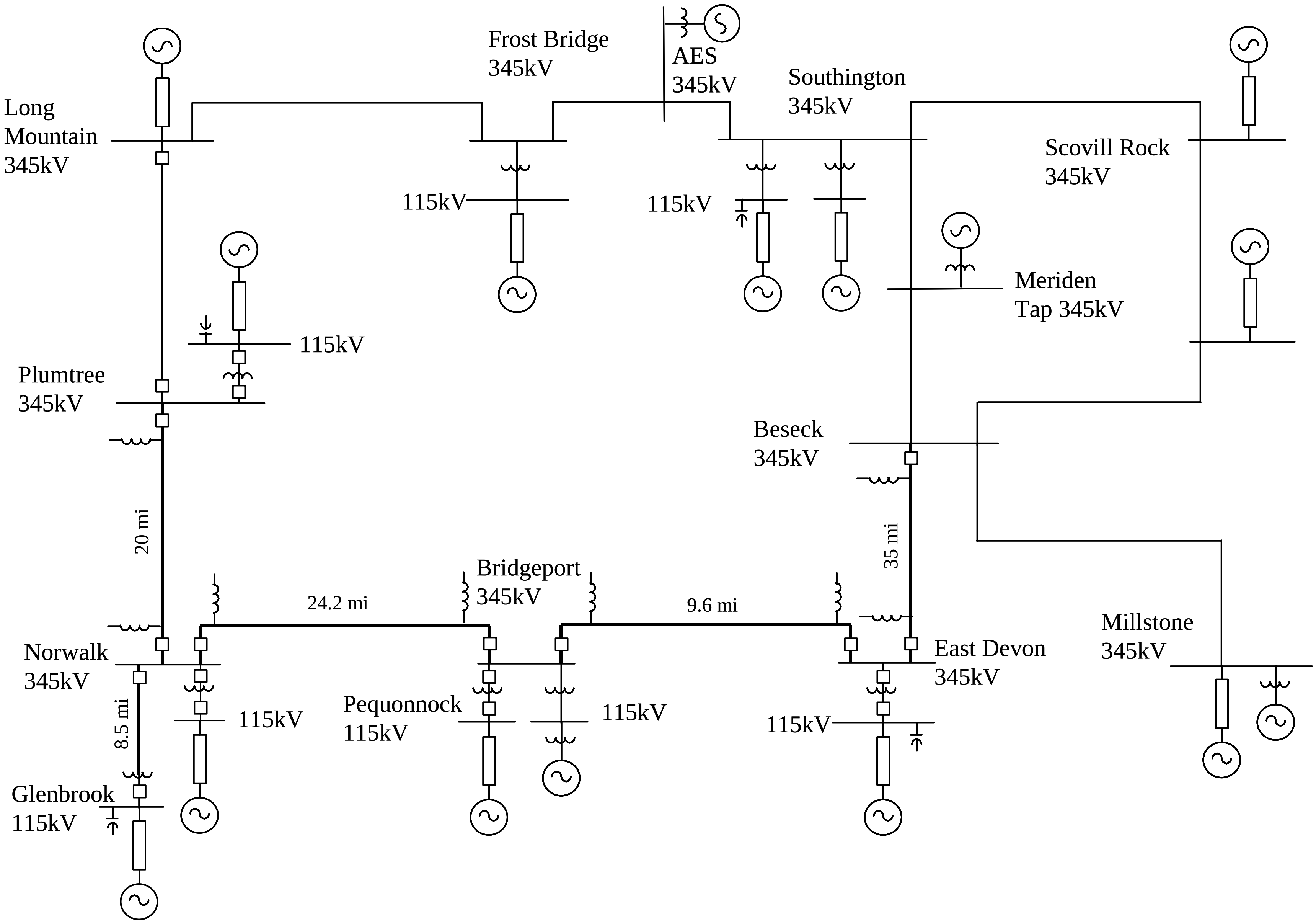

Figure 3-1. System Model One-Line Diagram

Table 3-2. Additional Cable Data for System Model

345 kV Cables			Length	Total for All Circuits	
Bus 1	**Bus 2**	**# Circuits**	**(mi)**	**B_1 (μmho/mi)**	**B_0 (μmho/mi)**
Plumtree	Norwalk	2	20	249.88	249.88
Norwalk	Glenbrook	1	8.5	124.94	124.94
Norwalk	Bridgeport/Pequonnock	2	24.2	249.88	249.88
Bridgeport/Pequonnock	East Devon	2	9.64	249.88	249.88
East Devon	Beseck	2	35	249.88	249.88

Table 3-3. Additional Overhead Line Data for System Model

345 kV O/H Lines			Length		
Bus 1	**Bus 2**	**# Circuits**	**(mi)**	**B_1 (μmho/mi)**	**B_0 (μmho/mi)**
Beseck	Meriden	1	8.08	7.4	4.5
Beseck	Haddam	1	18.69	7.32	4.79
Beseck	Millstone	1	41.38	7.355	4.72
Scovill Rock	Southington	1	19.36	7.026	4.88
Plumtree	Long Mtn	1	17.76	7.48	4.64
Long Mtn	Frost Bridge	1	20.6	5.7	4.3
Frost Bridge	AES-Southing	1	9.88	5.7	4.3
AES-Southing	Southington	1	2.84	5.7	4.3
Southington	Meriden	1	3.95	7.23	4.77
Meriden	Meriden Gen	1	1.8	7.23	4.77
Scovill Rock	Haddam	1	5.14	7.21	4.96

