Connecticut Cable Transient and Harmonic Study for East Shore Alternatives

Final Report
April 5, 2004

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

Power Systems Energy Consulting
General Electric International, Inc.
One River Road
Schenectady, NY 12345 USA

Foreword

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

Elizabeth R. Pratico
Power Systems Energy Consulting
General Electric International, Inc.
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

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Executive Summary

Study Objectives

GE Power Systems Energy Consulting (PSEC) has performed several switching transient and harmonic studies of the Northeast Utilities (NU) Bethel to Norwalk and Middletown to Norwalk 345 kV transmission cable projects that are proposed in southwestern Connecticut. In a recent study[1], harmonic and switching transient analyses were performed for the Middletown to Norwalk (M/N) project, with Devon-Beseck configured as a 33-mile overhead line. In another recent study[2], an alternate configuration was analyzed, with Devon-Beseck configured with 40-mile underground cables (three parallel cables). This is referred to as the “M/N-P1” configuration. It was found that this configuration resulted in a system driving-point impedance resonance at 2^{nd} harmonic and was not recommended. In the next study[3], another alternate configuration was analyzed, with Devon-Beseck configured with two sets of 10-mile underground cables (each with three parallel cables), with 14 miles of overhead line in the middle. This is referred to as the “M/N-P2” configuration. It was found that this configuration revealed significant risks that would require considerable limitations and restrictions on operating practices and future modifications of the system.

The focus of the study, documented in this report, is to analyze switching transients and harmonic characteristics of the East Shore Alternatives. In these alternatives, the Devon-Beseck line is replaced with a line from Devon to East Shore. There are two configurations. In configuration 1A, there are a 10-mile overhead line from Devon to a transition station at Orange and three parallel 7-mile cables from Orange to East Shore. In configuration 1B, there are three parallel 13-mile cables from Devon to East Shore. In this report, these are referred to as the “ES-1A” and “ES-1B” configurations. This cable addition increases the total 345 kV cable charging capacitance from about 1500 MVAR (for Plumtree to Norwalk and Norwalk to East Devon cables) to about 2000 MVAR in configuration 1A and to about 2300 MVAR in configuration 1B. The objective of the study is to investigate the harmonic impacts of these alternatives and evaluate switching transients with particular emphasis on equipment duty and power quality. This study was intended to investigate potential fatal flaws of the ES-1A and ES-1B configurations, rather than a more comprehensive study such as that which was recently performed for the M/N base configuration.

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].

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[1] Final Report on M/N Project dated November 2003

[2] Final Report on M/N-P1 Project dated November 2003

[3] Final Report on M/N-P2 Project dated December 2003

Conclusions and Recommendations

Harmonic and switching transient evaluation of the ES-1A and ES-1B configurations did not identify any overtly fatal flaws, and switching transient results were similar to those of the M/N configuration. Therefore, it is concluded that with the appropriate selection of equipment and implementation of operating practices, the ES-1A and ES-1B configurations could be feasible alternatives to the M/N configuration from a switching transients and harmonics perspective. However, since the harmonic characteristics of ES-1A and ES-1B are of significant concern, a more comprehensive study would be required to further evaluate the ES-1A and ES-1B configurations.

Controlled closing is recommended for energization of the East Shore cables and transformers. Implementation of controlled closing by applying circuit breakers with resistor preinsertion provides a universal and robust solution.

The use of circuit breakers with synchronous closing is potentially risky for cable energization due to the potential for persistent direct current offset, without sufficient ac component to cause natural current zeros. This can occur when a highly compensated (near 100% compensation) cable is energized at voltage zero, without resistor preinsertion. Existing ac circuit breaker standards do not address the ability to interrupt direct current. Because voltage-zero energization is the objective of synchronous breakers used for cable switching, this can be a significant issue if synchronous closing technology is applied. Therefore, it is essential that, if synchronous closing breakers are to be considered, the ability of the breakers to interrupt several hundred Amperes of direct current must be confirmed with the breaker manufacturer.

Critical fault clearing cases with sustained voltage across the breaker contacts above 750 kV exceed test values defined in ANSI C37.06 and would require review with the breaker manufacturer. These cases indicate the need for a higher temporary overvoltage and transient recovery voltage capability required for the breaker or could possibly be a driver for a higher circuit breaker voltage rating if the manufacturer cannot provide the capability with a 362 kV breaker.

While controlled closing nearly eliminates overvoltage and severe voltage distortion resulting from cable and transformer switching, it cannot eliminate overvoltages and distortion resulting from faults and equipment failure, such as circuit breaker restrikes during interruption. For such events, the criterion is that consequential equipment damage or misoperation should not occur. Faults and restrikes cause both transient and temporary overvoltages which appear both locally and sometimes at remote locations in the system. Transient overvoltages observed on the 345 kV system are limited by 294 kV-rated surge arresters, without exposing these arresters to energy duty in excess of the typical capability of such an arrester. Temporary overvoltages observed after fault clearing are within the typical withstand capability of this arrester rating.

Fault and restrike events also tend to create overvoltages at locations remote from the fault on the 115 kV system, particularly at capacitor bank locations. Some very high overvoltages were observed in this study's simulations, resulting from the oscillatory transient introduced by application of a 345 kV system fault. The natural-frequency oscillations of the 345 kV cable system appear to interact with the resonance of the 115 kV capacitor banks, greatly amplifying the transient. In the actual system, surge arresters located on the 115 kV system will limit these overvoltages.[4] Evaluation of the energy duty imposed on the 115 kV arresters was not within the scope of this study, but should be considered during system design to determine if arresters with greater energy rating should be applied. Fault clearing events also result in temporary overvoltages on the 115 kV system. The study results should be compared with the temporary overvoltage capability of existing surge arresters, to determine if arresters should be replaced with a higher voltage rating. The older silicon carbide arrester technology is ill-suited for application near large capacitances, and it is recommended that NU review the use of SiC arresters at 115 kV and 345 kV substations located near East Shore. NU should consider replacement of these arresters with metal-oxide surge arresters, especially at shunt capacitor bank locations. It is also recommended that NU review the filter component ratings at Branford due to the low-order harmonic distortion observed in the band-pass filters, which are tuned at 3rd and 5th harmonics.

With regard to harmonic characteristics, the ES-1A and ES-1B configurations resulted in impedance resonances marginally above the 2nd harmonic and marginally below the 3rd harmonic. Changes in system configuration could easily move the resonances to 2nd or 3rd harmonic. In the M/N configuration, there was a single impedance resonance between 2nd and 3rd harmonics, but in the ES-1A and ES-1B configurations there are two impedance resonances between 2nd and 3rd harmonics, all with similar magnitudes. Consequently, there are concerns regarding power system events involving transformer exciting current, such as energization and inrush due to fault clearing. With resonances near both 2nd and 3rd harmonics, the harmonic currents due to inrush could have an additive effect to produce more severe results than those with resonances at either harmonic.

Additional system contingencies could lead to more severe sustained overvoltage situations than observed in this study. A reasonable effort was made in this study to include first-contingency events likely to initiate a critical system response. However, higher-level contingencies, beyond routine planning criteria, may result in much more severe consequences to utility and consumer equipment. Extreme contingencies could result, for example, from a major regional disturbance such as a blackout. Equipment failures resulting from extreme resonant conditions during system breakup could greatly hinder power restoration efforts.

There are also concerns about being close to 2nd harmonic. Although the resonance is above 2nd harmonic, it is very close, and defining a design with a minimum safe margin above 2nd harmonic is a subjective call. There is significant concern in regard to the harmonic characteristics of the ES-1A and ES-1B configurations.

In summary, with the ES-1A and ES-1B configurations, it is expected that the system would be very sensitive to future upgrades and would require careful engineering to study changes in the transmission system, even at somewhat remote areas. With resonances near both 2nd

[4] Also, damping of the system at the relatively high frequency of this interaction (600 Hz – 1 kHz) may be greater than represented in the simulation model, due to skin effects in the transmission cables and overhead 1ines.

and 3rd harmonics, power system events involving transformer exciting current could be more severe with system configuration changes. Careful consideration would be required for specifying equipment to withstand transient and temporary overvoltages observed during switching events. A more comprehensive study is recommended further evaluate the East Shore alternatives.

1. Introduction

GE Power Systems Energy Consulting (PSEC) has performed several switching transient and harmonic studies of the Northeast Utilities (NU) Bethel to Norwalk and Middletown to Norwalk 345 kV transmission cable projects that are proposed in southwestern Connecticut. In a recent study[1], harmonic and switching transient analyses were performed for the Middletown to Norwalk (M/N) project, with Devon-Beseck configured as a 33-mile overhead line. In another recent study[2], an alternate configuration was analyzed, with Devon-Beseck configured with 40-mile underground cables (three parallel cables). This is referred to as the "M/N-P1" configuration. It was found that this configuration resulted in a system driving-point impedance resonance at 2nd harmonic and was not recommended. In the next study[3], another alternate configuration was analyzed, with Devon-Beseck configured with two sets of 10-mile underground cables (each with three parallel cables), with 14 miles of overhead line in the middle. This is referred to as the "M/N-P2" configuration. It was found that this configuration revealed significant risks that would require considerable limitations and restrictions on operating practices and future modifications of the system.

The focus of the study, documented in this report, is to analyze switching transients and harmonic characteristics of the East Shore Alternatives. In these alternatives, the Devon-Beseck line is replaced with a line from Devon to East Shore. There are two configurations. In configuration 1A, there are a 10-mile overhead line from Devon to a transition station at Orange and three parallel 7-mile cables from Orange to East Shore. In configuration 1B, there are three parallel 13-mile cables from Devon to East Shore. In this report, these are referred to as the "ES-1A" and "ES-1B" configurations. This cable addition increases the total 345 kV cable charging capacitance from about 1500 MVAR (for Plumtree to Norwalk and Norwalk to East Devon cables) to about 2000 MVAR in configuration 1A and to about 2300 MVAR in configuration 1B. The objective of the study is to investigate the harmonic impacts of these alternatives and evaluate switching transients with particular emphasis on equipment duty and power quality. This study was intended to investigate potential fatal flaws of the ES-1A and ES-1B configurations, rather than a more comprehensive study such as that which was recently performed for the M/N base configuration.

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].

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1 Final Report on M/N Project dated November 2003

2 Final Report on M/N-P1 Project dated November 2003

3 Final Report on M/N-P2 Project dated December 2003

2. Study Approach

The study was organized into two tasks:

1. Harmonic Analysis
2. Switching Transient Analysis

Task 1. Harmonic Analysis

The large shunt charging capacitance of cables can significantly affect the harmonic frequency response of the system. Resonances in the low-order harmonic range can be expected. There is an ambient level of harmonic distortion in any power system, due to nonlinear loads and power electronic equipment distributed throughout the system. The resonances formed by the cable charging can potentially amplify the ambient distortion to unacceptable levels. Harmonic currents may also add to the heating of the cable, and potentially constrain cable loadability. Harmonic resonance concerns were addressed by performing harmonic screening simulations. Frequency-domain simulations were performed using the EMTP model[1] to calculate the positive-sequence driving-point impedance versus frequency at Plumtree, Norwalk, Southington, East Shore, Devon, Frostbridge, Glenbrook, Singer, Devon, and Beseck. Comparison cases were performed with variation of the 115 kV capacitor banks in the system.

A total of 93 cases were performed to calculate the positive-sequence driving-point impedance with configurations 1A and 1B. The results of the harmonic analysis are provided in Section 4.

Task 2. Switching Transient Analysis

The switching transient analysis simulations included cable and line energization, transformer energization, and fault and clear cases to determine switching transient overvoltages and temporary overvoltages for evaluation of equipment duty and power quality. Equipment recommendations are focused on surge arresters and switchgear.

Except in the limited case of some recently introduced circuit breakers with synchronous switching, the timing of circuit breaker closing is essentially random with respect to the point on voltage wave. There is also typically a variation between the closing times of the individual breaker poles (phases). Some transient results are sensitive to the exact timing of switching. Because of the complexities involved, it is virtually impossible to precisely predict the breaker timing which produces the most severe transient results. For this reason, detailed design studies typically use extensive Monte Carlo analysis of randomly selected breaker timings. However, for the purpose of this study, breaker timing rules-of-thumb were utilized to produce results which roughly approach the worst-case results. Most energization cases were performed using fixed point-on-wave circuit breaker closing angles, e.g., closing

[1] The EMTP model is described in Section 3.

at voltage peaks or zeroes for cable energization cases, and voltage zeroes for transformer energization (to maximize inrush harmonics). Using fixed point-on-wave closing angles was sufficient to determine the switching transient issues associated with the cables and transformers. Circuit breakers were modeled with uncontrolled closing with closing angles adjusted based on the previous study experience, for comparison with the MN base configuration cases of the previous study. Selected cases were performed with pre-insertion resistors to analyze the mitigation of energization transients. Since this study was focused on fatal flaw analysis, statistical analysis was not performed. It should be noted that actual transient overvoltages could be higher than those presented in this report. Variation of fault application and clearing times were also based on the experience of the previous studies for evaluation of temporary overvoltages.

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

More than 50 simulation cases were performed to complete this part of the study. The results of the transient analysis are provided in Sections 5 and 6 for configurations 1A and 1B respectively.

3. System Model

An extensive model of the NU system in southwestern Connecticut was developed in the previous studies, including explicit representation of the 345 kV transmission system as far as Pleasant Valley, Manchester, Card, and Montville and the 115 kV transmission system as far as Campville, Berlin, East Meriden, and Green Hill. The 138 kV undersea cables to Northport were also included in the model. The transmission system beyond the extent of the model was represented by equivalent sources at each point where the model interfaces with the external system. Capacitor banks and load transformers were modeled throughout the explicitly-represented 115 kV system.

The model of the Middletown to Norwalk project was refined in the M/N project study and included a 33.3-mile overhead line between East Devon and Beseck 345 kV. In this study, the Beseck station was removed as well as associated line changes that were done previously for the M/N project. The following 345 kV lines were removed: Devon-Beseck, Meriden-Beseck, Southington-Scovill Rock, Beseck-Haddam Neck, and Beseck-Millstone. The following lines were added back in from the original existing model: Meriden-Haddam Neck and Southington-Millstone. Additionally, the East Shore-Scovill Rock line was modified to represent planned reconductoring based on input data from NU (R=0.00136 pu, X=0.01618 pu, B=0.28561 pu on 100 MVA). A new overhead line and three parallel cables were added between Devon and East Shore. This cable addition increases the total 345 kV cable charging capacitance from about 1500 MVAR (for Plumtree to Norwalk and Norwalk to East Devon cables) to about 2000 MVAR in configuration 1A and to about 2300 MVAR in configuration 1B.

Figure 3-1 shows the detail of the system model in the vicinity of the 345 kV cable projects. The configuration of cables, overhead lines, and shunt reactors is indicated. The 345 kV loop is shown in simplified form. The system model extends beyond the loop as described above. Circuit breakers indicated by lettered and numbered squares are used to describe the case simulation conditions. The detail of the Devon to East Shore additions for the ES-1A configuration is shown in Figure 3-2. Figure 3-3 shows the detail for ES-1B.

The cables were modeled as 2500 kcmil HPFF cable as in the M/N project, and the overhead line was of the same construction as the Devon-Beseck overhead line. Each of the variable (75-150 MVAR) shunt reactors on the cables was modeled with tap settings at 150 MVAR as a default. Surge arresters were modeled at the cable ends with a rating of 294 kV. Surge arresters at the East Shore 345/115 kV transformer terminals with given ratings of 276 kV and 90 kV. Finally, filter banks and reactors at Branford were modeled based on the input data provided in Table 3-1.

