APPENDIX E

CASE 5

Connecticut Cable Resonance Study for XLPE Alternative in Middletown to Norwalk Project

Summary Report
July, 2004

Prepared for:
Northeast Utilities

GE Energy
NU MN XLPE Summary Report (7-8).doc

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Foreword

This document was prepared by General Electric Company 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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Introduction

GE Energy's Energy Consulting group has performed a resonance study of an XLPE alternative in the Northeast Utilities (NU) Middletown to Norwalk 345 kV transmission cable project that is proposed in southwestern Connecticut. In this study, the two cables between Norwalk and Singer and the two cables between Singer and East Devon were represented as 3000 kcmil XLPE cable rather than 2500 kcmil HPFF cable, and one of the two HPFF cables between Plumtree and Norwalk was removed.

The objectives of this study were

- to investigate the change in the first resonance with the above modifications as compared to the proposed HPFF double circuit configuration, and
- to investigate the effect of representing reduced generation in the area.

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

System Representation

The system model used in the Middletown to Norwalk study was used in this study with modifications. The charging capacitance of the 3000 kcmil XLPE cables is approximately 60% of that of the 2500 kcmil HPFF cables. The following parameters were used to represent the 3000 kcmil XLPE cables (per circuit in pu on a 100 MVA base):

<u>Singer to Norwalk - 15.5 miles</u>
Rpos=0.0003477 pu
Rzero=0.00358118 pu
Xpos=0.00416198 pu
Xneg=0.0023779 pu
Bposzero=1.9637 pu

<u>East Devon to Singer - 8.1 miles</u>
Rpos=0.0001817 pu
Rzero=0.0018715 pu
Xpos=0.00217497 pu
Xneg=0.0012426 pu
Bposzero=1.0261907 pu

In addition to the above changes, one of the two 9.7-mile HPFF cable circuits between Plumtree and Norwalk was removed. The overhead line between East Devon and Beseck was the same as in the Middletown to Norwalk project.

NU determined that the two capacitor banks at Norwalk 115 kV would be removed with the addition of the Middletown to Norwalk project, and were removed from the model accordingly. Table 1 shows the modified capacitor bank data for this study, and indicates the total MVAR at each bus and the capacitor bank MVAR in service under peak and light load conditions. This study considered conditions with all capacitor banks in service and all capacitor banks out of service. Table 2 shows the generators included in the original ASPEN file, and the modified status originally provided for the Middletown to Norwalk (M/N) project, which indicates the generators that are on or off during peak and light load conditions. An additional generator dispatch scenario is given for "Light Post-Project," which depicts a more realistic scenario with more local generation off. This study considered the original light load dispatch of generators and the Light Post-Project dispatch with more local generation off.

Table 1. Modified Shunt Capacitor Conditions for System Model

Shunt Capacitors Substation	Voltage (kV)	# Units	All Banks MVAR (total)	Peak Load MVAR	Light Load MVAR
Southington 1	115	3	157.2	157.2	
Southington 2	115	3	157.2	157.2	
Frost Bridge	115	5	262.0	262.0	
Berlin	115	3	132.0	132.0	
Plumtree	115	2	92.2	0	
Glenbrook	115	5	190.8	151.2	
Darien	115	1	39.6	39.6	
Waterside	115	1	39.6	39.6	
Norwalk	115	0	0	0	
East Shore	115	2	84.0	84.0	
No. Haven	115	1	42.0	42.0	
Sackett	115	1	42.0	42.0	
Rocky River	115	1	25.2	25.2	
Stony Hill	115	1	25.2	25.2	
Cross Sound Filters	200	3	103.0 (61 – 25th, 32 – 41st, 10 – 21st)	103.0	103.0

Table 2. Modified Generator Conditions for System Model

GENERATOR	KV	ID	ST	STATUS (PEAK)	STATUS (LIGHT)	Light Post-Project	IDENTIFI-CATION NOTES
MILLSTON	22.8	1	1	on	on	On	
MILLSTON	22.8	1	1	on	on	On	
RESCO	115	1	1	on	on	On	Bridgeport
ROCKY RV	13.8	1	1	on	on	Off	
ROCKY RV	13.8	1	1	on	on	Off	
ROCKY RV	13.8	1	1	on	on	Off	
STEVENSO	6.9	1	1	off	off	Off	
NORWALK	27.6	1	0	off	off	Off	
BULLS BR	27.6	1	1	on	on	Off	
FORESTVI	13.8	1	1	on	on	On	
brdgphbr	18.4	2	1	off	off	Off	

GENERATOR	KV	ID	ST	STATUS (PEAK)	STATUS (LIGHT)	Light Post-Project	IDENTIFI-CATION NOTES
brdgphbr	20.2	3	1	on	on	Off	
brdgphbr	13.68	jt	1	off	off	Off	
COSCOBGE	13.8	1	1	off	off	Off	
COSCOBGE	13.8	2	1	off	off	Off	
COSCOBGE	13.8	3	1	off	off	Off	
DEVON 11	13.8	1	1	off	off	Off	
DEVON 12	13.8	1	1	off	off	Off	
DEVON 13	13.8	1	1	off	off	Off	
DEVON 14	13.8	1	1	off	off	Off	
English	13.68	8	1	off	off	Off	
English	13.68	7	1	off	off	Off	
ESHOREGE	13.8	1	1	on	on	Off	New Haven
G1/G2	13.8	1	1	off	off	Off	Wallingford
G3/G4	13.8	1	1	off	off	Off	Wallingford
G5	13.8	1	1	off	off	Off	Wallingford
GT1 (11)	16	1	1	off	off	Off	BE
GT2 (12)	16	1	1	off	off	Off	BE
Middleto	22	1	1	on	off	Off	Middletown
Milford	20.9	1	1	on	on	Off	
Milford	20.9	1	1	off	off	Off	
one (Meriden)	21	1	1	on	off	Off	Meriden
Shepaug	13.8	1	1	on	on	Off	
so norwa	4.8	1	1	off	off	Off	
so norwa	4.8	1	1	off	off	Off	
so norwa	13.8	1	1	off	off	Off	
ST1 (10)	16	1	1	off	off	Off	BE
Temp Gen (Waterside)	13.8	3	0	off	off	Off	Waterside
Temp Gen (Waterside)	13.8	1	0	off	off	Off	Waterside
Temp Gen (Waterside)	13.8	2	0	off	off	Off	Waterside
three (Meriden)	21	1	1	on	off	Off	Meriden
two (Meriden)	21	1	1	on	off	Off	Meriden
Unit 10	13.8	1	1	off	off	Off	Devon 10
Unit 6J- (Norwalk)	17.1	1	1	off	off	Off	Norwalk-1
Unit 6J- (Norwalk)	13.8	1	1	off	off	Off	Norwalk -10
Unit 6J- (Norwalk)	19	1	1	off	on	Off	Norwalk-2
Unit 7	13.2	1	1	on	off	Off	Devon
Unit 8	13.2	1	1	on	off	Off	Devon
walrecge	4.16	1	1	on	off	Off	

Resonance Results

The resonance effects of the XLPE alternative, including removal of one HPFF cable between Plumtree and Norwalk, was analyzed by evaluating the driving-point impedance versus frequency at various locations, with all capacitor banks in and out of service, and with the original light load and light post-project generator (local generation off) dispatches.

Table 3 shows the cases that were performed for the M/N-XLPE alternative and the resonant frequencies that were observed along with the corresponding impedance value at those frequencies, with the original light load generation dispatch. The resonant frequency is indicated by its harmonic number (HN), in per unit of 60 Hz, and impedance magnitude is in ohms. The corresponding driving-point impedance plots are provided in Appendix A. Table 4 shows the results with the local generation off (light post-project generator dispatch), and the corresponding driving-point impedance plots are provided in Appendix B.

Figure 1 is a comparison plot of the system impedance characteristic versus frequency at Plumtree 345 kV, illustrating the impact of the XLPE alternative on the resonance characteristics as compared with the proposed M/N project having HPFF cable and two HPFF cable circuits between Plumtree and Norwalk. Figure 2 is a similar comparison plot at Norwalk 345 kV.

Table 3. Resonant Frequencies for M/N-XLPE Project with Light Load Generation

			Resonant Frequency & Impedance (pu of 60Hz, Ohm)					
Case	Location	Capacitor Banks	Low		Middle		High	
			HN	Z(Ω)	HN	Z(Ω)	HN	Z(Ω)
M/N-XLPE_1A	Plumtree 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_1B	Plumtree 345 kV	All in Service	2.8	131	5.6	99	13.5	1495
M/N-XLPE_1C	Plumtree 345 kV	All Out of Service	3.5	220			11.8	349
M/N-XLPE_2A	Plumtree 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_2B	Plumtree 115 kV	All in Service	2.7	19	6.8	78	9.7	63
M/N-XLPE_2C	Plumtree 115 kV	All Out of Service	3.5	22			11.7 14.9	128 98
M/N-XLPE_3A	Norwalk 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_3B	Norwalk 345 kV	All in Service	2.8	150	5.7	160		
M/N-XLPE_3C	Norwalk 345 kV	All Out of Service	3.5	288				
M/N-XLPE_4A	Norwalk 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_4B	Norwalk 115 kV	All in Service	2.8	15	4.6	15		
M/N-XLPE_4C	Norwalk 115 kV	All Out of Service	3.5	19			8.3 16.0	24 33
M/N-XLPE_5A	Southington 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_5B	Southington 345 kV	All in Service	2.8	77	4.5	62	8.2 12.4	87 115
M/N-XLPE_5C	Southington 345 kV	All Out of Service	3.5	73			10.6	260
M/N-XLPE_6A	Southington 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_6B	Southington 115 kV	All in Service	2.7	11	4.5 5.3	24 32	9.4	127

M/N-XLPE_6C	Southington 115 kV	All Out of Service	3.4	9			10.3	29
M/N-XLPE_7A	East Shore 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_7B	East Shore 345 kV	All in Service	2.7	62	6.2	224	12.4 14.6	247 515
M/N-XLPE_7C	East Shore 345 kV	All Out of Service	3.4	66			10.3	245
M/N-XLPE_8A	Devon 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_8B	Devon 115 kV	All in Service	2.7	11				
M/N-XLPE_8C	Devon 115 kV	All Out of Service	3.5	14				
M/N-XLPE_9A	Frost Bridge 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_9B	Frost Bridge 115 kV	All in Service	2.8	18	4.5 5.6	26 43	8.3	34
M/N-XLPE_9C	Frost Bridge 115 kV	All Out of Service	3.4	12			10.3	27
M/N-XLPE_10A	Glenbrook 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_10B	Glenbrook 115 kV	All in Service	2.7	16	4.5 5.7	27 42		
M/N-XLPE_10C	Glenbrook 115 kV	All Out of Service	3.5	17	8.3	44	16.1	55
M/N-XLPE_11A	Singer 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_11B	Singer 345 kV	All in Service	2.8	146	5.6	177	13.5	391
M/N-XLPE_11C	Singer 345 kV	All Out of Service	3.5	286				
M/N-XLPE_12A	Devon 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_12B	Devon 345 kV	All in Service	2.8	141	5.6	162	13.5	512
M/N-XLPE_12C	Devon 345 kV	All Out of Service	3.5	270				
M/N-XLPE_13A	Beseck 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_13B	Beseck 345 kV	All in Service	2.8	69			12.5	308
M/N-XLPE_13C	Beseck 345 kV	All Out of Service	3.5	82			10.6	264

Table 4. Resonant Frequencies for M/N-XLPE Project with Local Generators Off

			Resonant Frequency & Impedance (pu of 60Hz, Ohm)					
Case	Location	Capacitor Banks	Low		Middle		High	
			HN	Z(Ω)	HN	Z(Ω)	HN	Z(Ω)
M/N-XLPE2_1A	Plumtree 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_1B	Plumtree 345 kV	All in Service	2.5	103	5.6	102	13.5	1453
M/N-XLPE2_1C	Plumtree 345 kV	All Out of Service	3.3	161			11.7	313
M/N-XLPE2_2A	Plumtree 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_2B	Plumtree 115 kV	All in Service	2.5	16	6.7	66	9.5	62
M/N-XLPE2_2C	Plumtree 115 kV	All Out of Service	3.2	18			11.7 14.9	119 89
M/N-XLPE2_3A	Norwalk 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_3B	Norwalk 345 kV	All in Service	2.5	121	5.6	167		
M/N-XLPE2_3C	Norwalk 345 kV	All Out of Service	3.3	210				
M/N-XLPE2_4A	Norwalk 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_4B	Norwalk 115 kV	All in Service	2.5	13	4.5	14		
M/N-XLPE2_4C	Norwalk 115 kV	All Out of Service	3.2	16			8.0 16.0	23 32
M/N-XLPE2_5A	Southington 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_5B	Southington 345 kV	All in Service	2.5	63	4.5	59	8.2 12.4	92 113
M/N-XLPE2_5C	Southington 345 kV	All Out of Service	3.2	62			10.4	238
M/N-XLPE2_6A	Southington 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_6B	Southington 115 kV	All in Service	2.4	10	4.5	23	9.4	119

					5.2	26		
M/N-XLPE2_6C	Southington 115 kV	All Out of Service	3.1	8			10.1	28
M/N-XLPE2_7A	East Shore 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_7B	East Shore 345 kV	All in Service	2.4	69	6.1	249	12.4 14.2	266 375
M/N-XLPE2_7C	East Shore 345 kV	All Out of Service	3.1	72			10.1	274
M/N-XLPE2_8A	Devon 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_8B	Devon 115 kV	All in Service	2.5	12				
M/N-XLPE2_8C	Devon 115 kV	All Out of Service	3.2	15				
M/N-XLPE2_9A	Frost Bridge 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_9B	Frost Bridge 115 kV	All in Service	2.5	14	4.5 5.6	24 42	8.3	35
M/N-XLPE2_9C	Frost Bridge 115 kV	All Out of Service	3.1	11			10.1	26
M/N-XLPE2_10A	Glenbrook 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_10B	Glenbrook 115 kV	All in Service	2.5	14	4.5 5.6	27 38		
M/N-XLPE2_10C	Glenbrook 115 kV	All Out of Service	3.2	15	8.1	42	16.1	53
M/N-XLPE2_11A	Singer 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_11B	Singer 345 kV	All in Service	2.5	119	5.6	184	13.5	377
M/N-XLPE2_11C	Singer 345 kV	All Out of Service	3.3	210				
M/N-XLPE2_12A	Devon 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_12B	Devon 345 kV	All in Service	2.5	116	5.6	168	13.5	498
M/N-XLPE2_12C	Devon 345 kV	All Out of Service	3.3	200				
M/N-XLPE2_13A	Beseck 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_13B	Beseck 345 kV	All in Service	2.5	57			12.4	297
M/N-XLPE2_13C	Beseck 345 kV	All Out of Service	3.2	67			10.4	238