Table 3-4. Additional Transformer Data for System Model

Transformers			
Substation	**Voltage (kV)**	**# Units**	**MVA (each)**
Plumtree	345/115/34.5	2	450
Norwalk	345/115	1	600
Bridgeport/Pequonnock	345/115	2	600
Bridgeport	115/16	3	217
East Devon	345/115	1	600
Milford	115/20.9	2	340
Millstone	345/22.8	4	2-840, 945 & 700
Meriden Gen	345/21	3	132
Southington	345/115/13.2	1	400
Southington	345/115/34.5	1	400
Southington	345/115	2	400
AES-Southing	345/16	3	240
Frost Bridge	345/115/34.5	1	600
Glenbrook	345/115	1	600

Table 3-5. Additional Shunt Reactor Data for System Model

Shunt Reactors			
Substation	**Voltage (kV)**	**# Units**	**MVAR (each)**
Plumtree	345	1	270
Norwalk	345	2	270 & 330
Bridgeport/Pequonnock	345	2	330 & 130
East Devon	345	2	130 & 475
Beseck	345	1	475

Table 3-6. Additional Shunt Capacitor Data for System Model

Shunt Capacitors			
Substation	**Voltage (kV)**	**# Units**	**MVAR (total)**
Plumtree	115	2	39.8
Devon	115	1	52.5
Glenbrook	115	8	348.1
Southington	115	3	157.2

4. Harmonic Analysis

The harmonic impact of the 345 kV cables was analyzed by evaluating the change in driving-point impedance versus frequency and ambient harmonic voltage distortion.

Driving-Point Impedance

Harmonic screening simulations were performed to calculate the positive-sequence driving-point impedance versus frequency at the Plumtree, Norwalk, Beseck, East Devon, and Bridgeport 345 kV buses. Comparison cases were performed with and without the 345 kV cables and with and without the 115 kV capacitor banks. Table 4-1 shows the cases that were performed and the resonant frequencies that were observed. The driving-point impedance plots are provided in Appendix B.

Table 4-1. Driving-Point Impedance Cases

				Resonant Frequency (pu of 60 Hz)		
Case	**Location**	**345 kV Cables**	**115 kV Cap Banks**	**Low**	**Middle**	**High**
1A	Plumtree 345 kV	IN	IN	2.7	6.5	11.3
1B	Plumtree 345 kV	OUT	IN			10.8
1C	Plumtree 345 kV	IN	OUT	2.7	6.5	11.3
2A	Norwalk 345 kV	IN	IN	2.7	6.5	
2B	Norwalk 345 kV	OUT	IN	4.2		
2C	Norwalk 345 kV	IN	OUT	2.7	6.5	
3A	Beseck 345 kV	IN	IN	2.7	6.5	11.3
3B	Beseck 345 kV	OUT	IN		6.7	
3C	Beseck 345 kV	IN	OUT	2.7	6.5	11.3
4A	Devon 345 kV	IN	IN	2.7		11.3
4B	Devon 345 kV	OUT	IN			12.5
4C	Devon 345 kV	IN	OUT	2.7		11.3
5A	Bridgeport 345 kV	IN	IN	2.7		11.3
5B	Bridgeport 345 kV	OUT	IN		6.2	
5C	Bridgeport 345 kV	IN	OUT	2.7		11.3

The driving-point impedance results indicate a shift of impedance resonances down near 3^{rd} harmonic with the addition of the 345 kV cables. Resonances are also appearing near 7^{th} and 11^{th} harmonics. This is of concern because of the existing harmonic distortion that would be amplified in this range. These resonances could also impact normal switching operations, such as transformer energization. The resonances did not change much with the variation of 115 kV capacitor banks.

Ambient Harmonic Voltage Distortion

The impact of the 345 kV cables on ambient harmonic voltage distortion levels was evaluated by superimposing a voltage distortion component on the each of the equivalent sources in the model, and comparing the results with and without the cables in service. The distortion spectrum was a typical combination of odd-order harmonics, which were at the magnitude limits specified in IEEE 519. The distortion voltage sources represented the ambient distortion that may be present without the cable system. Table 4-2 shows the distortion spectrum that was applied at the 345 kV and 115 kV equivalent source locations. The maximum individual harmonic distortion was applied at 5th harmonic, and the Total Harmonic Distortion (THD) is at the limits specified in IEEE 519.