Table 3-1. Branford Filter Parameters

Filter	**R (ohms)**	**L (mH)**	**C (μF)**
Branford West			
BP 3rd		22	36
BP 5th		22	13
HP	100	22	10
Qx1 reactor		152.527	
Qx2 reactor		408.013	
Branford East			
BP 3rd		22	36
BP 5th		22	13
HP	100	22	10
Qx1 reactor		287.591	
Qx2 reactor		272.009	

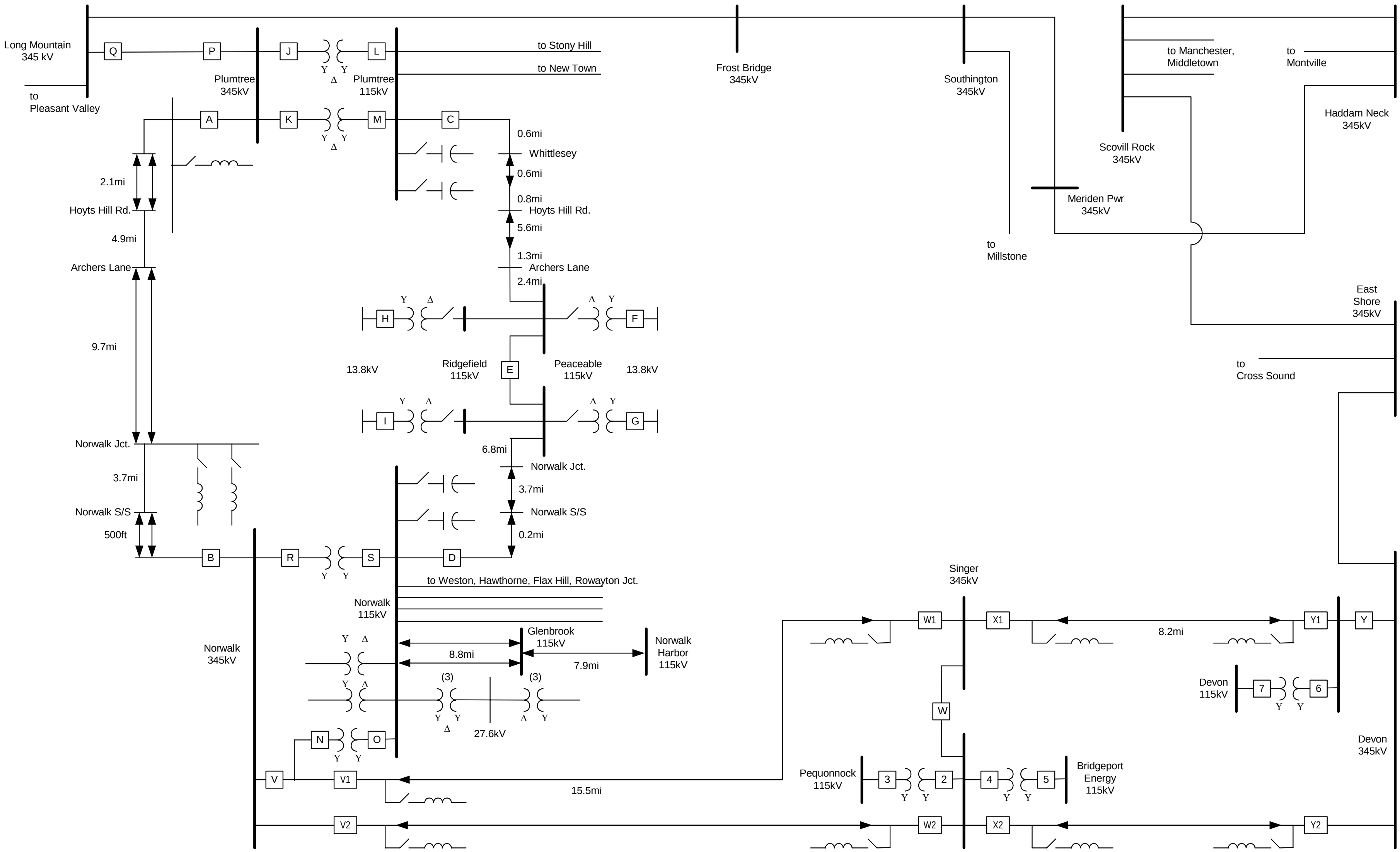

Figure 3-1. System Model One-Line Diagram for East Shore Alternatives

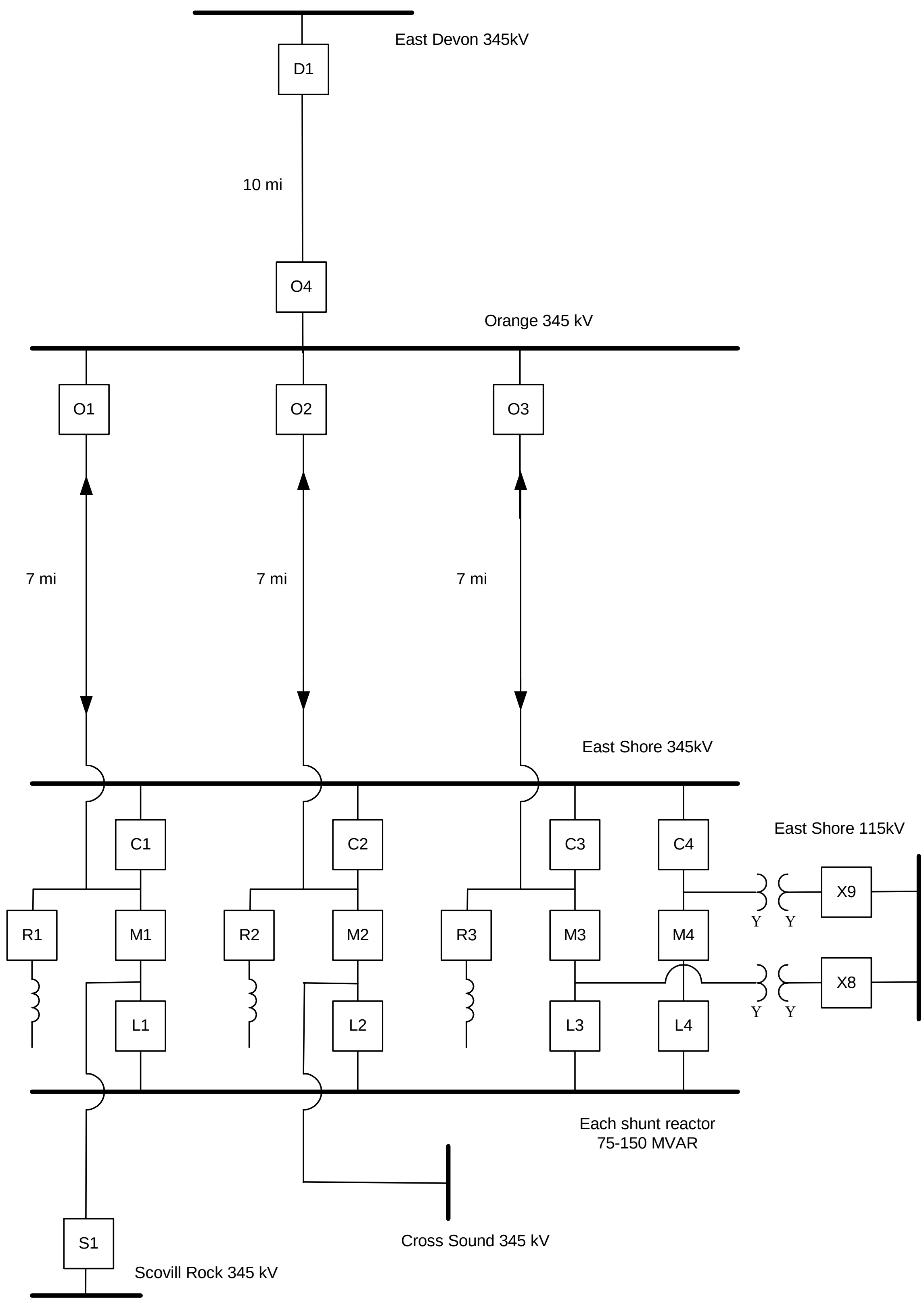

Figure 3-2. System Model One-Line Diagram of ES-1A Configuration

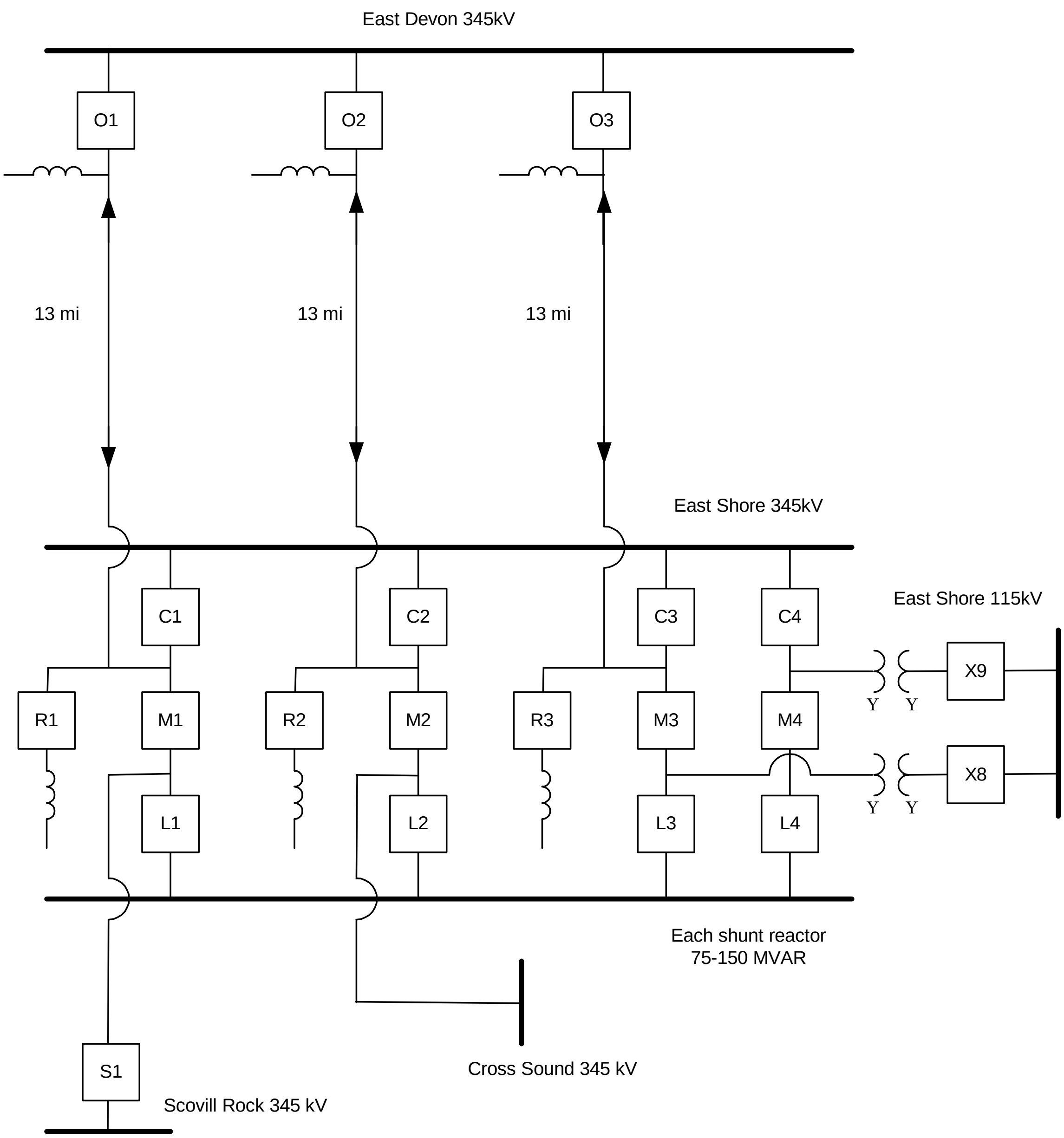

Figure 3-3. System Model One-Line Diagram of ES-1B Configuration

4. Harmonic Analysis

The harmonic impact of the East Shore Alternatives was analyzed by evaluating the driving-point impedance versus frequency at various locations.

Driving-Point Impedance

Harmonic screening simulations were performed to calculate the positive-sequence driving-point impedance versus frequency at the Plumtree, Norwalk, Singer, Devon, Orange, Southington, and East Shore 345 kV buses and at the Plumtree, Norwalk, Southington, Devon, Frost Bridge and Glenbrook 115 kV buses. Cases were performed for the ES-1A and ES-1B configurations with various capacitor bank allocations. In addition, selected cases were performed for the ES-1A configuration with the Devon-Orange line out of service (ES-1AW). Table 4-1 shows the cases that were performed for the ES-1A configuration and the resonant frequencies that were observed along with the corresponding impedance value at those frequencies. The resonant frequency is indicated by its harmonic number (HN), in per unit of 60 Hz, and impedance magnitude is in ohms. Table 4-2 shows a comparison of cases that were performed for the ES-1AW configuration with those cases for ES-1A. Table 4-3 shows the cases that were performed for the ES-1B configuration. For comparison purposes, the M/N base configuration cases from a previous study are shown in Table 4-4. The driving-point impedance plots for ES-1A, ES-1AW, and ES-1B are provided in Appendix A.

Table 4-1. Driving-Point Impedance Cases for ES-1A Configuration

			Resonant Frequency & Impedance (pu of 60Hz, Ohm)					
			Low		Middle		High	
Case	Location	Capacitor Banks	HN	Z(Ω)	HN	Z(Ω)	HN	Z(Ω)
ES1A_1A	Plumtree 345 kV	Light Load	2.4 2.8	93 189	7.9	138	11.9	153
ES1A_1B	Plumtree 345 kV	All in Service	2.2 2.6	110 121			11.9	553
ES1A_1C	Plumtree 345 kV	All Out of Service	2.4 2.8	92 191	7.6	134	11.8	153
ES1A_2A	Plumtree 115 kV	Light Load	2.3 2.8	11 18			13.9	116
ES1A_2B	Plumtree 115 kV	All in Service	2.2 2.6	14 16	6.8	70	9.7	52
ES1A_2C	Plumtree 115 kV	All Out of Service	2.3 2.8	11 18			13.9	116
ES1A_3A	Norwalk 345 kV	Light Load	2.4 2.8	119 248				
ES1A_3B	Norwalk 345 kV	All in Service	2.2 2.6	134 143			7.7	115
ES1A_3C	Norwalk 345 kV	All Out of Service	2.4 2.8	117 249				
ES1A_4A	Norwalk 115 kV	Light Load	2.3 2.8	9 15			8.3	23
ES1A_4B	Norwalk 115 kV	All in Service	2.2	12	4.9	22	15.6	183

			Resonant Frequency & Impedance (pu of 60Hz, Ohm)					
Case	Location	Capacitor Banks	Low		Middle		High	
			HN	Z(Ω)	HN	Z(Ω)	HN	Z(Ω)
			2.6	13				
ES1A_4C	Norwalk 115 kV	All Out of Service	2.3 2.8	9 15			8.3	23
ES1A_5A	Southington 345 kV	Light Load	2.3 2.7	41 52			10.3 11.9	333 284
ES1A_5B	Southington 345 kV	All in Service	2.2 2.6	55 51	4.3	146	8.1 13.0	131 131
ES1A_5C	Southington 345 kV	All Out of Service	2.3 2.8	41 52			10.3 11.9	333 284
ES1A_6A	Southington 115 kV	Light Load	2.3 2.7	6 7			10.1 11.8	30 26
ES1A_6B	Southington 115 kV	All in Service	2.2 2.6	9 7	4.3 5.4	30 40	9.6	66
ES1A_6C	Southington 115 kV	All Out of Service	2.3 2.7	6 7			10.1 11.8	30 26
ES1A_7A	East Shore 345 kV	Light Load	2.4 2.8	106 162			7.9	456
ES1A_7B	East Shore 345 kV	All in Service	2.2 2.6	109 81				
ES1A_7C	East Shore 345 kV	All Out of Service	2.4 2.8	104 162			7.7	449
ES1A_8A	Devon 115 kV	Light Load	2.3 2.8	9 12				
ES1A_8B	Devon 115 kV	All in Service	2.2 2.6	10 9				
ES1A_8C	Devon 115 kV	All Out of Service	2.3 2.8	9 12				
ES1A_9A	Frost Bridge 115 kV	Light Load	2.3 2.7	7 10			10.1	33
ES1A_9B	Frost Bridge 115 kV	All in Service	2.2 2.6	11 12	4.3 5.4	46 33	8.1	37
ES1A_9C	Frost Bridge 115 kV	All Out of Service	2.3 2.7	7 10			10.1	33
ES1A_10A	Glenbrook 115 kV	Light Load	2.3 2.8	8 13			8.4 16.1	41 57
ES1A_10B	Glenbrook 115 kV	All in Service	2.2 2.6	12 13	4.9	49		
ES1A_10C	Glenbrook 115 kV	All Out of Service	2.3 2.8	8 13			8.4 16.1	41 57
ES1A_11A	Singer 345 kV	Light Load	2.4 2.8	121 246				
ES1A_11B	Singer 345 kV	All in Service	2.2 2.6	134 137			11.9	289
ES1A_11C	Singer 345 kV	All Out of Service	2.4 2.8	120 247				
ES1A_12A	Devon 345 kV	Light Load	2.4 2.8	120 235				
ES1A_12B	Devon 345 kV	All in Service	2.2 2.6	131 129			11.9	259
ES1A_12C	Devon 345 kV	All Out of Service	2.4	118				