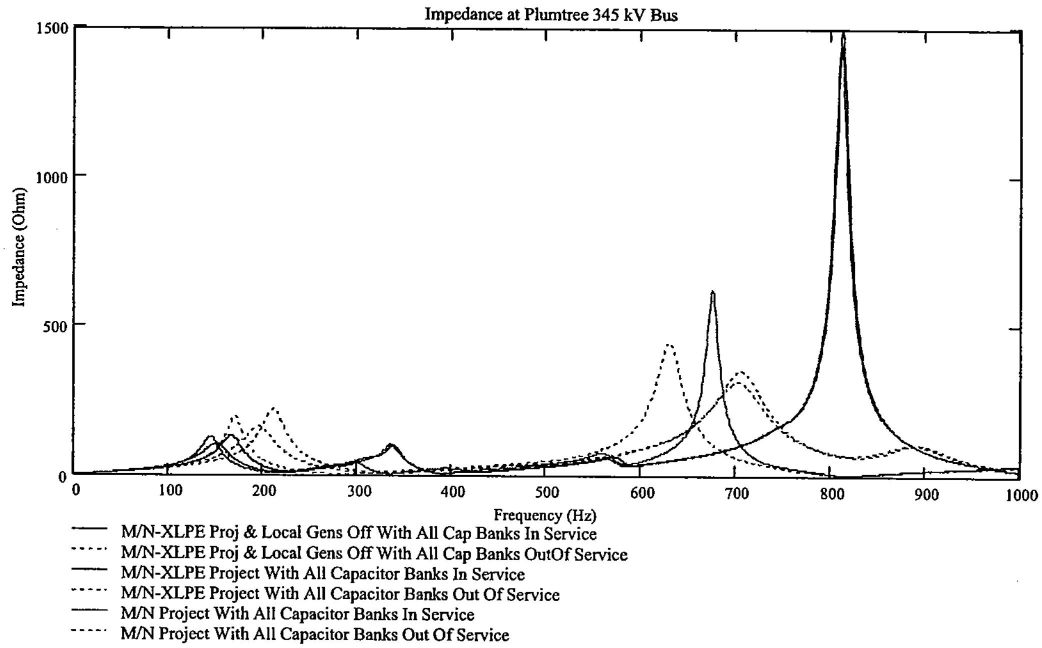


Figure 1. Impedance vs. Frequency at Plumtree 345 kV

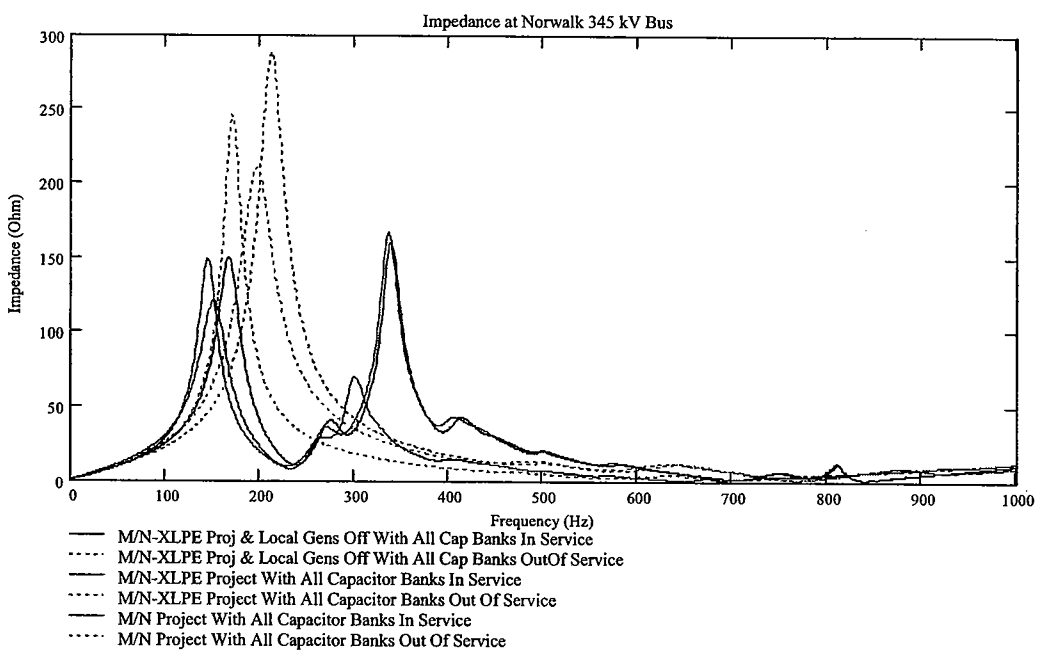


Figure 2. Impedance vs. Frequency at Norwalk 345 kV

Conclusions

Table 5 summarizes the variation in frequencies of the first resonance points for the M/N project and for the XLPE alternative, with the original light load generator dispatch and with more local generation off. In the proposed M/N project previously studied, the first resonance was between 2.4 and 2.8 pu of 60 Hz at most 345 kV buses, with all capacitor banks in and out of service, respectively. With the XLPE alternative and with the same generator dispatch, the first resonance is between 2.8 and 3.5 pu of 60 Hz at most 345 kV buses, with all capacitor banks in and out of service, respectively. With the XLPE alternative and with more local generation off, the first resonance is between 2.5 and 3.3 pu of 60 Hz at most 345 kV buses, with all capacitor banks in and out of service, respectively.

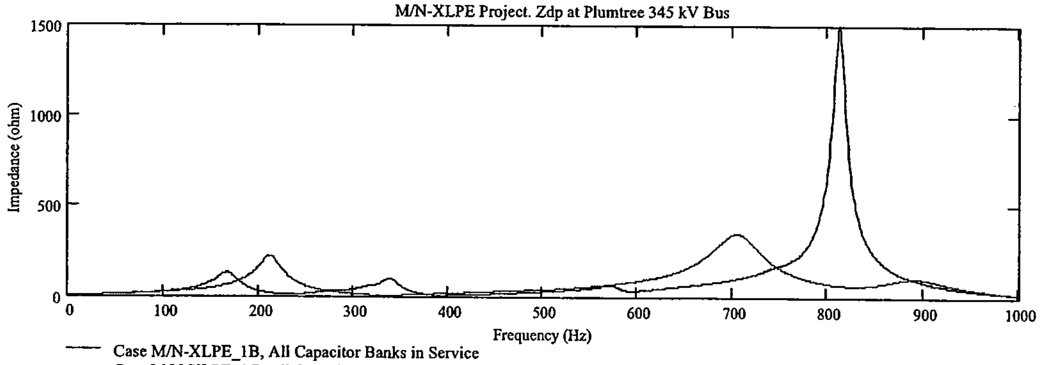
Table 5. Variation in Frequency of First Resonance Points (pu 60 Hz)

115 kV Capacitor Bank Conditions	M/N Project with HPFF Cable (Original Light Load Generator Dispatch)	M/N Project with XLPE Cable (Original Light Load Generator Dispatch)	M/N Project with XLPE Cable (Local Generators Off)
All in service	2.4	2.8	2.5
All out of service	2.8	3.5	3.3

As expected, the XLPE alternative results in a higher frequency of the first resonance, and removal of more local generators results in a lower frequency. Risk of sustained overvoltages due to transformer inrush is increased when resonances are near 3rd harmonic or below. Variation of 115 kV capacitor banks results in resonances above and below 3rd harmonic. If alternate voltage support solutions were investigated, the number of 115 kV capacitor banks could possibly be reduced, given enough physical space, money, and time. System outages are another important consideration, since a variety of outages would similarly cause variation in resonant frequencies, because of the effect of changing either the strength of the system or the effective charging capacitance in the system. Consideration of minimum generator dispatches and system outages (such as an outage of the line from East Devon to Beseck) which would weaken the system together with the maximum allowable 115 kV capacitor bank dispatches and 345 kV cable charging capacitance would result in the lowest frequencies of the first resonance. If all first resonances were located above 3rd harmonic, under such a range of variations, the risk of sustained overvoltages due to transformer inrush would be reduced. However, if varying system conditions result in resonances below 3rd harmonic, then extensive transient studies should be performed to investigate transformer inrush scenarios, under a range of system conditions. Fault and clear scenarios are particularly critical since special circuit breaker closing enhancements have no effect. If the XLPE alternative studied here is to be considered, then extensive transient studies would be recommended.

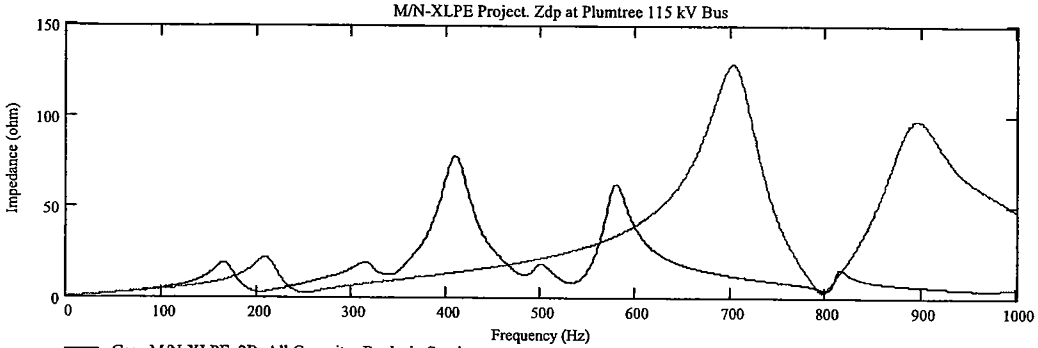
Appendix A Driving-Point Impedance Plots with Light Load Generation

M/N-XLPE Project. Zdp at Plumtree 345 kV Bus



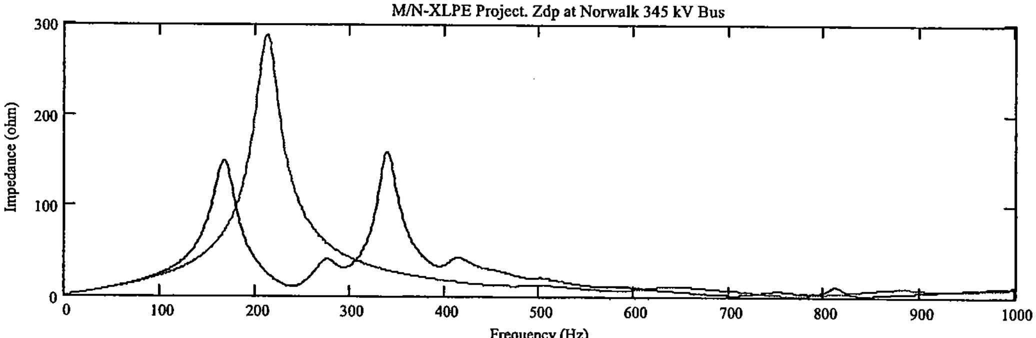
Case M/N-XLPE_1B, All Capacitor Banks in Service
Case M/N-XLPE_1C, All Capacitor Banks Out of Service

M/N-XLPE Project. Zdp at Plumtree 115 kV Bus

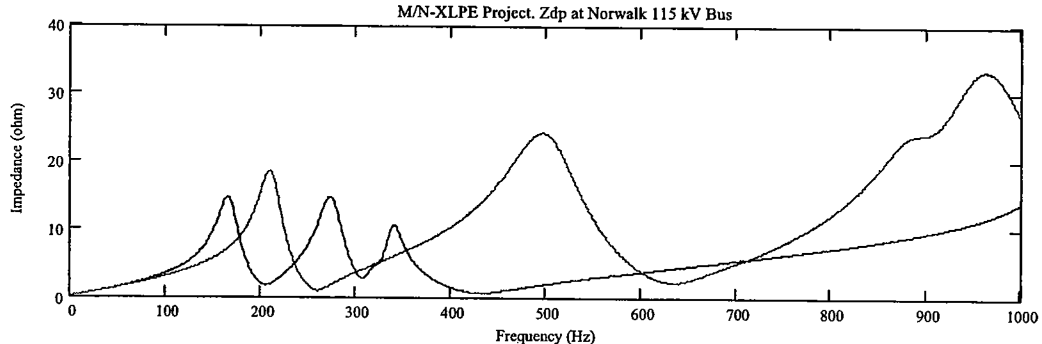


Case M/N-XLPE_2B, All Capacitor Banks in Service
Case M/N-XLPE_2C, All Capacitor Banks Out of Service

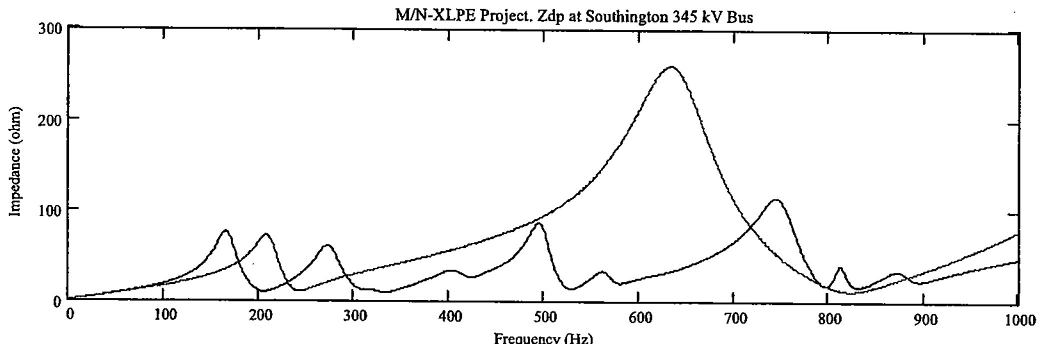
M/N-XLPE Project. Zdp at Norwalk 345 kV Bus



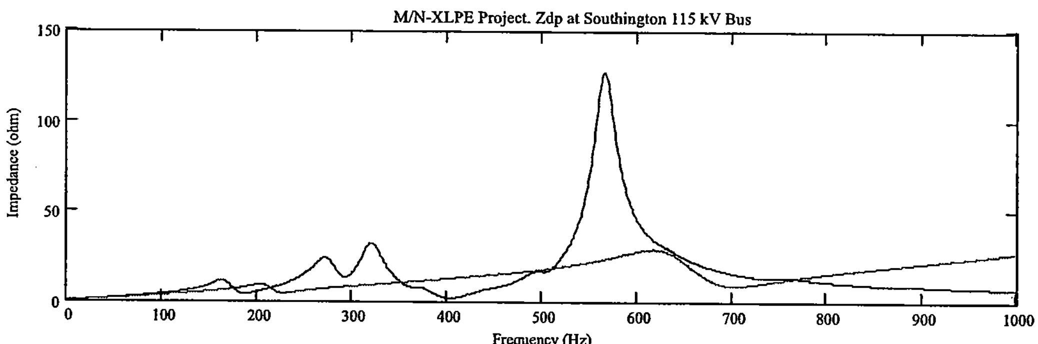
Case M/N-XLPE_3B, All Capacitor Banks in Service
Case M/N-XLPE_3C, All Capacitor Banks Out of Service



Case M/N-XLPE_4B, All Capacitor Banks in Service
Case M/N-XLPE_4C, All Capacitor Banks Out of Service

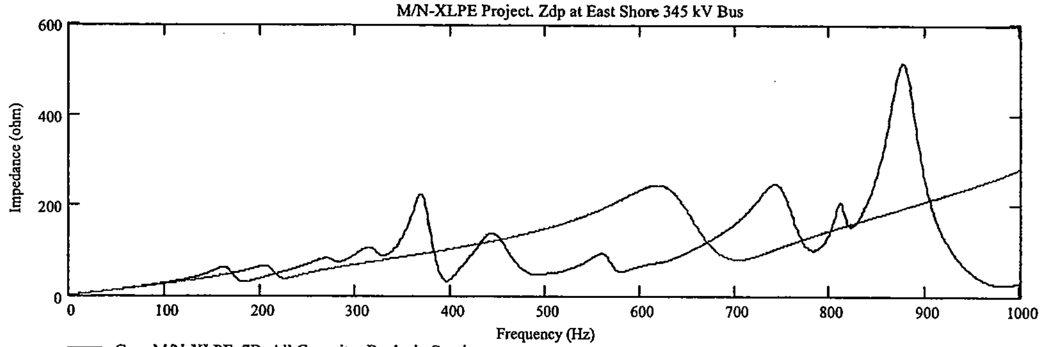


Case M/N-XLPE_5B, All Capacitor Banks in Service
Case M/N-XLPE_5C, All Capacitor Banks Out of Service



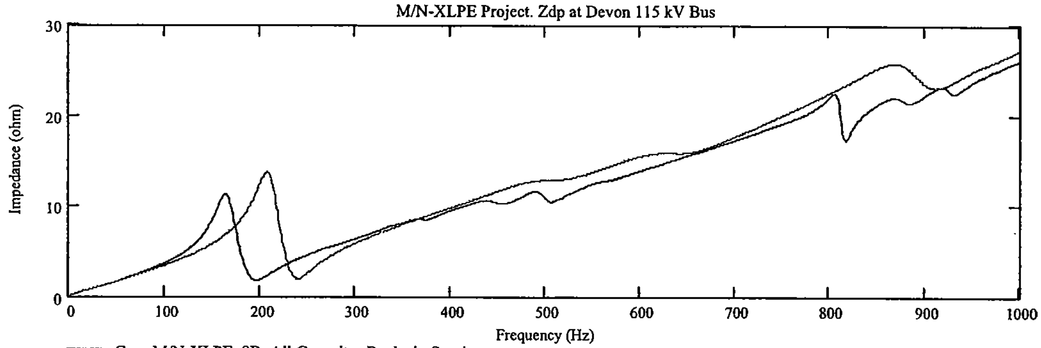
Case M/N-XLPE_6B, All Capacitor Banks in Service
Case M/N-XLPE_6C, All Capacitor Banks Out of Service