Table 4-2. Ambient Voltage Distortion Spectrum Applied at Equivalent Sources

Harmonic	345 kV Source	115 kV Source
3	0.50%	0.50%
5	1.00%	1.50%
7	0.68%	1.30%
11	0.43%	0.84%
13	0.37%	0.71%
17	0.28%	0.54%
19	0.25%	0.48%
23	0.21%	0.40%
25	0.19%	0.37%
THD	1.50%	2.50%

Since the relative phase between the harmonic sources could impact the results, by adding to or subtracting from the total voltage distortion, the ambient voltage distortion spectrum was applied at each of the twelve equivalent sources individually and then summed by root sum square (RSS) to determine the resulting voltage distortion at 345 kV and 115 kV buses in the system. This process was repeated without the 345 kV cables to compare the ambient distortion levels. Table 4-3 shows the harmonic voltages with the cables in service, and Table 4-4 shows the harmonic voltages with the cables out of service. Table 4-5 provides a ratio of the voltage distortion with the cables to the voltage distortion without the cables. Table 4-6 gives the cable currents resulting from the ambient harmonics.

The highest voltage distortion levels were observed at 7th harmonic, and were particularly high at some of the 115 kV buses. It was found that the 115 kV equivalent source at Pequonnock contributed a significant part of the ambient distortion at 7th harmonic, as compared with the other sources. With varying system conditions, a different source could be more significant. Comparison of the voltage ratios with and without the cables indicates that the greatest impact of the 345 kV cables is around 3rd and 7th harmonics. The high ratios observed at 25th harmonic are not as significant since the harmonic currents tend to be much lower there. Similarly, the highest cable currents were observed at 7th harmonic. These results are consistent with the driving-point impedance results.

Although the cable capacitance is approximately 90% compensated by the shunt reactors, the reactors do not eliminate the harmonic issues posed by the charging current. Capacitive admittance increases with frequency and inductive admittance decreases with frequency; thus the reactors do not cancel the cable charging at harmonic frequencies.

Table 4-3. Harmonic Voltages with Cables In Service

BUS	kV	3	5	7	11	13	17	19	23	25	THD
PLUMTREE	345	0.56%	0.25%	**2.38%**	0.20%	0.03%	0.11%	0.03%	0.02%	0.04%	**2.47%**
NORWALK	345	0.61%	0.26%	**2.30%**	0.02%	0.04%	0.04%	0.02%	0.01%	0.04%	**2.40%**
BRIDGEPORT	345	0.60%	0.54%	0.74%	0.20%	0.04%	0.02%	0.03%	0.01%	0.03%	1.11%
DEVON	345	0.58%	0.68%	**1.09%**	0.15%	0.04%	0.08%	0.01%	0.02%	0.09%	1.43%
BESECK	345	0.41%	0.72%	**4.39%**	0.19%	0.04%	0.10%	0.02%	0.01%	0.09%	**4.48%**
GLENBROOK	345	0.59%	0.34%	**2.30%**	0.02%	0.05%	0.06%	0.04%	0.04%	0.17%	**2.41%**
LONG MTN.	345	0.32%	0.32%	0.49%	0.23%	0.09%	0.08%	0.10%	0.07%	0.08%	0.73%
MILLSTONE	345	0.17%	0.38%	**1.53%**	0.18%	0.11%	0.07%	0.10%	0.10%	0.07%	**1.61%**
FROST BRIDGE	345	0.28%	0.36%	**2.48%**	0.14%	0.05%	0.05%	0.07%	0.05%	0.08%	**2.53%**
SCOVILLE ROCK	345	0.24%	0.44%	**2.32%**	0.16%	0.06%	0.06%	0.06%	0.06%	0.09%	**2.39%**
PLUMTREE	115	0.49%	0.32%	0.57%	0.36%	0.37%	0.22%	0.04%	0.01%	0.02%	0.99%
NORWALK	115	0.46%	**3.41%**	**10.53%**	0.07%	0.04%	0.02%	0.01%	0.01%	0.00%	**11.08%**
PEQUONNOCK	115	0.32%	**1.81%**	**23.91%**	0.19%	0.10%	0.04%	0.03%	0.01%	0.01%	**23.98%**
EAST DEVON	115	0.28%	0.34%	**3.09%**	0.25%	0.63%	0.14%	0.07%	0.03%	0.02%	**3.20%**
GLENBROOK	115	0.48%	**3.77%**	0.79%	0.10%	0.06%	0.02%	0.02%	0.01%	0.01%	**3.88%**
FROST BRIDGE	115	0.27%	0.44%	**3.51%**	0.13%	0.14%	0.08%	0.08%	0.07%	0.07%	**3.56%**
SOUTHINGTON Bus 2	115	0.24%	0.48%	**2.14%**	0.21%	0.15%	0.11%	0.11%	0.09%	0.09%	2.23%
SOUTHINGTON Bus 1	115	0.31%	0.65%	**9.74%**	0.15%	0.05%	0.02%	0.01%	0.01%	0.01%	**9.77%**