			Resonant Frequency & Impedance (pu of 60Hz, Ohm)					
Case	Location	Capacitor Banks	Low		Middle		High	
			HN	Z(Ω)	HN	Z(Ω)	HN	Z(Ω)
			2.8	236				
ES1A_13A	Orange 345 kV	Light Load	2.4 2.8	109 171			7.9	439
ES1A_13B	Orange 345 kV	All in Service	2.2 2.6	112 86				
ES1A_13C	Orange 345 kV	All Out of Service	2.4 2.8	107 170			7.7	427

Table 4-2. Driving-Point Impedance Cases for ES-1A with and without Devon-Orange Line

			Resonant Frequency & Impedance (pu of 60Hz, Ohm)					
Case	Location	Capacitor Banks	Low		Middle		High	
			HN	Z(Ω)	HN	Z(Ω)	HN	Z(Ω)
ES1A_1A	Plumtree 345 kV	Light Load	2.4 2.8	93 189	7.9	138	11.9	153
ES1A_1B	Plumtree 345 kV	All in Service	2.2 2.6	110 121			11.9	553
ES1A_1C	Plumtree 345 kV	All Out of Service	2.4 2.8	92 191	7.6	134	11.8	153
ES1AW_1A	Plumtree 345 kV	Light Load	2.3 2.6	152 246			10.2	293
ES1AW_1B	Plumtree 345 kV	All in Service	2.2 2.5	157 122			11.2	675
ES1AW_1C	Plumtree 345 kV	All Out of Service	2.3 2.6	152 247			10.2	292
ES1A_3A	Norwalk 345 kV	Light Load	2.4 2.8	119 248				
ES1A_3B	Norwalk 345 kV	All in Service	2.2 2.6	134 143			7.7	115
ES1A_3C	Norwalk 345 kV	All Out of Service	2.4 2.8	117 249				
ES1AW_3A	Norwalk 345 kV	Light Load	2.3 2.6	206 351				
ES1AW_3B	Norwalk 345 kV	All in Service	2.2 2.5	205 168				
ES1AW_3C	Norwalk 345 kV	All Out of Service	2.3 2.6	207 352				
ES1A_7A	East Shore 345 kV	Light Load	2.4 2.8	106 162			7.9	456
ES1A_7B	East Shore 345 kV	All in Service	2.2 2.6	109 81				
ES1A_7C	East Shore 345 kV	All Out of Service	2.4 2.8	104 162			7.7	449
ES1AW_7A	East Shore 345 kV	Light Load	2.3	85	4.1 4.5	605 511		
ES1AW_7B	East Shore 345 kV	All in Service	2.1	65	3.7 4.6	350 356		
ES1AW_7C	East Shore 345 kV	All Out of Service	2.3	83	4.2	556		

			Resonant Frequency & Impedance (pu of 60Hz, Ohm)					
Case	Location	Capacitor Banks	Low		Middle		High	
			HN	Z(Ω)	HN	Z(Ω)	HN	Z(Ω)
					4.6	707		
ES1A_11A	Singer 345 kV	Light Load	2.4 2.8	121 246				
ES1A_11B	Singer 345 kV	All in Service	2.2 2.6	134 137			11.9	289
ES1A_11C	Singer 345 kV	All Out of Service	2.4 2.8	120 247				
ES1AW_11A	Singer 345 kV	Light Load	2.3 2.6	216 366				
ES1AW_11B	Singer 345 kV	All in Service	2.2 2.5	212 172			11.2	241
ES1AW_11C	Singer 345 kV	All Out of Service	2.3 2.6	217 267				
ES1A_12A	Devon 345 kV	Light Load	2.4 2.8	120 235				
ES1A_12B	Devon 345 kV	All in Service	2.2 2.6	131 129			11.9	259
ES1A_12C	Devon 345 kV	All Out of Service	2.4 2.8	118 236				
ES1AW_12A	Devon 345 kV	Light Load	2.3 2.6	216 364				
ES1AW_12B	Devon 345 kV	All in Service	2.2 2.5	211 170				
ES1AW_12C	Devon 345 kV	All Out of Service	2.3 2.6	217 365				
ES1A_13A	Orange 345 kV	Light Load	2.4 2.8	109 171			7.9	439
ES1A_13B	Orange 345 kV	All in Service	2.2 2.6	112 86				
ES1A_13C	Orange 345 kV	All Out of Service	2.4 2.8	107 170			7.7	427
ES1AW_13A	Orange 345 kV	Light Load	2.3	87	4.1 4.5	627 532		
ES1AW_13B	Orange 345 kV	All in Service	2.1	66	3.7 4.6	360 372		
ES1AW_13C	Orange 345 kV	All Out of Service	2.3	85	4.2 4.6	577 738		

Table 4-3. Driving-Point Impedance Cases for ES-1B

			Resonant Frequency & Impedance (pu of 60Hz, Ohm)					
Case	Location	Capacitor Banks	Low		Middle		High	
			HN	Z(Ω)	HN	Z(Ω)	HN	Z(Ω)
ES1B_1A	Plumtree 345 kV	Light Load	2.3 2.7	104 163	8.8	404	15.9	94
ES1B_1B	Plumtree 345 kV	All in Service	2.2 2.6	108 100			9.1 15.3	187 122
ES1B_1C	Plumtree 345 kV	All Out of Service	2.3 2.7	104 166	8.8	388	15.9	94

			Resonant Frequency & Impedance (pu of 60Hz, Ohm)					
Case	Location	Capacitor Banks	Low		Middle		High	
			HN	Z(Ω)	HN	Z(Ω)	HN	Z(Ω)
ES1B_2A	Plumtree 115 kV	Light Load	2.3 2.7	11 16			8.7 13.7	45 123
ES1B_2B	Plumtree 115 kV	All in Service	2.2 2.5	14 13	6.7	75	10.1	65
ES1B_2C	Plumtree 115 kV	All Out of Service	2.3 2.7	11 16			8.7 13.7	43 123
ES1B_3A	Norwalk 345 kV	Light Load	2.3 2.7	137 216			16.1	96
ES1B_3B	Norwalk 345 kV	All in Service	2.2 2.6	134 118			15.3	87
ES1B_3C	Norwalk 345 kV	All Out of Service	2.3 2.7	135 218			16.1	95
ES1B_4A	Norwalk 115 kV	Light Load	2.3 2.7	9 13			8.0	26
ES1B_4B	Norwalk 115 kV	All in Service	2.2 2.6	11 11	4.8	24	15.3	155
ES1B_4C	Norwalk 115 kV	All Out of Service	2.3 2.7	9 13			8.0	26
ES1B_5A	Southington 345 kV	Light Load	2.3 2.7	43 50			10.7	375
ES1B_5B	Southington 345 kV	All in Service	2.2 2.5	55 46	4.3	157	8.1 12.8	125 131
ES1B_5C	Southington 345 kV	All Out of Service	2.3 2.7	43 50			10.7	375
ES1B_6A	Southington 115 kV	Light Load	2.3 2.6	7 7			10.4	33
ES1B_6B	Southington 115 kV	All in Service	2.1 2.5	8 7	4.3 5.4	31 44	9.6	88
ES1B_6C	Southington 115 kV	All Out of Service	2.3 2.6	7 7			10.4	33
ES1B_7A	East Shore 345 kV	Light Load	2.3 2.7	135 193			8.8 16.1	100 75
ES1B_7B	East Shore 345 kV	All in Service	2.2 2.6	127 97			9.1 10.1 15.3	57 45 60
ES1B_7C	East Shore 345 kV	All Out of Service	2.3 2.7	133 194			8.8 16.1	95 74
ES1B_8A	Devon 115 kV	Light Load	2.3 2.7	9 11				
ES1B_8B	Devon 115 kV	All in Service	2.2 2.5	10 7				
ES1B_8C	Devon 115 kV	All Out of Service	2.3 2.7	9 11				
ES1B_9A	Frost Bridge 115 kV	Light Load	2.3 2.7	7 9			10.4	30
ES1B_9B	Frost Bridge 115 kV	All in Service	2.2 2.5	11 11	4.3 5.5	53 31	8.1	35
ES1B_9C	Frost Bridge 115 kV	All Out of Service	2.3 2.7	7 9			10.4	30
ES1B_10A	Glenbrook 115 kV	Light Load	2.3 2.7	9 11			8.0 15.6	42 53

			Resonant Frequency & Impedance (pu of 60Hz, Ohm)					
Case	Location	Capacitor Banks	Low		Middle		High	
			HN	Z(Ω)	HN	Z(Ω)	HN	Z(Ω)
ES1B_10B	Glenbrook 115 kV	All in Service	2.2 2.5	11 11	4.8	50		
ES1B_10C	Glenbrook 115 kV	All Out of Service	2.3 2.7	9 11			8.0 15.6	42 53
ES1B_11A	Singer 345 kV	Light Load	2.3 2.7	141 217				
ES1B_11B	Singer 345 kV	All in Service	2.2 2.6	135 114				
ES1B_11C	Singer 345 kV	All Out of Service	2.3 2.7	140 219				
ES1B_12A	Devon 345 kV	Light Load	2.3 2.7	140 210			8.9	68
ES1B_12B	Devon 345 kV	All in Service	2.2 2.6	133 107				
ES1B_12C	Devon 345 kV	All Out of Service	2.3 2.7	139 211			8.9	63

Table 4-4. Driving-Point Impedance Cases for M/N Base Configuration

			Resonant Frequency & Impedance (pu of 60Hz, Ohm)					
Case	Location	Capacitor Banks	Low		Middle		High	
			HN	Z(Ω)	HN	Z(Ω)	HN	Z(Ω)
PH2_1A	Plumtree 345 kV	Light Load	2.8	192			10.5	449
PH2_1B	Plumtree 345 kV	All in Service	2.4	128			11.3	620
PH2_1C	Plumtree 345 kV	All Out of Service	2.8	194			10.5	445
PH2_2A	Plumtree 115 kV	Light Load	2.8	19	10.5	93	13.9	109
PH2_2B	Plumtree 115 kV	All in Service	2.4	17	6.6	70		
PH2_2C	Plumtree 115 kV	All Out of Service	2.8	19	10.5	93	13.9	109
PH2_3A	Norwalk 345 kV	Light Load	2.8	243				
PH2_3B	Norwalk 345 kV	All in Service	2.4	149	5.0	70		
PH2_3C	Norwalk 345 kV	All Out of Service	2.8	245				
PH2_4A	Norwalk 115 kV	Light Load	2.8	16	7.9	24		
PH2_4B	Norwalk 115 kV	All in Service	2.4	15	5.0	18	15.6	181
PH2_4C	Norwalk 115 kV	All Out of Service	2.8	16	7.9	24		
PH2_5A	Southington 345 kV	Light Load	2.8	60			10.4	259
PH2_5B	Southington 345 kV	All in Service	2.4	61	4.3	81	8.2	88
PH2_5C	Southington 345 kV	All Out of Service	2.8	60			10.3	250
PH2_6A	Southington 115 kV	Light Load					10.2	29
PH2_6B	Southington 115 kV	All in Service	4.3	26	5.4	38	11.3	126
PH2_6C	Southington 115 kV	All Out of Service					10.1	28
PH2_7A	East Shore 345 kV	Light Load	4.7	167			10.2	212
PH2_7B	East Shore 345 kV	All in Service	4.3	111	7.2	188	12.5 14.6	261 519
PH2_7C	East Shore 345 kV	All Out of Service					10.1	239
PH2_8A	Devon 115 kV	Light Load	2.8	13				
PH2_8B	Devon 115 kV	All in Service	2.4	11				
PH2_8C	Devon 115 kV	All Out of Service	2.8	13				
PH2_9A	Frost Bridge 115 kV	Light Load	2.8	11			10.4	30
PH2_9B	Frost Bridge 115 kV	All in Service	2.4	14	4.3	31	8.3	34

Case	Location	Capacitor Banks	Resonant Frequency & Impedance (pu of 60Hz, Ohm)					
			Low		Middle		High	
			HN	Z(Ω)	HN	Z(Ω)	HN	Z(Ω)
					5.4	40		
PH2_9C	Frost Bridge 115 kV	All Out of Service	2.8	11			10.4	29
PH2_10A	Glenbrook 115 kV	Light Load	2.8	14	8	42	16.0	56
PH2_10B	Glenbrook 115 kV	All in Service	2.4	15	5.0	45		
PH2_10C	Glenbrook 115 kV	All Out of Service	2.8	14	8	42	16.0	56
PH2_11A	Singer 345 kV	Light Load	2.8	237			10.5	136
PH2_11B	Singer 345 kV	All in Service	2.4	144	5.0	74	11.3	231
PH2_11C	Singer 345 kV	All Out of Service	2.8	239			10.5	135
PH2_12A	Devon 345 kV	Light Load	2.8	228			10.5	173
PH2_12B	Devon 345 kV	All in Service	2.4	139	5.0	67	11.3	318
PH2_12C	Devon 345 kV	All Out of Service	2.8	230			10.5	171
PH2_13A	Beseck 345 kV	Light Load	2.8	67			10.4	280
PH2_13B	Beseck 345 kV	All in Service	2.4	57			12.5	277
PH2_13C	Beseck 345 kV	All Out of Service	2.8	67			10.4	270

Comparison of the driving-point impedance results of the East Shore configurations with the M/N configuration indicate that with ES-1A and ES-1B, the lowest-frequency impedance resonance shifts down close to 2nd harmonic (from 2.4 to 2.1-2.2), with all capacitor banks in service. The added cable capacitance and weaker source at East Shore contribute to this shift. The results also indicate an additional resonance slightly below 3rd harmonic with the East Shore configurations. These resonances near 2nd and 3rd harmonics are observed throughout the Bethel to Norwalk and East Shore to Norwalk cable region. In these cases, the light load capacitor bank configuration is similar to the configuration with all capacitors out of service, except that the filter banks are in service at Cross Sound. Also, the Branford filters were modeled in the ES-1A and ES-1B configurations, but were not modeled in the M/N configuration.

Resonances are also appearing locally near 5th, 7th, and 11th harmonics with the ES-1A and ES-1B configurations. The resonant peak magnitudes at 5th harmonic are higher at some locations and lower at other locations. Resonances at 7th harmonic are appearing at more locations. The 5th and 7th harmonic resonances appear to be more dependent on local conditions. The 11th harmonic resonances are generally higher in magnitude with the ES-1A configuration and ES-1B configurations, but it some cases they are much smaller.

In the ES-1AW configuration, with the Devon-Orange line out of services, the 345 kV system is split and is compared to the ES-1A configuration. On the Devon side, the resonances near 2nd and 3rd harmonics are of higher magnitude and lower frequency. On the East Shore side, new resonances appear near 4th and 5th harmonics and are of very high magnitude.

Comparisons of harmonic resonance characteristics at 345 kV can be examined with different cable project configurations. Figure 4-1 shows the driving-point impedance vs. frequency at Plumtree 345 kV with the existing system, with the Bethel to Norwalk project, with the Middletown to Norwalk project base configuration, with the ES-1A configuration, and with the ES-1B configuration, with all capacitor banks in service. With the addition of each cable project, the resonances move from 3rd harmonic toward 2nd harmonic, and with the East Shore configurations another resonance is observed near 3rd harmonic. The impedance resonances with the ES-1A and ES-1B configurations are tuned just above 2nd harmonic and just below 3rd harmonic, with magnitudes similar to that of the existing system at 3rd harmonic.

Figure 4-2 shows the driving-point impedance vs. frequency at Norwalk 345 kV with the B/N project, with the M/N project base configuration, with the ES-1A configuration, and with the ES-1B configuration, with all capacitor banks in service. The impedance resonance characteristics at Norwalk 345 kV are similar to those at Plumtree 345 kV, except that the 5th harmonic resonance is more pronounced at Norwalk and the 11th harmonic resonance is much higher at Plumtree.

Figure 4-3 shows the driving-point impedance vs. frequency at Devon 345 kV with the M/N project base configuration, with the ES-1A configuration, and with the ES-1B configuration, with all capacitor banks in service and with all capacitor banks out of service. The plot indicates variation of the resonances near 11th harmonic. At East Shore, the B/N and M/N projects are similar to the existing system, and resonances at higher frequencies are much more pronounced, as shown in Figure 4-4. With the ES-1A and ES-1B configurations, the resonances near 2nd and 3rd harmonics are higher in magnitude than those of the existing system.

