CASE 5D

Connecticut Cable Resonance Study for Synchronous Condenser Option 2 (Case 5d) in Middletown to Norwalk Project

Summary Report
August 2004

Prepared for:
Northeast Utilities

GE Energy
NU MN XLPE SC2 Case 5d Report.doc

Connecticut Cable Resonance Study for Synchronous Condenser Option 2 (Case 5d) in Middletown to Norwalk Project

Summary Report
August 2004

Principal Contributors:
Sang Y. Lee
Elizabeth R. Pratico
Reigh A. Walling

Energy Consulting
GE Energy
One River Road
Schenectady, NY 12345 USA

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:

Elizabeth R. Pratico
Energy Consulting
GE Energy
1 River Road
Building 5, Room 310
Schenectady, New York 12345
Phone: (518) 385-5624
Fax: (518) 385-2860
E-mail: elizabeth.pratico@ps.ge.com

Legal Notice

This report was prepared by General Electric Company as an account of work sponsored by Northeast Utilities (NU). Neither NU nor GE, nor any person acting on behalf of either:

1. Makes any warranty or representation, expressed or implied, with respect to the use of any information contained in this report, or that the use of any information, apparatus, method, or process disclosed in the report may not infringe privately owned rights.

2. Assumes any liabilities with respect to the use of or for damage resulting from the use of any information, apparatus, method, or process disclosed in this report.

Table of Contents

Introduction

GE Energy's Energy Consulting group has performed a resonance study of "Synchronous Condenser Option 2" (Case 5d) in the Northeast Utilities (NU) Middletown to Norwalk 345 kV transmission cable project that is proposed in southwestern Connecticut. This option connects a 500 MVA synchronous condenser at East Devon 345 kV through a GSU and another 500 MVA synchronous condenser at Singer 345 kV. 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 the XLPE alternative, 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.

Two 500 MVA synchronous condensers were connected through GSUs: one at East Devon 345 kV and another at Singer 345 kV. The synchronous condenser was modeled as a voltage source behind a subtransient reactance Xd", assumed to be 25% (on 500 MVA base) which is similar to that of 4-pole turbine-generator units.[1] A 500 MVA GSU transformer with 10% impedance (on 500 MVA base) was assumed.

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):

Singer to Norwalk - 15.5 miles
Rpos=0.0003477 pu
Rzero=0.00358118 pu
Xpos=0.00416198 pu
Xzero=0.0023779 pu
Bposzero=1.9637 pu

East Devon to Singer - 8.1 miles
Rpos=0.0001817 pu

---

[1] T.J.E. Miller, *Reactive Power Control in Electric Systems*, John Wiley & Sons, Inc., 1982, p. 277.

Rzero=0.0018715 pu
Xpos=0.00217497 pu
Xzero=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			**All Banks**	**Peak Load**	**Light Load**
Substation	**Voltage (kV)**	**# Units**	**MVAR (total)**	**MVAR**	**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

* 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 Synchronous Condenser Option 2 (Case 5d), including XLPE cables from East Devon to Singer and Singer to Norwalk and 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 Synchronous Condenser Option 2 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.

Table 3. Resonant Frequencies for M/N-XLPE Project with Light Load Generation A 500 MVA Synchronous Condenser at East Devon & Singer 345 kV Buses

			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-SC2_1B	Plumtree 345 kV	All in Service	3.0	117	5.7	131	13.6	1480
M/N-XLPE-SC2_1C	Plumtree 345 kV	All Out of Service	3.9	218			11.8	330
M/N-XLPE-SC2_2B	Plumtree 115 kV	All in Service	2.9	19	6.9	74	9.7	63
M/N-XLPE-SC2_2C	Plumtree 115 kV	All Out of Service	3.8	23			11.8 15.0	128 96
M/N-XLPE-SC2_3B	Norwalk 345 kV	All in Service	3.0	123	5.8	182		
M/N-XLPE-SC2_3C	Norwalk 345 kV	All Out of Service	3.9	270				
M/N-XLPE-SC2_4B	Norwalk 115 kV	All in Service	3.0	14	4.6	16		
M/N-XLPE-SC2_4C	Norwalk 115 kV	All Out of Service	3.8	19			8.3 16.1	24 33
M/N-XLPE-SC2_5B	Southington 345 kV	All in Service	3.0	78	4.6	55	8.2 12.4	86 115
M/N-XLPE-SC2_5C	Southington 345 kV	All Out of Service	3.8	72			10.6	260
M/N-XLPE-SC2_6B	Southington 115 kV	All in Service	2.9	12	4.5 5.3	22 33	9.4	127
M/N-XLPE-SC2_6C	Southington 115 kV	All Out of Service	3.8	10			10.3	29
M/N-XLPE-SC2_7B	East Shore 345 kV	All in Service	2.9	65	6.2	224	12.4 14.6	247 514
M/N-XLPE-SC2_7C	East Shore 345 kV	All Out of Service	3.7	70			10.3	245
M/N-XLPE-SC2_8B	Devon 115 kV	All in Service	2.9	11				
M/N-XLPE-SC2_8C	Devon 115 kV	All Out of Service	3.8	13				
M/N-XLPE-SC2_9B	Frost Bridge 115 kV	All in Service	3.0	20	4.6 5.8	23 39	8.3	34
M/N-XLPE-SC2_9C	Frost Bridge 115 kV	All Out of Service	3.8	13			10.3	27
M/N-XLPE-SC2_10B	Glenbrook 115 kV	All in Service	2.9	16	4.6 5.8	30 38		
M/N-XLPE-SC2_10C	Glenbrook 115 kV	All Out of Service	3.8	17	8.3	43	16.2	55
M/N-XLPE-SC2_11B	Singer 345 kV	All in Service	3.0	113	5.8	185	13.6	403
M/N-XLPE-SC2_11C	Singer 345 kV	All Out of Service	3.9	253				
M/N-XLPE-SC2_12B	Devon 345 kV	All in Service	3.0	108	5.7	166	13.6	515
M/N-XLPE-SC2_12C	Devon 345 kV	All Out of Service	3.9	234				
M/N-XLPE-SC2_13B	Beseck 345 kV	All in Service	2.9	66			12.5	307
M/N-XLPE-SC2_13C	Beseck 345 kV	All Out of Service	3.8	79			10.6	264

Table 4. Resonant Frequencies for M/N-XLPE Project with Local Generators Off A 500 MVA Synchronous Condenser at East Devon & Singer 345 kV Buses

			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-SC2_1B	Plumtree 345 kV	All in Service	2.7	94	5.7	131	13.6	1427
M/N-XLPE2-SC2_1C	Plumtree 345 kV	All Out of Service	3.6	161			11.8	296
M/N-XLPE2-SC2_2B	Plumtree 115 kV	All in Service	2.7	16	6.8	62	9.5	63
M/N-XLPE2-SC2_2C	Plumtree 115 kV	All Out of Service	3.6	19			11.7 14.9	118 87
M/N-XLPE2-SC2_3B	Norwalk 345 kV	All in Service	2.7	101	5.7	184		
M/N-XLPE2-SC2_3C	Norwalk 345 kV	All Out of Service	3.7	199				
M/N-XLPE2-SC2_4B	Norwalk 115 kV	All in Service	3.0	14	4.6	16		
M/N-XLPE2-SC2_4C	Norwalk 115 kV	All Out of Service	3.6	16			8.1 16.0	23 32
M/N-XLPE2-SC2_5B	Southington 345 kV	All in Service	2.7	65	4.5	54	8.2 12.4	92 113
M/N-XLPE2-SC2_5C	Southington 345 kV	All Out of Service	3.5	62			10.4	238
M/N-XLPE2-SC2_6B	Southington 115 kV	All in Service	2.7	11	4.5 5.2	21 27	9.4	119
M/N-XLPE2-SC2_6C	Southington 115 kV	All Out of Service	3.5	9			10.1	28
M/N-XLPE2-SC2_7B	East Shore 345 kV	All in Service	2.6	73	6.1	247	12.4 14.2	267 373
M/N-XLPE2-SC2_7C	East Shore 345 kV	All Out of Service	3.5	76			10.1	274
M/N-XLPE2-SC2_8B	Devon 115 kV	All in Service	2.7	12				
M/N-XLPE2-SC2_8C	Devon 115 kV	All Out of Service	3.5	14				
M/N-XLPE2-SC2_9B	Frost Bridge 115 kV	All in Service	2.7	16	4.5 5.7	21 39	8.3	35
M/N-XLPE2-SC2_9C	Frost Bridge 115 kV	All Out of Service	3.5	11			10.1	26
M/N-XLPE2-SC2_10B	Glenbrook 115 kV	All in Service	2.7	15	4.5 5.8	29 35		
M/N-XLPE2-SC2_10C	Glenbrook 115 kV	All Out of Service	3.6	16	8.1	41	16.1	53
M/N-XLPE2-SC2_11B	Singer 345 kV	All in Service	2.7	94	5.7	187	13.6	385
M/N-XLPE2-SC2_11C	Singer 345 kV	All Out of Service	3.7	188				
M/N-XLPE2-SC2_12B	Devon 345 kV	All in Service	2.7	90	5.7	168	13.6	498
M/N-XLPE2-SC2_12C	Devon 345 kV	All Out of Service	3.7	175				
M/N-XLPE2-SC2_13B	Beseck 345 kV	All in Service	2.6	56			12.4	297
M/N-XLPE2-SC2_13C	Beseck 345 kV	All Out of Service	3.6	66			10.4	239

Conclusions

Table 5 summarizes the variation in frequencies of the first resonance points for the M/N project, for the XLPE alternative, for Synchronous Condenser Option 1, and for Synchronous Condenser Option 2, with the original light load generator dispatch. Table 6 summarizes the variation in frequencies of the first resonance points in the light post-project dispatch with more local generation off. With Synchronous Condenser Option 2 and with the original light load generator dispatch, the first resonance is between 3.0 and 3.9 pu of 60 Hz at most 345 kV buses, with all capacitor banks in and out of service, respectively. With Synchronous Condenser Option 2 and with more local generation off, the first resonance is between 2.7 and 3.6 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)
with Original Light Load Generator Dispatch

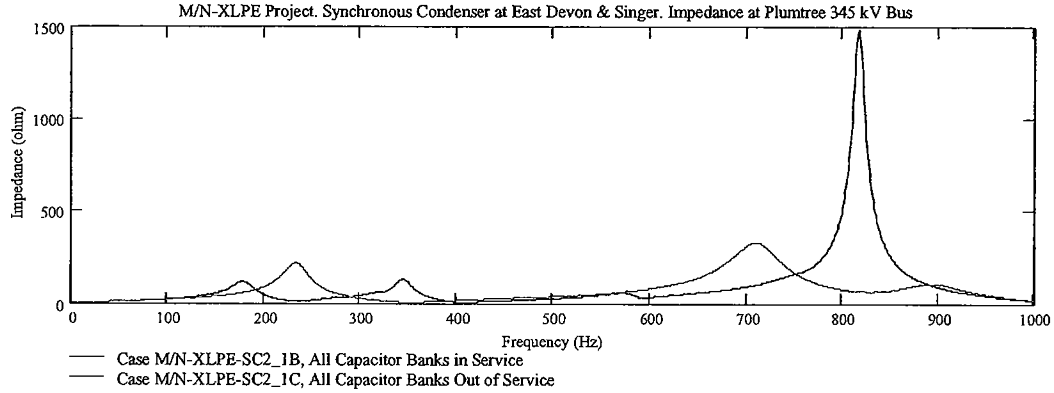
115 kV Capacitor Bank Conditions	M/N Project with HPFF Cable	M/N Project with XLPE Cable	Synchronous Condenser Option 1 (Case 5c)	Synchronous Condenser Option 2 (Case 5d)
All in service	2.4	2.8	2.9	3.0
All out of service	2.8	3.5	3.7	3.9

Table 6. Variation in Frequency of First Resonance Points (pu 60 Hz)
in Light Post-Project Dispatch with More Local Generators Off

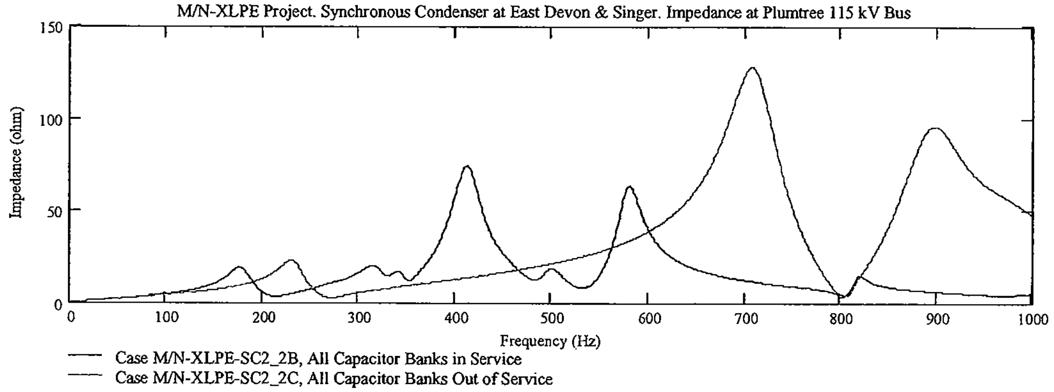
115 kV Capacitor Bank Conditions	M/N Project with HPFF Cable	M/N Project with XLPE Cable	Synchronous Condenser Option 1 (Case 5c)	Synchronous Condenser Option 2 (Case 5d)
All in service	-	2.5	2.6	2.7
All out of service	-	3.3	3.5	3.6

The addition of a second 500 MVA synchronous condenser at Singer results in a slightly higher frequency of the first resonance, as compared to the single synchronous condenser at East Devon. Since the short-circuit contribution at 345 kV of a 500 MVA synchronous condenser, with assumed impedances including GSU, is relatively small (about 2.4 kA) compared with the existing short-circuit levels, it has a relatively small impact on the resonant frequency. With the original light load generator dispatch and all capacitor banks in service, the frequency is 3.0 pu of 60 Hz. Risk of sustained overvoltages due to transformer inrush is increased when resonances are near 3rd harmonic or below. 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 Synchronous Condenser Option 2 (Case 5d) studied here is to be considered, then extensive transient studies would be recommended.