Table 4-4. Harmonic Voltages with Cables Out of Service

BUS	**kV**	**3**	**5**	**7**	**11**	**13**	**17**	**19**	**23**	**25**	**THD**
PLUMTREE	345	0.27%	0.62%	0.77%	**2.64%**	0.25%	0.10%	0.10%	0.20%	0.92%	**3.00%**
NORWALK	345	0.66%	**2.04%**	0.65%	0.17%	0.04%	0.02%	0.01%	0.01%	0.01%	**2.25%**
BRIDGEPORT	345	0.31%	**1.04%**	**1.77%**	0.14%	0.09%	0.03%	0.02%	0.01%	0.01%	**2.08%**
DEVON	345	0.16%	0.57%	0.58%	**1.33%**	**1.13%**	0.10%	0.05%	0.02%	0.02%	**1.94%**
BESECK	345	0.14%	0.39%	0.80%	0.20%	0.13%	0.62%	0.38%	0.08%	0.16%	1.19%
GLENBROOK	345	**1.37%**	**1.65%**	0.45%	0.09%	0.05%	0.02%	0.02%	0.01%	0.01%	**2.20%**
LONG MTN.	345	0.28%	0.63%	0.68%	**1.53%**	0.12%	0.22%	0.16%	0.26%	**1.08%**	**2.15%**
MILLSTONE	345	0.17%	0.37%	0.33%	0.17%	0.16%	0.42%	0.20%	0.07%	0.23%	0.78%
FROST BRIDGE	345	0.17%	0.48%	0.97%	0.71%	0.07%	0.31%	0.19%	0.14%	0.63%	**1.50%**
SCOVILLE ROCK	345	0.16%	0.41%	0.62%	0.19%	0.14%	0.49%	0.27%	0.05%	0.06%	0.98%
PLUMTREE	115	0.26%	0.65%	0.93%	**4.52%**	0.53%	0.20%	0.10%	0.09%	0.33%	**4.71%**
NORWALK	115	0.66%	**2.04%**	0.65%	0.17%	0.04%	0.02%	0.01%	0.01%	0.01%	2.25%
PEQUONNOCK	115	0.44%	1.47%	**2.50%**	0.20%	0.12%	0.04%	0.03%	0.01%	0.01%	**2.94%**
EAST DEVON	115	0.16%	0.57%	0.58%	1.33%	1.13%	0.10%	0.05%	0.02%	0.02%	1.94%
GLENBROOK	115	1.37%	**1.65%**	0.45%	0.09%	0.05%	0.02%	0.02%	0.01%	0.01%	2.20%
FROST BRIDGE	115	0.18%	0.59%	1.28%	0.57%	0.10%	0.12%	0.09%	0.08%	0.24%	1.56%
SOUTHINGTON Bus 2	115	0.16%	0.52%	0.70%	0.27%	0.18%	0.35%	0.18%	0.08%	0.11%	1.04%
SOUTHINGTON Bus 1	115	0.16%	0.69%	**3.10%**	0.56%	0.07%	0.10%	0.04%	0.01%	0.02%	**3.23%**

Table 4-5. Ratio of Voltage with Cables to Voltage without Cables

BUS	kV	3	5	7	11	13	17	19	23	25	THD
PLUMTREE	345	**2.08**	0.40	**3.08**	0.07	0.14	1.07	0.30	0.08	0.04	0.82
NORWALK	345	0.92	0.13	**3.57**	0.13	0.98	**2.49**	**2.28**	**2.31**	**8.20**	1.07
BRIDGEPORT	345	1.94	0.52	0.42	1.39	0.43	0.59	1.35	0.85	**3.79**	0.53
DEVON	345	**3.52**	1.20	1.89	0.11	0.04	0.82	0.28	0.70	**4.89**	0.74
BESECK	345	**2.96**	1.83	**5.52**	0.96	0.33	0.16	0.06	0.09	0.59	**3.75**
GLENBROOK	345	0.43	0.20	**5.15**	0.27	0.89	**2.55**	**2.69**	**4.32**	**24.06**	1.10
LONG MTN.	345	1.15	0.51	0.72	0.15	0.74	0.37	0.60	0.28	0.08	0.34
MILLSTONE	345	1.04	1.04	**4.58**	1.01	0.70	0.17	0.48	1.37	0.31	**2.07**
FROST BRIDGE	345	1.66	0.76	**2.57**	0.20	0.72	0.17	0.34	0.36	0.12	1.69
SCOVILLE ROCK	345	1.54	1.08	**3.77**	0.84	0.46	0.11	0.23	1.06	1.40	**2.45**
PLUMTREE	115	1.88	0.49	0.61	0.08	0.69	1.08	0.44	0.15	0.05	0.21
NORWALK	115	0.70	1.67	**16.31**	0.43	0.99	1.07	1.03	1.02	0.95	**4.92**
PEQUONNOCK	115	0.74	1.23	**9.56**	0.92	0.83	1.03	1.02	1.02	1.02	**8.14**
EAST DEVON	115	1.67	0.59	**5.33**	0.19	0.55	1.46	1.25	1.16	1.31	1.65
GLENBROOK	115	0.35	**2.29**	1.75	1.07	1.05	1.03	1.02	1.02	1.06	1.77
FROST BRIDGE	115	1.52	0.75	**2.73**	0.23	1.34	0.70	0.85	0.82	0.27	**2.27**
SOUTHINGTON Bus 2	115	1.48	0.93	**3.03**	0.77	0.84	0.32	0.61	1.08	0.81	**2.15**
SOUTHINGTON Bus 1	115	1.94	0.93	**3.14**	0.27	0.72	0.17	0.25	0.69	0.40	**3.02**