M/N-XLPE Project. Zdp at East Shore 345 kV Bus



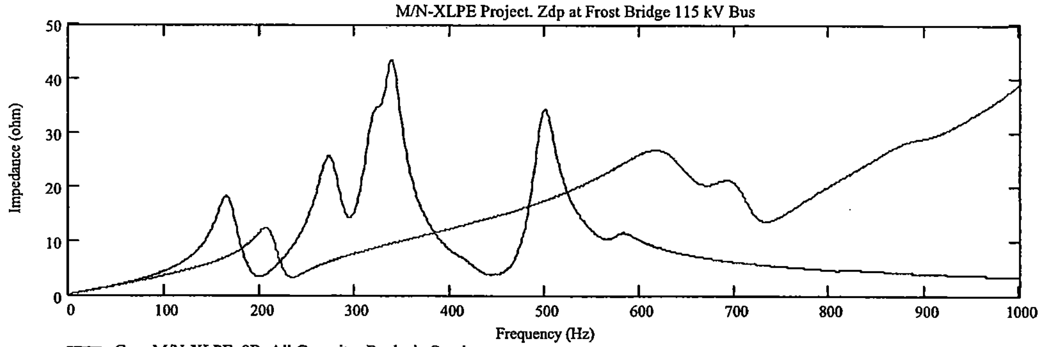
Case M/N-XLPE_7B, All Capacitor Banks in Service
Case M/N-XLPE_7C, All Capacitor Banks Out of Service

M/N-XLPE Project. Zdp at Devon 115 kV Bus

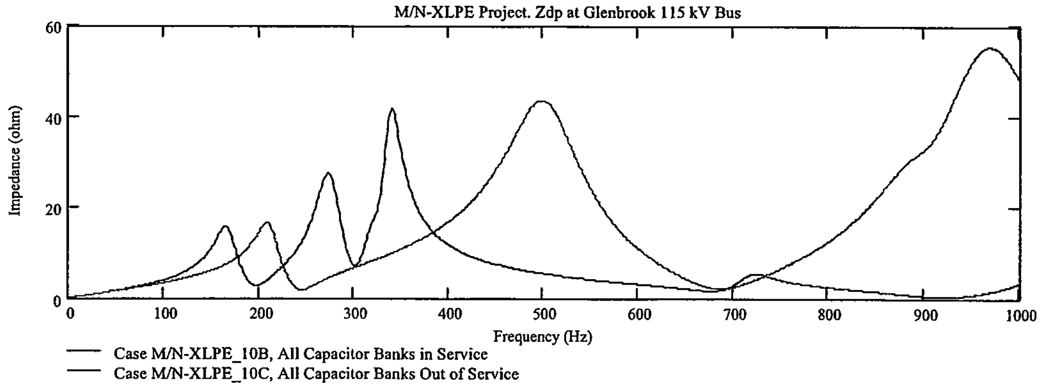


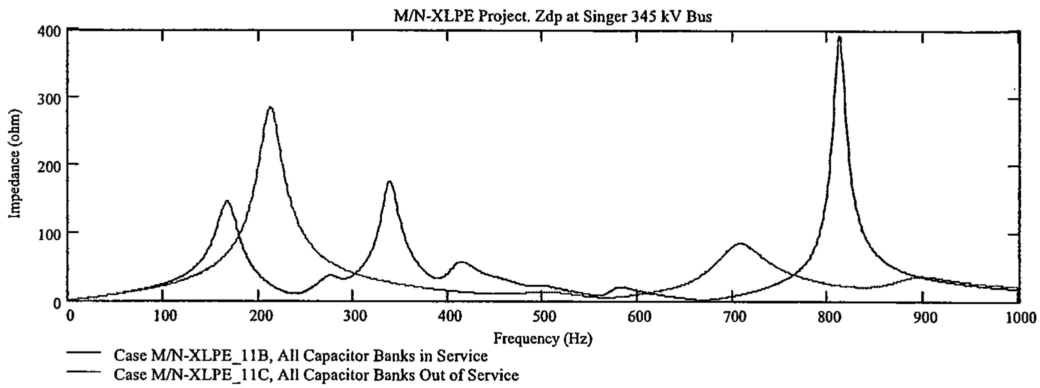
Case M/N-XLPE_8B, All Capacitor Banks in Service
Case M/N-XLPE_8C, All Capacitor Banks Out of Service

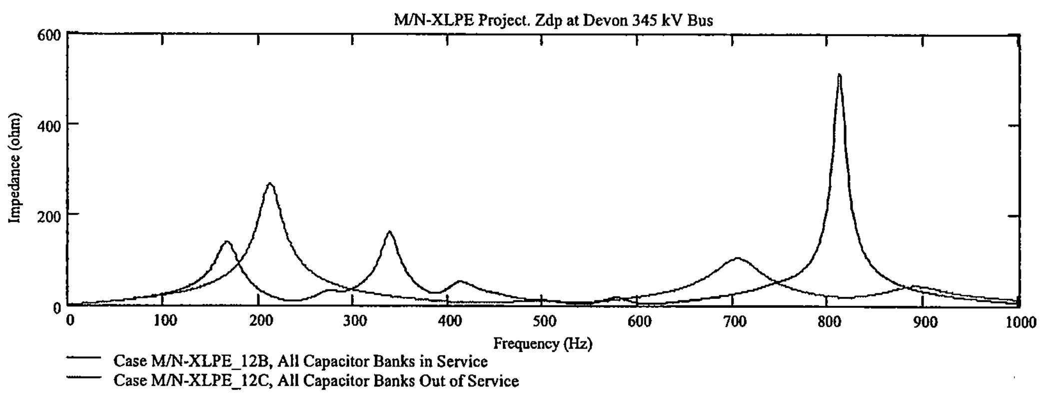
M/N-XLPE Project. Zdp at Frost Bridge 115 kV Bus

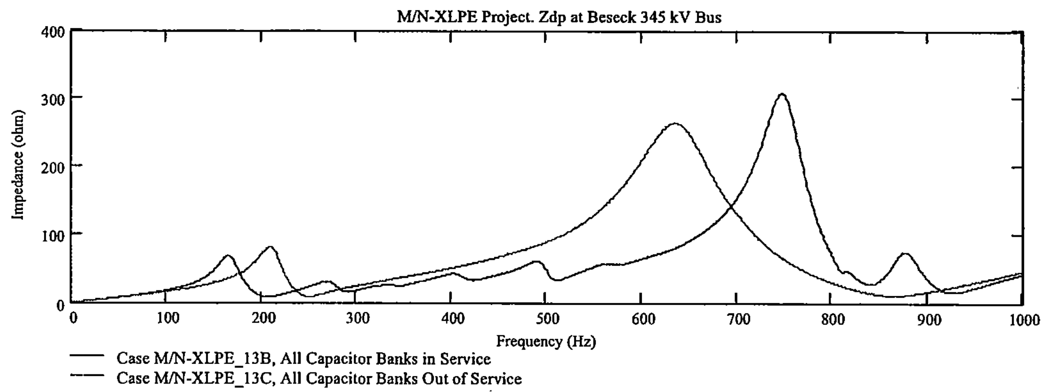


Case M/N-XLPE_9B, All Capacitor Banks in Service
Case M/N-XLPE_9C, All Capacitor Banks Out of Service


M/N-XLPE Project. Zdp at Glenbrook 115 kV Bus
60
40
20
0
Impedance (ohm)
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE_10B, All Capacitor Banks in Service
Case M/N-XLPE_10C, All Capacitor Banks Out of Service

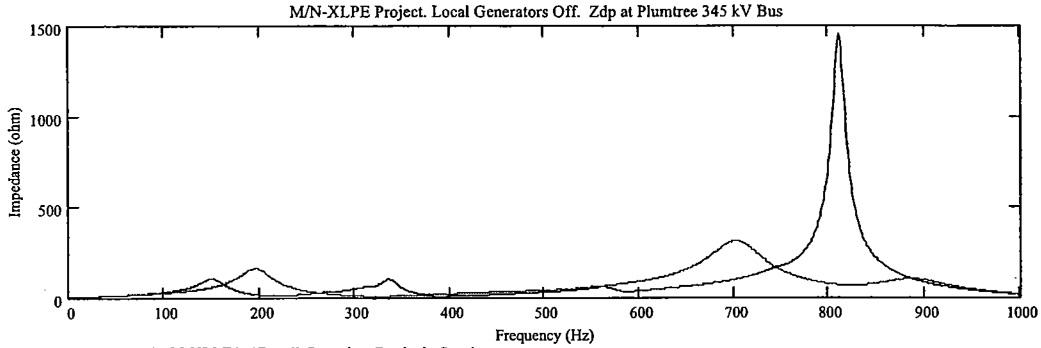

M/N-XLPE Project. Zdp at Singer 345 kV Bus
400
300
200
100
0
Impedance (ohm)
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE_11B, All Capacitor Banks in Service
Case M/N-XLPE_11C, All Capacitor Banks Out of Service


M/N-XLPE Project. Zdp at Devon 345 kV Bus
600
400
200
0
Impedance (ohm)
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE_12B, All Capacitor Banks in Service
Case M/N-XLPE_12C, All Capacitor Banks Out of Service


M/N-XLPE Project. Zdp at Beseck 345 kV Bus
Impedance (ohm)
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE_13B, All Capacitor Banks in Service
Case M/N-XLPE_13C, All Capacitor Banks Out of Service

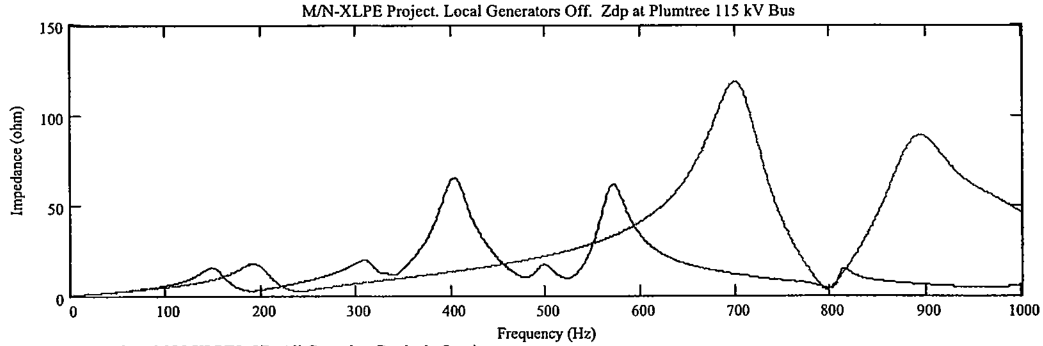
Appendix B Driving-Point Impedance Plots with Local Generators Off

M/N-XLPE Project. Local Generators Off. Zdp at Plumtree 345 kV Bus



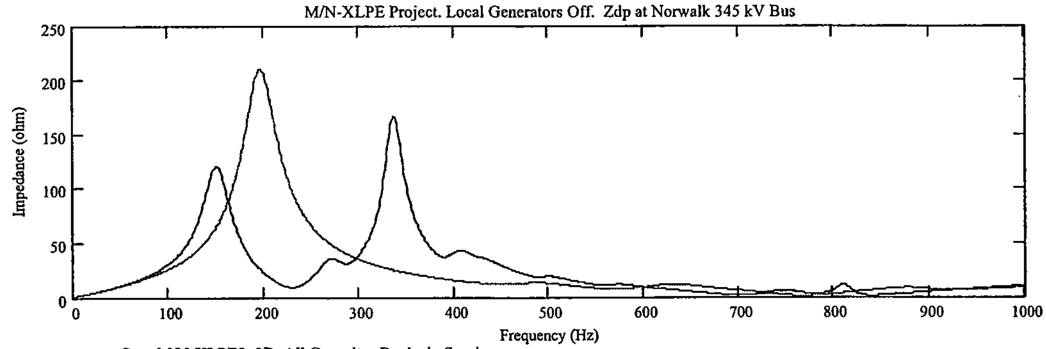
Case M/N-XLPE2_1B, All Capacitor Banks in Service
Case M/N-XLPE2_1C, All Capacitor Banks Out of Service

M/N-XLPE Project. Local Generators Off. Zdp at Plumtree 115 kV Bus



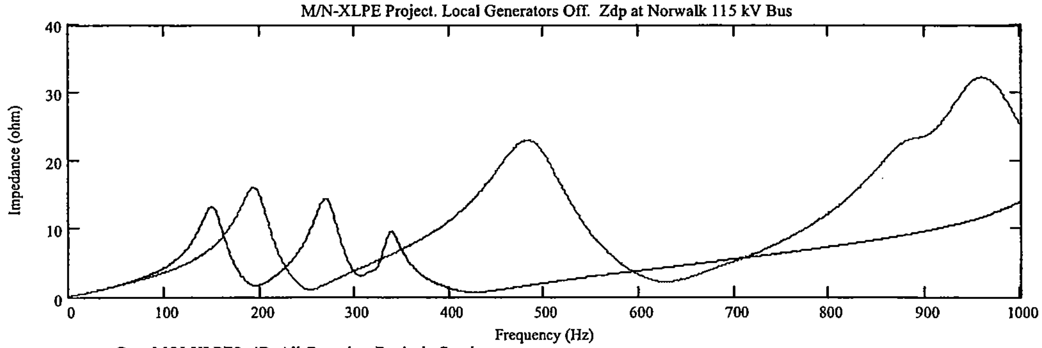
Case M/N-XLPE2_2B, All Capacitor Banks in Service
Case M/N-XLPE2_2C, All Capacitor Banks Out of Service

M/N-XLPE Project. Local Generators Off. Zdp at Norwalk 345 kV Bus



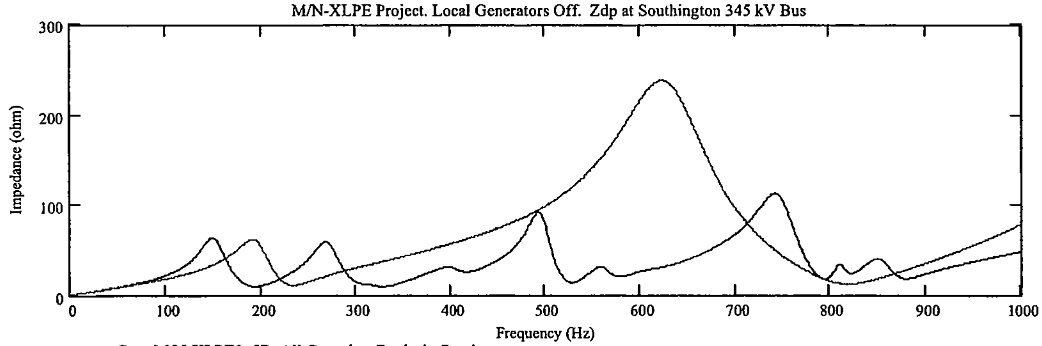
Case M/N-XLPE2_3B, All Capacitor Banks in Service
Case M/N-XLPE2_3C, All Capacitor Banks Out of Service

M/N-XLPE Project. Local Generators Off. Zdp at Norwalk 115 kV Bus



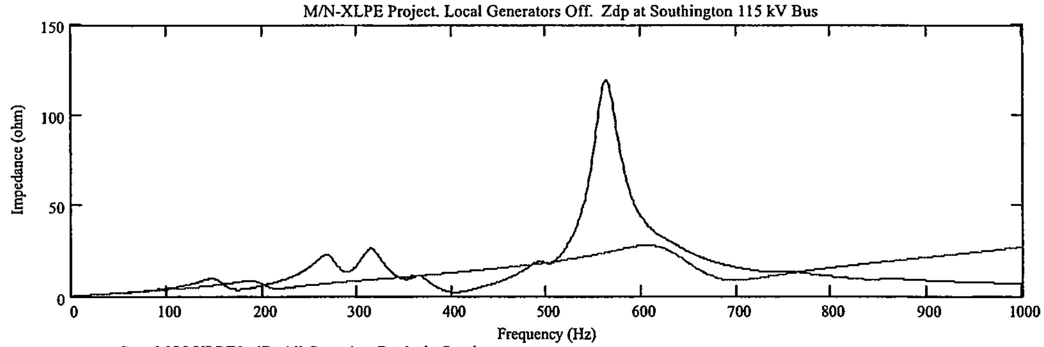
—— Case M/N-XLPE2_4B, All Capacitor Banks in Service
—— Case M/N-XLPE2_4C, All Capacitor Banks Out of Service