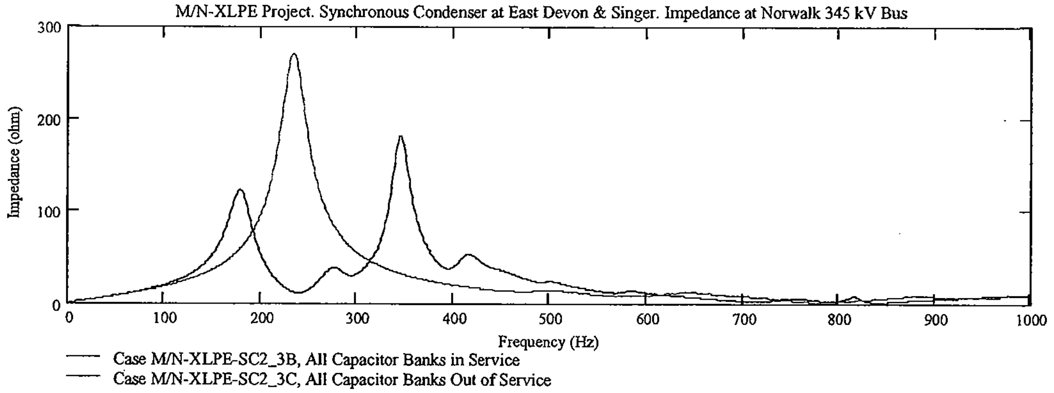
Appendix A Driving-Point Impedance Plots with Light Load Generation


M/N-XLPE Project. Synchronous Condenser at East Devon & Singer. Impedance at Plumtree 345 kV Bus

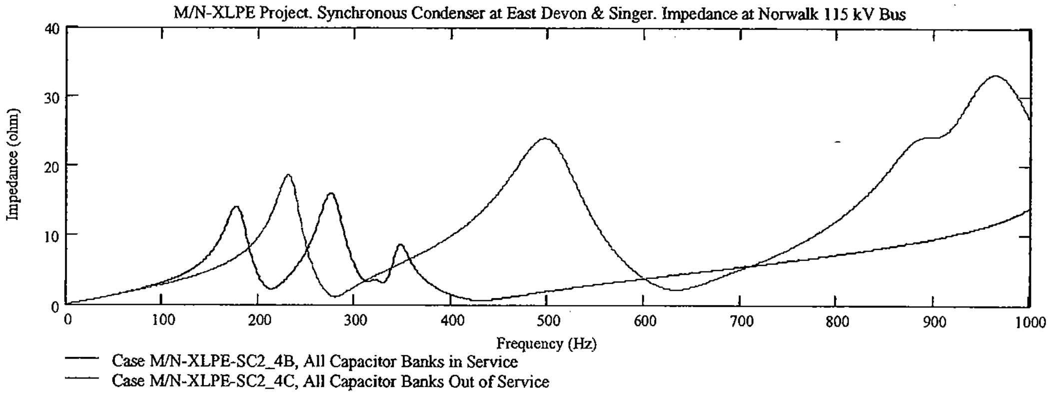
Case M/N-XLPE-SC2_1B, All Capacitor Banks in Service
Case M/N-XLPE-SC2_1C, All Capacitor Banks Out of Service

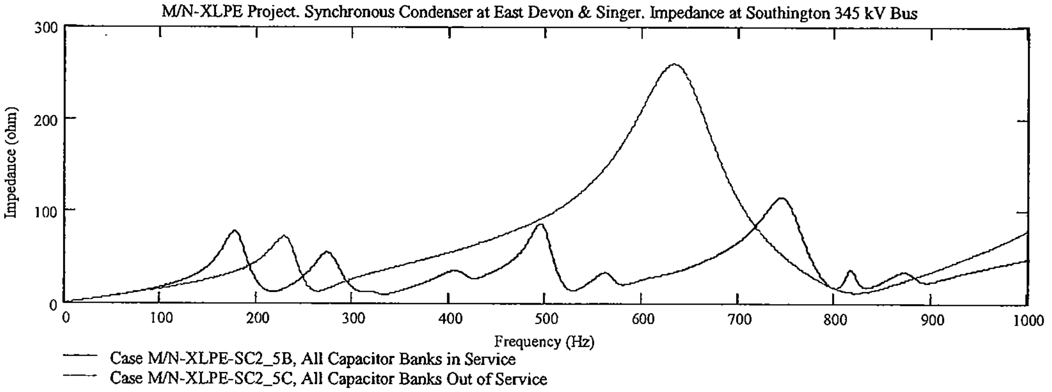

M/N-XLPE Project. Synchronous Condenser at East Devon & Singer. Impedance at Plumtree 115 kV Bus

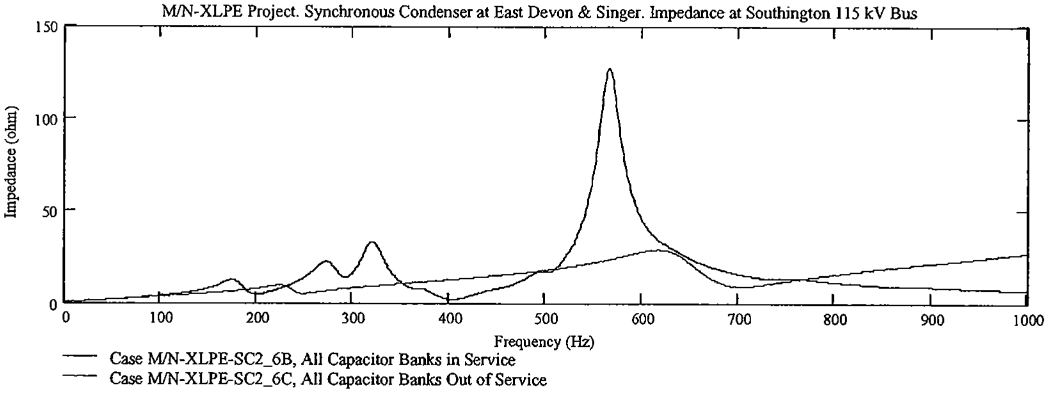
Case M/N-XLPE-SC2_2B, All Capacitor Banks in Service
Case M/N-XLPE-SC2_2C, All Capacitor Banks Out of Service


M/N-XLPE Project. Synchronous Condenser at East Devon & Singer. Impedance at Norwalk 345 kV Bus

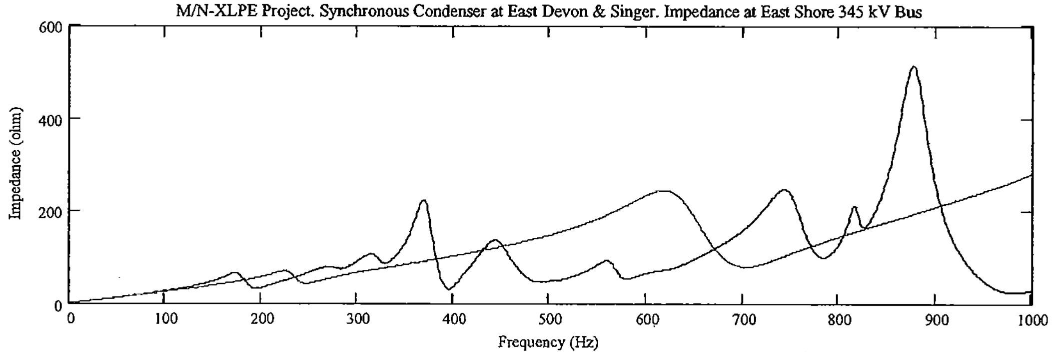
Case M/N-XLPE-SC2_3B, All Capacitor Banks in Service
Case M/N-XLPE-SC2_3C, All Capacitor Banks Out of Service


M/N-XLPE Project. Synchronous Condenser at East Devon & Singer. Impedance at Norwalk 115 kV Bus


M/N-XLPE Project. Synchronous Condenser at East Devon & Singer. Impedance at Southington 345 kV Bus

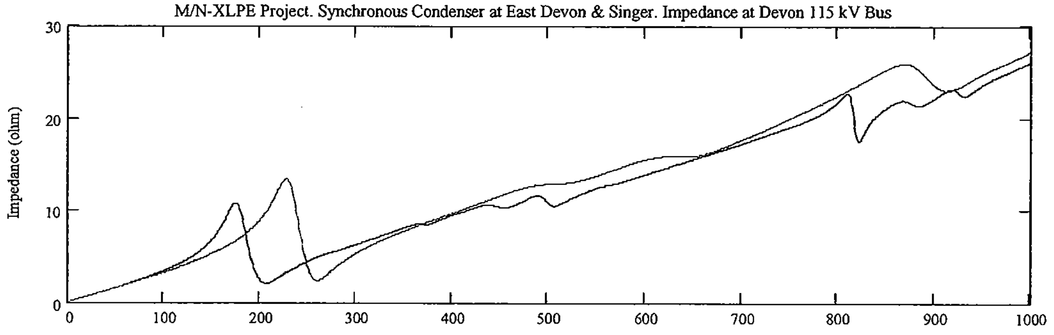

M/N-XLPE Project. Synchronous Condenser at East Devon & Singer. Impedance at Southington 115 kV Bus

M/N-XLPE Project. Synchronous Condenser at East Devon & Singer. Impedance at East Shore 345 kV Bus



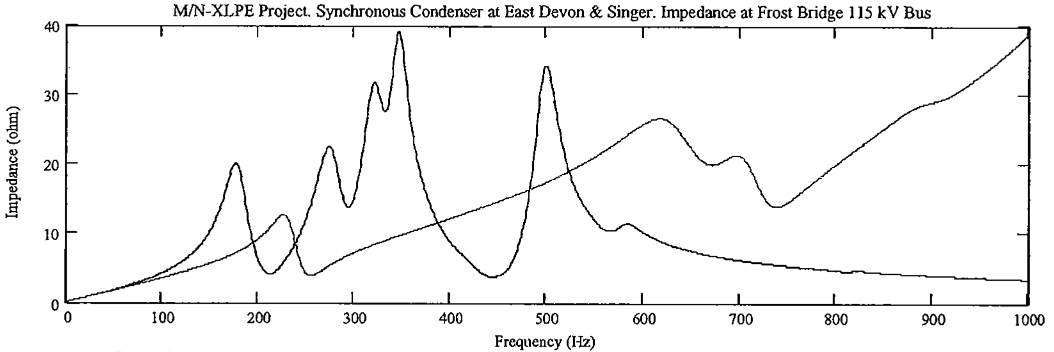
—— Case M/N-XLPE-SC2_7B, All Capacitor Banks in Service
—— Case M/N-XLPE-SC2_7C, All Capacitor Banks Out of Service

M/N-XLPE Project. Synchronous Condenser at East Devon & Singer. Impedance at Devon 115 kV Bus

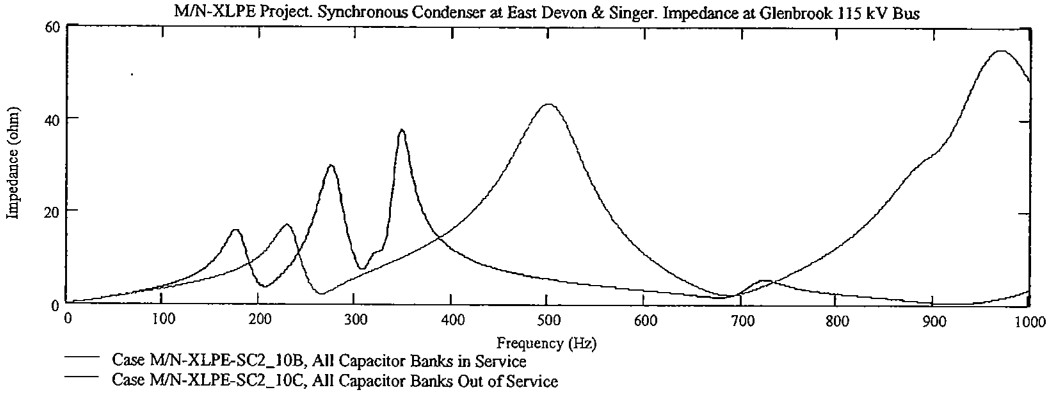


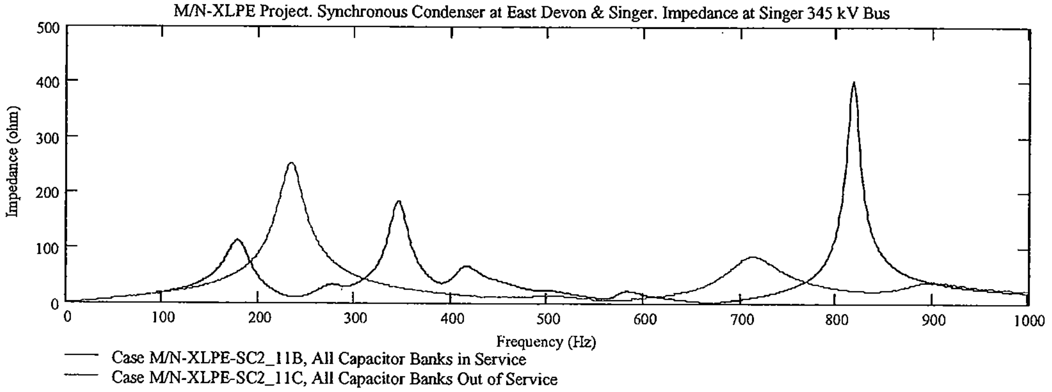
—— Case M/N-XLPE-SC2_8B, All Capacitor Banks in Service
—— Case M/N-XLPE-SC2_8C, All Capacitor Banks Out of Service

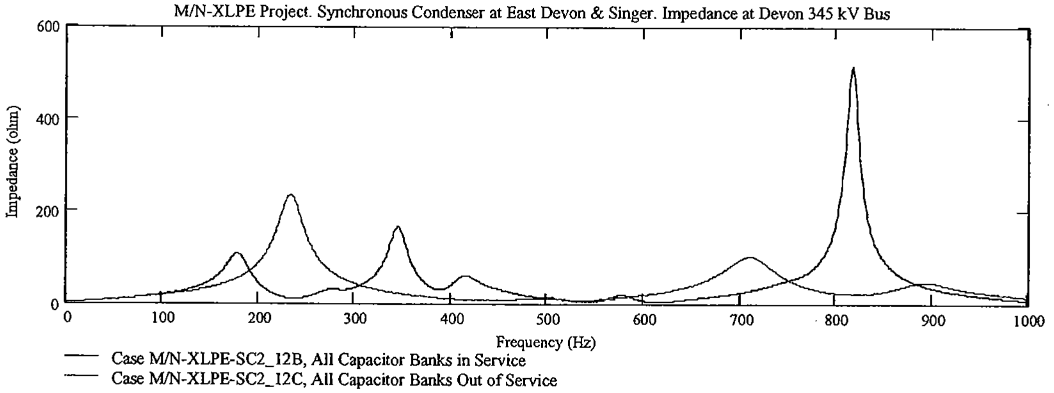
M/N-XLPE Project. Synchronous Condenser at East Devon & Singer. Impedance at Frost Bridge 115 kV Bus