Table 4-6. Harmonic Currents (Amps) in Cables

345 kV CABLE	3	5	7	11	13	17	19	23	25	THD
PLUMTREE-NORWALK	19	12	81	2	3	3	1	1	1	84
NORWALK-PLUMTREE	6	10	93	15	3	8	1	1	1	95
NORWALK-GLENBROOK	6	32	17	1	1	2	1	1	6	37
GLENBROOK-NORWALK	8	31	18	0	0	0	0	0	0	36
NORWALK-BRIDGEPORT	9	48	37	15	3	7	1	1	6	64
BRIDGEPORT-NORWALK	13	33	171	2	3	7	1	1	7	175
BRIDGEPORT-DEVON	6	45	313	2	3	7	1	1	7	317
DEVON-BRIDGEPORT	12	32	307	10	2	4	2	1	2	309
DEVON-BESECK	8	36	333	10	2	4	2	1	2	335
BESECK-DEVON	30	32	97	3	2	2	1	1	1	107

The results of the harmonic screening study indicate the potential for harmonic resonance issues. The harmonic screening analysis has focused on the relative magnitude of the harmonic resonance results, rather than detailed quantitative evaluation, for several reasons. The objective of the screening study was to identify potential harmonic resonance concerns. In a more detailed harmonic study, a much larger portion of the system would be represented to obtain a higher fidelity model at harmonic frequencies. The model used in the screening study is likely to have less damping at 7^{th} harmonic than there would be in the real system. Also, a more detailed harmonic study would consider more contingency cases and system harmonic current injection profiles. If NU plans to go forward with cables at 345 kV, then a more detailed harmonic study would be recommended.

5. Transient Analysis

The switching transient impact of the 345 kV cables was analyzed by simulating cable energization, cable de-energization, transformer energization, and fault clearing. The voltage at 115 kV buses was also monitored to screen for voltage magnification.

Cable Energization

Cable energization simulations were performed on each of the 345 kV cables. Table 5-1 shows the cases that were performed. The cable energization plots are provided in Appendix C.

Table 5-1. Cable Energization Cases

Case	Operation	Operating Breaker	System Conditions
1	Energize Plumtree-Norwalk Cable	Plumtree 345 kV	Norwalk cable end open.
1S	Energize Plumtree-Norwalk Cable	Plumtree 345 kV	Norwalk cable end open. Controlled closing.
1Z	Energize Plumtree-Norwalk Cable	Plumtree 345 kV	Norwalk cable end open. Controlled closing. Surge arrester at Norwalk end.
1X	Energize Plumtree-Norwalk Line/Cable	Plumtree 345 kV	Partial O/H line and cable.
2	Energize Norwalk-Plumtree Cable	Norwalk 345 kV	Plumtree cable end open.
3	Energize Norwalk-Bridgeport Cable	Norwalk 345 kV	Bridgeport cable end open.
4	Energize Bridgeport-Norwalk Cable	Bridgeport 345 kV	Norwalk cable end open.
5	Energize Bridgeport-Devon Cable	Bridgeport 345 kV	Devon cable end open.
6	Energize Devon-Bridgeport Cable	Devon 345 kV	Bridgeport cable end open.
7	Energize Devon-Beseck Cable	Devon 345 kV	Beseck cable end open.
8	Energize Beseck-Devon Cable	Beseck 345 kV	Devon cable end open.
9	Energize Norwalk-Glenbrook Cable	Norwalk 345 kV	Glenbrook transformer open at 115kV side.
10	Energize Norwalk-Glenbrook Cable	Glenbrook 115kV	Norwalk cable end open.

In terms of transient and temporary overvoltages (TOVs), the worst cases were observed when energizing the Plumtree-Norwalk cable and the Norwalk-Glenbrook cable. Figure 5-1 shows a sample plot of energizing the Plumtree-Norwalk cable (Case 1) during the first 100 ms. Although the peak transient voltage is less than 2 pu, and not normally considered excessive, there is a large 3rd harmonic component which contributes to a high temporary overvoltage. This could exceed the TOV capability of various equipment nearby, including surge arresters. Also, this voltage distortion could propagate down to the consumer level, affecting power quality.

Three mitigating cases were simulated to evaluate improvements for the Plumtree-Norwalk cable. In Case 1S, the Plumtree circuit breaker was modeled with controlled closing. Transient voltages are usually minimized when the breaker is closed near voltage zero on each phase. Since the control is not perfect, the case simulated the breaker closing 1 ms after the voltage zeroes, for a more realistic test. Unfortunately, Case 1S was actually a bit worse than Case 1 in terms of the resulting TOV. The alternate set of closing angles stimulated a more severe inrush case for the shunt reactors at the cable ends, resulting in a larger 3rd harmonic component.