M/N-XLPE Project. Local Generators Off. Zdp at Southington 345 kV Bus

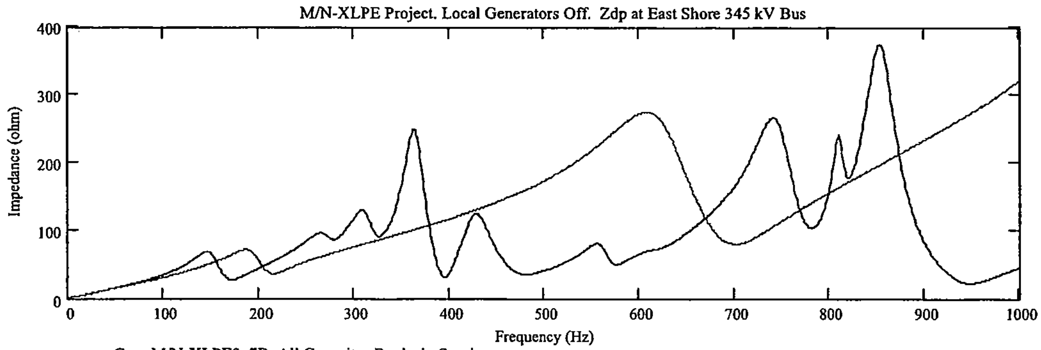


—— Case M/N-XLPE2_5B, All Capacitor Banks in Service
—— Case M/N-XLPE2_5C, All Capacitor Banks Out of Service

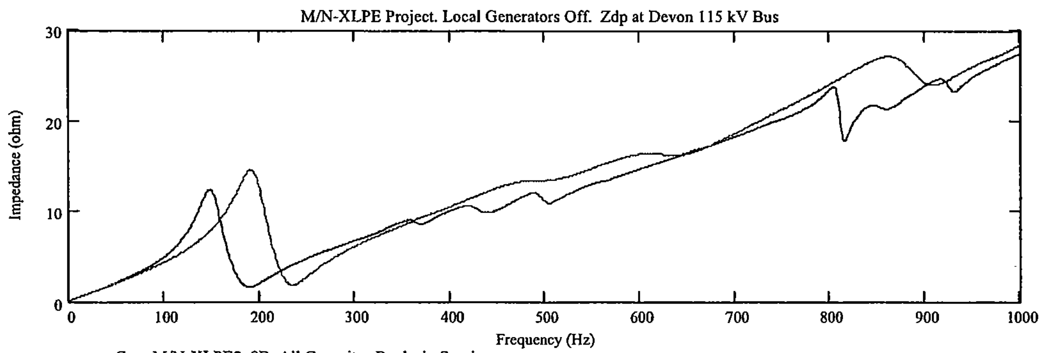
M/N-XLPE Project. Local Generators Off. Zdp at Southington 115 kV Bus



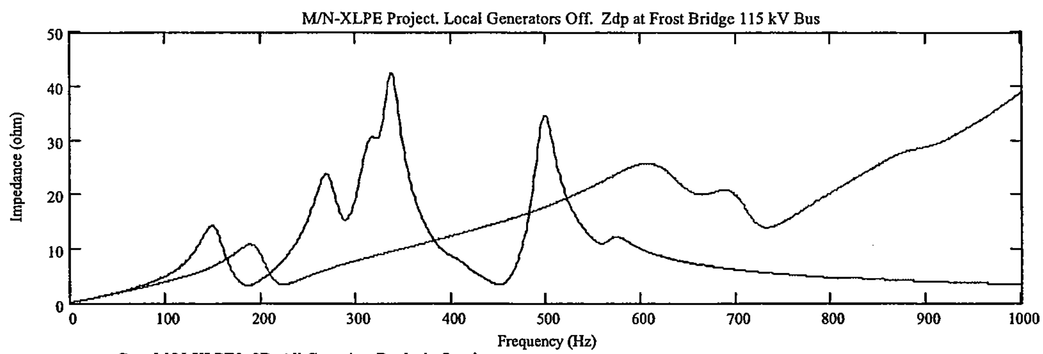
—— Case M/N-XLPE2_6B, All Capacitor Banks in Service
—— Case M/N-XLPE2_6C, All Capacitor Banks Out of Service



—— Case M/N-XLPE2_7B, All Capacitor Banks in Service
—— Case M/N-XLPE2_7C, All Capacitor Banks Out of Service

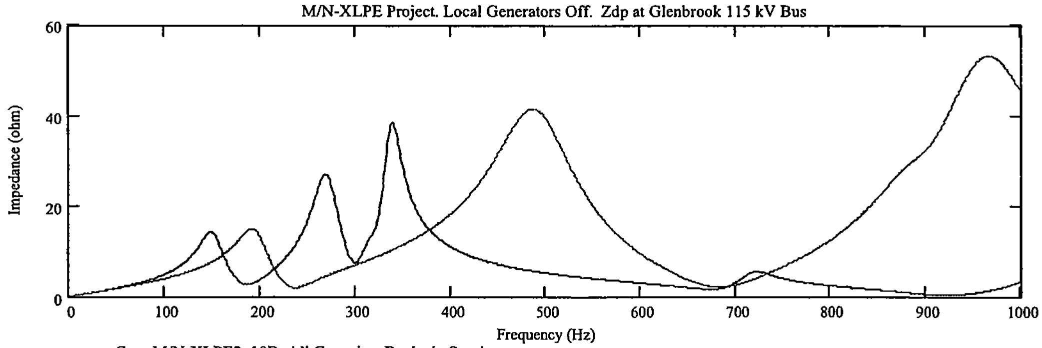


—— Case M/N-XLPE2_8B, All Capacitor Banks in Service
—— Case M/N-XLPE2_8C, All Capacitor Banks Out of Service



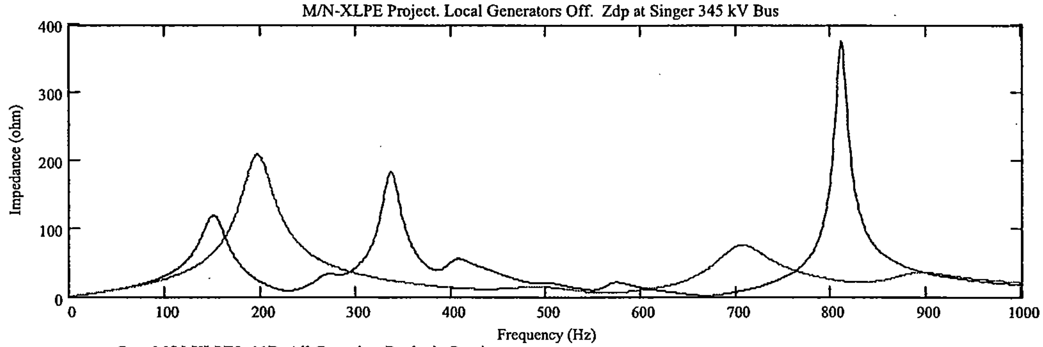
—— Case M/N-XLPE2_9B, All Capacitor Banks in Service
—— Case M/N-XLPE2_9C, All Capacitor Banks Out of Service

M/N-XLPE Project. Local Generators Off. Zdp at Glenbrook 115 kV Bus



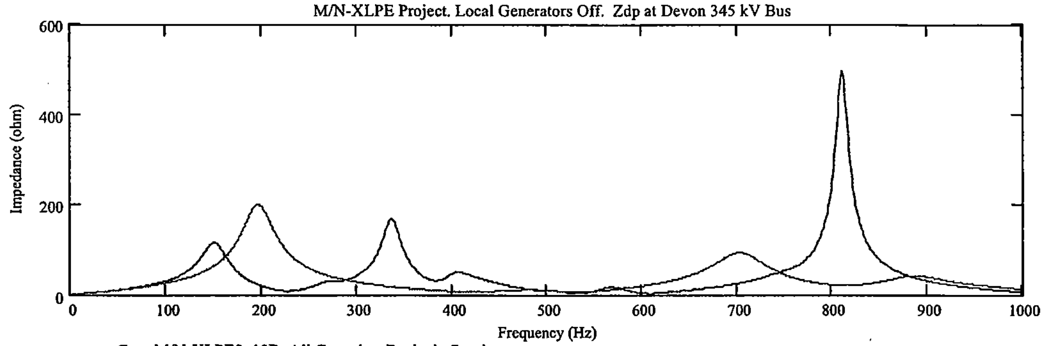
Case M/N-XLPE2_10B, All Capacitor Banks in Service
Case M/N-XLPE2_10C, All Capacitor Banks Out of Service

M/N-XLPE Project. Local Generators Off. Zdp at Singer 345 kV Bus

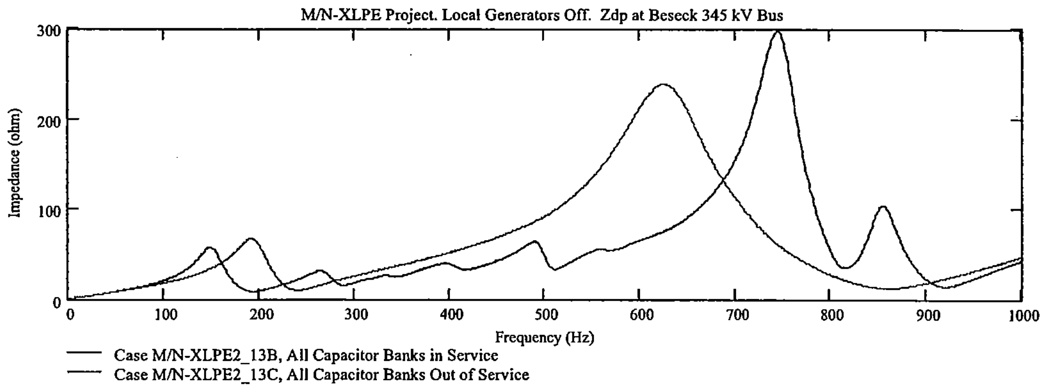


Case M/N-XLPE2_11B, All Capacitor Banks in Service
Case M/N-XLPE2_11C, All Capacitor Banks Out of Service

M/N-XLPE Project. Local Generators Off. Zdp at Devon 345 kV Bus



Case M/N-XLPE2_12B, All Capacitor Banks in Service
Case M/N-XLPE2_12C, All Capacitor Banks Out of Service



M/N-XLPE Project. Local Generators Off. Zdp at Beseck 345 kV Bus
Impedance (ohm)
300
200
100
0
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE2_13B, All Capacitor Banks in Service
Case M/N-XLPE2_13C, All Capacitor Banks Out of Service

CASE 6

Connecticut Cable Resonance Study for XLPE Alternative in Middletown to Norwalk Project

Summary Report
July 2004

Prepared for:
Northeast Utilities

GE Energy
NU MN XLPE Alternative Report.doc

Connecticut Cable Resonance Study for XLPE Alternative in Middletown to Norwalk Project

Summary Report
July 2004

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Foreword

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Table of Contents

Introduction

GE Energy's Energy Consulting group has performed a resonance study of an XLPE alternative in the Northeast Utilities (NU) Middletown to Norwalk 345 kV transmission cable project that is proposed in southwestern Connecticut. In this study, the two cables between Norwalk and Singer and the two cables between Singer and East Devon were represented as 3000 kcmil XLPE cable rather than 2500 kcmil HPFF cable, and one of the two HPFF cables between Plumtree and Norwalk was removed.

The objectives of this study were

- to investigate the change in the first resonance with the above modifications as compared to the proposed HPFF double circuit configuration, and
- to investigate the effect of representing reduced generation in the area.

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

System Representation

The system model used in the Middletown to Norwalk study was used in this study with modifications. The charging capacitance of the 3000 kcmil XLPE cables is approximately 60% of that of the 2500 kcmil HPFF cables. The following parameters were used to represent the 3000 kcmil XLPE cables (per circuit in pu on a 100 MVA base):

<u>Singer to Norwalk - 15.5 miles</u>
Rpos=0.0003477 pu
Rzero=0.00358118 pu
Xpos=0.00416198 pu
Xneg=0.0023779 pu
Bposzero=1.9637 pu

<u>East Devon to Singer - 8.1 miles</u>
Rpos=0.0001817 pu
Rzero=0.0018715 pu
Xpos=0.00217497 pu
Xneg=0.0012426 pu
Bposzero=1.0261907 pu

In addition to the above changes, one of the two 9.7-mile HPFF cable circuits between Plumtree and Norwalk was removed. The overhead line between East Devon and Beseck was the same as in the Middletown to Norwalk project.

NU determined that the two capacitor banks at Norwalk 115 kV would be removed with the addition of the Middletown to Norwalk project, and were removed from the model accordingly. Table 1 shows the modified capacitor bank data for this study, and indicates the total MVAR at each bus and the capacitor bank MVAR in service under peak and light load conditions. This study considered conditions with all capacitor banks in service and all capacitor banks out of service. Table 2 shows the generators included in the original ASPEN file, and the modified status originally provided for the Middletown to Norwalk (M/N) project, which indicates the generators that are on or off during peak and light load conditions. An additional generator dispatch scenario is given for "Light Post-Project," which depicts a more realistic scenario with more local generation off. This study considered the original light load dispatch of generators and the Light Post-Project dispatch with more local generation off.

An additional shunt capacitor condition is shown in the last column of Table 1, where some 115 kV capacitor banks in the "All Banks In" condition (column 4 of Table 1) are taken out of service. This reduced bank condition has no capacitors on at Plumtree, only 205.6 MVAr at Frost Bridge, and only 75.6 MVAr at Glenbrook. This condition was considered in connection with the Light Post-Project generation dispatch and the original light load dispatch.

Table 1. Modified Shunt Capacitor Conditions for System Model

Shunt Capacitors			**All Banks**	**Peak Load**	**Light Load**	**Reduced Banks**
Substation	**Voltage (kV)**	**# Units**	**MVAR (total)**	**MVAR**	**MVAR**	**MVAR**
Southington 1	115	3	157.2	157.2		157.2
Southington 2	115	3	157.2	157.2		157.2
Frost Bridge	115	5	262.0	262.0		205.6
Berlin	115	3	132.0	132.0		132.0
Plumtree	115	2	92.2	0		0
Glenbrook	115	5	190.8*	151.2		75.6
Darien	115	1	39.6	39.6		39.6
Waterside	115	1	39.6	39.6		39.6
Norwalk	115	0	0	0		0
East Shore	115	2	84.0	84.0		84.0
No. Haven	115	1	42.0	42.0		42.0
Sackett	115	1	42.0	42.0		42.0
Rocky River	115	1	25.2	25.2		25.2
Stony Hill	115	1	25.2	25.2		25.2
Cross Sound Filters	200	3	103.0 (61 – 25th, 32 – 41st, 10 – 21st)	103.0	103.0	103.0

* Actual maximum including Glenbrook Statcom is 335 MVAR (additional MVAR not included in analysis)

Table 2. Modified Generator Conditions for System Model

GENERATOR	KV	ID	ST	STATUS (PEAK)	STATUS (LIGHT)	Light Post-Project	IDENTIFI-CATION NOTES
MILLSTON	22.8	1	1	on	on	On	
MILLSTON	22.8	1	1	on	on	On	
RESCO	115	1	1	on	on	On	Bridgeport
ROCKY RV	13.8	1	1	on	on	Off	
ROCKY RV	13.8	1	1	on	on	Off	
ROCKY RV	13.8	1	1	on	on	Off	
STEVENSO	6.9	1	1	off	off	Off	
NORWALK	27.6	1	0	off	off	Off	
BULLS BR	27.6	1	1	on	on	Off	
FORESTVI	13.8	1	1	on	on	On	
brdgphbr	18.4	2	1	off	off	Off	
brdgphbr	20.2	3	1	on	on	Off	
brdgphbr	13.68	jt	1	off	off	Off	
COSCOBGE	13.8	1	1	off	off	Off	
COSCOBGE	13.8	2	1	off	off	Off	
COSCOBGE	13.8	3	1	off	off	Off	
DEVON 11	13.8	1	1	off	off	Off	
DEVON 12	13.8	1	1	off	off	Off	
DEVON 13	13.8	1	1	off	off	Off	
DEVON 14	13.8	1	1	off	off	Off	
English	13.68	8	1	off	off	Off	
English	13.68	7	1	off	off	Off	
ESHOREGE	13.8	1	1	on	on	Off	New Haven
G1/G2	13.8	1	1	off	off	Off	Wallingford
G3/G4	13.8	1	1	off	off	Off	Wallingford
G5	13.8	1	1	off	off	Off	Wallingford
GT1 (11)	16	1	1	off	off	Off	BE
GT2 (12)	16	1	1	off	off	Off	BE
Middleto	22	1	1	on	off	Off	Middletown
Milford	20.9	1	1	on	on	Off	
Milford	20.9	1	1	off	off	Off	
one (Meriden)	21	1	1	on	off	Off	Meriden
Shepaug	13.8	1	1	on	on	Off	
so norwa	4.8	1	1	off	off	Off	
so norwa	4.8	1	1	off	off	Off	
so norwa	13.8	1	1	off	off	Off	
ST1 (10)	16	1	1	off	off	Off	BE
Temp Gen (Waterside)	13.8	3	0	off	off	Off	Waterside
Temp Gen (Waterside)	13.8	1	0	off	off	Off	Waterside
Temp Gen (Waterside)	13.8	2	0	off	off	Off	Waterside
three (Meriden)	21	1	1	on	off	Off	Meriden

GENERATOR	KV	ID	ST	STATUS (PEAK)	STATUS (LIGHT)	Light Post-Project	IDENTIFI-CATION NOTES
two (Meriden)	21	1	1	on	off	Off	Meriden
Unit 10	13.8	1	1	off	off	Off	Devon 10
Unit 6J- (Norwalk)	17.1	1	1	off	off	Off	Norwalk-1
Unit 6J- (Norwalk)	13.8	1	1	off	off	Off	Norwalk -10
Unit 6J- (Norwalk)	19	1	1	off	on	Off	Norwalk-2
Unit 7	13.2	1	1	on	off	Off	Devon
Unit 8	13.2	1	1	on	off	Off	Devon
walrecge	4.16	1	1	on	off	Off	

Resonance Results

The resonance effects of the XLPE alternative, including removal of one HPFF cable between Plumtree and Norwalk, was analyzed by evaluating the driving-point impedance versus frequency at various locations, with all capacitor banks in and out of service, and with the original light load and light post-project generator (local generation off) dispatches.