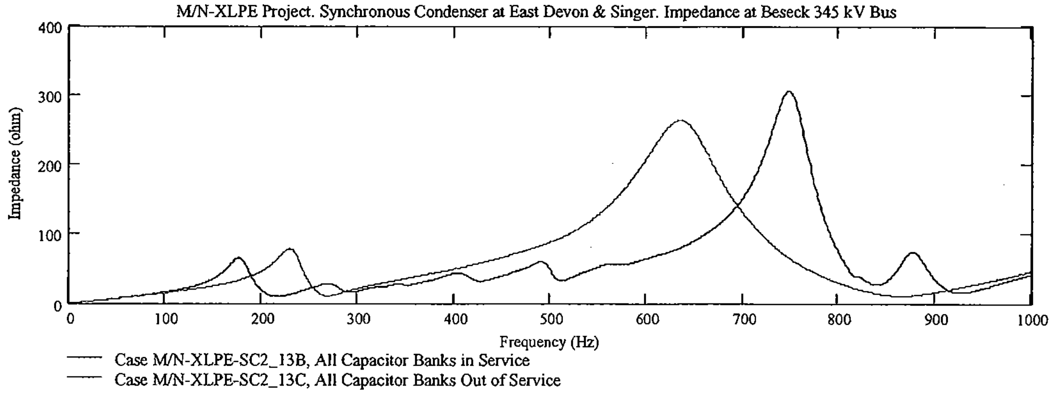


—— Case M/N-XLPE-SC2_9B, All Capacitor Banks in Service
—— Case M/N-XLPE-SC2_9C, All Capacitor Banks Out of Service

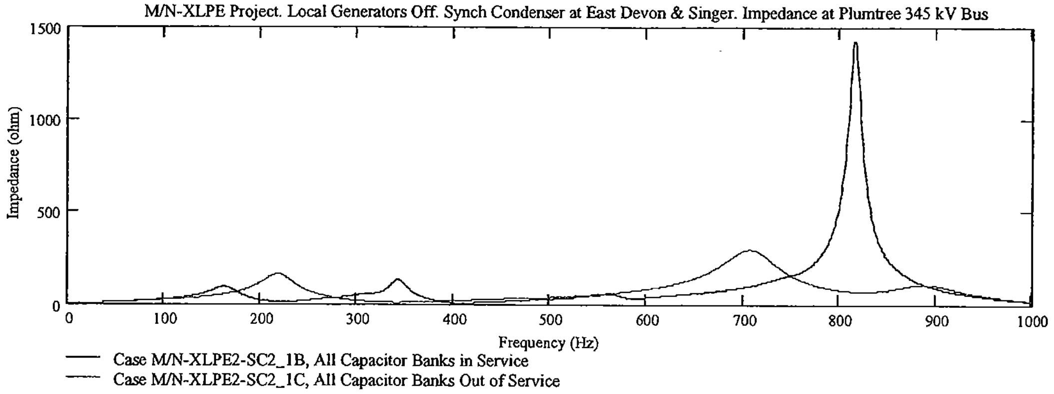

M/N-XLPE Project. Synchronous Condenser at East Devon & Singer. Impedance at Glenbrook 115 kV Bus
Impedance (ohm)
60
40
20
0
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE-SC2_10B, All Capacitor Banks in Service
Case M/N-XLPE-SC2_10C, All Capacitor Banks Out of Service

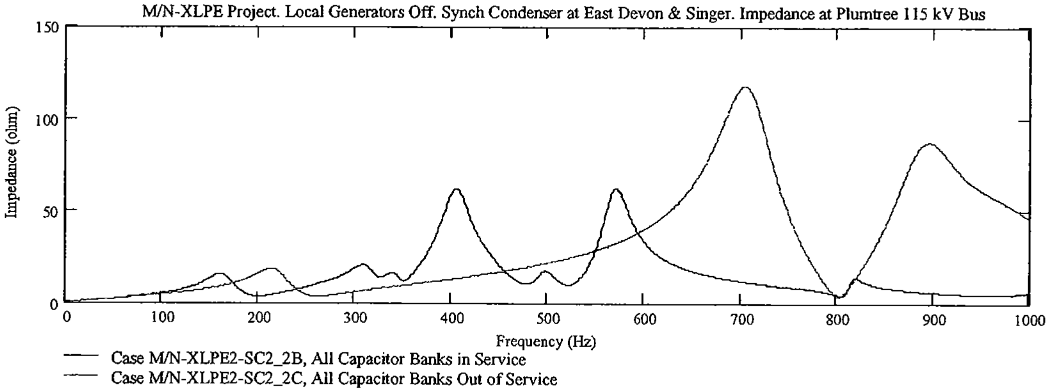

M/N-XLPE Project. Synchronous Condenser at East Devon & Singer. Impedance at Singer 345 kV Bus
Impedance (ohm)
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE-SC2_11B, All Capacitor Banks in Service
Case M/N-XLPE-SC2_11C, All Capacitor Banks Out of Service

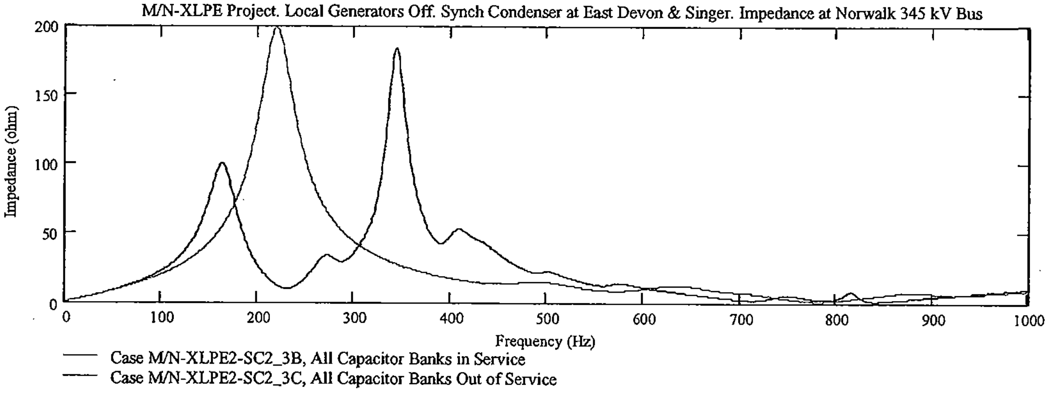

M/N-XLPE Project. Synchronous Condenser at East Devon & Singer. Impedance at Devon 345 kV Bus
Impedance (ohm)
600
400
200
0
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE-SC2_12B, All Capacitor Banks in Service
Case M/N-XLPE-SC2_12C, All Capacitor Banks Out of Service

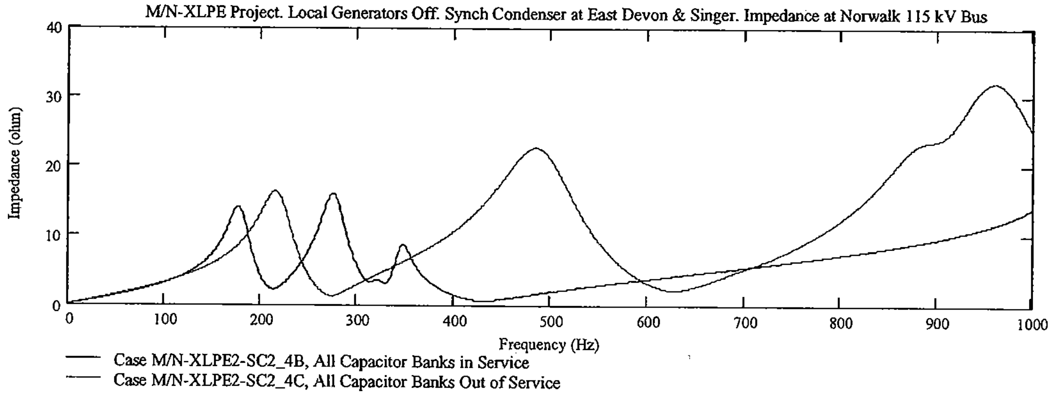

M/N-XLPE Project. Synchronous Condenser at East Devon & Singer. Impedance at Beseck 345 kV Bus
Impedance (ohm)
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE-SC2_13B, All Capacitor Banks in Service
Case M/N-XLPE-SC2_13C, All Capacitor Banks Out of Service

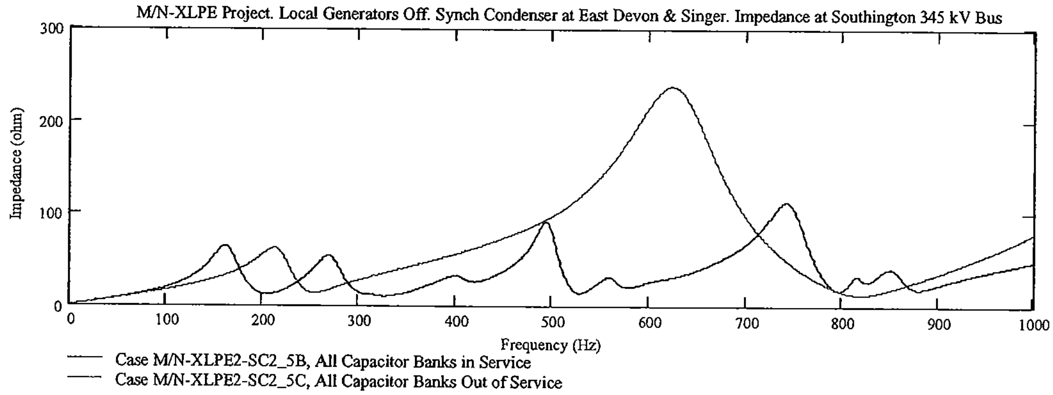
Appendix B Driving-Point Impedance Plots with Local Generators Off

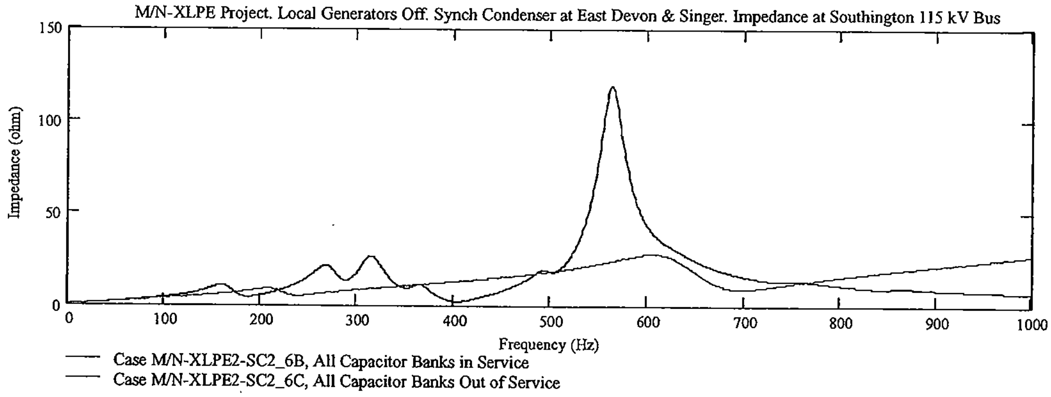


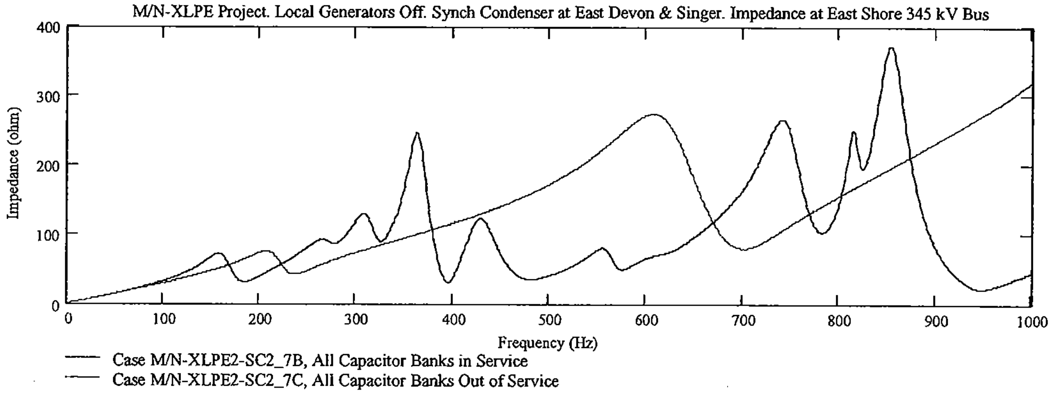




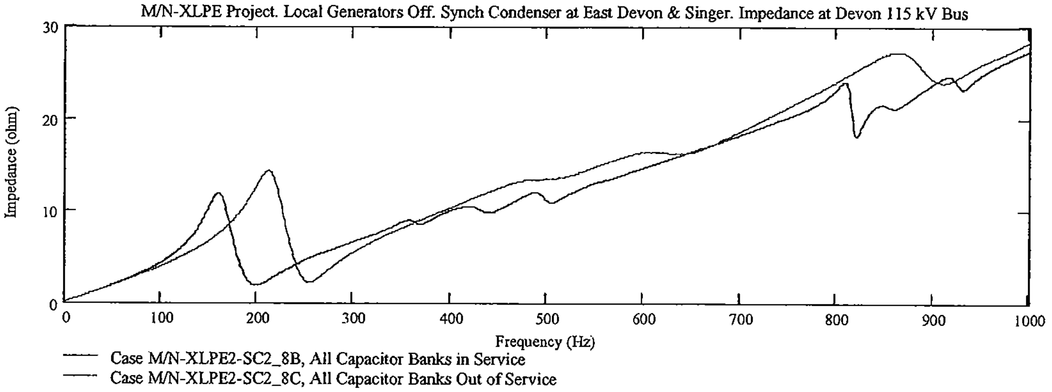

M/N-XLPE Project. Local Generators Off. Synch Condenser at East Devon & Singer. Impedance at Norwalk 115 kV Bus
Impedance (ohm)
40
30
20
10
0
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE2-SC2_4B, All Capacitor Banks in Service
Case M/N-XLPE2-SC2_4C, All Capacitor Banks Out of Service