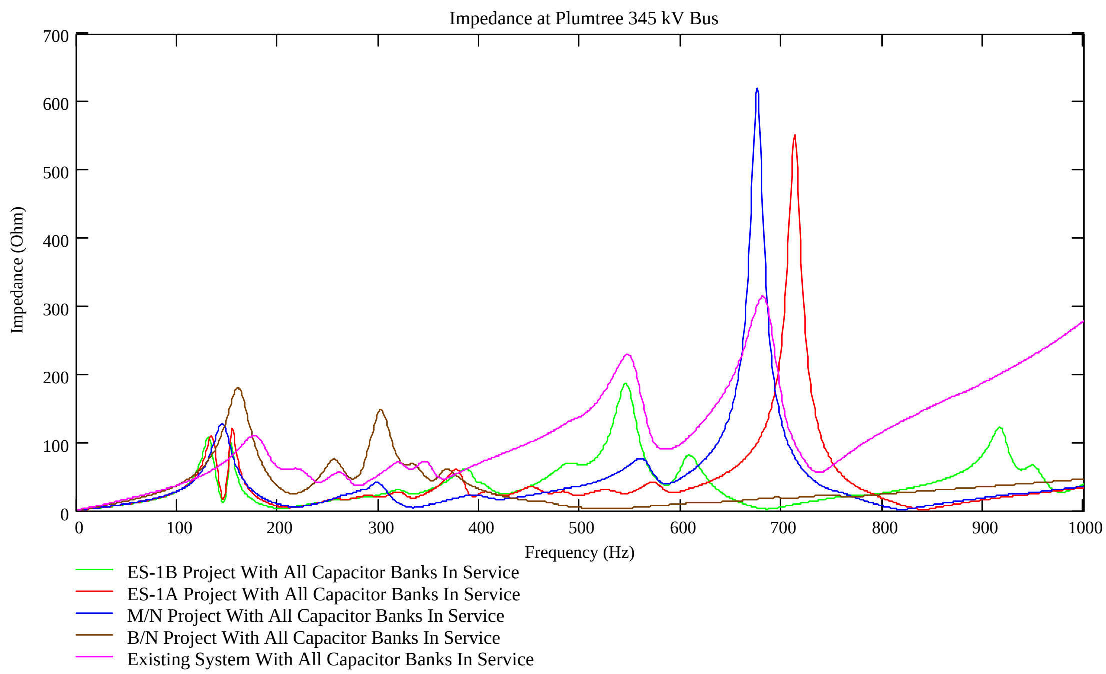

Figure 4-1. Impedance vs. Frequency at Plumtree 345 kV

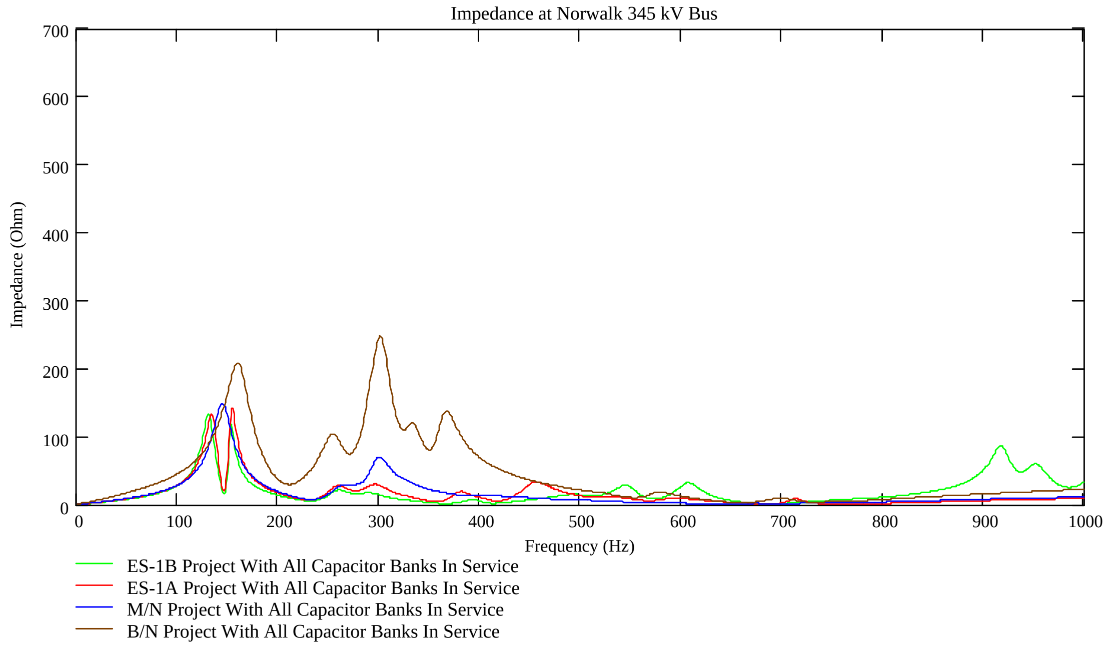

Figure 4-2. Impedance vs. Frequency at Norwalk 345 kV

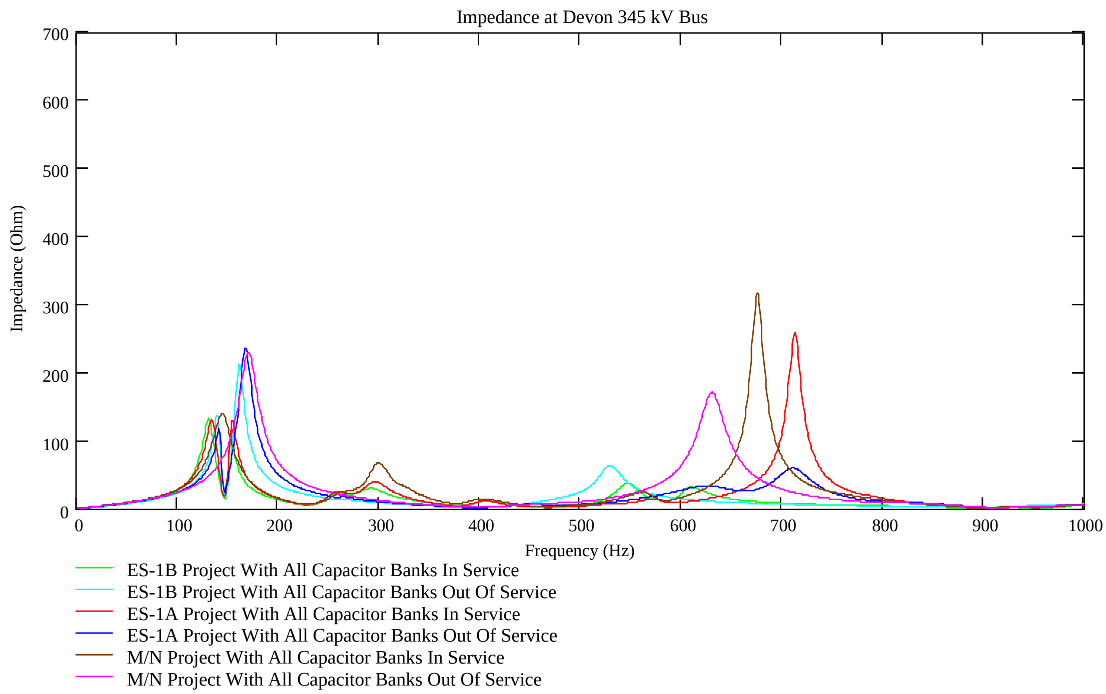

Figure 4-3. Impedance vs. Frequency at Devon 345 kV

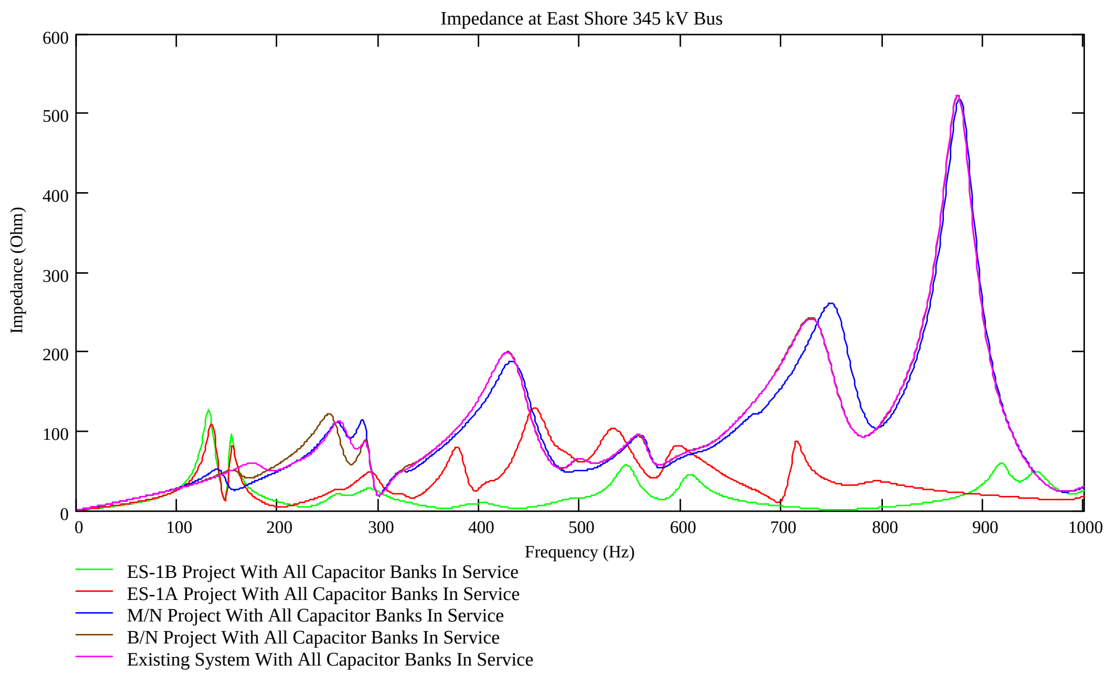

Figure 4-4. Impedance vs. Frequency at East Shore 345 kV

Second Harmonic Resonance Risk Evaluation

The East Shore alternatives resulted in an impedance resonance marginally above the 2nd harmonic. Changes in system configuration could easily move the resonance to 2nd harmonic or below. Consequently, there are similar concerns with this configuration as there were for the M/N-P1 configuration with 40 miles of cable, which had an impedance resonance at 2nd harmonic.

Under normal circumstances, there is little stimulus of the 2nd harmonic because most nonlinear loads produce virtually all of their current distortion in the odd-order harmonics (exceptions are arc furnaces, lamp dimmers, and some consumer-device half-wave dc power supplies). However, there are a number of circumstances where substantial 2nd harmonic stimulus can take place. Existence of system driving point impedance resonances near the 2nd harmonic increases the risk of severe distortion and consequent elevated peak overvoltages and complex control and protection interactions. Designing a system configuration which results in an impedance resonance at 2nd harmonic is potentially very risky and is not recommended.

The most significant source for 2nd harmonic stimulus in a power system is transformer exciting current. Transformer exciting current is very highly distorted, and is composed almost entirely of odd-order harmonics during normal excitation. With asymmetric (i.e., offset) saturation, both even- and odd-order harmonics are produced, which tend to decrease as a function of 1/(HN). Thus, transformers characteristically produce large 2nd harmonic components during offset saturation. Large-scale injection of these current harmonics in a system resonant in the same frequency range can result in severe voltage distortion and elevated peak voltages.

Asymmetric transformer saturation is usually the result of flux offsets due to transformer energization and fault clearing. Inrush can persist for many seconds. Another source of asymmetric saturation is geomagnetic disturbances, which can be present for periods of several days. Severe geomagnetic disturbances, resulting from solar storms, can cause currents at very low frequency (or quasi-dc currents) to flow in the earth. These currents are known as geomagnetically-induced currents (GIC) which can flow into the power system through grounded-wye transformers and can cause asymmetric transformer saturation throughout the power system. The resulting transformer exciting currents, rich in 2nd harmonic, can result in severe and persistent voltage distortion.[1] A blackout of Hydro-Quebec in 1989 has been attributed to second harmonic distortion due to GIC interacting with a protective scheme. GIC issues have been frequently observed in the Hudson Valley region of New York, and in New Jersey where large GSU transformers were destroyed at a nuclear power plant (not due to harmonic distortion, however this indicates that GIC is present in the Northeast).

Severe distortion at a particular harmonic, resulting from asymmetric transformer saturation, often occurs when the system is resonant just below that harmonic. This was observed in the study of the M/N project, in which the system was tuned below 3rd harmonic (between 2.4 and 2.8). When a system is resonant below the given harmonic, the system impedance is inherently capacitive at that harmonic (which can be seen as impedance decreasing with frequency at that harmonic; i.e., negative slope). The capacitive nature of the system forms a resonance with the non-linear inductance of the transformer, which can result in severe voltage distortion during inrush situations, such as energization or inrush following fault clearing.

The same relationship applies to a system that is resonant at 2nd harmonic. However, the severity of the distortion would be expected to be even more severe since the 2nd harmonic currents are about 1.5 times higher than 3rd harmonic currents. In the ES-1A and ES-1B configurations, it was found that the system is resonant just above 2nd harmonic, with all cables and lines in service and all 115 kV capacitor banks in service. Changes in system configuration could easily move the resonance to 2nd harmonic or below, such as loss of lines or generators or addition of cables or capacitor banks at 115 kV. All of these examples, which could weaken the system or add capacitance, could occur either during normal operation or in planned upgrades to the NU system.

In a system that is resonant at 2nd harmonic, the potential for control interactions of certain power electronic equipment is increased. These include HVDC converter terminals, Statcoms, Static Var Compensators (SVCs), and drive system loads. Complex interactions between conventional HVDC systems and system 2nd harmonic resonance, resulting in system instability, have been documented. The HVDC terminal at nearby Cross Sound is a voltage-source-inverter-based converter. The vulnerability of this new technology to 2nd

[1] R. A. Walling, A. H. Khan, "Characteristics of Transformer Exciting-Current During Geomagnetic Disturbances," IEEE Transactions on Power Delivery, Vol. 6, No. 4, October 1991, pp.1707-1713.

harmonic interactions has not been reported in the literature. A Statcom is currently in the plans for installation at Glenbrook 115 kV, which is very close to Norwalk. The potential for interaction between this Statcom and system 2^{nd} harmonic resonance is also not known. Control schemes should be evaluated with the expected impedance resonance characteristics in a cycle-by-cycle transient analysis. Controls for drive system loads could also be affected by a 2^{nd} harmonic resonance in the system. The potential effects of a 2^{nd} harmonic resonance on control interactions could be widely distributed, and vulnerable locations could be difficult to identify.

The potential for misoperation of particular protection schemes can be increased in a system that is resonant at 2^{nd} harmonic. For example, schemes that are based on phase comparison or that monitor zero crossings could be prone to misoperation if currents have a high harmonic content.

While not as severe an issue as distortion driven by transformer saturation, a resonance at 2^{nd} harmonic will tend to aggravate the issue of steady-state even-order harmonic distortion caused by the minority of loads injecting even harmonics. Some suggest that current guidelines for 2^{nd} harmonic distortion current injection are too high.[2] Existence of a system resonance at 2^{nd} harmonic has the same impact on voltage distortion as a large increase in harmonic current injection.

Summary

The East Shore alternatives resulted in impedance resonances marginally above the 2^{nd} harmonic and marginally below the 3^{rd} harmonic. Changes in system configuration could easily move the resonances to 2^{nd} and/or 3^{rd} harmonics or below. Consequently, there are concerns regarding power system events involving transformer exciting current, such as energization and inrush due to fault clearing. With resonances near both 2^{nd} and 3^{rd} harmonics, the harmonic currents due to inrush could have an additive effect to produce more severe results than those with resonances at either harmonic. There are also concerns, as discussed above, about being close to 2^{nd} harmonic. Although the resonance is above 2^{nd} harmonic, it is very close, and defining a design with a minimum safe margin above 2^{nd} harmonic is a subjective call. There is significant concern in regard to the harmonic characteristics of the ES-1A and ES-1B configurations.

[2] Orr, J.A.; Emanuel, A.E., "On the need for strict second harmonic limits," Proceedings of 8th International Conference on Harmonics and Quality of Power, 1998, Vol. 1, Oct. 1998, pp. 176 –181.