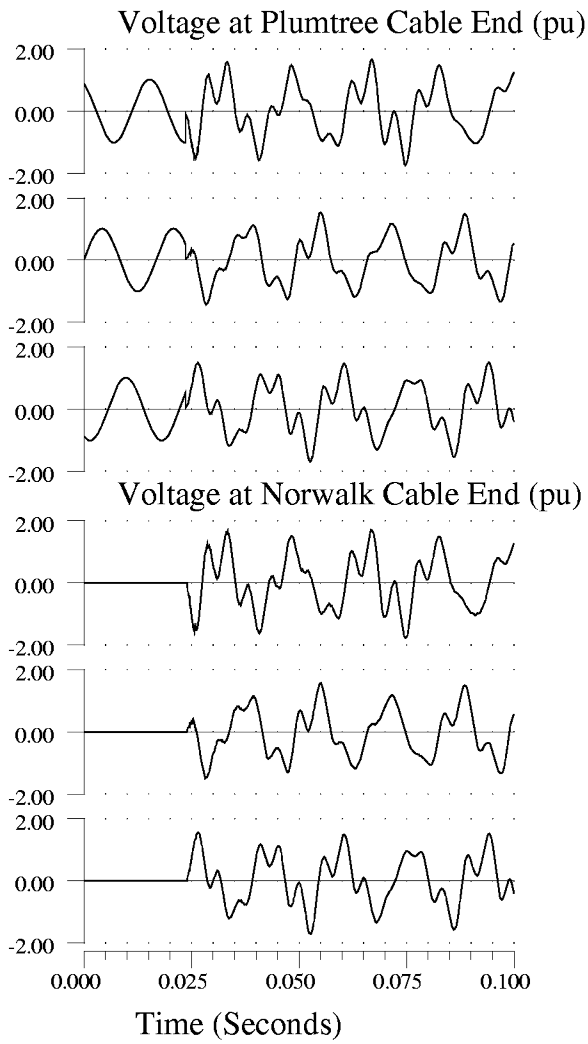

Figure 5-1. Energizing Plumtree-Norwalk Cable (Case 1)

In Case1Z, a 264 kV surge arrester was modeled at the Norwalk cable end, and the case simulated controlled closing as in Case 1S. The voltage waveform was not noticeably modified by the arrester, since the protective level is about 1.9 pu. The resulting arrester energy rose to 900 kJ in 200 ms, which is about half of its energy capability. However, the TOV is about 1.6 pu, which is marginal in terms of the arrester's capability to withstand the TOV duty.

In a third mitigating case, Case 1X was performed to evaluate a sample configuration of combined cable and overhead line from Plumtree to Norwalk. Figure 5-2 shows the configuration that was modeled. There were no shunt reactors modeled for this configuration.

Plumtree	———	J1	◄──►	J2	———	J3	◄──►	J4	———	Norwalk
	O/H 5 mi		Cable 2 mi		O/H 6 mi		Cable 2 mi		O/H 5 mi	

Figure 5-2. Plumtree-Norwalk Cable/Overhead Line Configuration for Case 1X Only

In Case 1X, the combined cable and overhead line produced more favorable results than Case 1 with 20 miles of cable. The shunt reactor inrush was also eliminated in this case, which may have contributed to its improvement. The 3^{rd} harmonic distortion and temporary overvoltage were much lower. However, some voltage magnification was observed at Plumtree 115 kV, which was not very significant in Case 1. The voltages at each cable/overhead line junction were also monitored, and no particular problems were observed. However, depending on the configuration of cables and overhead lines, an alternate arrangement could potentially have resonant points at the junctions, leading to voltage amplification. It appears that a reduced length of cable from Plumtree to Norwalk could improve the switching performance. If NU plans to design an alternate cable/overhead line arrangement, then further study is of critical importance.

The configuration of the transformer and breaker at Glenbrook is of particular concern, since the current plan has no 345 kV circuit breaker at Glenbrook but only a 115 kV circuit breaker. This requires that the 345/115 kV transformer and 345 kV cable are energized and de-energized together. Severe overvoltages were observed in these cases, and were particularly high in Case 10, when switching from Glenbrook 115 kV. Sustained overvoltages of 2.5 pu were observed, with a growing transient oscillation. This would exceed the TOV capability of equipment nearby. A circuit breaker at 345 kV between the transformer and cable is recommended here.

Other switching transient simulation results indicate the presence of voltage magnification at some of the 115 kV capacitor banks when switching the 345 kV cables. In some cases, the transient overvoltages were higher at the 115 kV buses than at the 345 kV cables because of resonances formed between the 345 kV cable capacitance, the 115 kV bank capacitance, and the impedance between them. Voltage magnification was observed at Plumtree, Southington, Devon, and Norwalk 115 kV.

When energizing the Norwalk-Bridgeport cable and the Devon-Beseck cable, switching transients exceeded 2 pu. However, the temporary overvoltages were not as severe as those cases described above.

Restrike analysis was not in the scope of this study, but it is important to note that transient and temporary overvoltages would be far worse with a trapped charge existing on the cable.