Table 3 shows the cases that were performed for the M/N-XLPE alternative and the resonant frequencies that were observed along with the corresponding impedance value at those frequencies, with the original light load generation dispatch. The resonant frequency is indicated by its harmonic number (HN), in per unit of 60 Hz, and impedance magnitude is in ohms. The corresponding driving-point impedance plots are provided in Appendix A. Table 4 shows the results with the local generation off (light post-project generator dispatch), and the corresponding driving-point impedance plots are provided in Appendix B. Tables 3 and 4 includes rows corresponding to the cases where some capacitor banks are taken out of service as shown in the last column of Table 1. This reduced capacitive shunt MVAr has an impact of raising the first resonance frequency in the order of 0.1-0.2 pu (6-12 Hz).

Figure 1 is a comparison plot of the system impedance characteristic versus frequency at Plumtree 345 kV, illustrating the impact of the XLPE alternative on the resonance characteristics as compared with the proposed M/N project having HPFF cable and two HPFF cable circuits between Plumtree and Norwalk. Figure 2 is a similar comparison plot at Norwalk 345 kV.

Table 3. Resonant Frequencies for M/N-XLPE Project with Light Load Generation

Case	Location	Capacitor Banks	Resonant Frequency & Impedance (pu of 60Hz, Ohm)					
			Low		Middle		High	
			HN	Z(Ω)	HN	Z(Ω)	HN	Z(Ω)
M/N-XLPE_1A	Plumtree 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_1B	Plumtree 345 kV	All in Service	2.8	131	5.6	99	13.5	1495
M/N-XLPE_1C	Plumtree 345 kV	All Out of Service	3.5	220			11.8	349
M/N-XLPE_1D	Plumtree 345 kV	Some Out of Service	2.9	137			11.6 13.9	254 428
M/N-XLPE_2A	Plumtree 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_2B	Plumtree 115 kV	All in Service	2.7	19	6.8	78	9.7	63
M/N-XLPE_2C	Plumtree 115 kV	All Out of Service	3.5	22			11.7 14.9	128 98
M/N-XLPE_2D	Plumtree 115 kV	Some Out of Service	2.9	17	7.6	32	11.6	104
M/N-XLPE_3A	Norwalk 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_3B	Norwalk 345 kV	All in Service	2.8	150	5.7	160		
M/N-XLPE_3C	Norwalk 345 kV	All Out of Service	3.5	288				
M/N-XLPE_3D	Norwalk 345 kV	Some Out of Service	3.0	164	4.9 6.3	86 78		
M/N-XLPE_4A	Norwalk 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_4B	Norwalk 115 kV	All in Service	2.8	15	4.6	15		

M/N-XLPE_4C	Norwalk 115 kV	All Out of Service	3.5	19			8.3 16.0	24 33
M/N-XLPE_4D	Norwalk 115 kV	Some Out of Service	2.9	14	4.8 6.2	13 19	2.6	13
M/N-XLPE_5A	Southington 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_5B	Southington 345 kV	All in Service	2.8	77	4.5	62	8.2 12.4	87 115
M/N-XLPE_5C	Southington 345 kV	All Out of Service	3.5	73			10.6	260
M/N-XLPE_5D	Southington 345 kV	Some Out of Service	2.9	86	4.8	68	8.7 12.5	57 110
M/N-XLPE_6A	Southington 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_6B	Southington 115 kV	All in Service	2.7	11	4.5 5.3	24 32	9.4	127
M/N-XLPE_6C	Southington 115 kV	All Out of Service	3.4	9			10.3	29
M/N-XLPE_6D	Southington 115 kV	Some Out of Service	2.9	13	4.8	36	9.5	122
M/N-XLPE_7A	East Shore 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_7B	East Shore 345 kV	All in Service	2.7	62	6.2	224	12.4 14.6	247 515
M/N-XLPE_7C	East Shore 345 kV	All Out of Service	3.4	66			10.3	245
M/N-XLPE_7D	East Shore 345 kV	Some Out of Service	2.9	68	6.2	226	12.4 14.6	243 515
M/N-XLPE_8A	Devon 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_8B	Devon 115 kV	All in Service	2.7	11				
M/N-XLPE_8C	Devon 115 kV	All Out of Service	3.5	14				
M/N-XLPE_8D	Devon 115 kV	Some Out of Service	2.9	12				
M/N-XLPE_9A	Frost Bridge 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_9B	Frost Bridge 115 kV	All in Service	2.8	18	4.5 5.6	26 43	8.3	34
M/N-XLPE_9C	Frost Bridge 115 kV	All Out of Service	3.4	12			10.3	27
M/N-XLPE_9D	Frost Bridge 115 kV	Some Out of Service	2.9	19	5.7	59	8.8	50
M/N-XLPE_10A	Glenbrook 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_10B	Glenbrook 115 kV	All in Service	2.7	16	4.5 5.7	27 42		
M/N-XLPE_10C	Glenbrook 115 kV	All Out of Service	3.5	17	8.3	44	16.1	55
M/N-XLPE_10D	Glenbrook 115 kV	Some Out of Service	2.9	14	4.8 6.3	19 51		
M/N-XLPE_11A	Singer 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_11B	Singer 345 kV	All in Service	2.8	146	5.6	177	13.5	391
M/N-XLPE_11C	Singer 345 kV	All Out of Service	3.5	286				
M/N-XLPE_11D	Singer 345 kV	Some Out of Service	3.0	162				
M/N-XLPE_12A	Devon 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_12B	Devon 345 kV	All in Service	2.8	141	5.6	162	13.5	512
M/N-XLPE_12C	Devon 345 kV	All Out of Service	3.5	270				
M/N-XLPE_12D	Devon 345 kV	Some Out of Service	3.0	156				
M/N-XLPE_13A	Beseck 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE_13B	Beseck 345 kV	All in Service	2.8	69			12.5	308
M/N-XLPE_13C	Beseck 345 kV	All Out of Service	3.5	82			10.6	264
M/N-XLPE_13D	Beseck 345 kV	Some Out of Service	2.9	77			12.5	274

Table 4. Resonant Frequencies for M/N-XLPE Project with Local Generators Off

			Resonant Frequency & Impedance (pu of 60Hz, Ohm)					
Case	Location	Capacitor Banks	Low		Middle		High	
			HN	Z(Ω)	HN	Z(Ω)	HN	Z(Ω)
M/N-XLPE2_1A	Plumtree 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_1B	Plumtree 345 kV	All in Service	2.5	103	5.6	102	13.5	1453
M/N-XLPE2_1C	Plumtree 345 kV	All Out of Service	3.3	161			11.7	313
M/N-XLPE2_1D	Plumtree 345 kV	Some Out of Service	2.7	107			11.5 13.8	227 412
M/N-XLPE2_2A	Plumtree 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_2B	Plumtree 115 kV	All in Service	2.5	16	6.7	66	9.5	62
M/N-XLPE2_2C	Plumtree 115 kV	All Out of Service	3.2	18			11.7 14.9	119 89
M/N-XLPE2_2D	Plumtree 115 kV	Some Out of Service	2.6	14	7.4	30	11.5	97
M/N-XLPE2_3A	Norwalk 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_3B	Norwalk 345 kV	All in Service	2.5	121	5.6	167		
M/N-XLPE2_3C	Norwalk 345 kV	All Out of Service	3.3	210				
M/N-XLPE2_3D	Norwalk 345 kV	Some Out of Service	2.7	129	4.8 6.2	76 89		
M/N-XLPE2_4A	Norwalk 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_4B	Norwalk 115 kV	All in Service	2.5	13	4.5	14		
M/N-XLPE2_4C	Norwalk 115 kV	All Out of Service	3.2	16			8.0 16.0	23 32
M/N-XLPE2_4D	Norwalk 115 kV	Some Out of Service	2.6	13	4.7 6.2	13 17		
M/N-XLPE2_5A	Southington 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_5B	Southington 345 kV	All in Service	2.5	63	4.5	59	8.2 12.4	92 113
M/N-XLPE2_5C	Southington 345 kV	All Out of Service	3.2	62			10.4	238
M/N-XLPE2_5D	Southington 345 kV	Some Out of Service	2.6	69	4.8	63	8.6 12.4	63 107
M/N-XLPE2_6A	Southington 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_6B	Southington 115 kV	All in Service	2.4	10	4.5 5.2	23 26	9.4	119
M/N-XLPE2_6C	Southington 115 kV	All Out of Service	3.1	8			10.1	28
M/N-XLPE2_6D	Southington 115 kV	Some Out of Service	2.6	11	4.8	33	9.4	115
M/N-XLPE2_7A	East Shore 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_7B	East Shore 345 kV	All in Service	2.4	69	6.1	249	12.4 14.2	266 375
M/N-XLPE2_7C	East Shore 345 kV	All Out of Service	3.1	72			10.1	274
M/N-XLPE2_7D	East Shore 345 kV	Some Out of Service	2.6	75	6.1	248	12.4 14.2	262 374
M/N-XLPE2_8A	Devon 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_8B	Devon 115 kV	All in Service	2.5	12				
M/N-XLPE2_8C	Devon 115 kV	All Out of Service	3.2	15				
M/N-XLPE2_8D	Devon 115 kV	Some Out of Service	2.6	13				
M/N-XLPE2_9A	Frost Bridge 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_9B	Frost Bridge 115 kV	All in Service	2.5	14	4.5 5.6	24 42	8.3	35
M/N-XLPE2_9C	Frost Bridge 115 kV	All Out of Service	3.1	11			10.1	26

M/N-XLPE2_9D	Frost Bridge 115 kV	Some Out of Service	2.6	15	5.6	53	8.7	51
M/N-XLPE2_10A	Glenbrook 115 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_10B	Glenbrook 115 kV	All in Service	2.5	14	4.5 5.6	27 38		
M/N-XLPE2_10C	Glenbrook 115 kV	All Out of Service	3.2	15	8.1	42	16.1	53
M/N-XLPE2_10D	Glenbrook 115 kV	Some Out of Service	2.6	13	4.7 6.2	20 48		
M/N-XLPE2_11A	Singer 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_11B	Singer 345 kV	All in Service	2.5	119	5.6	184	13.5	377
M/N-XLPE2_11C	Singer 345 kV	All Out of Service	3.3	210				
M/N-XLPE2_11D	Singer 345 kV	Some Out of Service	2.7	129				
M/N-XLPE2_12A	Devon 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_12B	Devon 345 kV	All in Service	2.5	116	5.6	168	13.5	498
M/N-XLPE2_12C	Devon 345 kV	All Out of Service	3.3	200				
M/N-XLPE2_12D	Devon 345 kV	Some Out of Service	2.7	126				
M/N-XLPE2_13A	Beseck 345 kV	Light Load	-	-	-	-	-	-
M/N-XLPE2_13B	Beseck 345 kV	All in Service	2.5	57			12.4	297
M/N-XLPE2_13C	Beseck 345 kV	All Out of Service	3.2	67			10.4	238
M/N-XLPE2_13D	Beseck 345 kV	Some Out of Service	2.6	63			12.5	266

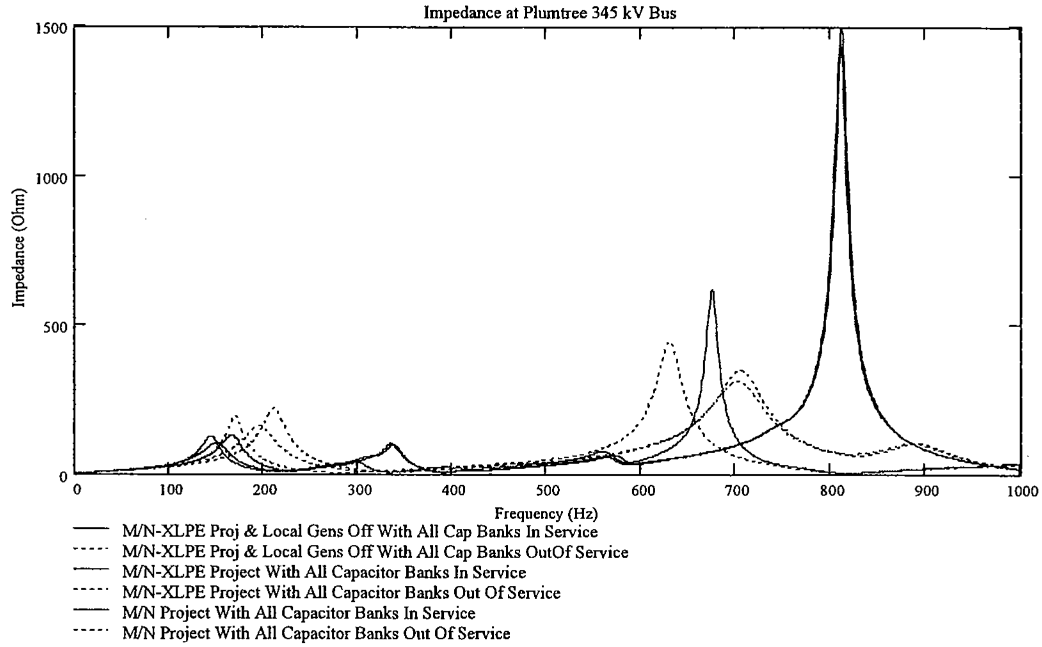


Figure 1. Impedance vs. Frequency at Plumtree 345 kV

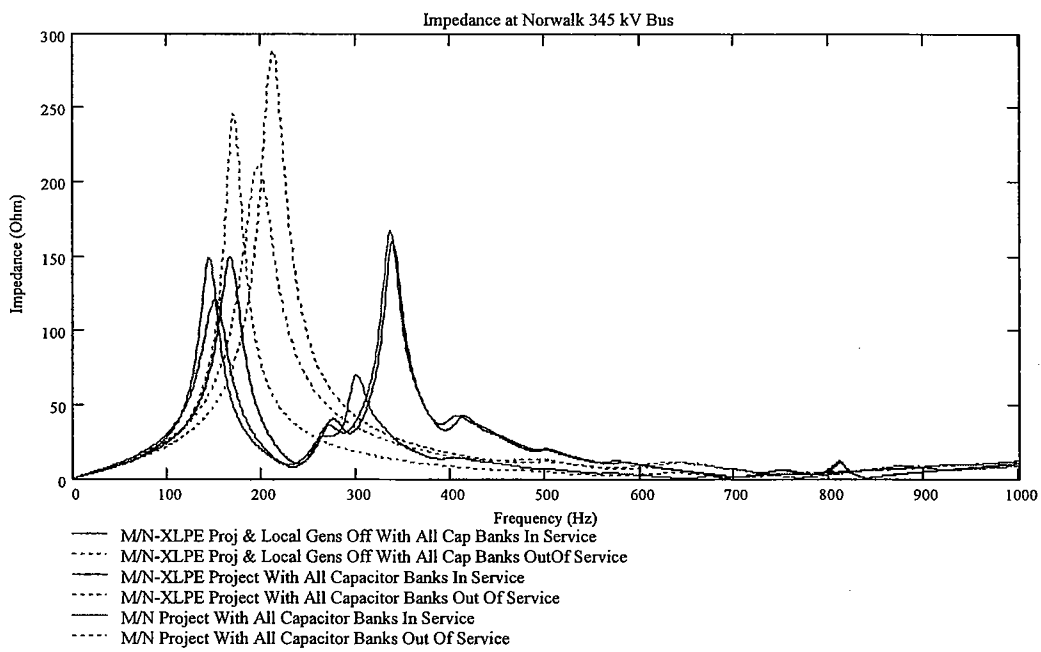


Figure 2. Impedance vs. Frequency at Norwalk 345 kV

Conclusions

Table 5 summarizes the variation in frequencies of the first resonance points for the M/N project and for the XLPE alternative, with the original light load generator dispatch and with more local generation off. In the proposed M/N project previously studied, the first resonance was between 2.4 and 2.8 pu of 60 Hz at most 345 kV buses, with all capacitor banks in and out of service, respectively. With the XLPE alternative (removing about 600 MVAR of charging including the 9.7-mi HPFF section) and with the same generator dispatch, the first resonance is between 2.8 and 3.5 pu of 60 Hz at most 345 kV buses, with all capacitor banks in and out of service, respectively. With the XLPE alternative and with more local generation off, the first resonance is between 2.5 and 3.3 pu of 60 Hz at most 345 kV buses, with all capacitor banks in and out of service, respectively. Removing some 115 kV capacitor banks at Plumtree, Frost Bridge and Glenbrook (removing about 264 MVAR – or 409 MVAR including removal of Glenbrook Statcom) had only a minor impact on the first resonance points. It raises the first resonance frequency from 2.5 pu to 2.6 or 2.7 pu with local generators off, and from 2.8 pu to 2.9 or 3.0 pu with the original light load generator dispatch.