5. Switching Transient Analysis for ES-1A

The critical issues that were examined in regard to switching cables and transformers and clearing faults, for East Shore Alternative 1A, were power quality and equipment duty. Different criteria were applied for evaluation of transient and temporary overvoltages and distortion resulting from routine switching operations, and results from contingencies such as faults and equipment failures. Sustained and distorted overvoltages, resulting from routine cable and transformer switching, are not acceptable when considering power quality throughout the system. For fault and equipment failure events, avoidance of consequential equipment damage was the driving criterion. Equipment must be able to withstand temporary overvoltages, and circuit breakers must be capable of successfully interrupting under these conditions. In this fatal flaw analysis, selected cases were simulated to evaluate routine switching operations and to investigate scenarios where the impedance resonances near 2nd and 3rd harmonics could adversely impact the switching transient and temporary overvoltages.

Table 5-1 provides a case list of the switching transient simulations that were performed for ES-1A and includes the operating breaker, open breakers, fault type and location, shunt reactor settings, capacitor bank dispatch, switch timing, and other system conditions. The corresponding simulation case plots can be found in Appendix B. Eight pages of plots for each case are included in the Appendix, and the complete set of plots is included separately on a CD. The first two pages are summary pages for the Devon-East Shore cables, line, and transformers, and the Norwalk-Singer and Singer-Devon cables, including cable end voltages, surge arrester energies, and circuit breaker voltages. Quantities at each cable end are superposed on each plot. The next two pages show the voltages for each of the three cables between Devon and East Shore and the transformer voltages. Two pages of 345 kV bus voltages and two pages of 115 kV bus voltages are also included.

Energization Strategy

Several cases were simulated to energize each of the three cables from each end with uncontrolled closing, and selected cases were performed with pre-insertion resistors. Case scenarios were simulated energizing the cables starting from the Devon end and starting from the East Shore end. Figure 5-1 shows the 115 kV bus voltages and capacitor bank locations during energization of the first cable from the East Shore end. The capacitive switching transient is amplified at Sackett, with a peak of 2.03 pu. Figure 5-2 shows that the use of a pre-insertion resistor in the same case mitigates the capacitive switching transient. Cable energization transients from the East Shore end and the Orange end were similar.

Energization of the 10-mile overhead line between Devon and Orange was performed without line-end arresters and with uncontrolled closing, and it resulted in high transient voltages. Line-end arresters and/or controlled closing should be used for line energization, and further study is recommended to evaluate line terminal and substation equipment with regard to insulation coordination.

Table 5-1. Switching Transient Simulation Case List

Switching Cases: East Shore Config. 1A

Shunt Reactor Settings (MVAR)

Case #	Operation	Operating Breaker	Open Breakers	Fault Type	Fault Location	E. Shore (3 Cables) Setting of each of 3 reactors	Nor-Sng1		Nor-Sng2		Sng-Dev1		Sng-Dev2		Plum-Norw			Arresters	Pre-Ins Resistor	Cap Banks	Switch Timing	System Conditions
							Nor	Sng	Nor	Sng	Sng	Dev	Sng	Dev	Plm	Nor1	Nor2					
Energize Cable/Overhead E. Shore to Devon																						
ESD- 1	Energize	C1	O1,M1,O2,C2,M2,O3,C3,M3,D1,O4			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-PhA	
ESD- 1A	Energize	C1	O1,M1,O2,C2,M2,O3,C3,M3,D1,O4			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
ESD- 1F	Energize	C1	O1,M1,O2,C2,M2,O3,C3,M3,D1,O4	A-g	Orange end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
ESD- 1R	Energize	C1	O1,M1,O2,C2,M2,O3,C3,M3,D1,O4			150	100	100	100	100	75	75	75	75	75	150	75	IN	350Ω	Pk. Load	Vzero-PhA	
ESD- 2	Energize	C1	O1,M1,O2,C2,M2,D1,O4			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vpeak-PhA	
ESD- 3	Energize	C1	O1,M1,D1,O4			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vpeak-PhA	
ESD- 3F	Energize	C1	O1,M1,D1,O4	A-g	Orange end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
ESD- 4	Energize	O4	D1			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vpeak-all	
Energize Cable/Overhead Devon to E. Shore																						
DES- 1	Energize	D1	O4			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vpeak-all	
DES- 1A	Energize	D1	O4,O1,C1,M1,O2,C2,M2,O3,C3,M3			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vpeak-all	
DES- 2	Energize	O1	C1,M1,O2,C2,M2,O3,C3,M3			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-PhA	
DES- 2F	Energize	O1	C1,M1,O2,C2,M2,O3,C3,M3	A-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
DES- 2R	Energize	O1	C1,M1,O2,C2,M2,O3,C3,M3			150	100	100	100	100	75	75	75	75	75	150	75	IN	350Ω	Pk. Load	Vzero-PhA	
DES- 3	Energize	O1	C1,M1,O2,C2,M2			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vpeak-PhA	
DES- 4	Energize	O1	C1,M1			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vpeak-PhA	
DES- 4F	Energize	O1	C1,M1	A-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
Energize East Shore Transformer																						
ES- 1	Energize	C4	M4,X9			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
ES- 2	Energize	C4	M4,X9			150	100	100	100	100	75	75	75	75	75	150	75	IN		Lt. Load	Vzero-all	
ES- 3	Energize	C4	M4,X9,D1,O4			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
Energize Devon Transformer																						
6- 1	Energize	6	7			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
6- 2	Energize	6	7			150	100	100	100	100	75	75	75	75	75	150	75	IN		Lt. Load	Vzero-all	
6- 3	Energize	6	7,V1,W1,V2,W2			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	Norwalk-Singer cables out
6- 3R	Energize	6	7,V1,W1,V2,W2			150	100	100	100	100	75	75	75	75	75	150	75	IN	350Ω	Pk. Load	Vzero-all	Norwalk-Singer cables out
Energize Singer Transformer																						
2- 1	Energize	2	3			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
2- 2	Energize	2	3			150	100	100	100	100	75	75	75	75	75	150	75	IN		Lt. Load	Vzero-all	
Energize Norwalk Transformer																						
N- 1	Energize	N	O			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
N- 2	Energize	N	O			150	100	100	100	100	75	75	75	75	75	150	75	IN		Lt. Load	Vzero-all	
Fault and Clear (apply fault at t=1cy)																						
F- 1	Stub Fault & Clr	Fault		ABC-g	E. Shore 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy (1cy + 4cy)
F- 1A	Stub Fault & Clr	Fault	D1,O4	ABC-g	E. Shore 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy (1cy + 4cy)
F- 2	Stub Fault & Clr	Fault		A-g	E. Shore 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy
F- 2A	Stub Fault & Clr	Fault	D1,O4	A-g	E. Shore 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy
F- 3	Stub Fault & Clr	Fault		ABC-g	Devon 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy
F- 4	Stub Fault & Clr	Fault		A-g	Devon 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy
F- 5	Stub Fault & Clr	Fault		ABC-g	Singer 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy
F- 6	Stub Fault & Clr	Fault		A-g	Singer 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy
F- 7	Stub Fault & Clr	Fault		ABC-g	Norwalk 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy
F- 8	Stub Fault & Clr	Fault		A-g	Norwalk 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy
F- 9	De-energize	O1,C1	M1	ABC-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open both at t=5cy
F- 10	De-energize	O1,C1	M1	A-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open both at t=5cy
F- 11	De-energize	D1,O4		ABC-g	Orange end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open both at t=5cy
F- 12	De-energize	D1,O4		A-g	Orange end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open both at t=5cy
F- 13	De-energize	D1,C1,C2,C3	M1,M2,M3	ABC-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open D1 at t=5cy, open C1,C2,C3 at t=6cy
F- 14	De-energize	D1,C1,C2,C3	M1,M2,M3	A-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open D1 at t=5cy, open C1,C2,C3 at t=6cy

Table 5-1. Switching Transient Simulation Case List

Switching Cases: East Shore Config. 1A

Case #	Operation	Operating Breaker	Open Breakers	Fault Type	Fault Location	E. Shore (3 Cables) Setting of each of 3 reactors	Shunt Reactor Settings (MVAR) Nor-Sng1		Nor-Sng2		Sng-Dev1		Sng-Dev2		Plum-Norw			Arresters	Pre-Ins Resistor	Cap Banks	Switch Timing	System Conditions
							Nor	Sng	Nor	Sng	Sng	Dev	Sng	Dev	Plm	Nor1	Nor2					
F- 15	De-energize	S1,L1	M1	ABC-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		fault on Scovill - E.Shore line, open both at t=5cy
F- 16	De-energize	S1,L1	M1	A-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		fault on Scovill - E.Shore line, open both at t=5cy
F- 17	De-energize	O3,C3,L3,X8		ABC-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open O3,C3 at t=5cy, L3 at 11cy, X8 at 14cy
F- 18	De-energize	O3,C3,L3,X8		A-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open O3,C3 at t=5cy, L3 at 11cy, X8 at 14cy
F- 19	De-energ. & Recl.	D1,O4,D1,O4	fault removed before reclose	ABC-g	Orange end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open D1,O4 at t=5cy, remove fault, reclose D1 at t=10cy, close O4 at t=16cy
F- 20	De-energ. & Recl.	D1,O4,D1,O4	fault removed before reclose	A-g	Orange end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open D1,O4 at t=5cy, remove fault, reclose D1 at t=10cy, close O4 at t=16cy
F- 21	De-energ. & Recl.	D1,O4,D1,C1, C2,C3	M1,M2,M3, fault remains during reclose	ABC-g	Orange end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open D1,O4 at t=5cy, reclose D1 at t=10cy, open D1 at t=14cy, open C1,C2,C3 at t=16cy
F- 22	De-energ. & Recl.	D1,O4,D1,C1, C2,C3	M1,M2,M3, fault remains during reclose	A-g	Orange end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open D1,O4 at t=5cy, reclose D1 at t=10cy, open D1 at t=14cy, open C1,C2,C3 at t=16cy
F- 23	De-energize	D1,C1,C2,C3	M1,M2,M3	ABC-g	Orange line end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open D1 at t=5cy, open C1,C2,C3 at t=6cy
F- 24	De-energize	D1,C1,C2,C3	M1,M2,M3	A-g	Orange line end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open D1 at t=5cy, open C1,C2,C3 at t=6cy
F- 25	De-energ, Restrike	O1,C1	M1,R1			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Restrk PhA	
F- 26	De-energ, Restrike	C1,O1	M1,R1			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Restrk PhA	
F- 27	De-energize	V1,W1		A-g	Singer end	150	75	0	75	75	75	75	75	75	75	150	75	IN		Pk. Load	Bkr W1 last	open at t=5,11cy (like NSF-1 case from M/N study)
F- 28	De-energize	X1,Y1		A-g	Singer end	150	75	75	75	75	75	0	75	75	75	150	75	IN		Pk. Load	Bkr Y1 last	open at t=5,11cy (like SDF-1 case from M/N study)

Reclosing of the 10-mile overhead line between Devon and Orange was also examined without line-end arresters and with uncontrolled closing, and it resulted in high transient voltages near 3.5 pu at the Orange end. Scenarios included successful and unsuccessful reclosing from the Devon end with three-phase-to-ground and single-phase-to-ground faults. Figure 5-3 shows 345 kV bus voltages during unsuccessful reclosing for a three-phase-to-ground fault. The fault clearing following the reclose results in higher levels of distortion than the first fault clearing due to transformer inrush with increased flux offset. While the overvoltages in the system do not appear excessive in terms of equipment withstand (except at the line end), power quality should be evaluated and caution is advised. Line-end arresters and/or controlled closing should be used for reclosing, and further study is recommended to evaluate line terminal and substation equipment with regard to insulation coordination.

Transformer energization scenarios were also examined. Figure 5-4 shows the energization of the Devon 345/115 kV transformer without pre-insertion resistors and with the Norwalk-Singer cables out of service, and it indicates a distorted voltage with a temporary overvoltage magnitude less than 1.5 pu. Cable currents are also distorted. Figure 5-5 indicates that the use of a pre-insertion resistor in the same case improves the temporary overvoltage distortion due to inrush. The magnitude of distortion in the cable currents is also reduced. Figure 5-6 shows the energization of the East Shore transformer without pre-insertion resistors and with the Devon-Orange line open. The simulation indicates that with the Devon-Orange line open and the cables connected at East Shore, the East Shore area is more susceptible to sustained overvoltages due to transformer inrush. This condition should be avoided.

Equipment Specification Issues

Various fault and clear scenarios were also studied. In Figure 5-7, the Norwalk-Singer cable is faulted and removed from service with delayed breaker opening. A sustained overvoltage is developed across the circuit breaker contacts due to the cable charge ringing down with the shunt reactor and voltage distortion caused by transformer inrush following fault clearing. The circuit breaker transient recovery voltage (TRV) is nearly 700 kV. TRVs above 750 kV were observed in single-pole restrike cases on the East Shore cable. This exceeds the TRV capability defined for 362 kV breakers in ANSI C37.06. Higher test voltages or breaker ratings could be required and should be reviewed by the breaker manufacturer.

Temporary overvoltages (TOVs) were observed in various fault clearing simulations. The highest TOVs were observed in stub fault and clear cases, where a 3-phase-to-ground or 1-phase-to-ground fault was applied at a bus and then cleared after 5 cycles. The transformer inrush contributes to high TOVs following the fault clearing. Figure 5-8 shows a stub fault and clear simulation case with a 3-phase-to-ground fault at Singer 345 kV, resulting in a distorted temporary overvoltage. In this case, a TOV of 1.55 pu was observed which could last seconds due to the transformer inrush after fault clearing. The surge arresters at the cable ends must be capable of withstanding this TOV. Based on the GE Tranquell guide, the 294 kV arrester could withstand a 1.55 pu TOV for 15 seconds with 1 per unit prior energy or 150 seconds with no prior energy. The TOV would decay over time, and the inrush is expected to decay within 15 seconds. Therefore, the TOV duty is within the capability of this arrester. The TOV capability of the actual surge arresters procured should be confirmed.

Another potential concern regarding low-order harmonic distortion is the duty of the Branford filters, since the band-pass filters are tuned at 3rd and 5th harmonics. The capacitor voltages of the Branford filters were plotted in selected cases based on the highest voltages observed at Branford 115 kV. Figure 5-9 shows the voltages for the case above with a stub fault and clearing at Singer 345 kV. It is recommended that the filter component ratings be reviewed at Branford.

Surge arrester energy was evaluated by simulating a single-pole restrike during cable de-energization. Figure 5-10 shows an energy duty simulation case for the surge arresters on the East Shore-Orange cable, with the shunt reactor out of service. In this case, the cable is de-energized by opening breakers at East Shore and Orange, and a restrike occurs at East Shore causing voltage and current flow to be re-established in one phase. Despite some optimistic claims, no breaker is restrike free, and surge arresters should be rated to survive the energy duty in such cases. After the restrike on one phase, the arrester conducts with an energy duty of about 300 kiloJoules (kJ) with a peak current of 3.2 kA. Based on the GE Tranquell guide, the energy capability of the 294 kV rated arrester is 1800 kJ with a peak current of 2 kA. Design limits vary for currents above 2 kA and depend on the waveshape. According to GE surge arrester guidelines, it is expected that the arrester can withstand this duty. The current and energy capabilities of the actual surge arresters procured should be confirmed.

115 kV Equipment Considerations

High transient voltages at 115 kV buses were observed in various cases primarily at Rocky River, as in previous studies, and also at Sackett and others. For example, with a stub fault and clear at Singer, a transient voltage of 2.5 pu was observed at Rocky River 115 kV. There is a widely-documented phenomenon, called voltage magnification, where oscillations between two coupled resonant circuits can result in magnified voltage oscillations in the second circuit due to oscillations in the first. Magnification is most severe when the driving circuit (the 345 kV system in this case) has a much larger capacitance than the driven system (115 kV capacitor bank). This phenomenon is most commonly reported as the result of switching a large capacitor bank in the vicinity of a smaller capacitor bank nearby on a lower-voltage system. However, as seen in this and previous studies of the cable projects, the 345 kV fault oscillations appear to instigate this magnification phenomenon. A surge arrester at Rocky River would limit the transient voltage, but would discharge significant current in this case. Fault clearing events also resulted in temporary overvoltages on the 115 kV system. It is recommended that arrester energy and TOV duty be evaluated in the 115 kV system.