Surge arresters, which were not included in the simulation model in most cases, provide protection of equipment insulation from these overvoltages. However, the critical issue is whether an arrester can survive the overvoltages. A multi-column surge arrester is most likely necessary to withstand the high overvoltages observed in these cases. It is possible that the required arrester may require capabilities beyond normal multi-column arresters, and specially-designed units may be required.

Circuit breakers with controlled closing or pre-insertion resistors could also help to control switching transients. The duty on the insertion resistor would need to be evaluated to confirm rating.

Cable De-energization

Cable de-energization simulations were performed on each of the 345 kV cables. Table 5-2 shows the cases that were performed. The cable de-energization plots are provided in Appendix D.

Table 5-2. Cable De-energization Cases

Case	Operation	Operating Breaker	System Conditions
1	De-energize Plumtree-Norwalk Cable	Plumtree 345 kV	Norwalk cable end open.
2	De-energize Norwalk-Plumtree Cable	Norwalk 345 kV	Plumtree cable end open.
3	De-energize Norwalk-Bridgeport Cable	Norwalk 345 kV	Bridgeport cable end open.
4	De-energize Bridgeport-Norwalk Cable	Bridgeport 345 kV	Norwalk cable end open.
5	De-energize Bridgeport-Devon Cable	Bridgeport 345 kV	Devon cable end open.
6	De-energize Devon-Bridgeport Cable	Devon 345 kV	Bridgeport cable end open.
7	De-energize Devon-Beseck Cable	Devon 345 kV	Beseck cable end open.
8	De-energize Beseck-Devon Cable	Beseck 345 kV	Devon cable end open.
9	De-energize Norwalk-Glenbrook Cable	Norwalk 345 kV	Glenbrook transformer open at 115kV side.
10	De-energize Norwalk-Glenbrook Cable	Glenbrook 115kV	Norwalk cable end open.

With the exception of the Norwalk-Glenbrook cable, the transients observed in the de-energization cases were not excessive. Since the cables are approximately 90% compensated by shunt reactors, the cables ring down at a frequency near 60 Hz when de-energized. This causes the voltage across the opening circuit breaker to have a “beat frequency” effect. It resembles a 60 Hz duty from opening asynchronous systems. These normal-frequency recovery voltages should be reviewed by the breaker manufacturer. The highest recovery voltage observed in these cases was 600 kV.

The Norwalk-Glenbrook cable rings down with a square wave when de-energized because of the transformer that is connected. This causes a more unusual voltage waveform across the opening circuit breaker. The Transient Recovery Voltages (TRV) capability may be exceeded when Glenbrook 115 kV is the last to open. According to ANSI C37.06-1997, the TRV capability ranges from about 225 kV to 260 kV, depending on the current interrupted, which makes the observed TRV marginal in Case 10. This observation supports the recommendation to have a circuit breaker at Glenbrook 345 kV.

Transformer Energization

Transformer energization simulations were performed on the 345/115 kV transformers at Norwalk, Bridgeport, Plumtree, and Devon. Table 5-3 shows the cases that were performed. The transformer energization plots are provided in Appendix E.

Table 5-3. Transformer Energization Cases

Case	Operation	Operating Breaker	System Conditions
1	Energize Norwalk 345/115kV Transformer	Norwalk 345 kV	Norwalk 115 kV open.
2	Energize Bridgeport 345/115kV Transformer	Bridgeport 345 kV	Bridgeport 115 kV open.
3	Energize Plumtree 345/115kV Transformer	Plumtree 345 kV	Plumtree 115 kV open.
4	Energize Devon 345/115kV Transformer	Devon 345 kV	Devon 115 kV open.

In terms of transient and temporary overvoltages (TOVs), the worst cases were observed when energizing the Plumtree transformer. Although the peak transient voltage is less than 2 pu, and not normally considered excessive, there is a large 3rd harmonic component which contributes to a high temporary overvoltage at Plumtree 115 kV. Also, there is a large harmonic component in the cable currents during inrush. The cable currents don't appear to be a thermal issue, but could potentially affect protection.

Fault Clearing

Fault clearing simulations were performed on selected cables and overhead lines under normal and backup clearing (backfeeding) scenarios. Table 5-4 shows the cases that were performed. The fault clearing plots are provided in Appendix F.

Table 5-4. Fault Clearing Cases

Case	Operation	Operating Breaker	System Conditions
1	Clear Fault on Plumtree-Norwalk cable	Norwalk 115 kV	SLGF at Plumtree. Other cables at Norwalk opened.
2	Clear Fault on Norwalk-Glenbrook cable	Glenbrook 115 kV	SLGF at Norwalk.
3	Clear Fault on Devon-Beseck cable	East Devon 115 kV	SLGF at Beseck. Other cables at Devon opened.
4	Fault Long Mountain-Plumtree Line & Clear	Plumtree 345 kV	3-ph-g fault at Plumtree. Open both ends after 3 cycles.

The first three cases simulated a single-line-to-ground fault on three cables, one of the 345 kV breakers failed to clear the fault, and the fault was cleared from 115 kV. This backup clearing scenario resulted in backfeeding the 345 kV cable from 115 kV. The TRV at Glenbrook 115 kV was marginal and was acceptable in the other cases. The transients were not excessive in these cases.