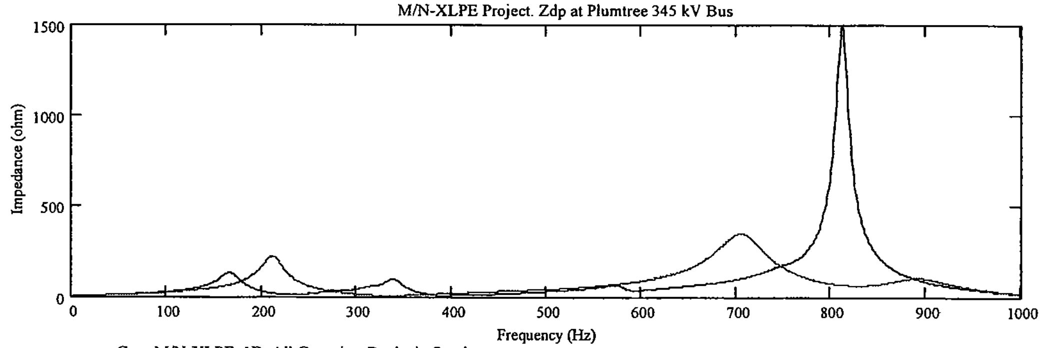
Table 5. Variation in Frequency of First Resonance Points (pu 60 Hz)

115 kV Capacitor Bank Conditions	M/N Project with HPFF Cable (Original Light Load Generator Dispatch)	M/N Project with XLPE Cable (Original Light Load Generator Dispatch)	M/N Project with XLPE Cable (Local Generators Off)
All in service	2.4	2.8	2.5
Reduced banks		2.9-3.0	2.6-2.7
All out of service	2.8	3.5	3.3

As expected, the XLPE alternative results in a higher frequency of the first resonance, and removal of more local generators results in a lower frequency. Risk of sustained overvoltages due to transformer inrush is increased when resonances are near 3rd harmonic or below. Variation of 115 kV capacitor banks results in resonances above and below 3rd harmonic. If alternate voltage support solutions were investigated, the number of 115 kV capacitor banks could possibly be reduced, given enough physical space, money, and time. System outages are another important consideration, since a variety of outages would similarly cause variation in resonant frequencies, because of the effect of changing either the strength of the system or the effective charging capacitance in the system. Consideration of minimum generator dispatches and system outages (such as an outage of the line from East Devon to Beseck) which would weaken the system together with the maximum allowable 115 kV capacitor bank dispatches and 345 kV cable charging capacitance would result in the lowest frequencies of the first resonance. If all first resonances were located above 3rd harmonic, under such a range of variations, the risk of sustained overvoltages due to transformer inrush would be reduced. However, if varying system conditions result in resonances below 3rd harmonic, then extensive transient studies should be performed to investigate transformer inrush scenarios, under a range of system conditions. Fault and clear scenarios are particularly critical since special circuit breaker closing enhancements have no effect. If the XLPE alternative studied here is to be considered, then extensive transient studies would be recommended.

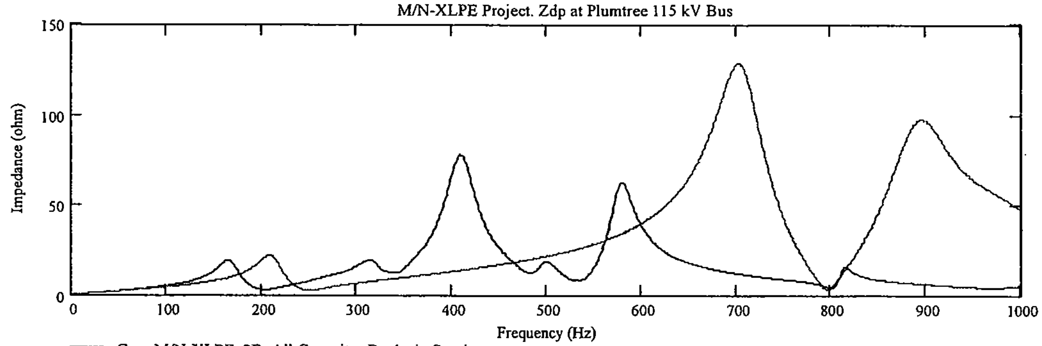
Appendix A Driving-Point Impedance Plots with Light Load Generation

M/N-XLPE Project. Zdp at Plumtree 345 kV Bus



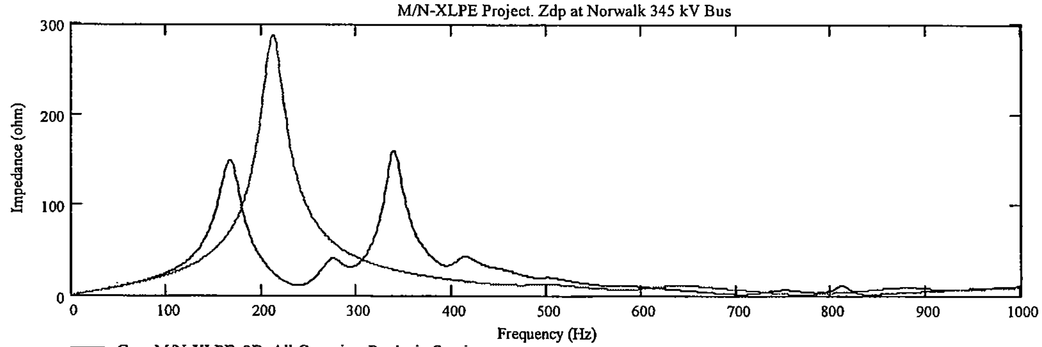
—— Case M/N-XLPE_1B, All Capacitor Banks in Service
—— Case M/N-XLPE_1C, All Capacitor Banks Out of Service

M/N-XLPE Project. Zdp at Plumtree 115 kV Bus



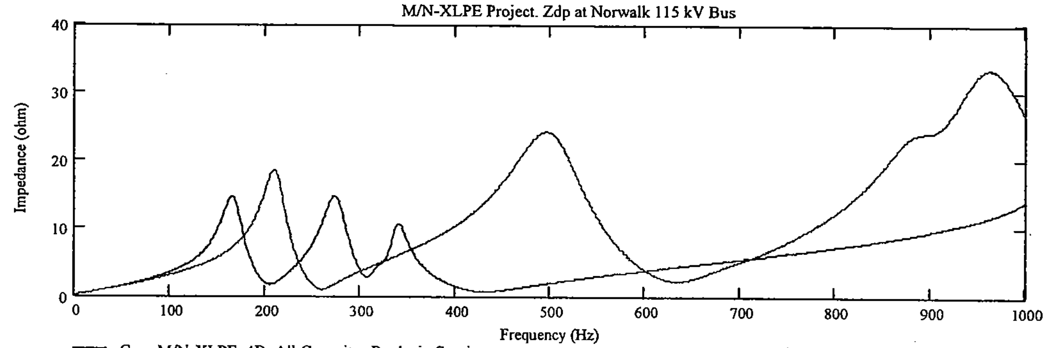
—— Case M/N-XLPE_2B, All Capacitor Banks in Service
—— Case M/N-XLPE_2C, All Capacitor Banks Out of Service

M/N-XLPE Project. Zdp at Norwalk 345 kV Bus



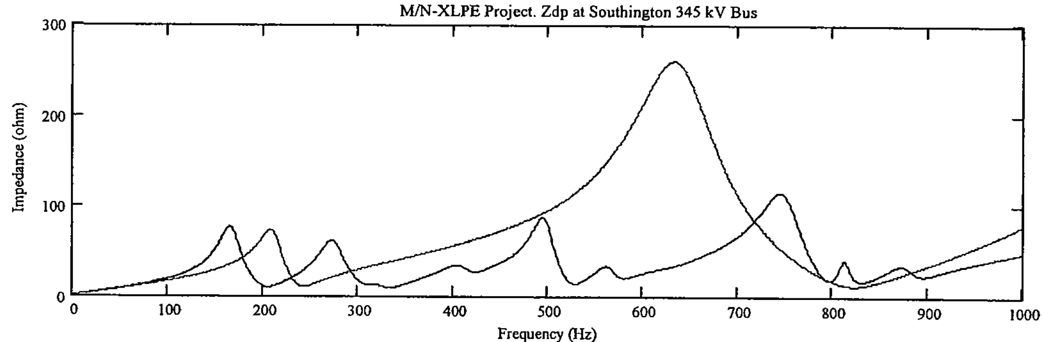
—— Case M/N-XLPE_3B, All Capacitor Banks in Service
—— Case M/N-XLPE_3C, All Capacitor Banks Out of Service

M/N-XLPE Project. Zdp at Norwalk 115 kV Bus



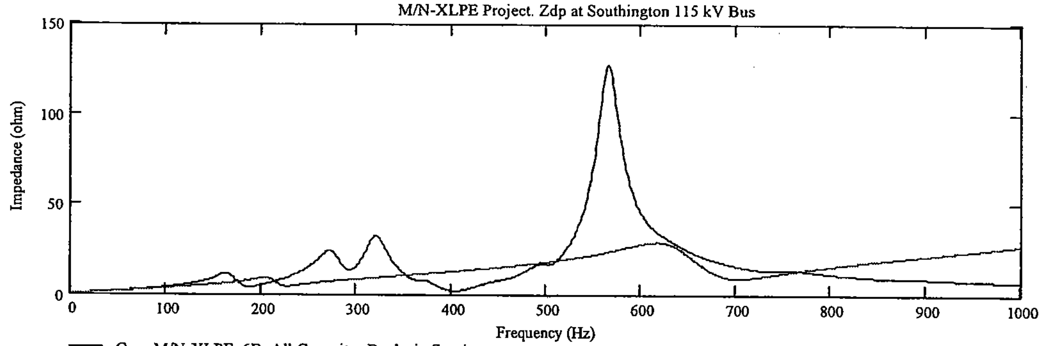
Case M/N-XLPE_4B, All Capacitor Banks in Service
Case M/N-XLPE_4C, All Capacitor Banks Out of Service

M/N-XLPE Project. Zdp at Southington 345 kV Bus



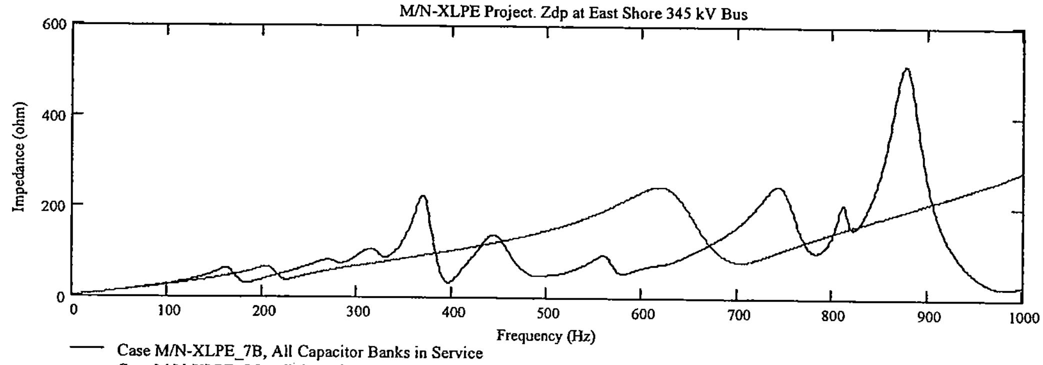
Case M/N-XLPE_5B, All Capacitor Banks in Service
Case M/N-XLPE_5C, All Capacitor Banks Out of Service

M/N-XLPE Project. Zdp at Southington 115 kV Bus



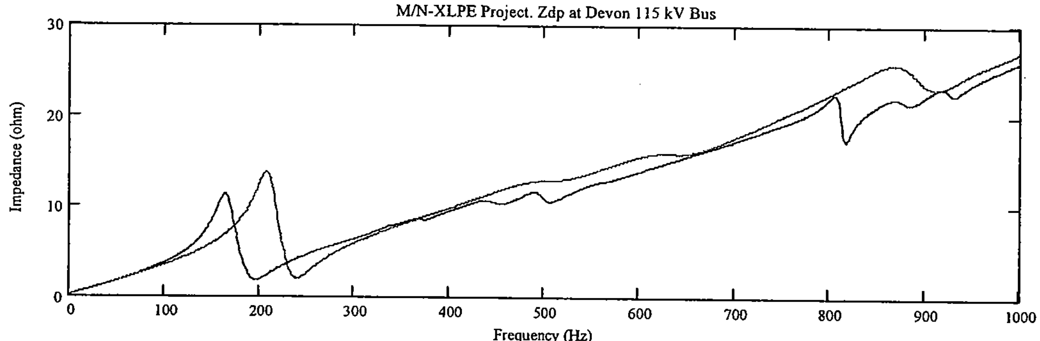
Case M/N-XLPE_6B, All Capacitor Banks in Service
Case M/N-XLPE_6C, All Capacitor Banks Out of Service

M/N-XLPE Project. Zdp at East Shore 345 kV Bus



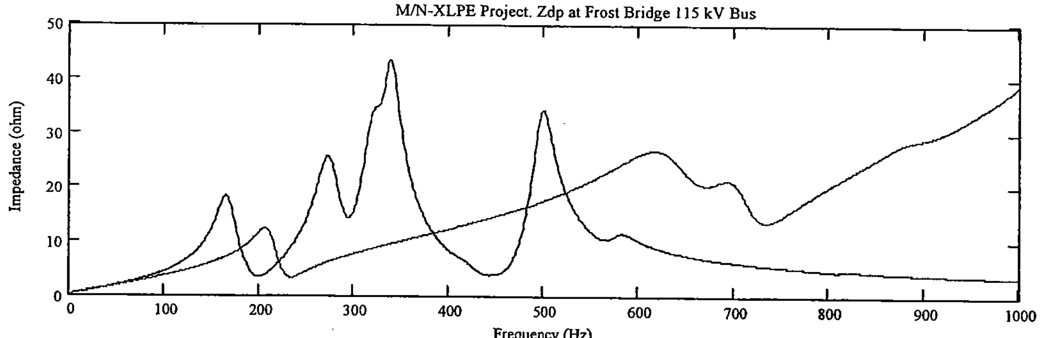
Case M/N-XLPE_7B, All Capacitor Banks in Service
Case M/N-XLPE_7C, All Capacitor Banks Out of Service