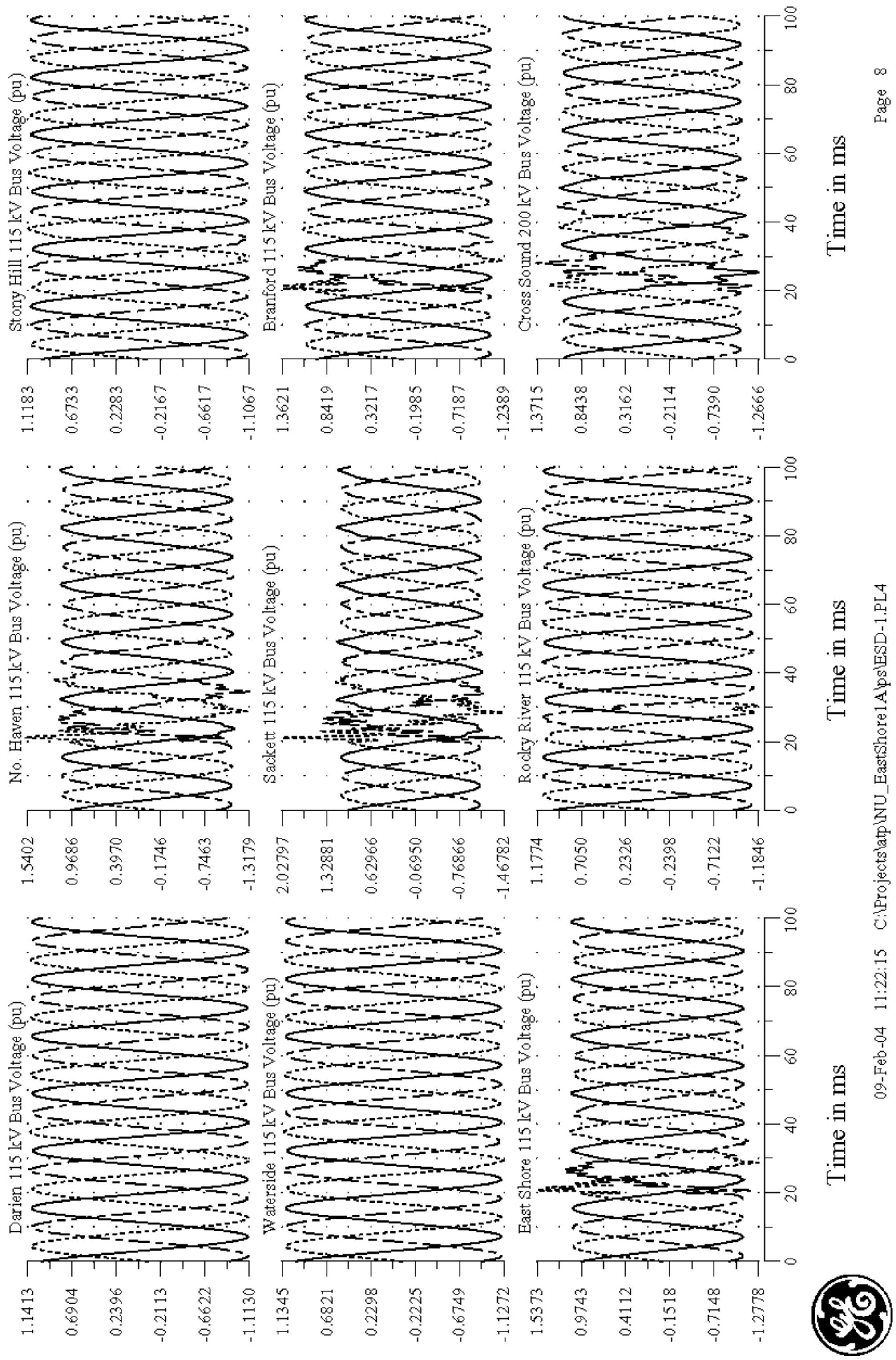

Figure 5-1. Energization of 1st Cable at East Shore (Case ESD-1)

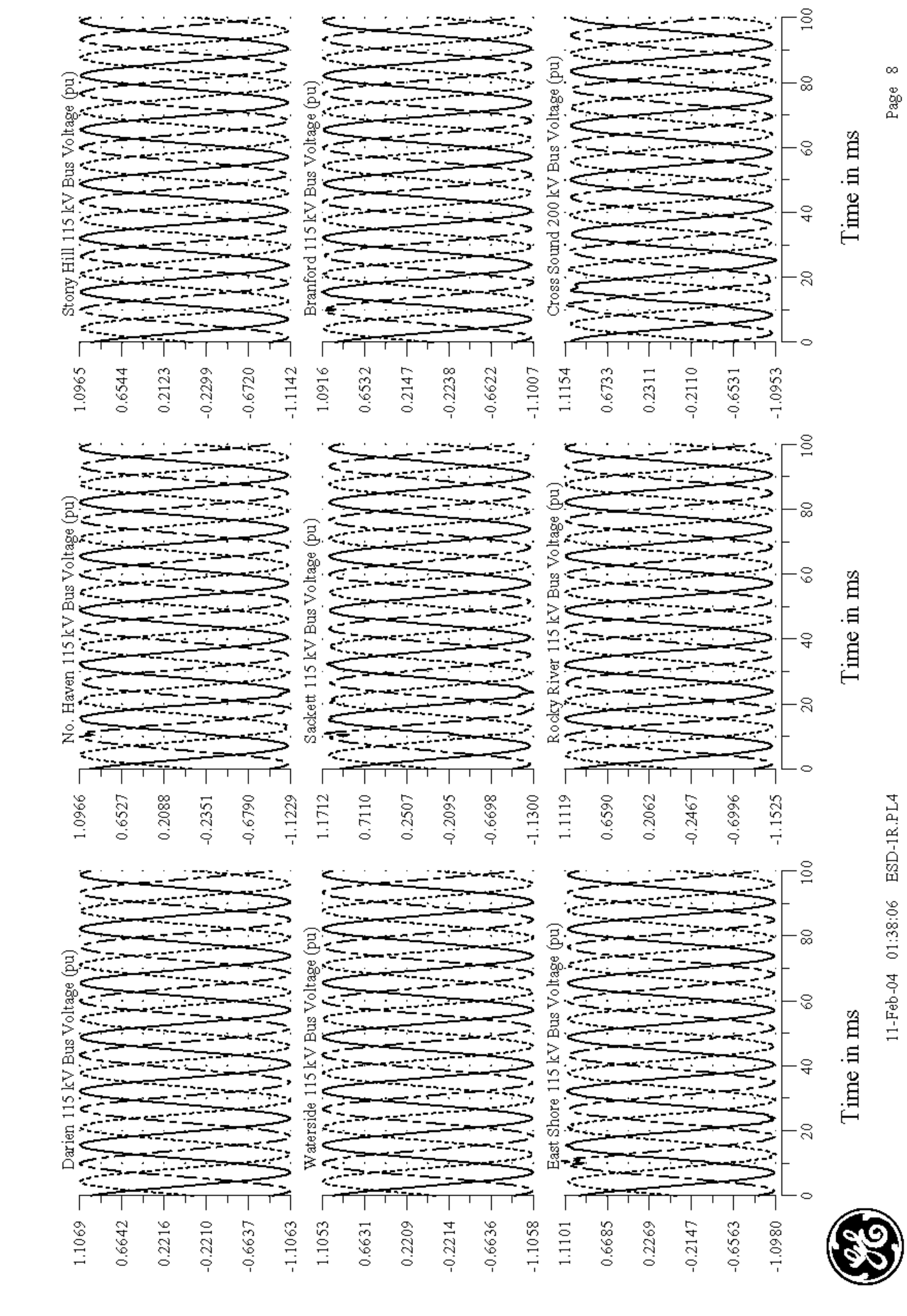

Figure 5-2. Energization of 1st Cable at East Shore, with Pre-Insertion Resistor (Case ESD-1R)

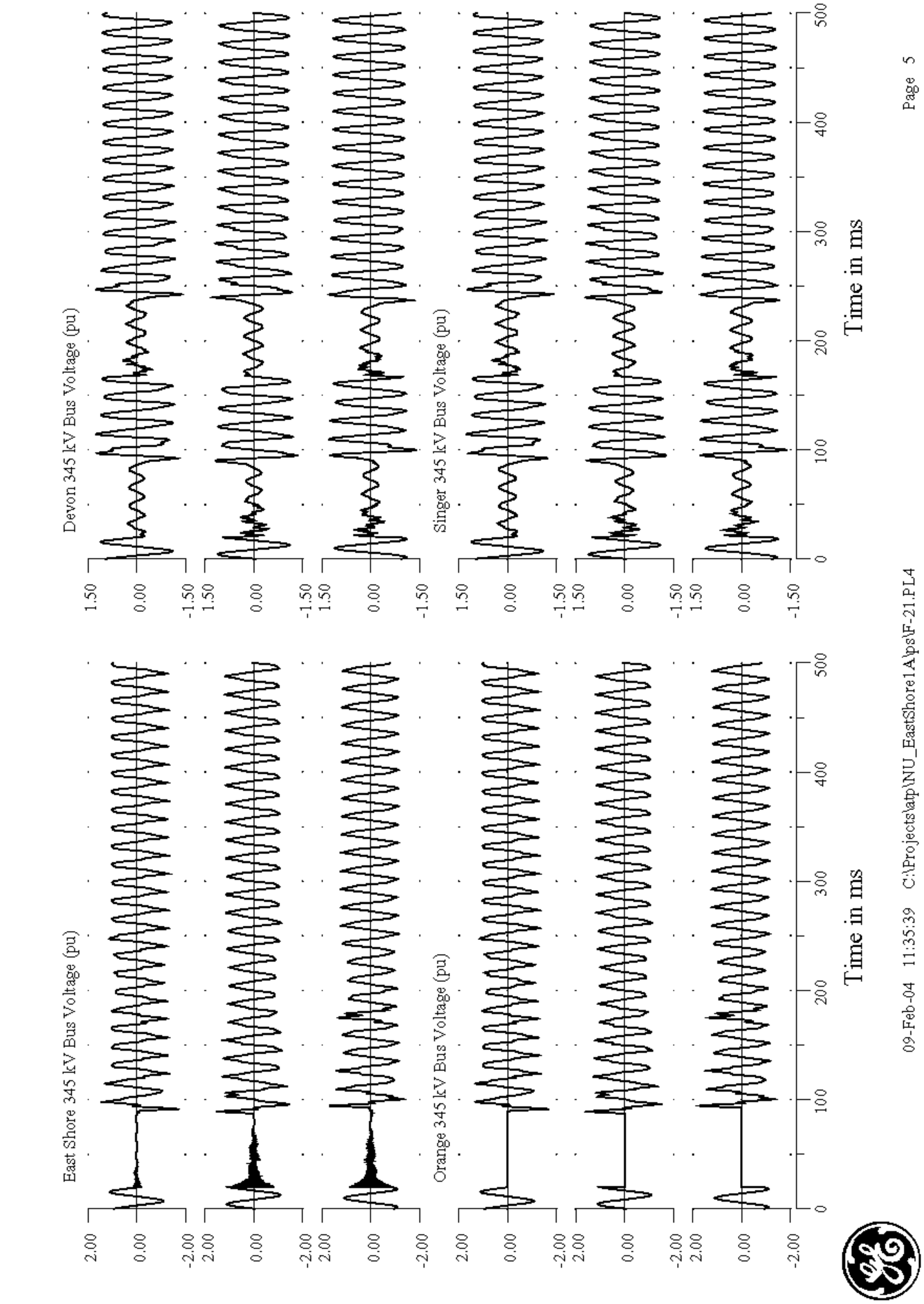

Figure 5-3. Reclosing of Devon-East Shore Line (Case F-21)

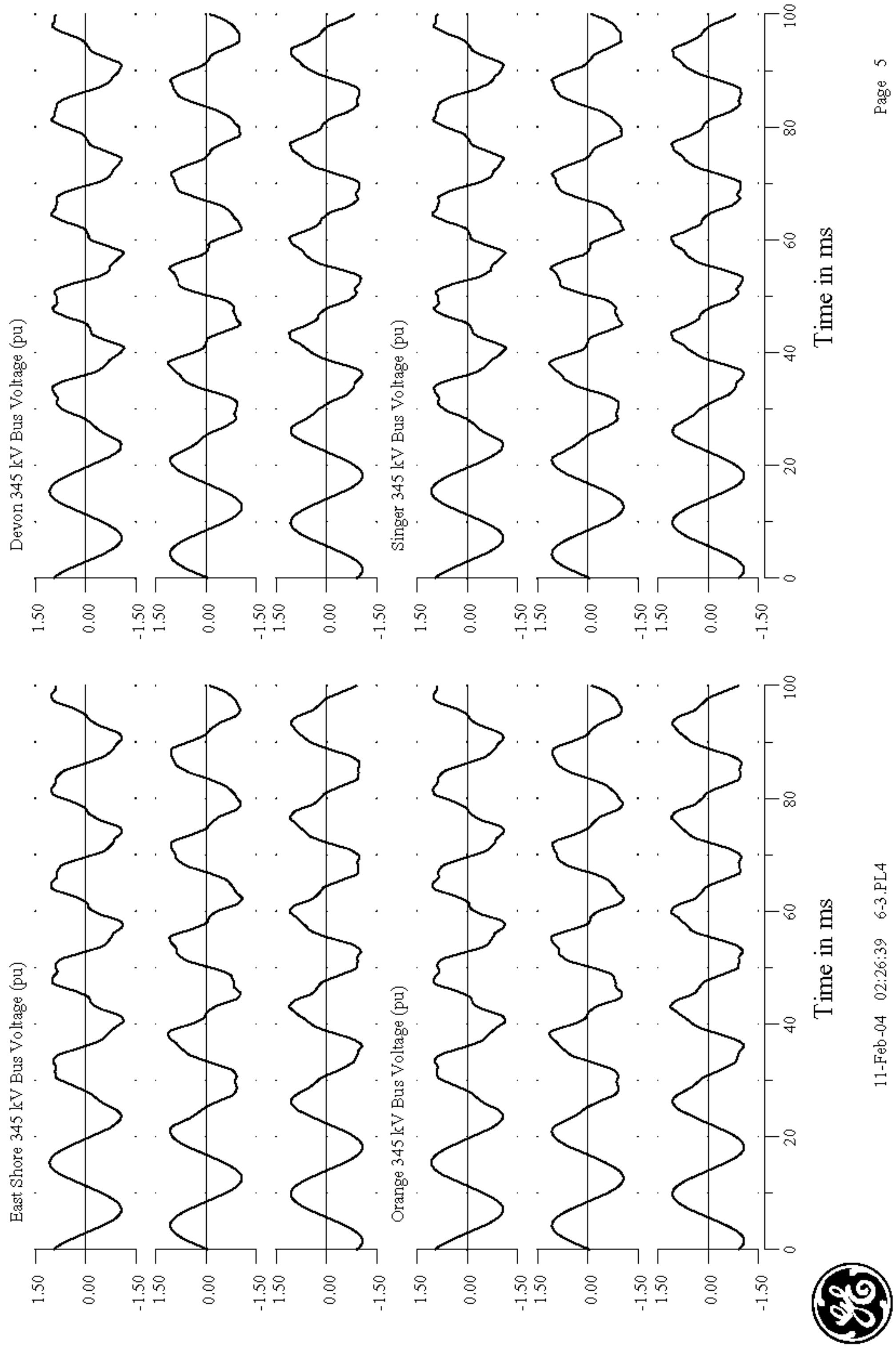

Figure 5-4. Energization of Devon Transformer, with Norwalk-Singer Open (Case 6-3)