M/N-XLPE Project. Local Generators Off. Synch Condenser at East Devon & Singer. Impedance at Southington 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-SC2_5B, All Capacitor Banks in Service
Case M/N-XLPE2-SC2_5C, All Capacitor Banks Out of Service

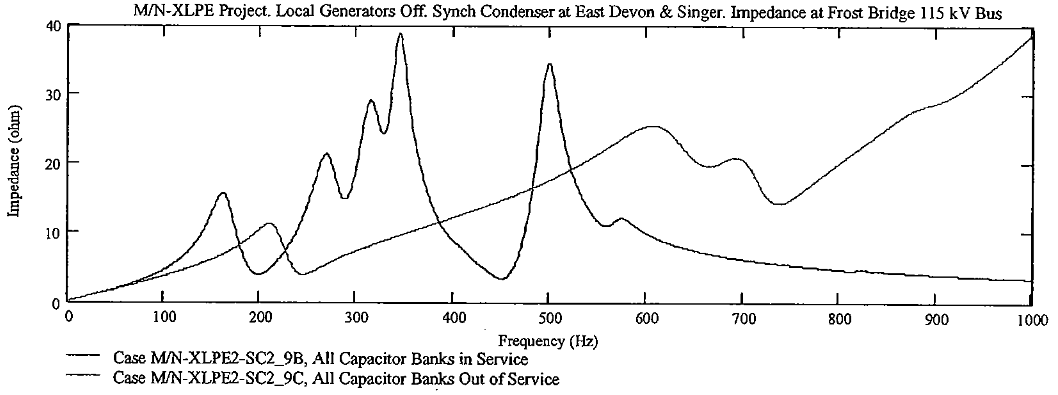

M/N-XLPE Project. Local Generators Off. Synch Condenser at East Devon & Singer. Impedance at Southington 115 kV Bus
Impedance (ohm)
150
100
50
0
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE2-SC2_6B, All Capacitor Banks in Service
Case M/N-XLPE2-SC2_6C, All Capacitor Banks Out of Service



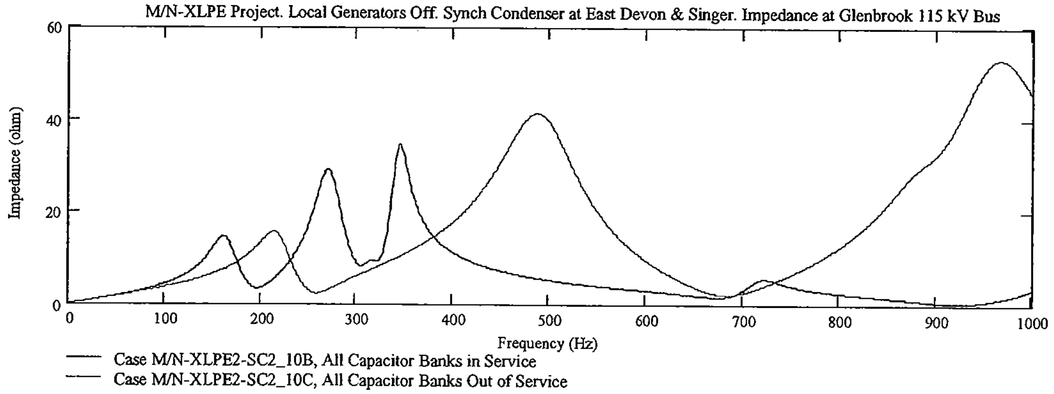
M/N-XLPE Project. Local Generators Off. Synch Condenser at East Devon & Singer. Impedance at East Shore 345 kV Bus

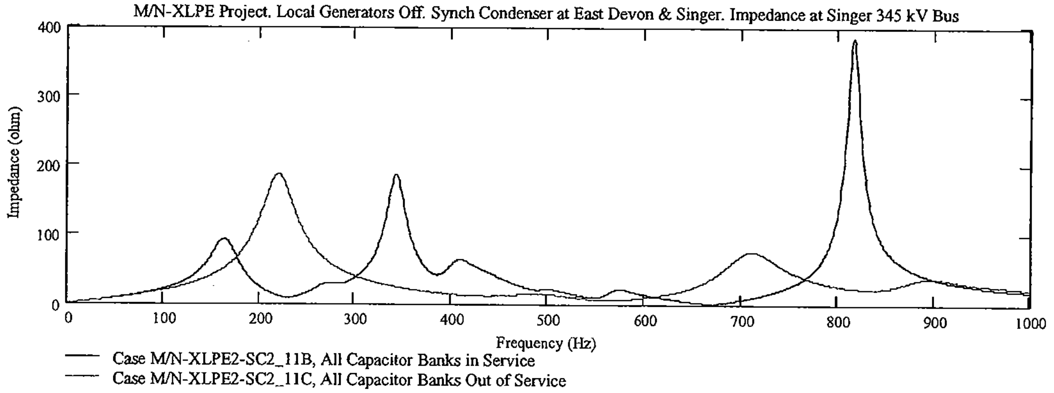


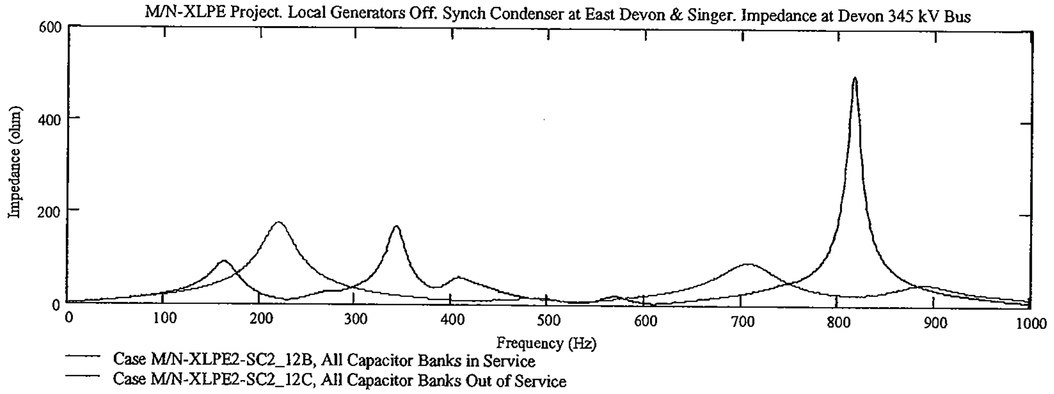
M/N-XLPE Project. Local Generators Off. Synch Condenser at East Devon & Singer. Impedance at Devon 115 kV Bus

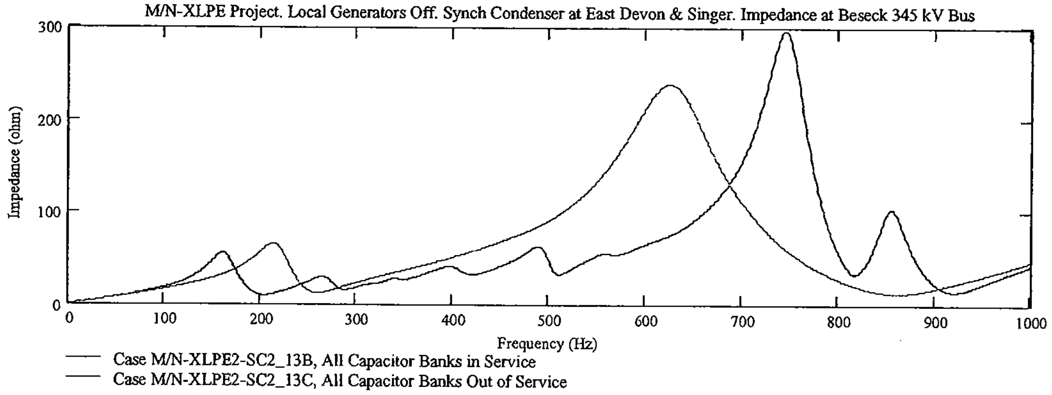


M/N-XLPE Project. Local Generators Off. Synch Condenser at East Devon & Singer. Impedance at Frost Bridge 115 kV Bus


M/N-XLPE Project. Local Generators Off. Synch Condenser at East Devon & Singer. Impedance at Glenbrook 115 kV Bus


M/N-XLPE Project. Local Generators Off. Synch Condenser at East Devon & Singer. Impedance at Singer 345 kV Bus


M/N-XLPE Project. Local Generators Off. Synch Condenser at East Devon & Singer. Impedance at Devon 345 kV Bus


M/N-XLPE Project. Local Generators Off. Synch Condenser at East Devon & Singer. Impedance 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-SC2_13B, All Capacitor Banks in Service
Case M/N-XLPE2-SC2_13C, All Capacitor Banks Out of Service

CASE 7

Connecticut Cable Resonance Study for XLPE Alternative in Middletown to Norwalk Project (Cases 5, 6, 7)

Summary Report, Rev. 1
August 2004

Prepared for:
Northeast Utilities

Connecticut Cable Resonance Study for XLPE Alternative in Middletown to Norwalk Project (Cases 5, 6, 7)

Summary Report, Rev. 1
August 2004

Principal Contributors:
Einar Larsen
Sang Y. Lee
Elizabeth R. Pratico
Reigh A. Walling

Energy Consulting
GE Energy
One River Road
Schenectady, NY 12345 USA

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:

Elizabeth R. Pratico
Energy Consulting
GE Energy
1 River Road
Building 5, Room 310
Schenectady, New York 12345
Phone: (518) 385-5624
Fax: (518) 385-2860
E-mail: elizabeth.pratico@ps.ge.com

Legal Notice

This report was prepared by General Electric Company as an account of work sponsored by Northeast Utilities (NU). Neither NU nor GE, nor any person acting on behalf of either:

1. Makes any warranty or representation, expressed or implied, with respect to the use of any information contained in this report, or that the use of any information, apparatus, method, or process disclosed in the report may not infringe privately owned rights.

2. Assumes any liabilities with respect to the use of or for damage resulting from the use of any information, apparatus, method, or process disclosed in this report.

Table of Contents

Introduction

GE Energy's Energy Consulting group has performed a resonance study of an XLPE alternative (Case 5) 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. Two additional variations were studied to analyze the effect of reduced capacitor banks at Plumtree, Frost Bridge and Glenbrook (Case 6) and further reduced capacitor banks at Frost Bridge, Glenbrook, Southington, Rocky River, and Stony Hill (Case 7). Although Case 7 includes replacement of 115 kV shunt capacitors with statcoms, this study does not include statcoms and represents the first step of evaluating the replacement of shunt capacitors with an alternate device for voltage regulation by considering only the removal of shunt capacitors.

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
Xzero=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
Xzero=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. Additional shunt capacitor conditions are shown in the last two columns of Table 1, where some 115 kV capacitor banks in the "All Banks In" condition (column 4) are taken out of service. The reduced bank condition for Case 6 has no capacitors at Plumtree, only 205.6 MVAr at Frost Bridge, and only 75.6 MVAr at Glenbrook. The reduced bank condition for Case 7 has no capacitors at Plumtree, Frost Bridge, Glenbrook, Southington, Rocky River, and Stony Hill.

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			All Banks	Peak Load	Light Load	Reduced Banks: Case 6	Reduced Banks: Case 7
Substation	**Voltage (kV)**	**# Units**	**MVAR**	**MVAR**	**MVAR**	**MVAR**	**MVAR**
Southington 1	115	3	157.2	157.2		157.2	0
Southington 2	115	3	157.2	157.2		157.2	0
Frost Bridge	115	5	262.0	262.0		205.6	0
Berlin	115	3	132.0	132.0		132.0	132.0
Plumtree	115	2	92.2	0		0	0
Glenbrook	115	5	190.8*	151.2		75.6	0
Darien	115	1	39.6	39.6		39.6	39.6
Waterside	115	1	39.6	39.6		39.6	39.6
Norwalk	115	0	0	0		0	0
East Shore	115	2	84.0	84.0		84.0	84.0
No. Haven	115	1	42.0	42.0		42.0	42.0
Sackett	115	1	42.0	42.0		42.0	42.0
Rocky River	115	1	25.2	25.2		25.2	0
Stony Hill	115	1	25.2	25.2		25.2	0
Cross Sound Filters	200	3	103.0 (61 – 25th, 32 – 41st, 10 – 21st)	103.0	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 (Case 5), 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. The reduced capacitor bank configurations (Case 6 and Case 7) were also evaluated under the original light load and light post-project generator 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 include rows corresponding to the cases where some capacitor banks are taken out of service as shown in the last two columns of Table 1. The Case 6 results with reduced banks are given in the M/N-XLPE_#D rows and the Case 7 results with further reduced banks are given in the M/N-XLPE_#E rows. The Case 6 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), while the Case 7 reduced banks has a more significant impact raising the first resonance frequency by 0.5-0.6 pu.