M/N-XLPE Project. Zdp at Devon 115 kV Bus

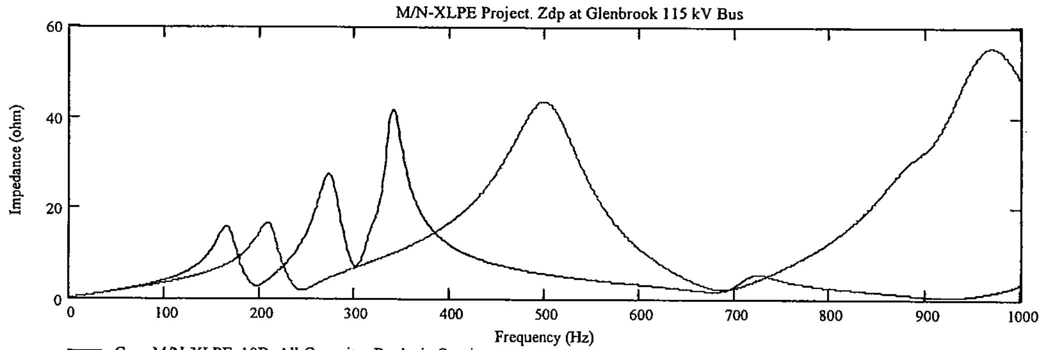


Case M/N-XLPE_8B, All Capacitor Banks in Service
Case M/N-XLPE_8C, All Capacitor Banks Out of Service

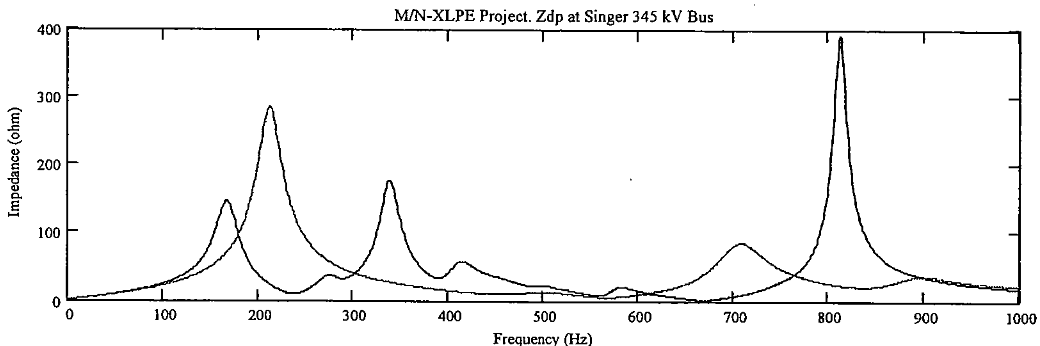
M/N-XLPE Project. Zdp at Frost Bridge 115 kV Bus



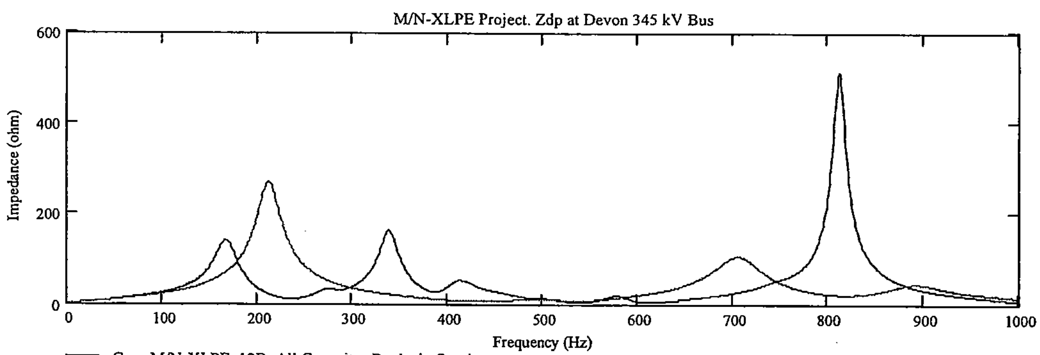
Case M/N-XLPE_9B, All Capacitor Banks in Service
Case M/N-XLPE_9C, All Capacitor Banks Out of Service



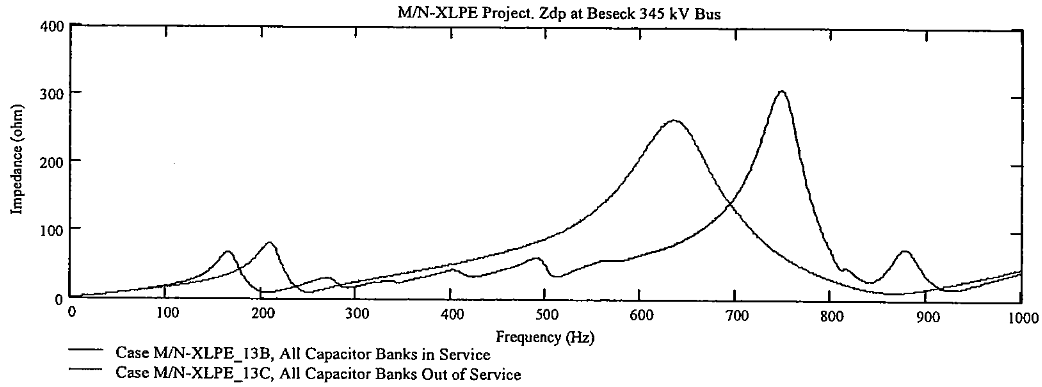
Case M/N-XLPE_10B, All Capacitor Banks in Service
Case M/N-XLPE_10C, All Capacitor Banks Out of Service



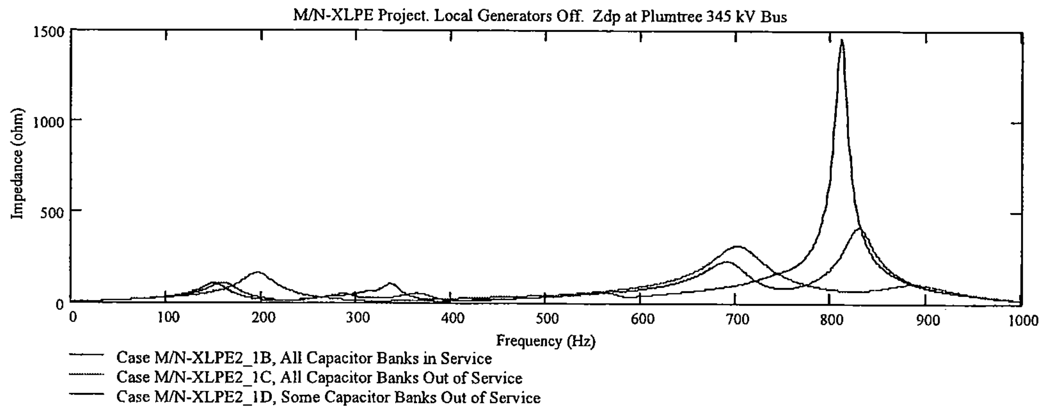
Case M/N-XLPE_11B, All Capacitor Banks in Service
Case M/N-XLPE_11C, All Capacitor Banks Out of Service

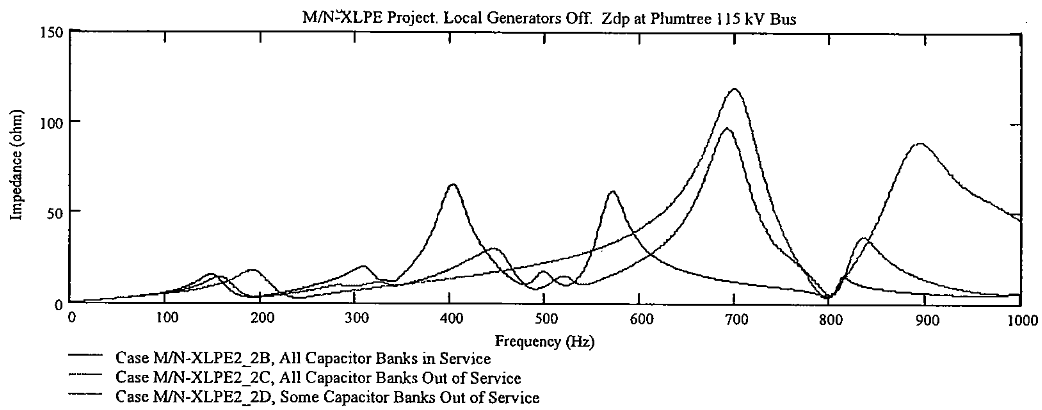


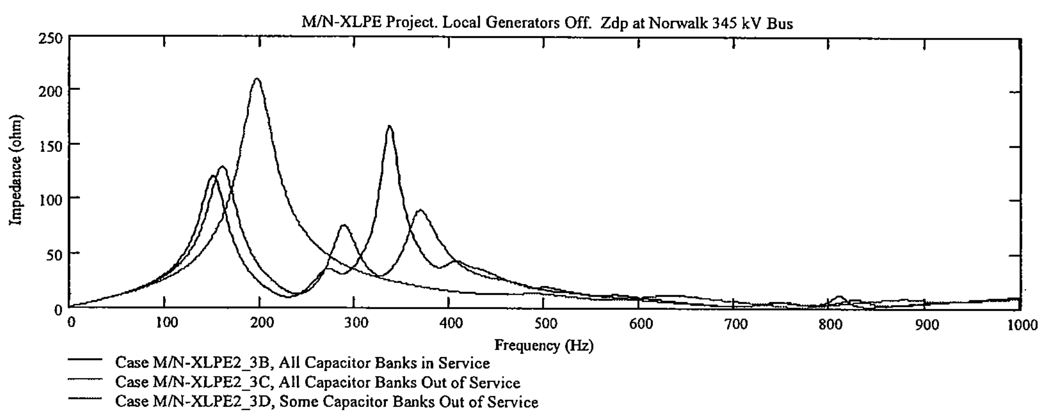
Case M/N-XLPE_12B, All Capacitor Banks in Service
Case M/N-XLPE_12C, All Capacitor Banks Out of Service

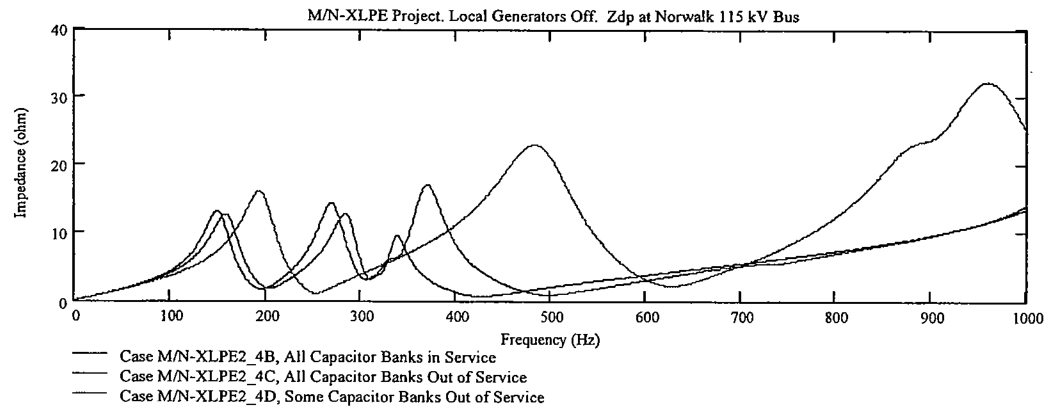

M/N-XLPE Project. Zdp at Beseck 345 kV Bus
400
300
200
100
0
Impedance (ohm)
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE_13B, All Capacitor Banks in Service
Case M/N-XLPE_13C, All Capacitor Banks Out of Service

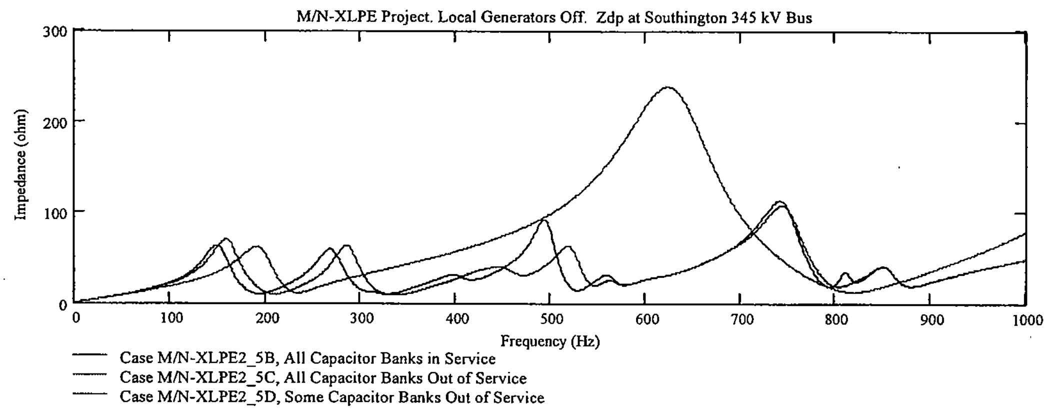
Appendix B Driving-Point Impedance Plots with Local Generators Off

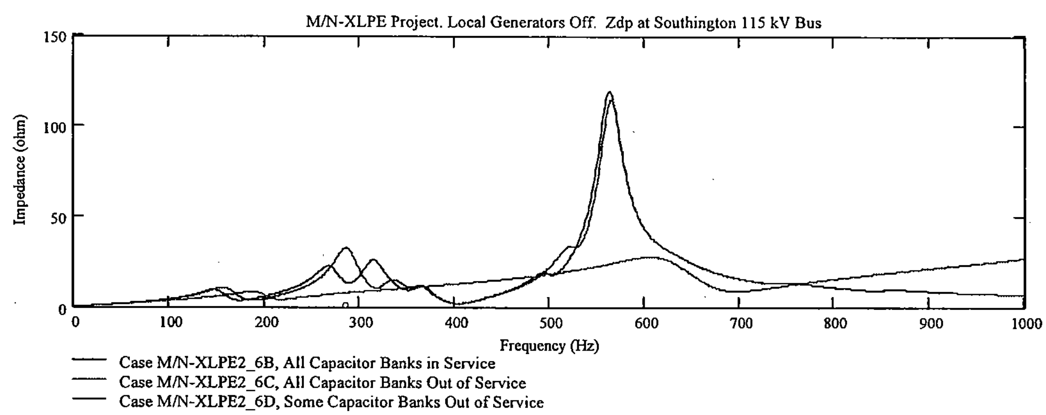


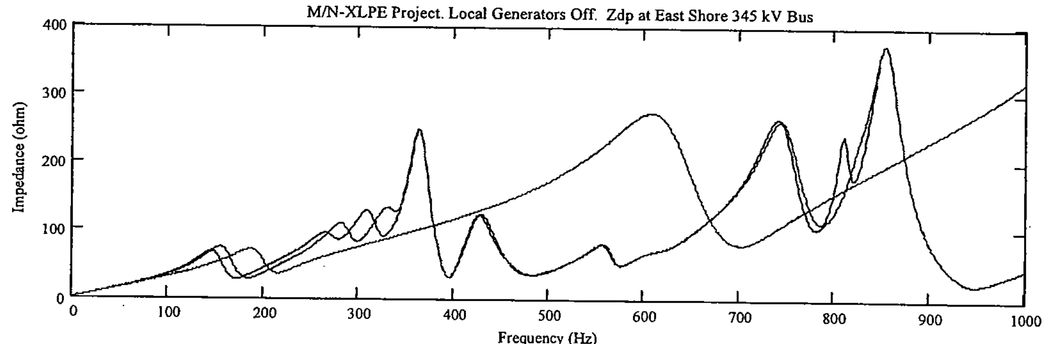




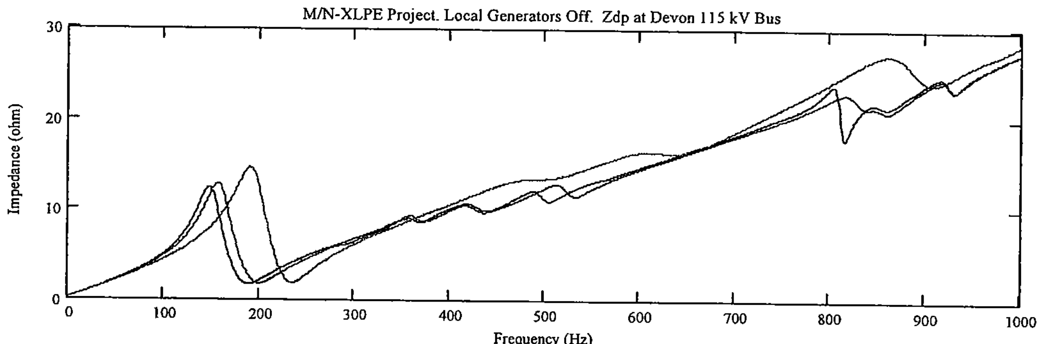

M/N-XLPE Project. Local Generators Off. Zdp at Norwalk 115 kV Bus
Impedance (ohm)
Frequency (Hz)
Case M/N-XLPE2_4B, All Capacitor Banks in Service
Case M/N-XLPE2_4C, All Capacitor Banks Out of Service
Case M/N-XLPE2_4D, Some Capacitor Banks Out of Service