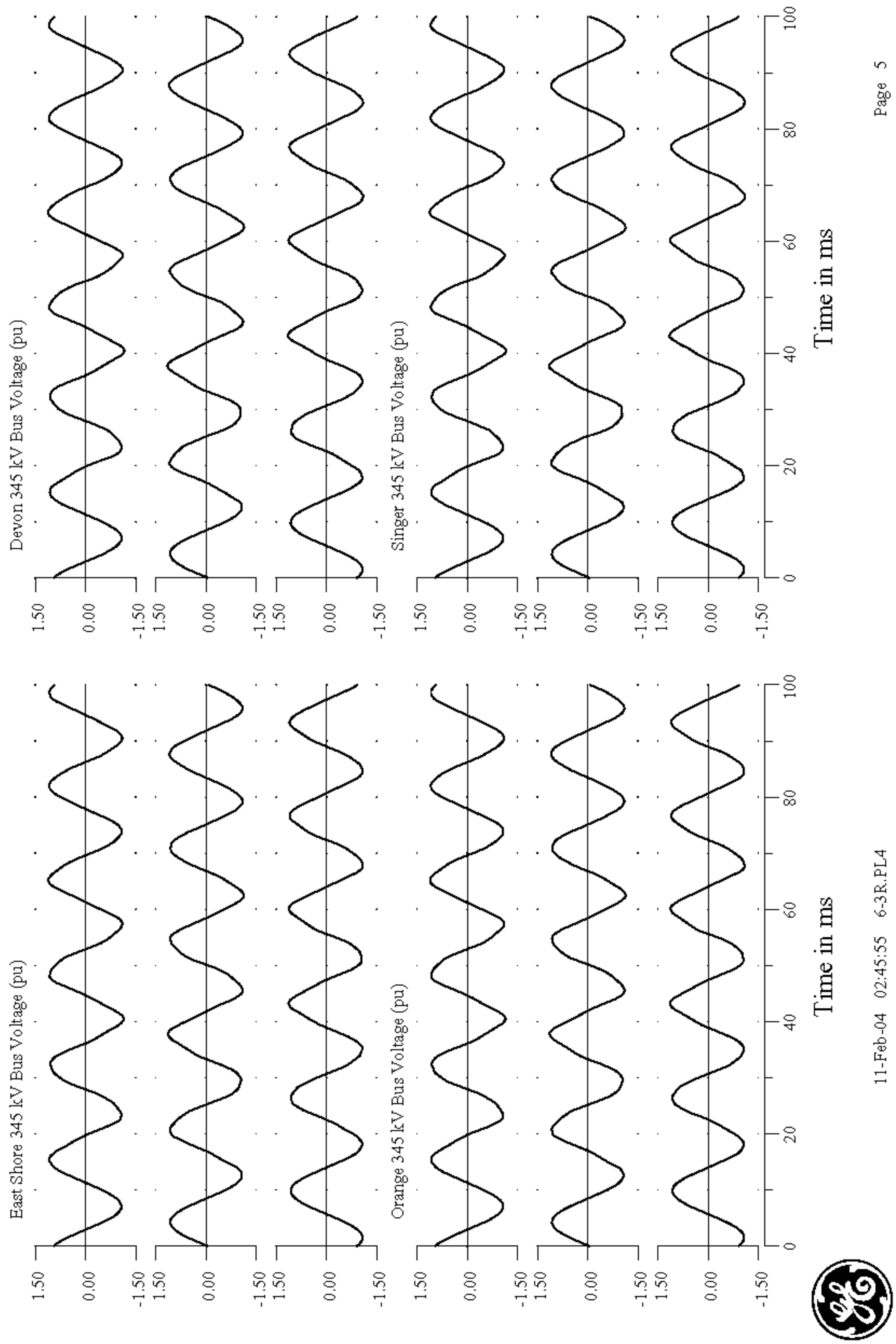

Figure 5-5. Energization of Devon Transformer, with Norwalk-Singer Open and with PIR (Case 6-3R)

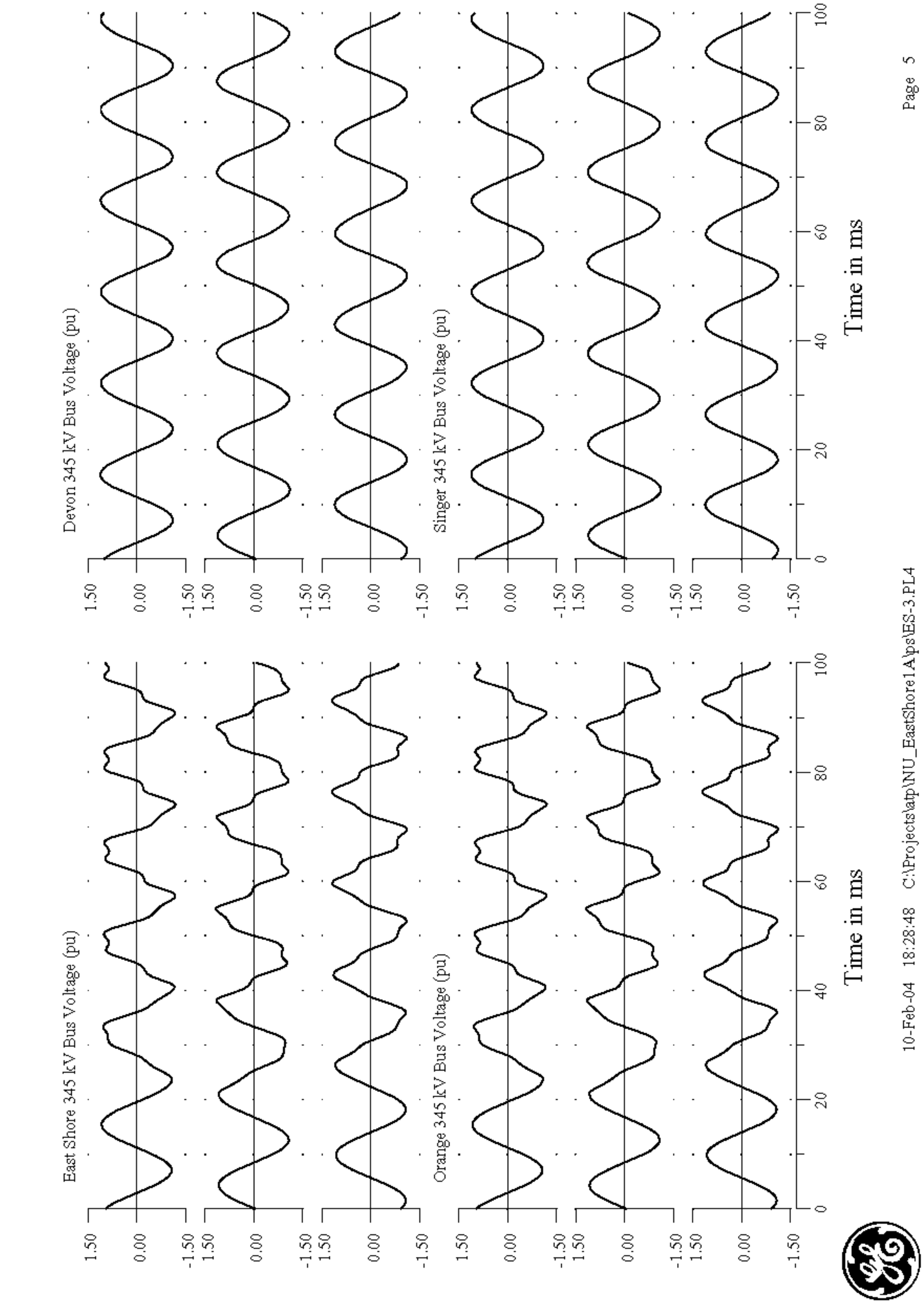

Figure 5-6. Energization of East Shore Transformer, with Devon-Orange Open (Case ES-3)

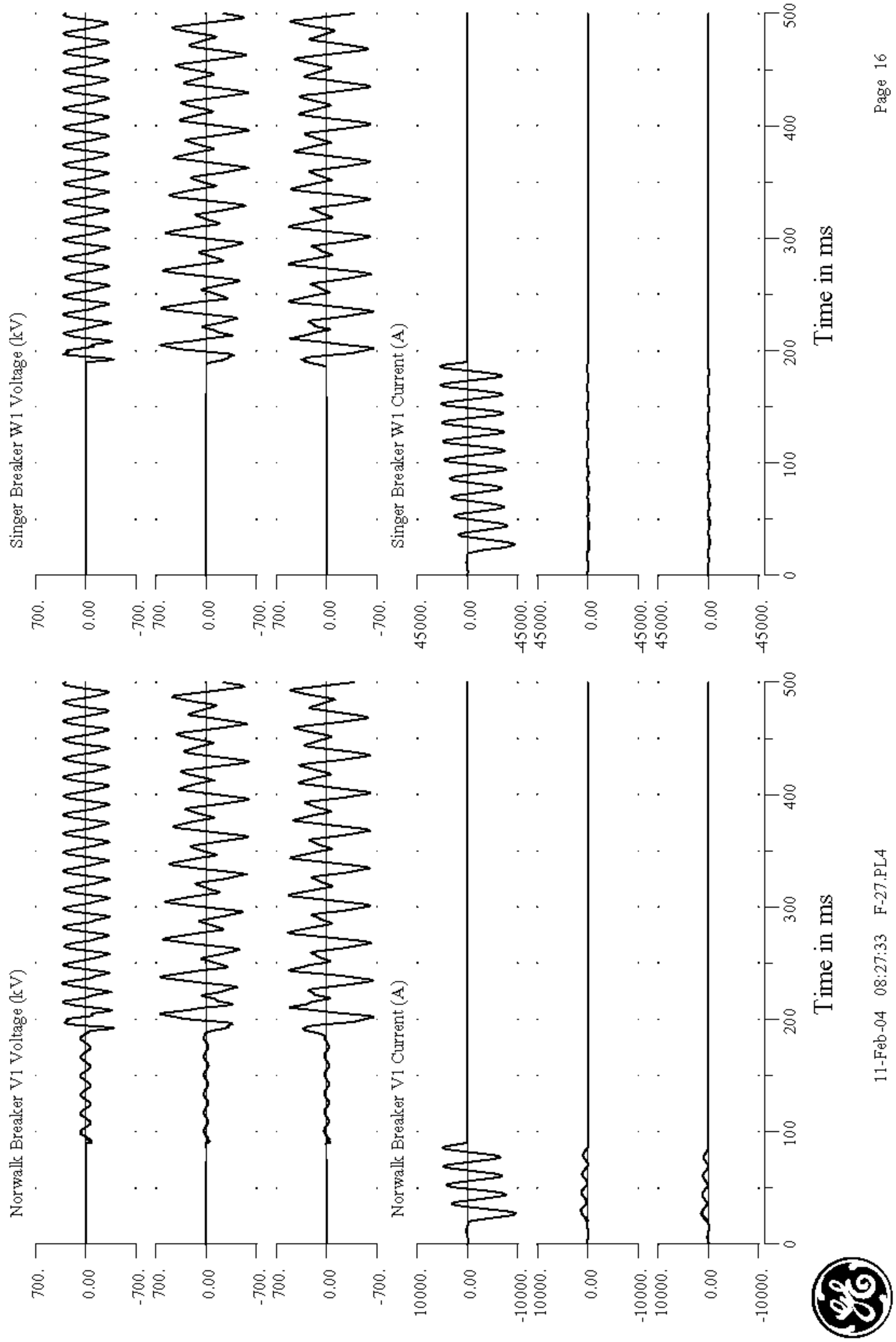

Figure 5-7. Fault & Clear Norwalk-Singer Cable (Case F-27)

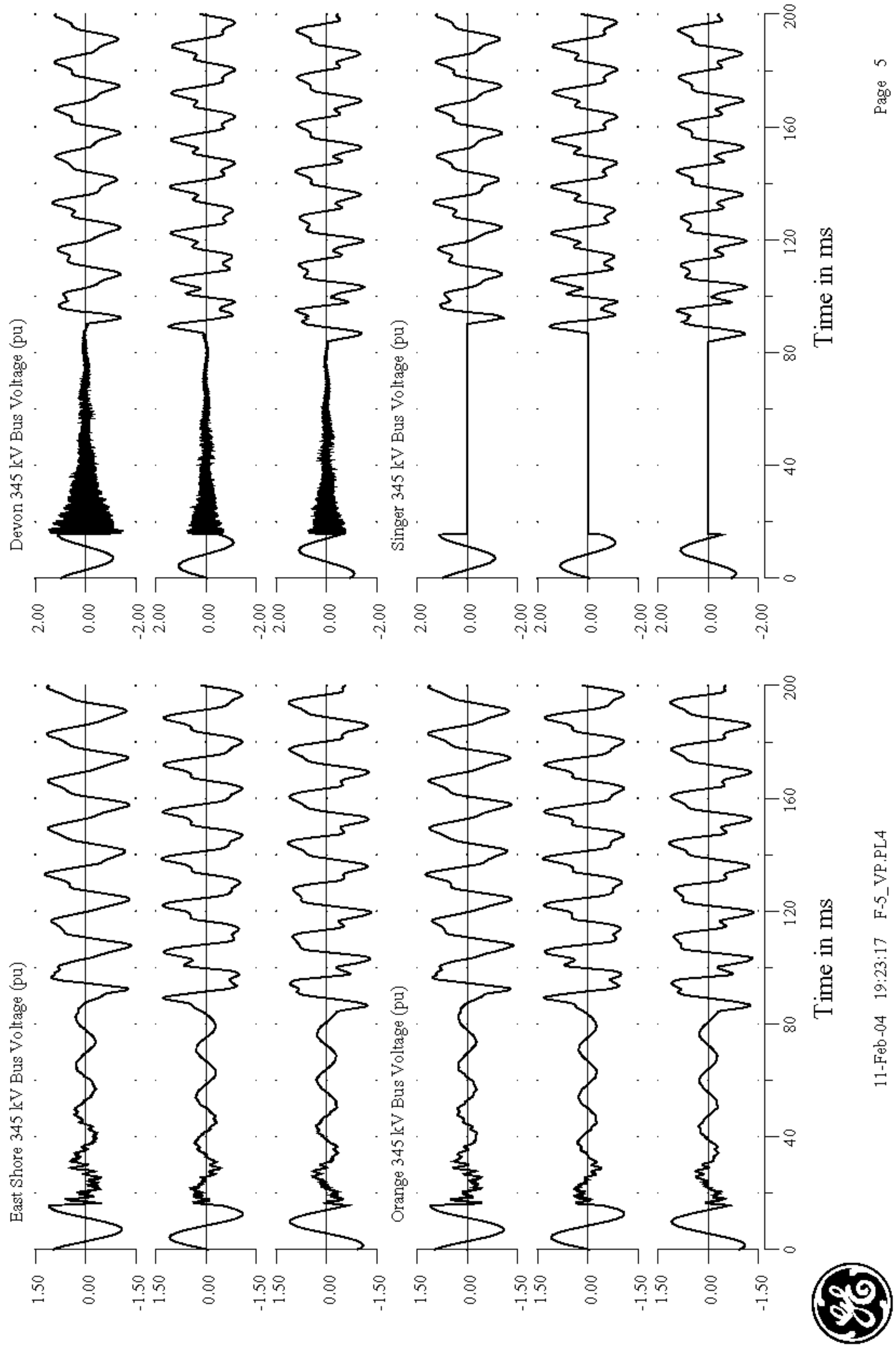

Figure 5-8. Stub Fault & Clear at Singer – Bus Voltages (Case F-5_VP)