Figure 1 is a comparison plot of the system impedance characteristic versus frequency at Plumtree 345 kV, illustrating the impact of the XLPE alternative (Case 5) 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_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	Reduced Banks	2.9	137			11.6 13.9	254 428
M/N-XLPE_1E	Plumtree 345 kV	Case 7 Banks	3.4	178			11.8	356
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	Reduced Banks	2.9	17	7.6	32	11.6	104
M/N-XLPE_2E	Plumtree 115 kV	Case 7 Banks	3.3	19			11.7 15.1	129 114
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	Reduced Banks	3.0	164	4.9	86		

					6.3	78		
M/N-XLPE_3E	Norwalk 345 kV	Case 7 Banks	3.4	232				
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	Reduced Banks	2.9	14	4.8 6.2	13 19	2.6	13
M/N-XLPE_4E	Norwalk 115 kV	Case 7 Banks	3.3	18			6.9	22
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	Reduced Banks	2.9	86	4.8	68	8.7 12.5	57 110
M/N-XLPE_5E	Southington 345 kV	Case 7 Banks	3.3	72			11.5	272
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	Reduced Banks	2.9	13	4.8	36	9.5	122
M/N-XLPE_6E	Southington 115 kV	Case 7 Banks	3.3	10	5.6	29		
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	Reduced Banks	2.9	68	6.2	226	12.4 14.6	243 515
M/N-XLPE_7E	East Shore 345 kV	Case 7 Banks	3.2	75	5.5 6.2	172 168	14.5	625
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	Reduced Banks	2.9	12				
M/N-XLPE_8E	Devon 115 kV	Case 7 Banks	3.3	13				
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	Reduced Banks	2.9	19	5.7	59	8.8	50
M/N-XLPE_9E	Frost Bridge 115 kV	Case 7 Banks	3.3	12			11.4	33
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	Reduced Banks	2.9	14	4.8 6.3	19 51		
M/N-XLPE_10E	Glenbrook 115 kV	Case 7 Banks	3.3	17	6.9	49		
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	Reduced Banks	3.0	162				
M/N-XLPE_11E	Singer 345 kV	Case 7 Banks	3.4	230				
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	Reduced Banks	3.0	156				
M/N-XLPE_12E	Devon 345 kV	Case 7 Banks	3.4	219				
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	Reduced Banks	2.9	77			12.5	274
M/N-XLPE_13E	Beseck 345 kV	Case 7 Banks	3.3	76			11.6	343

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_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	Reduced Banks	2.7	107			11.5 13.8	227 412
M/N-XLPE2_1E	Plumtree 345 kV	Case 7 Banks	3.0	129			11.7	321
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	Reduced Banks	2.6	14	7.4	30	11.5	97
M/N-XLPE2_2E	Plumtree 115 kV	Case 7 Banks	3.0	15			11.7 15.0	119 104
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	Reduced Banks	2.7	129	4.8 6.2	76 89		
M/N-XLPE2_3E	Norwalk 345 kV	Case 7 Banks	3.1	167				
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	Reduced Banks	2.6	13	4.7 6.2	13 17		
M/N-XLPE2_4E	Norwalk 115 kV	Case 7 Banks	3.0	15	6.7	20		
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	Reduced Banks	2.6	69	4.8	63	8.6 12.4	63 107
M/N-XLPE2_5E	Southington 345 kV	Case 7 Banks	3.0	60			11.5	270
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	Reduced Banks	2.6	11	4.8	33	9.4	115
M/N-XLPE2_6E	Southington 115 kV	Case 7 Banks	2.9	9	5.4	23		
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	Reduced Banks	2.6	75	6.1	248	12.4 14.2	262 374
M/N-XLPE2_7E	East Shore 345 kV	Case 7 Banks	2.9	83	5.4	217	14.0	532
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	Reduced Banks	2.6	13				
M/N-XLPE2_8E	Devon 115 kV	Case 7 Banks	3.0	14			14.6	26
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	Reduced Banks	2.6	15	5.6	53	8.7	51
M/N-XLPE2_9E	Frost Bridge 115 kV	Case 7 Banks	2.9	10			11.3	32
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	Reduced Banks	2.6	13	4.7 6.2	20 48		
M/N-XLPE2_10E	Glenbrook 115 kV	Case 7 Banks	3.0	15	6.8	46		
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	Reduced Banks	2.7	129				
M/N-XLPE2_11E	Singer 345 kV	Case 7 Banks	3.1	167				
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	Reduced Banks	2.7	126				
M/N-XLPE2_12E	Devon 345 kV	Case 7 Banks	3.1	160				
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	Reduced Banks	2.6	63			12.5	266
M/N-XLPE2_13E	Beseck 345 kV	Case 7 Banks	3.0	63			11.6	341

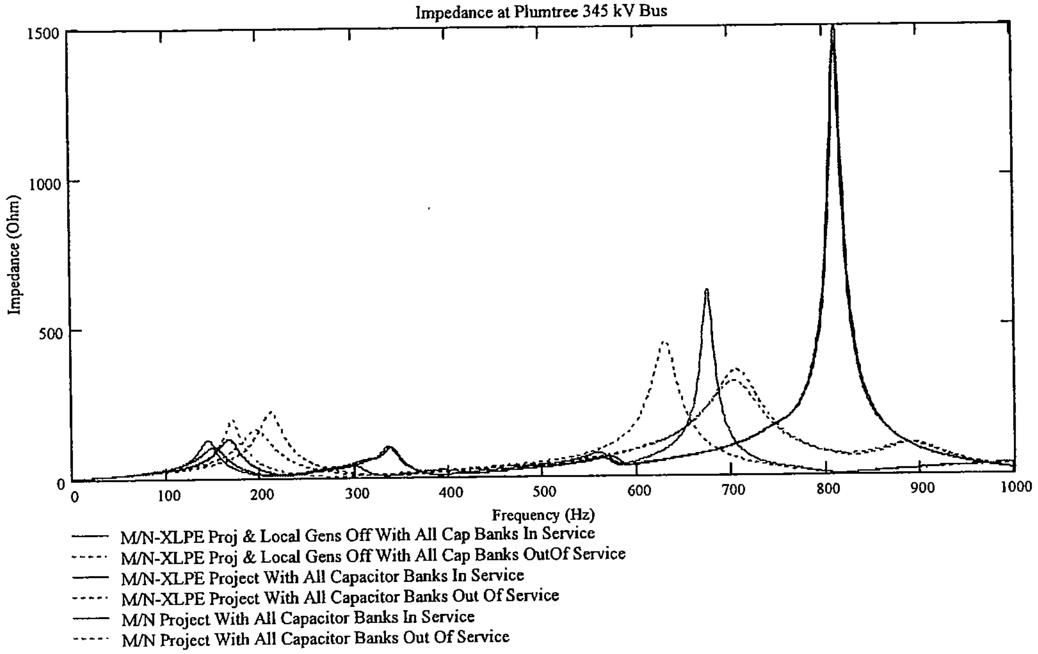


Figure 1. Impedance vs. Frequency at Plumtree 345 kV

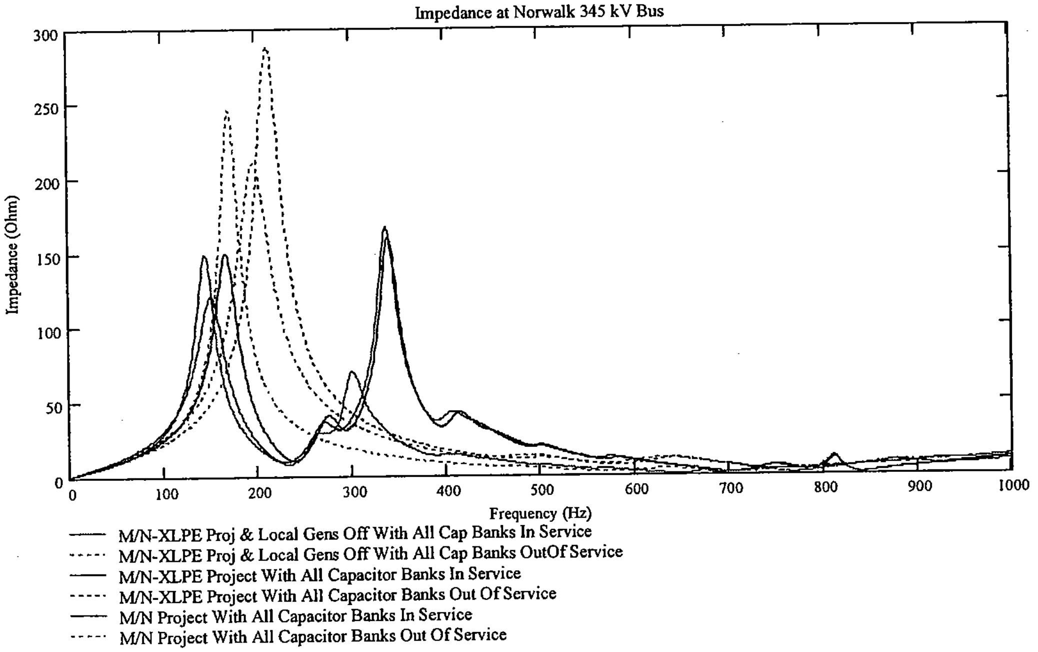


Figure 2. Impedance vs. Frequency at Norwalk 345 kV

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, Case 5, (removing about 600 MVAR of charging including one of the 9.7-mi HPFF cables) 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 (Case 6) at Plumtree, Frost Bridge and Glenbrook (removing about 264 MVAR[1]) 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. Further reduction of capacitor banks (Case 7) had a more significant impact, as discussed below.

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 (Case 5[2])	2.4	2.8	2.5
Reduced banks (Case 6)		2.9-3.0	2.6-2.7
Further reduced banks (Case 7)		3.2-3.4	2.9-3.1
All out of service (Case 5)	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. Variations in the number of 115 kV capacitor banks in service results in resonances above and below 3rd harmonic. It is possible that alternate voltage support solutions could

---

[1] Additional shunt capacitor banks (145 MVAR) later revealed to exist at Glenbrook were not included in the analysis. If these are included, then Case 6 shunt capacitor bank removal would be about 409 MVAR in the actual system.

[2] Case 5 in this table refers to the XLPE cable alternative with all capacitor banks in service and all capacitor banks out of service, while Case 6 and Case 7 have the same cable configuration as Case 5 but different capacitor bank conditions.

reduce the number of 115 kV capacitor banks needed to maintain required voltage levels, given enough physical space, money, and time resources. System outages are another important consideration, since a variety of temporary or more permanent contingencies would similarly cause variation in resonant frequencies. The outages shift resonant characteristics by changing either the strength of the system or the effective charging capacitance in the system. Minimum generator dispatches and system outages, such as an outage of the line from East Devon to Beseck, should be considered, since they could severely weaken the system. A further weakened system together with the maximum required 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 well 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 (e.g., faults of transmission lines, substation buses, and equipment and the clearing of such faults) are particularly critical since special circuit breaker closing enhancements have no effect. If any of the XLPE alternatives studied here are to be considered, then extensive transient studies would be recommended.

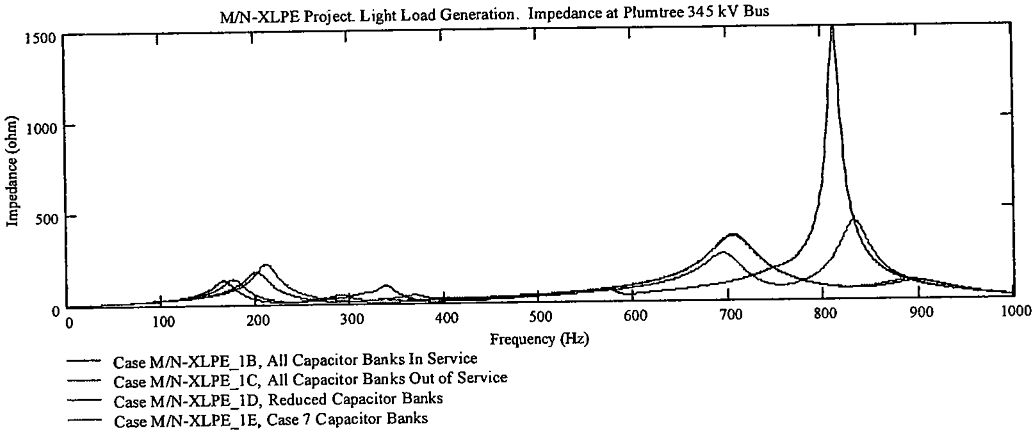
Removing more 115 kV capacitor banks (Case 7) at Frost Bridge, Glenbrook, Southington, Rocky River, and Stony Hill (totaling about 910 MVAR[3]) had a more significant impact on the first resonance points. It raises the first resonance frequency from 2.5 pu to about 3.0 pu with local generators off, and from 2.8 pu to about 3.3 pu with the original light load generator dispatch. Statcoms to be considered in Case 7, in place of shunt capacitor banks, include two 150 MVAR statcoms at Glenbrook, one 150 MVAR statcom at Stony Hill, one 300 MVAR statcom at Frost Bridge, and one 300 MVAR statcom at Southington. Due to the short time constraints of this study, the statcoms were not modeled. There are various statcom designs and control systems and a range of operating points. Frequency-domain analysis requires highly sophisticated modeling for which there was insufficient time. Since the statcom control interaction could be extremely complex and expected to have some impact in the frequency range of interest, more detailed modeling and time-domain analysis are recommended. Simulations should include a variety of system conditions, including weakened generation dispatches and outages, and a range of disturbance scenarios.

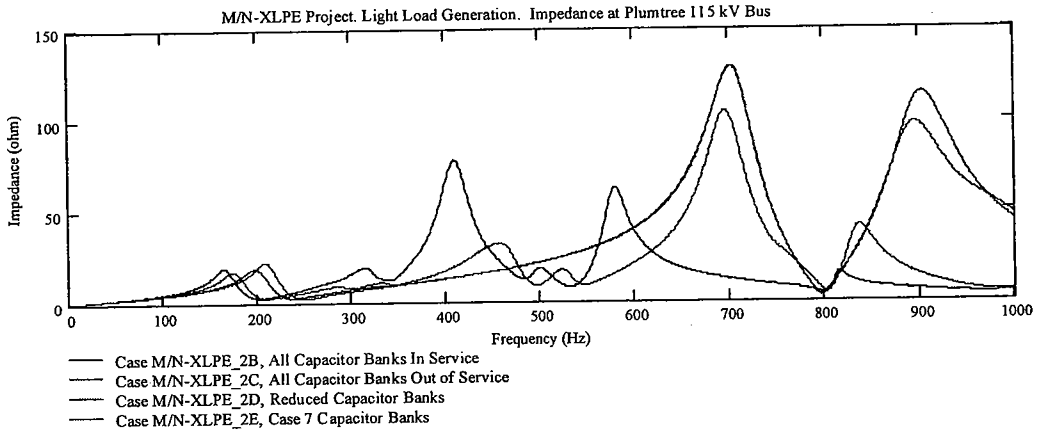
Even with reduced system capacitance and resonances above the third harmonic, faults in this system are still likely to result in moderate distortion and temporary overvoltages. Unless specifically designed to accommodate this system behavior, a statcom may be prone to protective tripping for self-protection. Thus, it is important to evaluate the impact of system resonant behavior on the statcoms, and ensure that they are appropriately specified to avoid tripping as a result of system faults. Failure to do so could potentially result in simultaneous tripping of multiple statcoms as a consequence of a fault, which could be at a particularly vulnerable period for the system from a fundamental-frequency voltage stability standpoint.