M/N-XLPE Project. Local Generators Off. Zdp at Southington 345 kV Bus
Impedance (ohm)
Frequency (Hz)
Case M/N-XLPE2_5B, All Capacitor Banks in Service
Case M/N-XLPE2_5C, All Capacitor Banks Out of Service
Case M/N-XLPE2_5D, Some Capacitor Banks Out of Service

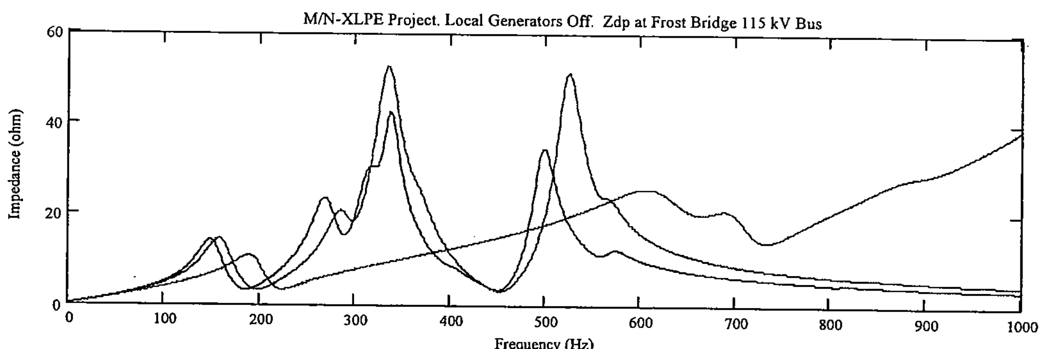

M/N-XLPE Project. Local Generators Off. Zdp at Southington 115 kV Bus
Impedance (ohm)
Frequency (Hz)
Case M/N-XLPE2_6B, All Capacitor Banks in Service
Case M/N-XLPE2_6C, All Capacitor Banks Out of Service
Case M/N-XLPE2_6D, Some Capacitor Banks Out of Service



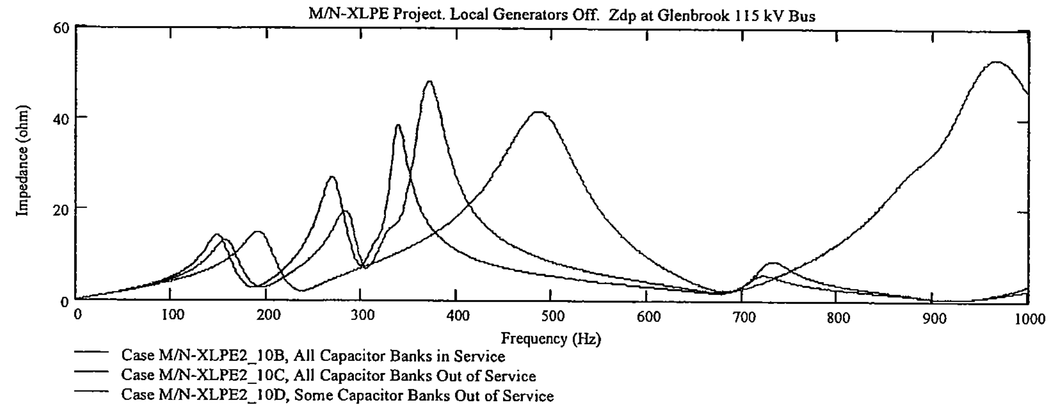
Case M/N-XLPE2_7B, All Capacitor Banks in Service
Case M/N-XLPE2_7C, All Capacitor Banks Out of Service
Case M/N-XLPE2_7D, Some Capacitor Banks Out of Service

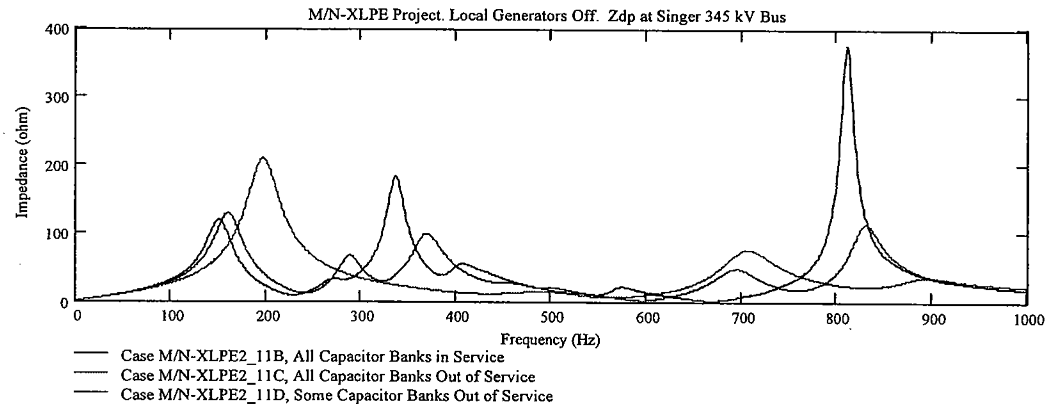


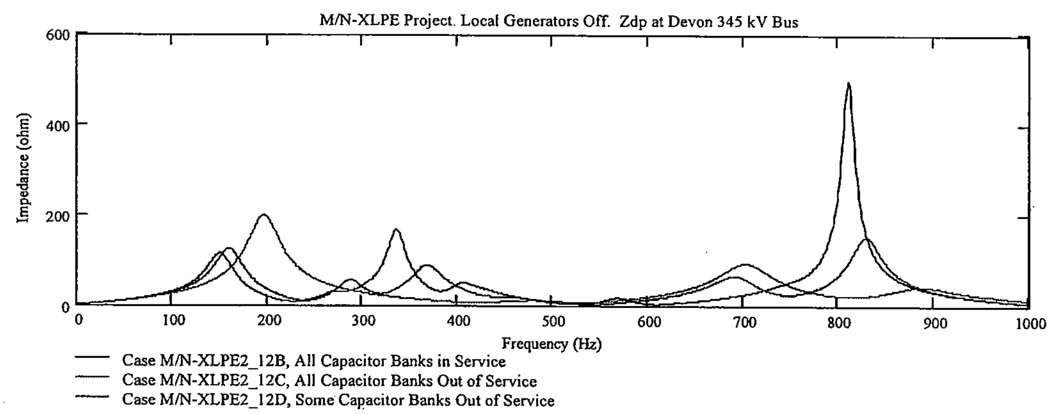
Case M/N-XLPE2_8B, All Capacitor Banks in Service
Case M/N-XLPE2_8C, All Capacitor Banks Out of Service
Case M/N-XLPE2_8D, Some Capacitor Banks Out of Service

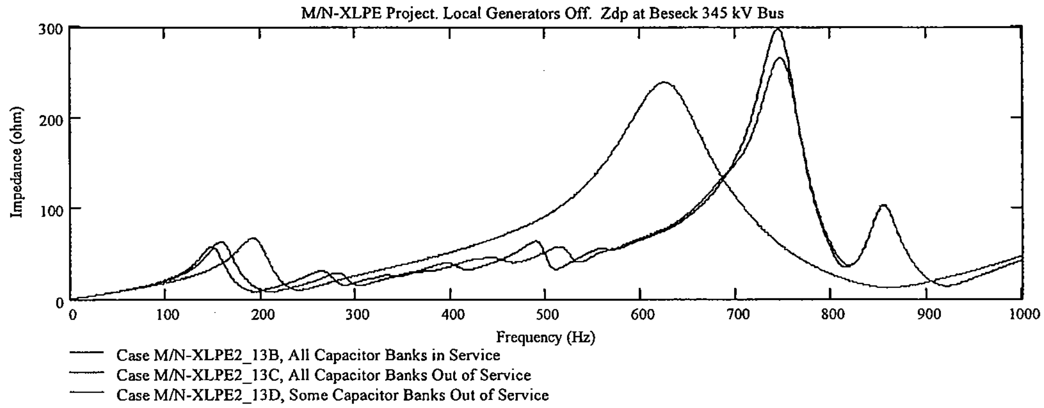


Case M/N-XLPE2_9B, All Capacitor Banks in Service
Case M/N-XLPE2_9C, All Capacitor Banks Out of Service
Case M/N-XLPE2_9D, Some Capacitor Banks Out of Service


M/N-XLPE Project. Local Generators Off. Zdp at Glenbrook 115 kV Bus
Impedance (ohm)
60
40
20
0
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE2_10B, All Capacitor Banks in Service
Case M/N-XLPE2_10C, All Capacitor Banks Out of Service
Case M/N-XLPE2_10D, Some Capacitor Banks Out of Service


M/N-XLPE Project. Local Generators Off. Zdp at Singer 345 kV Bus
Impedance (ohm)
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE2_11B, All Capacitor Banks in Service
Case M/N-XLPE2_11C, All Capacitor Banks Out of Service
Case M/N-XLPE2_11D, Some Capacitor Banks Out of Service


M/N-XLPE Project. Local Generators Off. Zdp at Devon 345 kV Bus
Impedance (ohm)
600
400
200
0
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE2_12B, All Capacitor Banks in Service
Case M/N-XLPE2_12C, All Capacitor Banks Out of Service
Case M/N-XLPE2_12D, Some Capacitor Banks Out of Service



M/N-XLPE Project. Local Generators Off. Zdp at Beseck 345 kV Bus
Impedance (ohm)
300
200
100
0
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE2_13B, All Capacitor Banks in Service
Case M/N-XLPE2_13C, All Capacitor Banks Out of Service
Case M/N-XLPE2_13D, Some Capacitor Banks Out of Service

CASE 5A

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

Prepared for:

Northeast Utilities

July 2004

GE Energy
Schenectady, NY

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

July 2004

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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 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 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 report[1], 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 1204-1997[2]. 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

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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 semi-conductor 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 report[3]. 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 rectifier[ii] and inverter[iii] 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

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[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 11^{th}, 13^{th}, 23^{rd}, and 25^{th} harmonics. Sometimes filters are also required which are tuned to non-characteristic harmonics, such as the 3^{rd} 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 study[4]. 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.

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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

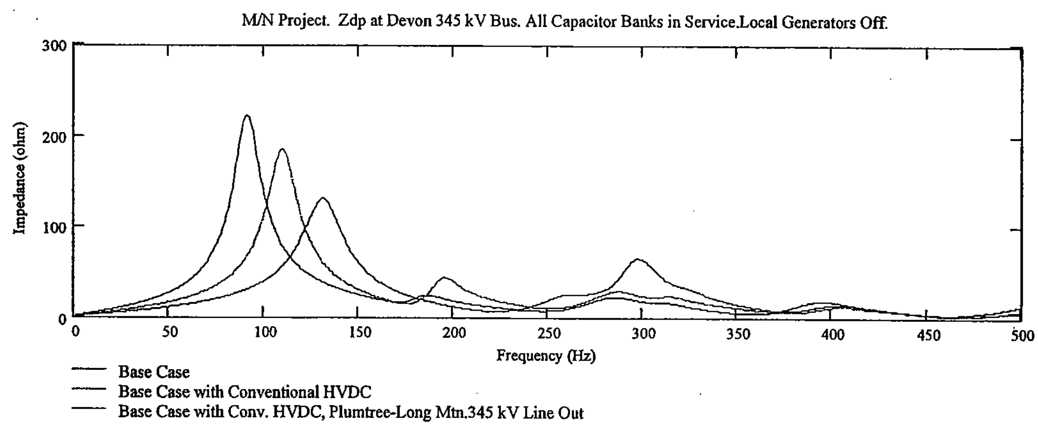

Figure 1. *Driving point impedance versus frequency at the East Devon 345 kV ac bus with HPFF ac cables.*

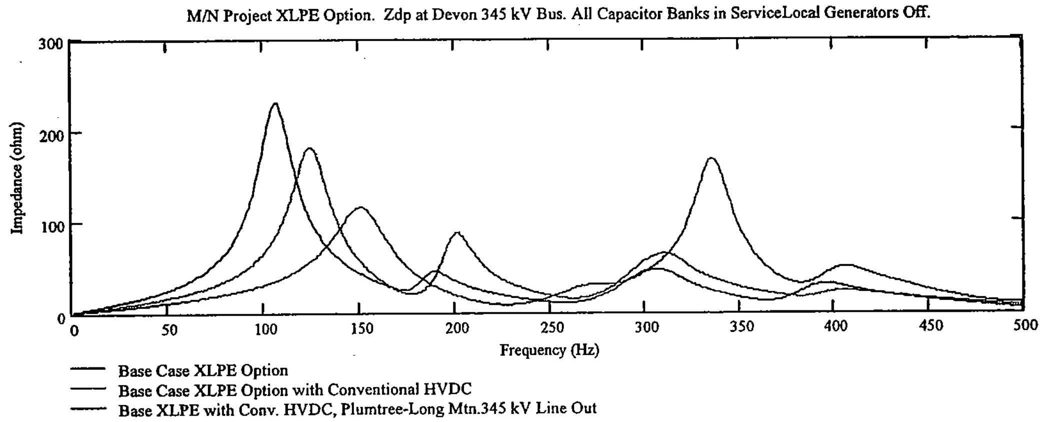

Figure 2. *Driving point impedance versus frequency at the East Devon 345 kV ac bus with XLPE ac cables.*

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	*(not analyzed)*
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

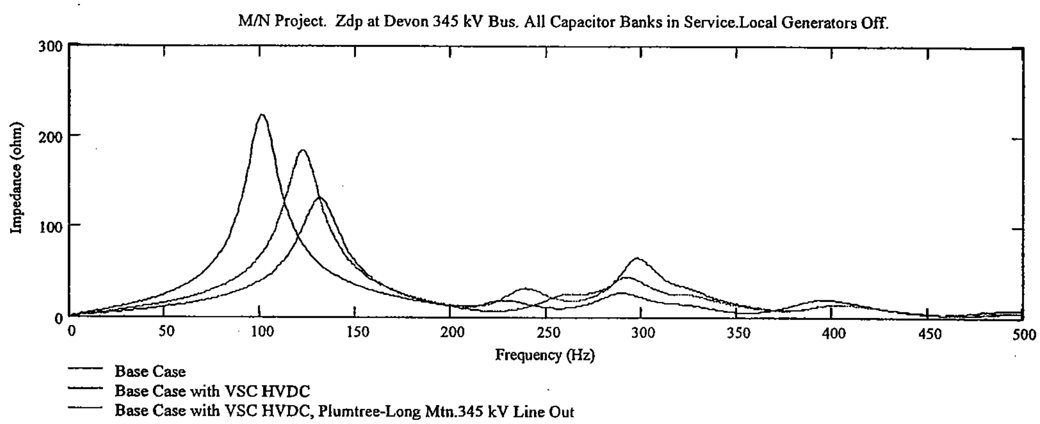

Figure 3. *Driving point impedance versus frequency at the East Devon 345 kV ac bus with HPFF ac cables.*

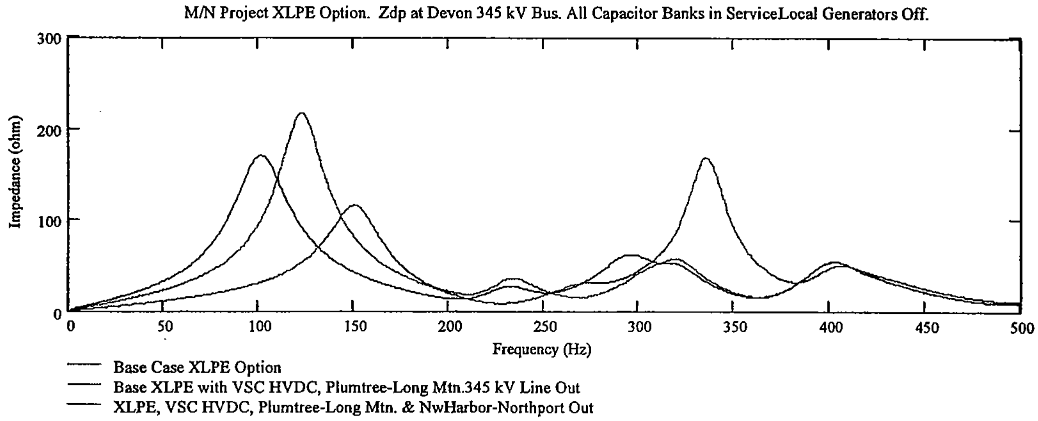

Figure 4. *Driving point impedance versus frequency at the East Devon 345 kV ac bus with XLPE ac cables.*

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

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[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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