The fourth case simulated a three-phase-to-ground fault on the Long Mountain-Plumtree line, with clearing after three cycles. The purpose of this case was to observe the recovery of the Plumtree-Norwalk cable and Plumtree transformers after the fault with a weakened system, due to the line outage. The resulting transients were less than 2 pu and not excessively distorted.

The results of the switching transient analysis indicate the potential for severe transient and temporary overvoltages. Voltage magnification was observed in some cases at nearby 115 kV buses where other capacitor banks are located. Voltage distortion observed in switching cases could propagate down to the consumer level, having a detrimental effect on power quality.

If an alternate arrangement of cables and overhead lines is planned, then further transient analysis would be recommended to re-evaluate switching and harmonic resonance issues and to perform a more detailed mitigation analysis.

6. Conclusions and Recommendations

Although the cable capacitance is approximately 90% compensated by the shunt reactors, the reactors do not eliminate the harmonic issues posed by the charging current. Capacitive admittance increases with frequency and inductive admittance decreases with frequency; thus the reactors do not cancel the cable charging at harmonic frequencies.

The results of the harmonic screening study indicate the potential for harmonic resonance issues. The large shunt charging capacitance of the 345 kV cable system, interacting with the system inductances, inherently results in resonances at low-order harmonic frequencies. Resonances at low-order harmonics are of particular concern because substantial harmonic currents typically exist at these orders, driven by ordinary nonlinear loads such as discharge lighting, consumer electronic equipment, and industrial drive systems. These resonances will shift around with varying system strength, greatly enhancing the probability that the system resonant frequencies will from time to time coincide with the harmonic frequencies existing in the system. Resonances coincident with a driven harmonic results in significant amplification of harmonic voltage and current distortion. Voltage distortion could propagate down to the consumer level, having a detrimental effect on power quality. Harmonic currents and voltages amplified by resonances can also adversely affect utility equipment. If NU plans to go forward with cables at 345 kV, then a more detailed harmonic study would be recommended, which would use a higher fidelity model at harmonic frequencies and would include more contingency cases and system harmonic current injection profiles.

The results of the switching transient analysis indicate the potential for severe transient and temporary overvoltages. While surge arresters can limit the magnitude of the overvoltages, it is expected that the severity of the transients may exceed the capability of normally-rated surge arresters to survive the event. (Detailed arrester duty evaluation was not in the scope of this limited feasibility assessment, but is a necessary step in the development of this project.) Increasing the voltage rating of the surge arresters will decrease arrester duty, but the diminished transient voltage protection may not adequately protect existing equipment insulation. The voltage transients caused by routine cable switching are likely to permeate to the customer level, creating potential power quality issues. The worst cases were observed when energizing the Plumtree-Norwalk cable and the Norwalk-Glenbrook cable. In these cases, a high temporary overvoltage exists, in which the voltage is elevated for a sustained period. Also, the distorted waveform has a natural frequency of low order, which would tend to propagate to the customer load.

Voltage magnification was observed in some cases at nearby 115 kV buses where other capacitor banks are located, when switching the 345 kV cables. Voltage magnification can occur when resonances form between the 345 kV cable capacitance, the 115 kV bank capacitance, and the impedance between them. The transient voltage can be amplified at the 115 kV bus, which can affect the power quality at the customer load.

The configuration of the transformer and breaker at Glenbrook is of particular concern, since the current plan has no 345 kV circuit breaker at Glenbrook but only a 115 kV circuit breaker. This requires that the 345/115 kV transformer and 345 kV cable are energized and de-energized together. Severe overvoltages, with a growing transient oscillation, were observed when switching from Glenbrook 115 kV. There are also potential transient recovery voltage concerns when opening the breaker at Glenbrook 115 kV. A circuit breaker at 345 kV between the transformer and cable is recommended here.

Sample mitigating cases investigated breakers with controlled closing, surge arresters, and an alternate configuration of a cable with an overhead line and cable combination. Breakers with controlled closing may not provide an "automatic fix" by closing at voltage zeroes, since this condition can be worse with shunt reactor inrush. Surge arresters would help to reduce the highest transient voltage peaks, but may have to be specially rated to withstand the high overvoltage duty that would be imposed. Replacing some cable with overhead line may improve switching transient performance because of reduced capacitance, but would need further study to investigate transient issues specific to the line/cable junctions. Pre-insertion resistors could also help, but may need to be specially rated to withstand the switching duty. If an alternate arrangement of cables and overhead lines is planned, then further transient analysis would be recommended to re-evaluate switching and harmonic resonance issues and to perform a more detailed mitigation analysis.

The study results indicate that the proposed 345 kV cable project has significant harmonic resonance issues, power quality concerns, and potential challenges for equipment duty.

Appendix A – System Parameters

Appendix B – Driving-Point Impedance Plots

Appendix C – Cable Energization Case Plots

Appendix D – Cable De-Energization Case Plots

Appendix E – Transformer Energization Case Plots

Appendix F – Fault Clearing Case Plots