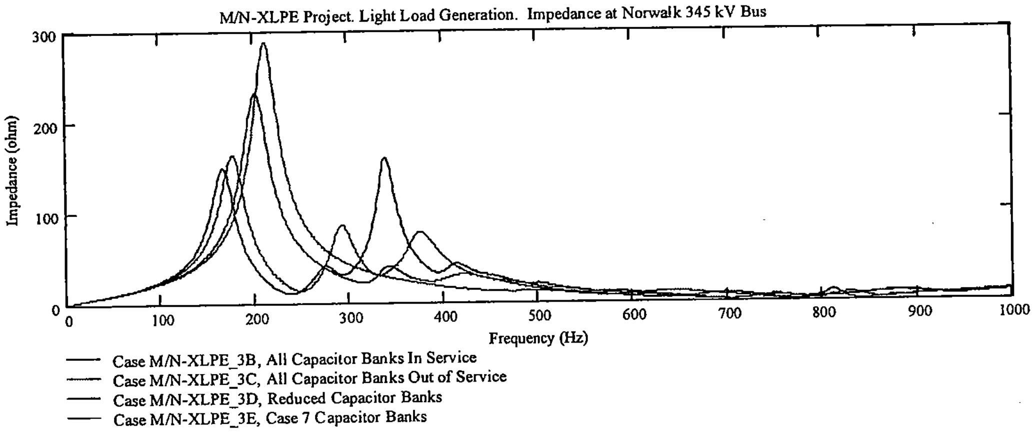
---

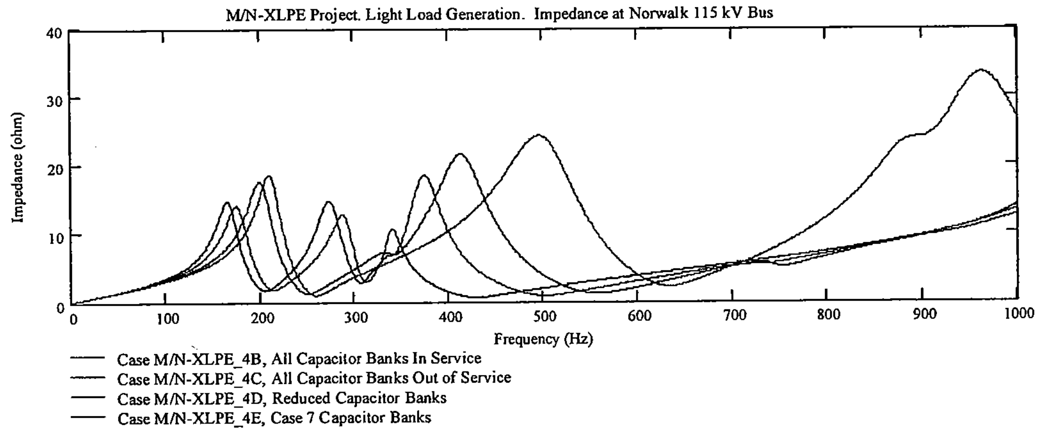
[3] Additional shunt capacitor banks (145 MVAR) later revealed to exist at Glenbrook were not included in the analysis. If these are included, then Case 7 shunt capacitor bank removal would be about 1055 MVAR in the actual system.

Appendix A Driving-Point Impedance Plots with Light Load Generation

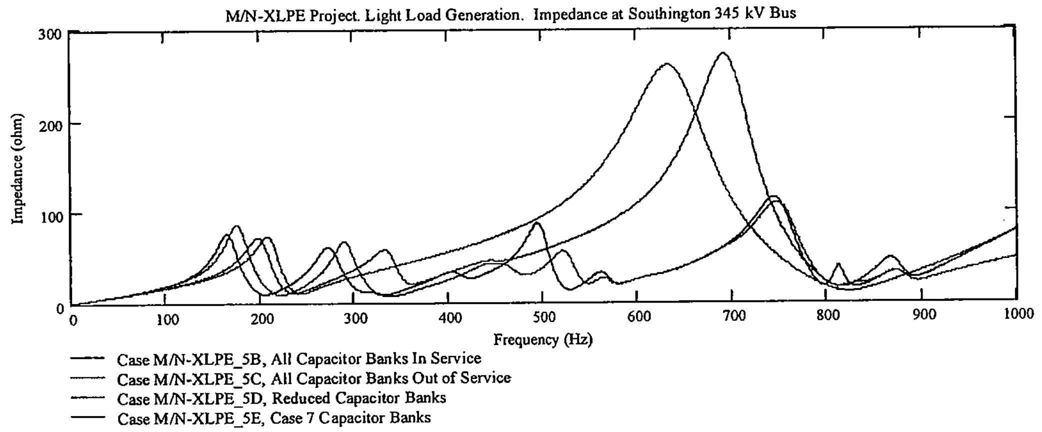

M/N-XLPE Project. Light Load Generation. Impedance at Plumtree 345 kV Bus


M/N-XLPE Project. Light Load Generation. Impedance at Plumtree 115 kV Bus

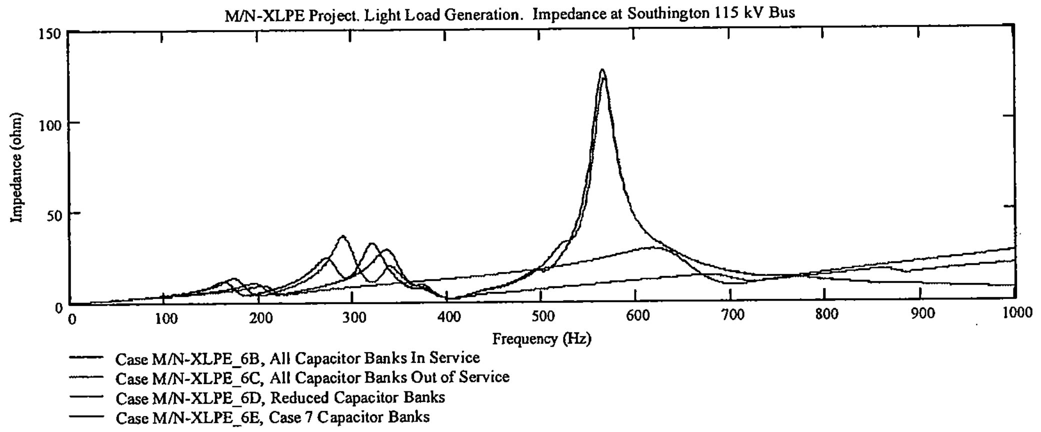

M/N-XLPE Project. Light Load Generation. Impedance at Norwalk 345 kV Bus


M/N-XLPE Project. Light Load Generation. Impedance 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
- Case M/N-XLPE_4D, Reduced Capacitor Banks
- Case M/N-XLPE_4E, Case 7 Capacitor Banks

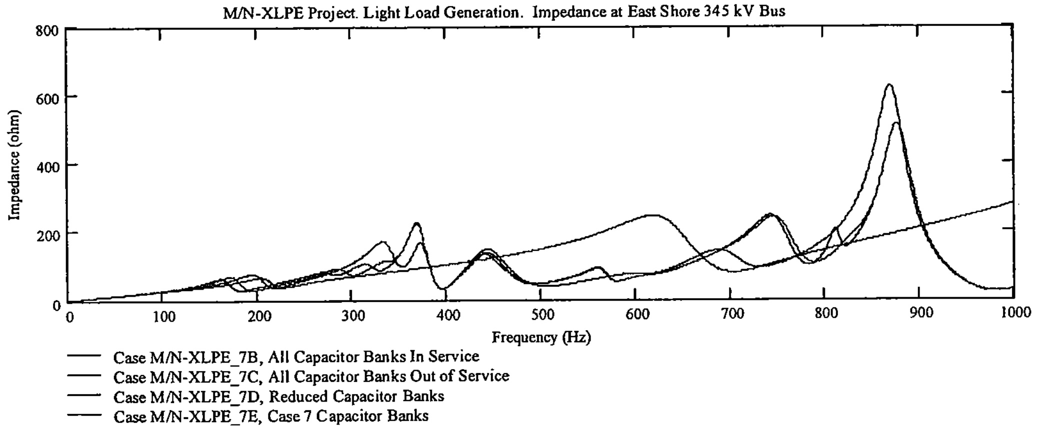

M/N-XLPE Project. Light Load Generation. Impedance at Southington 345 kV Bus

- Case M/N-XLPE_5B, All Capacitor Banks In Service
- Case M/N-XLPE_5C, All Capacitor Banks Out of Service
- Case M/N-XLPE_5D, Reduced Capacitor Banks
- Case M/N-XLPE_5E, Case 7 Capacitor Banks

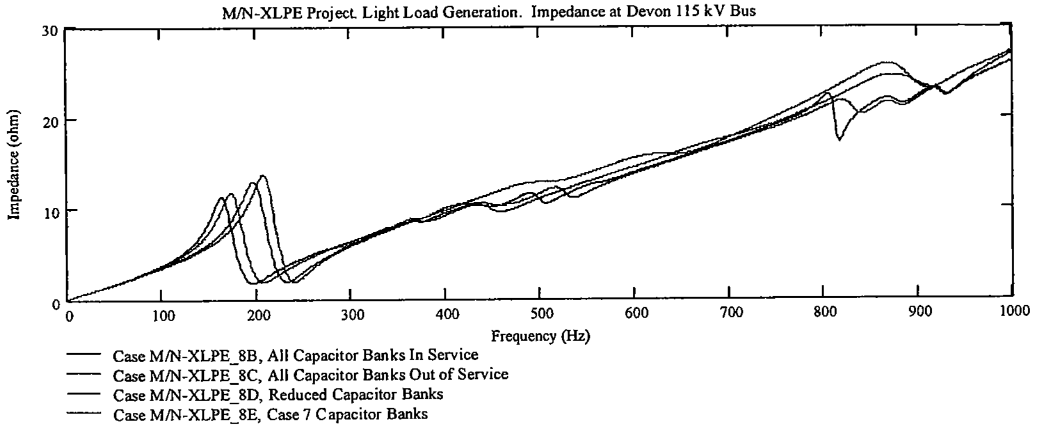

M/N-XLPE Project. Light Load Generation. Impedance at Southington 115 kV Bus

- Case M/N-XLPE_6B, All Capacitor Banks In Service
- Case M/N-XLPE_6C, All Capacitor Banks Out of Service
- Case M/N-XLPE_6D, Reduced Capacitor Banks
- Case M/N-XLPE_6E, Case 7 Capacitor Banks

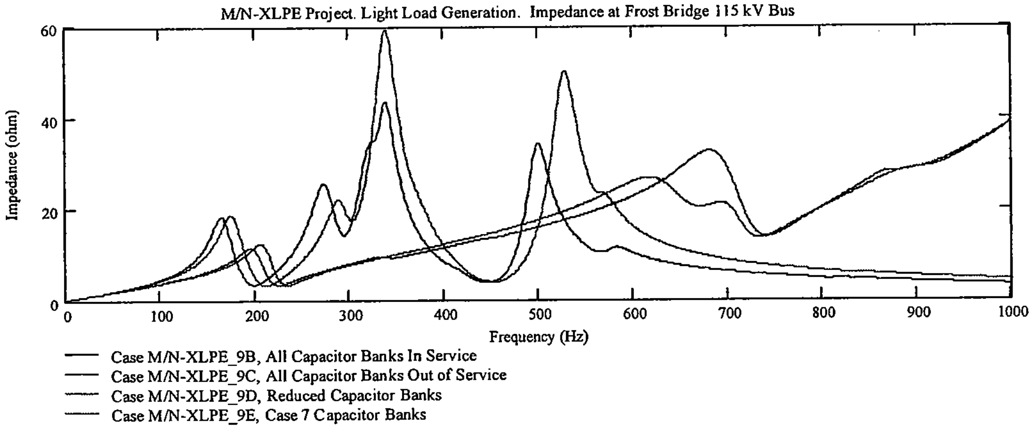
M/N-XLPE Project. Light Load Generation. Impedance at East Shore 345 kV Bus

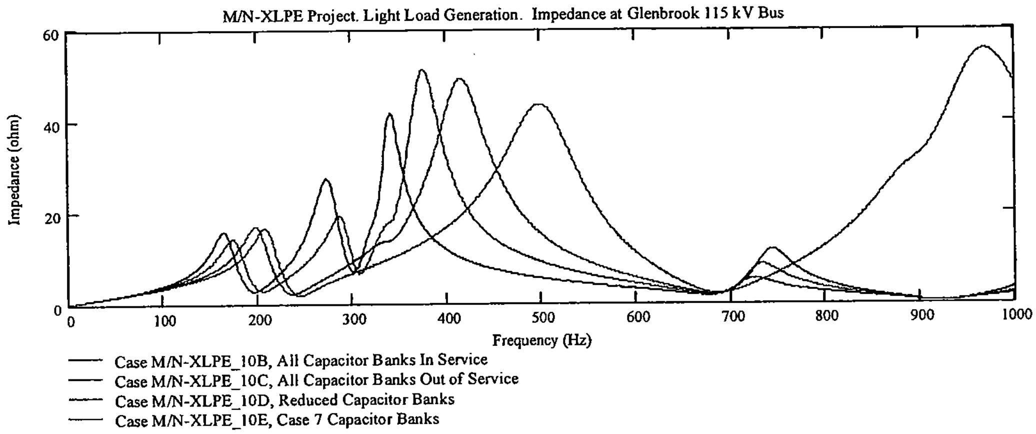


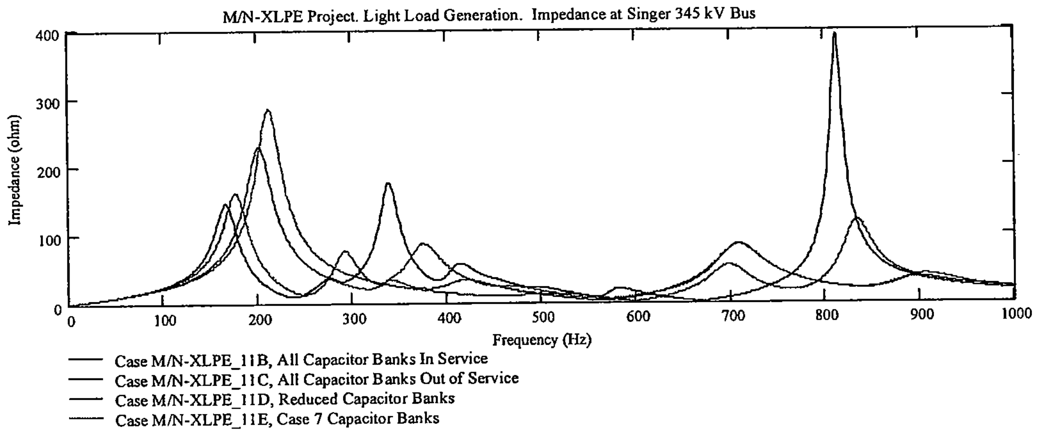
M/N-XLPE Project. Light Load Generation. Impedance at Devon 115 kV Bus

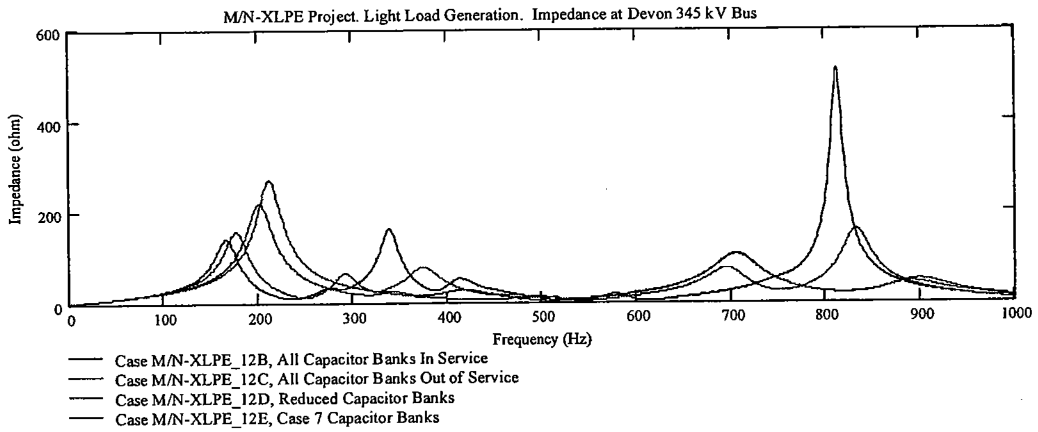


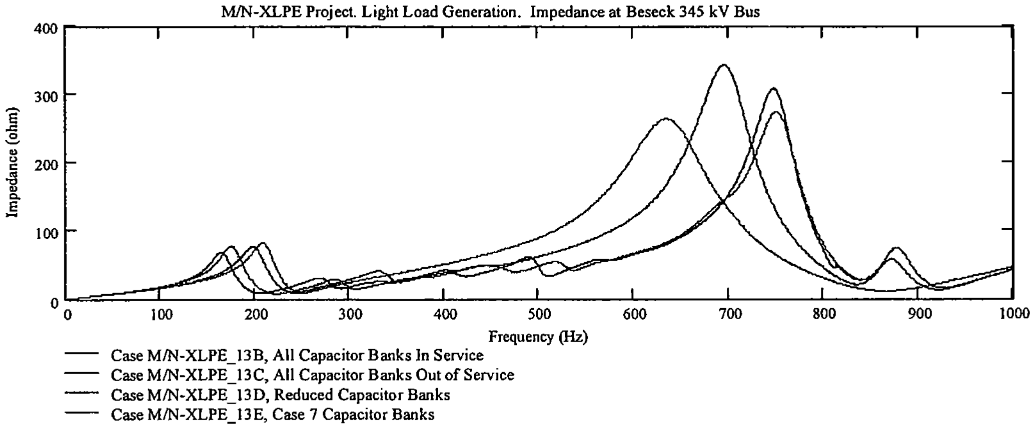
M/N-XLPE Project. Light Load Generation. Impedance at Frost Bridge 115 kV Bus



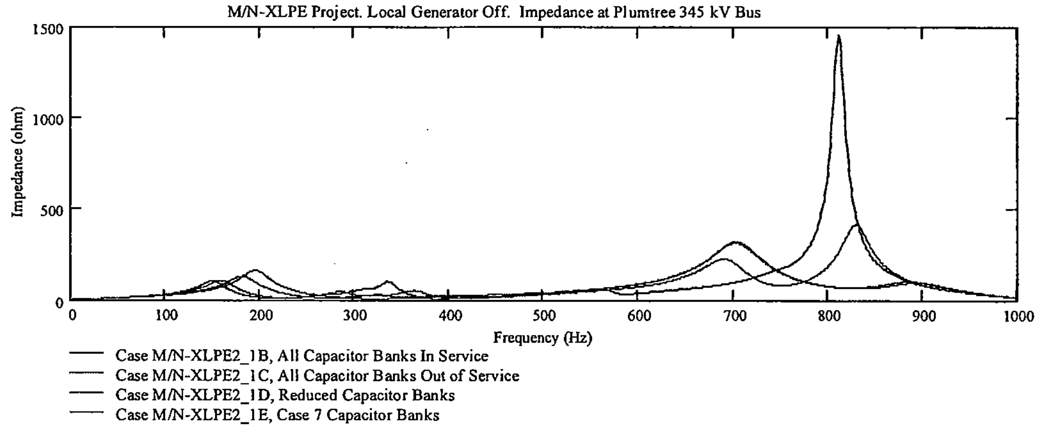

M/N-XLPE Project. Light Load Generation. Impedance at Glenbrook 115 kV Bus

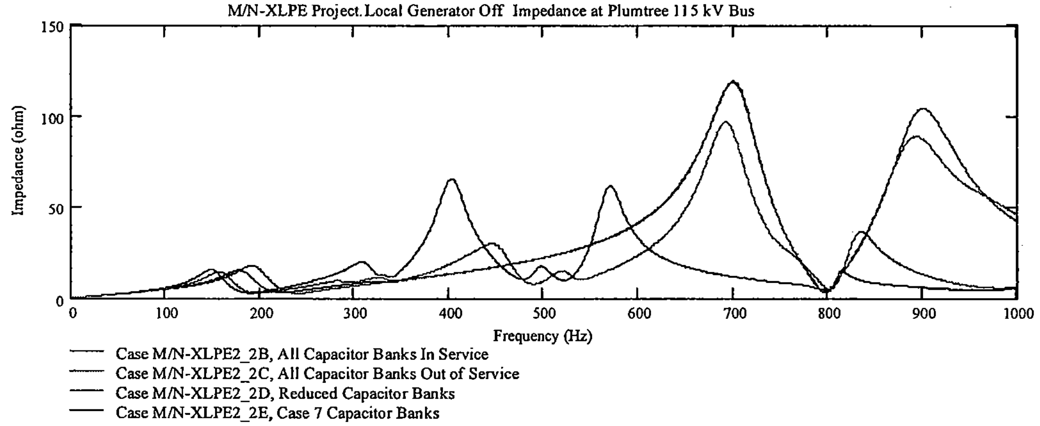

M/N-XLPE Project. Light Load Generation. Impedance at Singer 345 kV Bus

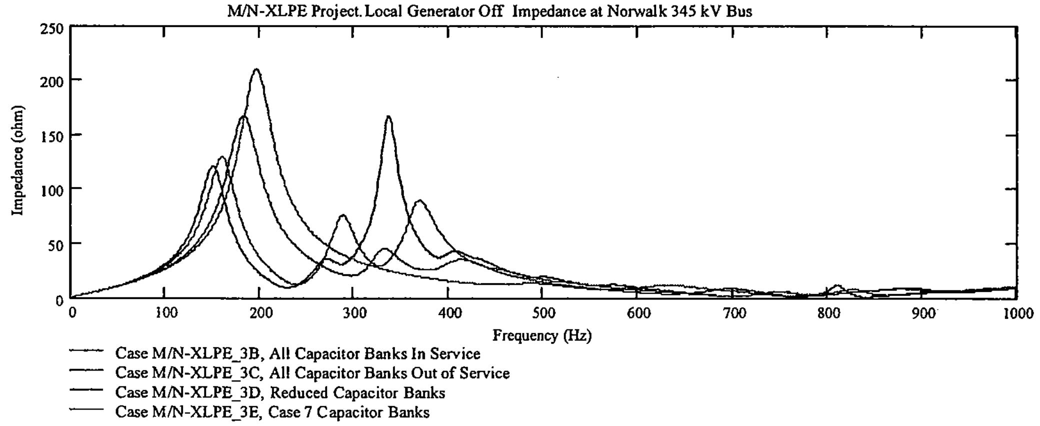

M/N-XLPE Project. Light Load Generation. Impedance at Devon 345 kV Bus

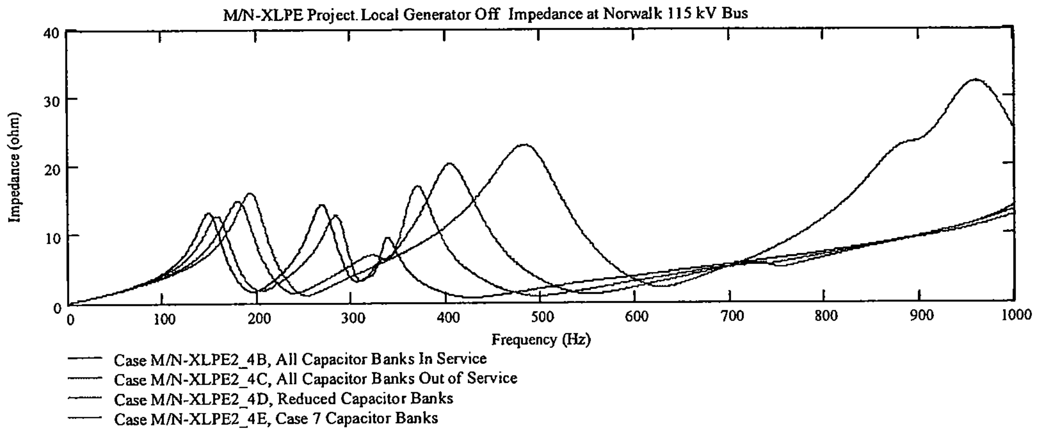

M/N-XLPE Project. Light Load Generation. Impedance at Beseck 345 kV Bus
Impedance (ohm)
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE_13B, All Capacitor Banks In Service
Case M/N-XLPE_13C, All Capacitor Banks Out of Service
Case M/N-XLPE_13D, Reduced Capacitor Banks
Case M/N-XLPE_13E, Case 7 Capacitor Banks

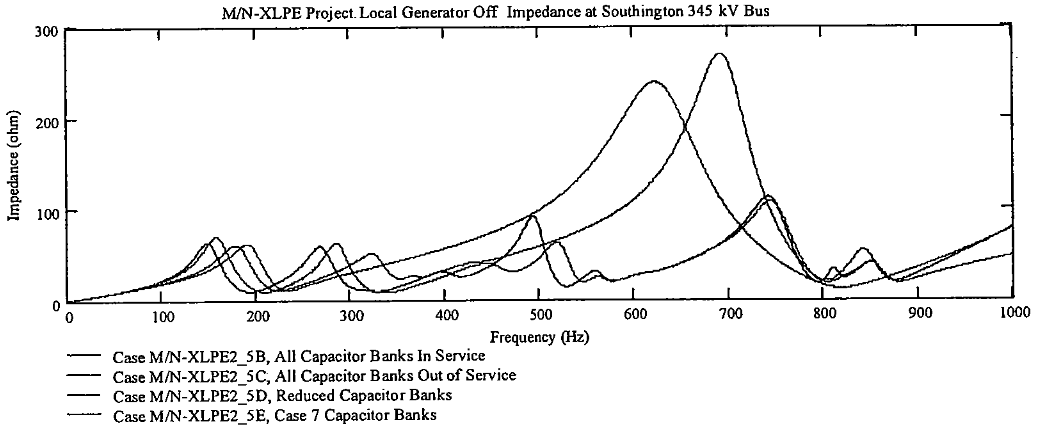
Appendix B Driving-Point Impedance Plots with Local Generators Off

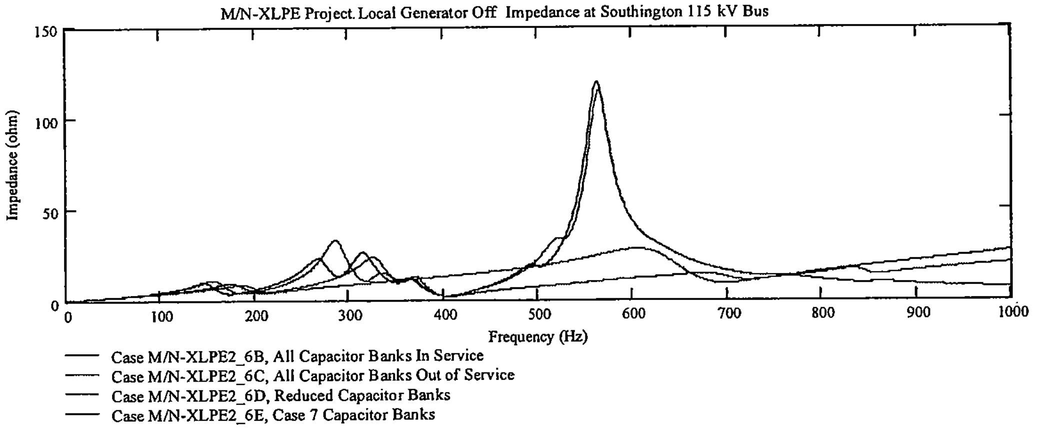


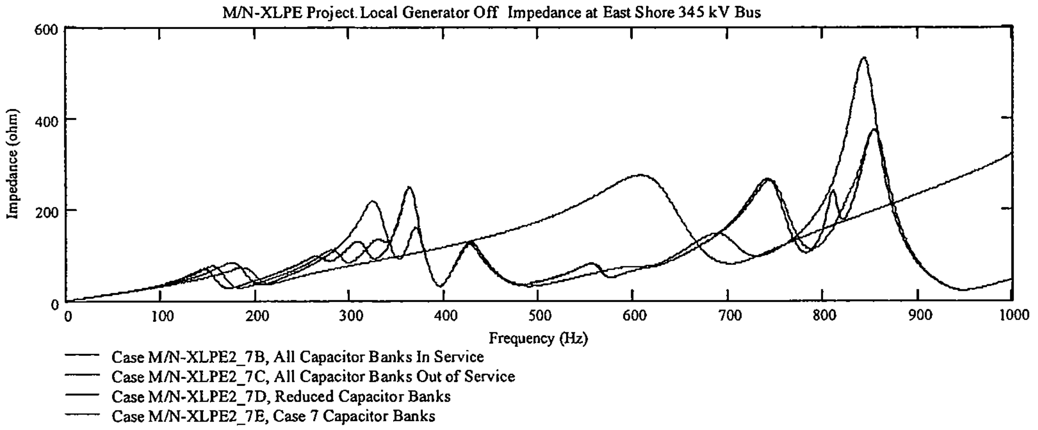


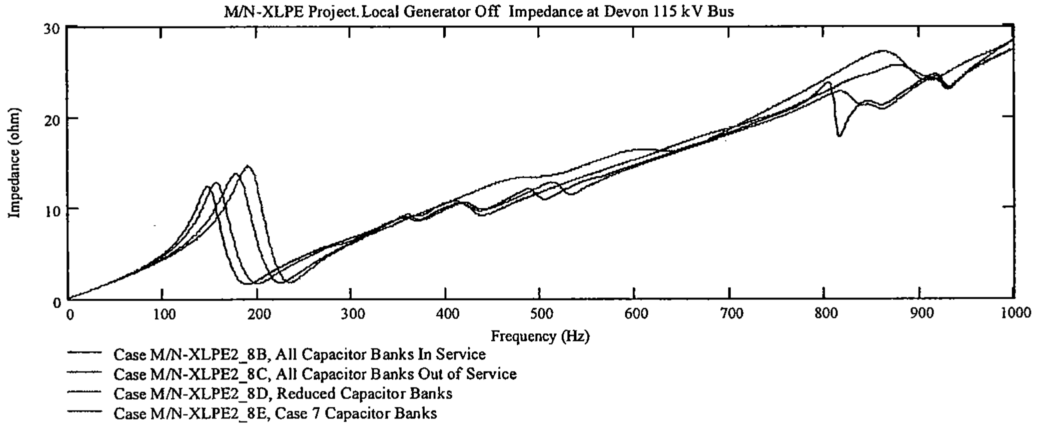


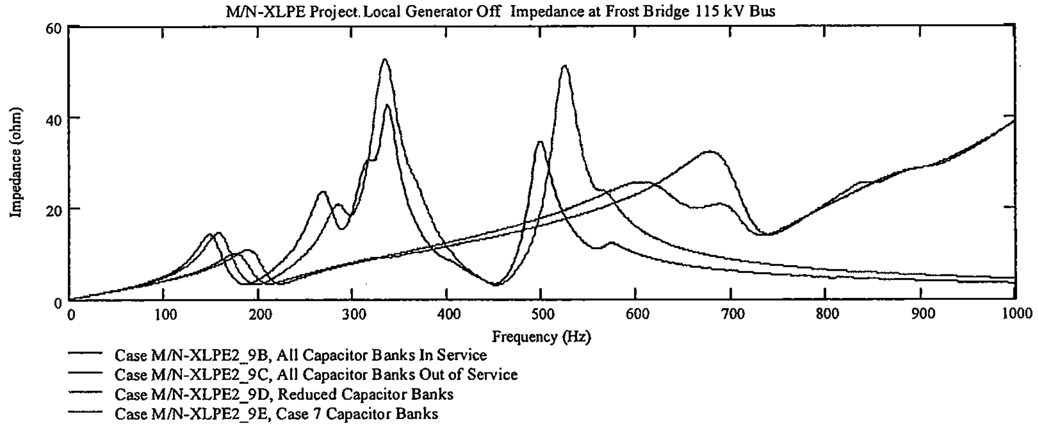

M/N-XLPE Project. Local Generator Off Impedance at Norwalk 115 kV Bus
Impedance (ohm)
0
10
20
30
40
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE2_4B, All Capacitor Banks In Service
Case M/N-XLPE2_4C, All Capacitor Banks Out of Service
Case M/N-XLPE2_4D, Reduced Capacitor Banks
Case M/N-XLPE2_4E, Case 7 Capacitor Banks

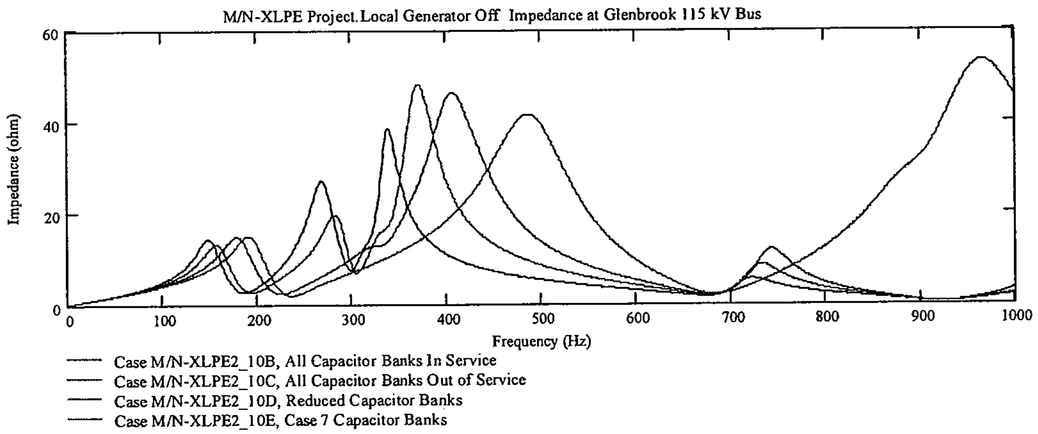

M/N-XLPE Project. Local Generator Off Impedance at Southington 345 kV Bus
Impedance (ohm)
0
100
200
300
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE2_5B, All Capacitor Banks In Service
Case M/N-XLPE2_5C, All Capacitor Banks Out of Service
Case M/N-XLPE2_5D, Reduced Capacitor Banks
Case M/N-XLPE2_5E, Case 7 Capacitor Banks


M/N-XLPE Project. Local Generator Off Impedance at Southington 115 kV Bus
Impedance (ohm)
0
50
100
150
0
100
200
300
400
500
600
700
800
900
1000
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, Reduced Capacitor Banks
Case M/N-XLPE2_6E, Case 7 Capacitor Banks

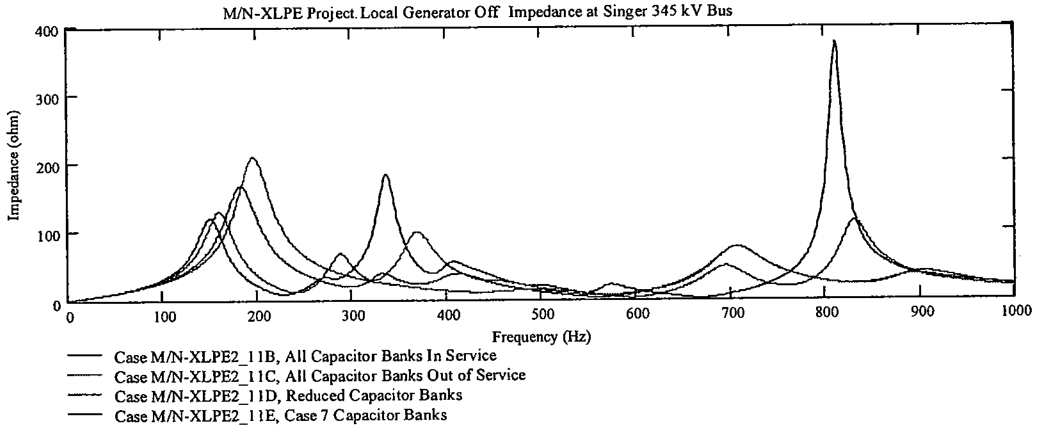

M/N-XLPE Project. Local Generator Off Impedance at East Shore 345 kV Bus
Impedance (ohm)
600
400
200
0
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE2_7B, All Capacitor Banks In Service
Case M/N-XLPE2_7C, All Capacitor Banks Out of Service
Case M/N-XLPE2_7D, Reduced Capacitor Banks
Case M/N-XLPE2_7E, Case 7 Capacitor Banks


M/N-XLPE Project. Local Generator Off Impedance at Devon 115 kV Bus
Impedance (ohm)
30
20
10
0
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
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, Reduced Capacitor Banks
Case M/N-XLPE2_8E, Case 7 Capacitor Banks

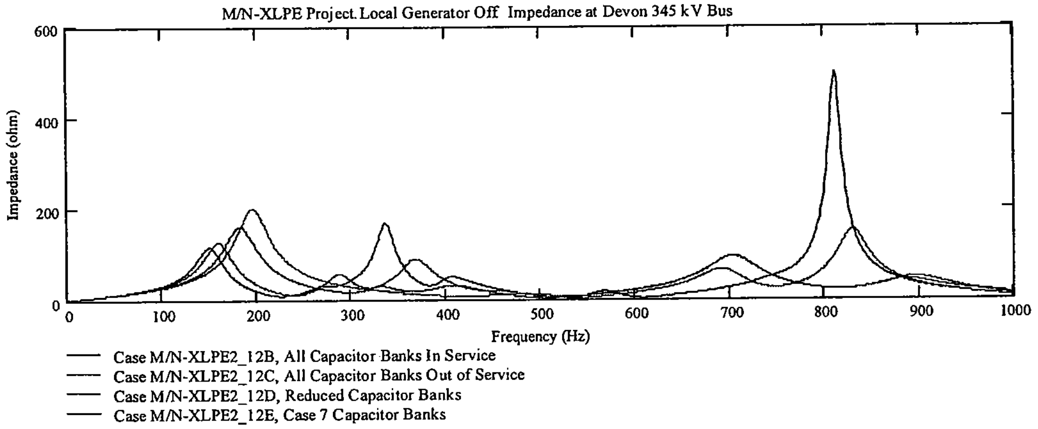

M/N-XLPE Project. Local Generator Off Impedance at Frost Bridge 115 kV Bus
Impedance (ohm)
60
40
20
0
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)
Case M/N-XLPE2_9B, All Capacitor Banks In Service
Case M/N-XLPE2_9C, All Capacitor Banks Out of Service
Case M/N-XLPE2_9D, Reduced Capacitor Banks
Case M/N-XLPE2_9E, Case 7 Capacitor Banks


M/N-XLPE Project.Local Generator Off Impedance at Glenbrook 115 kV Bus

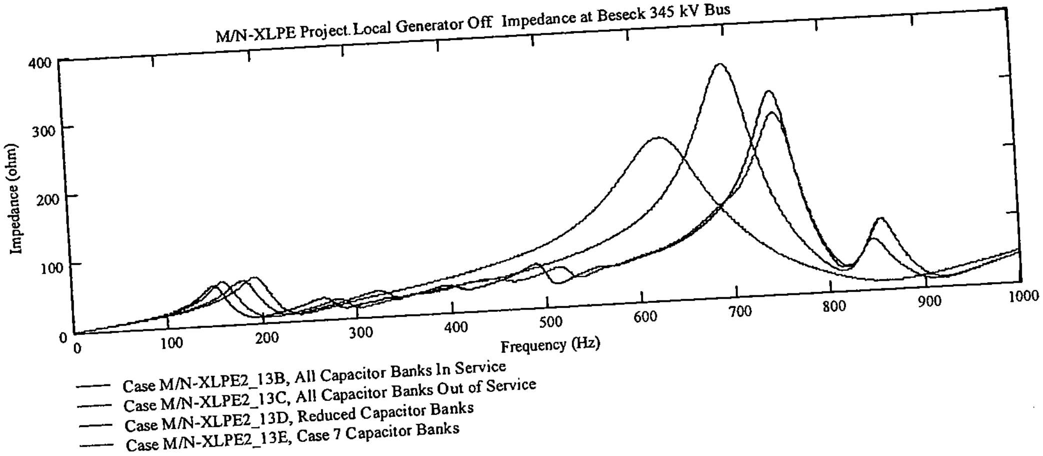
- Case M/N-XLPE2_10B, All Capacitor Banks In Service
- Case M/N-XLPE2_10C, All Capacitor Banks Out of Service
- Case M/N-XLPE2_10D, Reduced Capacitor Banks
- Case M/N-XLPE2_10E, Case 7 Capacitor Banks


M/N-XLPE Project.Local Generator Off Impedance 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
- Case M/N-XLPE2_11D, Reduced Capacitor Banks
- Case M/N-XLPE2_11E, Case 7 Capacitor Banks


M/N-XLPE Project.Local Generator Off Impedance 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
- Case M/N-XLPE2_12D, Reduced Capacitor Banks
- Case M/N-XLPE2_12E, Case 7 Capacitor Banks


M/N-XLPE Project. Local Generator Off Impedance at Beseck 345 kV Bus
Impedance (ohm)
0
100
200
300
400
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
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, Reduced Capacitor Banks
Case M/N-XLPE2_13E, Case 7 Capacitor Banks

APPENDIX F

Frequency of First System Resonance (per unit of 60 Hz) in Varying System Configurations

Item # -- Configuration ---	All Capacitors in Service Light Generator Dispatch	No Caps Light Generator Dispatch
1. Existing System	2.9	8.8
2. B-N Configuration X'	2.7	3.7
3. M-N Project as Proposed	2.4	2.8
4. M-N Project Plus 20 Miles UG	2.2	2.4
5. M-N Project Plus 40 Miles UG	2.0	2.2
6. Beseck to East Shore and All UG East Shore to East Devon	2.2	2.3
7. M-N Project with all HPFF replaced with XLPE and one HPFF in B-N removed (case 5)	2.8	3.5
8. M-N Project with all HPFF replaced with XLPE, one HPFF in B-N removed, and reduced maximum caps (case 6)	2.9-3.0	3.5
9. Start with the M-N proposed Project, replace both 345-kV HPFF cables between East Devon and Singer and Singer to Norwalk with XLPE, replace 345-kV overhead between Beseck and East Devon with HVDC lines, and remove one of the 345-kV HPFF cables in the Bethel to Norwalk Project from service. (case 5a)	2.1 conventional HVDC (with local generation OOS and XLPE from E.D. to Norwalk) 1.8 conventional HVDC (with local generation OOS and HPFF from E.D. to Norwalk) 2.0 VSC-HVDC (with local generation OOS and HPFF cables from E.D to Norwalk – XLPE not evaluated)	Not evaluated
10. Start with the M-N proposed Project, replace both 345-kV HPFF cables between East Devon and Singer with XLPE, replace both 345-kV HPFF cables between Singer and Norwalk with HVDC lines, and between Beseck and East Devon with HVDC lines, and remove one of the 345-kV HPFF cables in the Bethel to Norwalk Project from service. (case 5b)	2.9	3.8
11. Start with the M-N proposed Project, replace both 345-kV HPFF cables between East Devon and Singer with XLPE, replace both 345-kV HPFF cables between Singer and Norwalk with XLPE, remove one of the 345-kV HPFF cables in the Bethel to Norwalk Project from service, add a 500 MVA synchronous condensor at East Devon(case 5c)	2.9	3.7
12. Start with the M-N proposed Project, replace both 345-kV HPFF cables between East Devon and Singer with XLPE, replace both 345-kV HPFF cables between Singer and Norwalk with XLPE, remove one of the 345-kV HPFF cables in the Bethel to Norwalk Project from service, add a 500 MVA synchronous condensor at East Devon, and add a 500 MVA synchronous condensor at Singer (case 5d)	3.0	3.9
13. M-N Project with all HPFF replaced with XLPE, one HPFF in B-N removed, and new statcoms at Glenbrook, Stony Hill, Frost Bridge, and Southington (case 7)	3.2-3.4	3.5