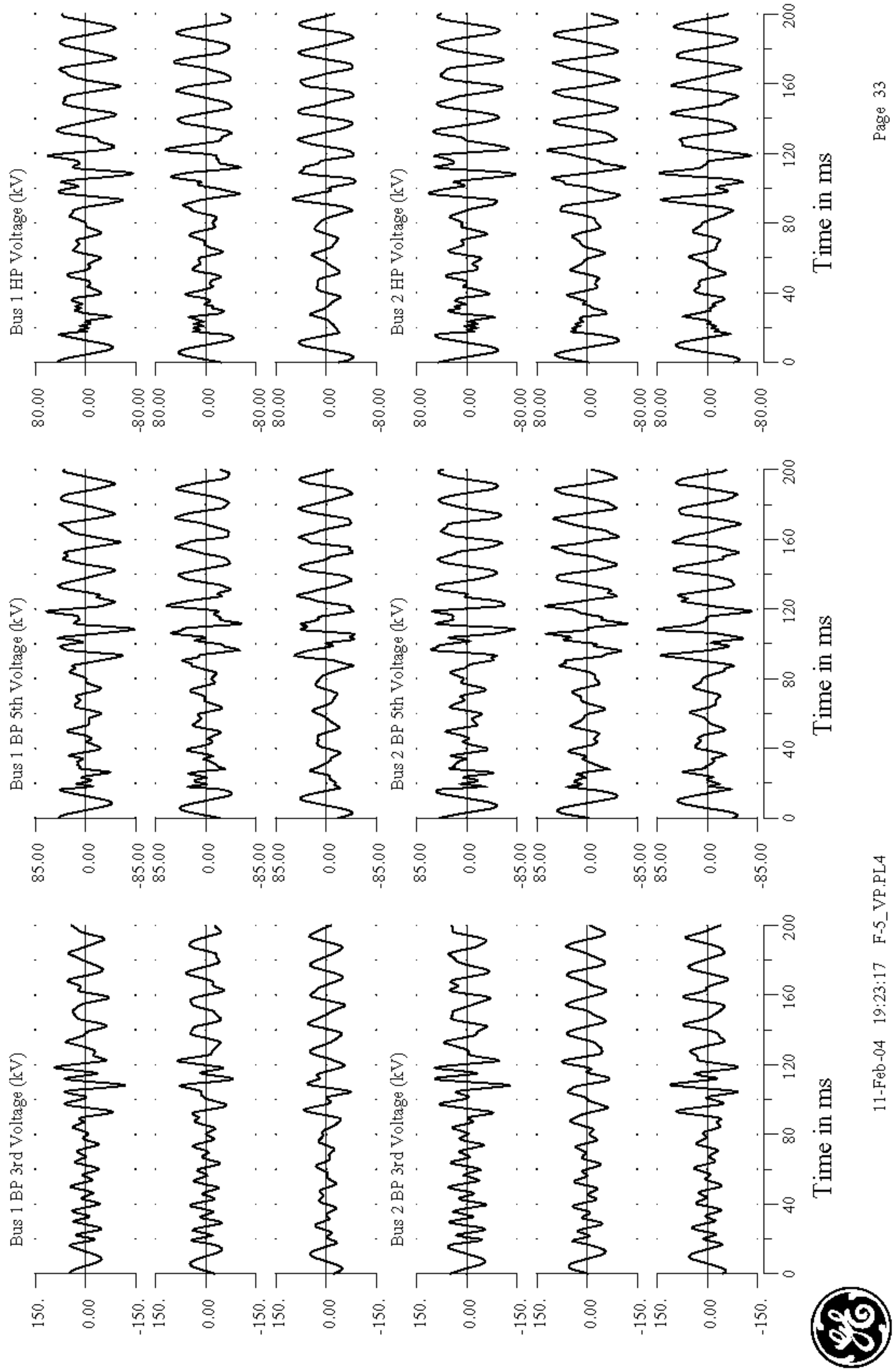

Figure 5-9. Stub Fault & Clear at Singer – Branford Filter Capacitors (Case F-5_VP)

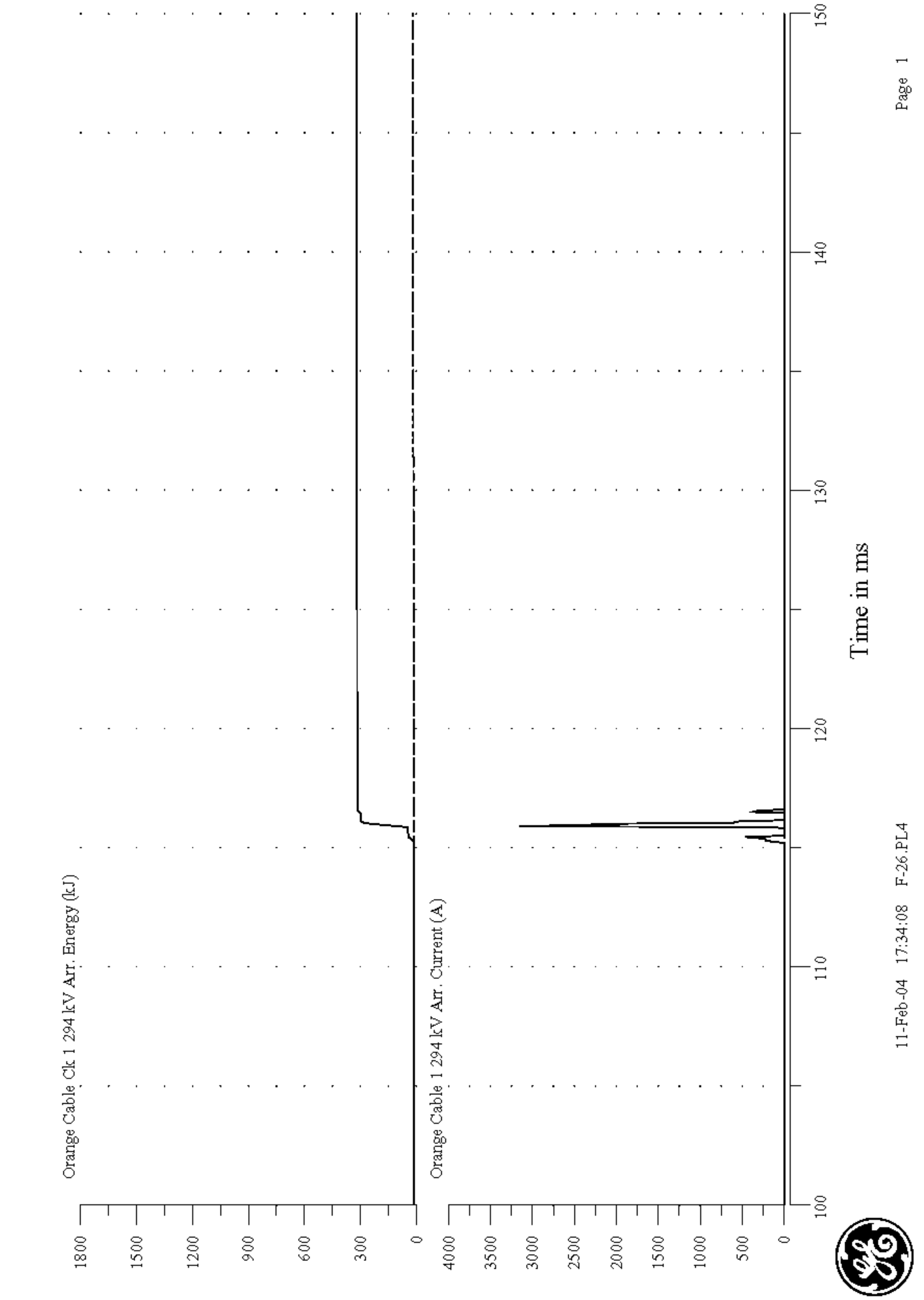

Figure 5-10. De-Energize and Restrike East Shore Cable (Case F-26)

6. Switching Transient Analysis for ES-1B

A similar analysis was performed for East Shore Alternative 1B as was performed for East Shore Alternative 1A. The critical issues that were examined in regard to switching cables and transformers and clearing faults were power quality and equipment duty. Different criteria were applied for evaluation of transient and temporary overvoltages and distortion resulting from routine switching operations, and results from contingencies such as faults and equipment failures. Sustained and distorted overvoltages, resulting from routine cable and transformer switching, are not acceptable when considering power quality throughout the system. For fault and equipment failure events, avoidance of consequential equipment damage was the driving criterion. Equipment must be able to withstand temporary overvoltages, and circuit breakers must be capable of successfully interrupting under these conditions. In this fatal flaw analysis, selected cases were simulated to evaluate routine switching operations and to investigate scenarios where the impedance resonances near 2nd and 3rd harmonics could adversely impact the switching transient and temporary overvoltages.

Table 6-1 provides a case list of the switching transient simulations that were performed for ES-1B and includes the operating breaker, open breakers, fault type and location, shunt reactor settings, capacitor bank dispatch, switch timing, and other system conditions. The case list used in the ES-1B analysis is essentially the same as the one for ES-1A with exception of the cases associated with the removed overhead line from Devon to Orange 345 kV. The corresponding simulation case plots can be found in Appendix C. Eight pages of plots for each case are included in the Appendix, and the complete set of plots is included separately on a CD. The first two pages are summary pages for the Devon-East Shore cables, line, and transformers, and the Norwalk-Singer and Singer-Devon cables, including cable end voltages, surge arrester energies, and circuit breaker voltages. Quantities at each cable end are superposed on each plot. The next two pages show the voltages for each of the three cables between Devon and East Shore and the transformer voltages. Two pages of 345 kV bus voltages and two pages of 115 kV bus voltages are also included.

The overall conclusion is that the East Shore Alternative 1B results don't differ significantly from the East Shore Alternative 1A results.

Energization Strategy

Several cases were simulated to energize each of the three cables from each end with uncontrolled closing, and selected cases were performed with pre-insertion resistors. Case scenarios were simulated energizing the cables starting from the Devon end and starting from the East Shore end. Figure 6-1 shows the 115 kV bus voltages and capacitor bank locations during energization of the first cable from the East Shore end. The capacitive switching transient is amplified at Sackett, with a peak of 2.05 pu. Figure 6-2 shows that the use of a pre-insertion resistor in the same case mitigates the capacitive switching transient. Cable energization transients from the East Shore end and the Devon end were similar.

Table 6-1. Switching Transient Simulation Case List

Switching Cases: East Shore Config. 1B

Shunt Reactor Settings (MVAR)

Case #	Operation	Operating Breaker	Open Breakers	Fault Type	Fault Location	E. Shore (3 Cables) Setting of each of 6 reactors	Nor-Sng1 Nor	Nor-Sng1 Sng	Nor-Sng2 Nor	Nor-Sng2 Sng	Sng-Dev1 Sng	Sng-Dev1 Dev	Sng-Dev2 Sng	Sng-Dev2 Dev	Plum-Norw Plm	Plum-Norw Nor1	Plum-Norw Nor2	Arresters	Pre-Ins Resistor	Cap Banks	Switch Timing	System Conditions
Energize Cable E. Shore to Devon																						
ESD- 1	Energize	C1	O1,M1,O2,C2,M2,O3,C3,M3			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-PhA	
ESD- 1A	Energize	C1	O1,M1,O2,C2,M2,O3,C3,M3			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
ESD- 1F	Energize	C1	O1,M1,O2,C2,M2,O3,C3,M3	A-g	Devon end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
ESD- 1R	Energize	C1	O1,M1,O2,C2,M2,O3,C3,M3			150	100	100	100	100	75	75	75	75	75	150	75	IN	350Ω	Pk. Load	Vzero-PhA	
ESD- 2	Energize	C1	O1,M1,O2,C2,M2			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vpeak-PhA	
ESD- 3	Energize	C1	O1,M1			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vpeak-PhA	
ESD- 3F	Energize	C1	O1,M1	A-g	Devon end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
Energize Cable Devon to E. Shore																						
DES- 2	Energize	O1	C1,M1,O2,C2,M2,O3,C3,M3			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-PhA	
DES- 2F	Energize	O1	C1,M1,O2,C2,M2,O3,C3,M3	A-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
DES- 2R	Energize	O1	C1,M1,O2,C2,M2,O3,C3,M3			150	100	100	100	100	75	75	75	75	75	150	75	IN	350Ω	Pk. Load	Vzero-PhA	
DES- 3	Energize	O1	C1,M1,O2,C2,M2			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vpeak-PhA	
DES- 4	Energize	O1	C1,M1			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vpeak-PhA	
DES- 4F	Energize	O1	C1,M1	A-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
Energize East Shore Transformer																						
ES- 1	Energize	C4	M4,X9			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
ES- 2	Energize	C4	M4,X9			150	100	100	100	100	75	75	75	75	75	150	75	IN		Lt. Load	Vzero-all	
ES- 3	Energize	C4	M4,X9,O1,O2,O3			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
Energize Devon Transformer																						
6- 1	Energize	6	7			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
6- 2	Energize	6	7			150	100	100	100	100	75	75	75	75	75	150	75	IN		Lt. Load	Vzero-all	
6- 3	Energize	6	7,V1,W1,V2,W2			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	Norwalk-Singer cables out
6- 3R	Energize	6	7,V1,W1,V2,W2			150	100	100	100	100	75	75	75	75	75	150	75	IN	350Ω	Pk. Load	Vzero-all	Norwalk-Singer cables out
Energize Singer Transformer																						
2- 1	Energize	2	3			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
2- 2	Energize	2	3			150	100	100	100	100	75	75	75	75	75	150	75	IN		Lt. Load	Vzero-all	
Energize Norwalk Transformer																						
N- 1	Energize	N	O			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Vzero-all	
N- 2	Energize	N	O			150	100	100	100	100	75	75	75	75	75	150	75	IN		Lt. Load	Vzero-all	
Fault and Clear (apply fault at t=1cy)																						
F- 1	Stub Fault & Clr	Fault		ABC-g	E. Shore 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy (1cy + 4cy)
F- 1A	Stub Fault & Clr	Fault	O1,O2,O3	ABC-g	E. Shore 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy (1cy + 4cy)
F- 2	Stub Fault & Clr	Fault		A-g	E. Shore 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy
F- 2A	Stub Fault & Clr	Fault	O1,O2,O3	A-g	E. Shore 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy
F- 3	Stub Fault & Clr	Fault		ABC-g	Devon 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy
F- 4	Stub Fault & Clr	Fault		A-g	Devon 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy
F- 5	Stub Fault & Clr	Fault		ABC-g	Singer 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy
F- 6	Stub Fault & Clr	Fault		A-g	Singer 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy
F- 7	Stub Fault & Clr	Fault		ABC-g	Norwalk 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy
F- 8	Stub Fault & Clr	Fault		A-g	Norwalk 345 kV	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open t=5cy
F- 9	De-energize	O1,C1	M1	ABC-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open both at t=5cy
F- 10	De-energize	O1,C1	M1	A-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open both at t=5cy
F- 15	De-energize	S1,L1	M1	ABC-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		fault on Scovill - E.Shore line, open both at t=5cy
F- 16	De-energize	S1,L1	M1	A-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		fault on Scovill - E.Shore line, open both at t=5cy
F- 17	De-energize	O3,C3,L3,X8		ABC-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open O3,C3 at t=5cy, L3 at 11cy, X8 at 14cy
F- 18	De-energize	O3,C3,L3,X8		A-g	E. Shore end	150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load		open O3,C3 at t=5cy, L3 at 11cy, X8 at 14cy
F- 25	De-energ, Restrike	O1,C1	M1,R1			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Restrk PhA	
F- 26	De-energ, Restrike	C1,O1	M1,R1			150	100	100	100	100	75	75	75	75	75	150	75	IN		Pk. Load	Restrk PhA	
F- 27	De-energize	V1,W1		A-g	Singer end	150	75	0	75	75	75	75	75	75	75	150	75	IN		Pk. Load	Bkr W1 last	open at t=5,11cy (like NSF-1 case from M/N study)
F- 28	De-energize	X1,Y1		A-g	Singer end	150	75	75	75	75	75	0	75	75	75	150	75	IN		Pk. Load	Bkr Y1 last	open at t=5,11cy (like SDF-1 case from M/N study)

Transformer energization scenarios were also examined. Figure 6-3 shows the energization of the Devon 345/115 kV transformer without pre-insertion resistors and with the Norwalk-Singer cables out of service, and it indicates a distorted voltage with a temporary overvoltage magnitude less than 1.5 pu. Cable currents are also distorted. Figure 6-4 indicates that the use of a pre-insertion resistor in the same case improves the temporary overvoltage distortion due to inrush. The magnitude of distortion in the cable currents is also reduced. Figure 6-5 shows the energization of the East Shore transformer without pre-insertion resistors and with the Devon-East Shore cables open at Devon. The simulation indicates that with the Devon-East Shore cables open at Devon and the cables connected at East Shore, the East Shore area is more susceptible to sustained overvoltages due to transformer inrush. This condition should be avoided.

Equipment Specification Issues

Various fault and clear scenarios were also studied. In Figure 6-6, the Singer-Devon cable is faulted and removed from service with delayed breaker opening. A sustained overvoltage is developed across the circuit breaker contacts due to the cable charge ringing down with the shunt reactor and voltage distortion caused by transformer inrush following fault clearing. The circuit breaker transient recovery voltage (TRV) is nearly 700 kV. TRVs near 750 kV were observed in single-pole restrike cases on the East Shore cable. This exceeds the TRV capability defined for 362 kV breakers in ANSI C37.06. Higher test voltages or breaker ratings could be required and should be reviewed by the breaker manufacturer.

Temporary overvoltages (TOVs) were observed in various fault clearing simulations. The highest TOVs were observed in stub fault and clear cases, where a 3-phase-to-ground or 1-phase-to-ground fault was applied at a bus and then cleared after 5 cycles. The transformer inrush contributes to high TOVs following the fault clearing. Figure 6-7 shows a stub fault and clear simulation case with a 3-phase-to-ground fault at Singer 345 kV, resulting in a distorted temporary overvoltage. In this case, a TOV less than 1.5 pu was observed which could last seconds due to the transformer inrush after fault clearing. The surge arresters at the cable ends must be capable of withstanding this TOV. Based on the GE Tranquell guide, the 294 kV arrester could withstand a 1.5 pu TOV for about 100 seconds with 1 per unit prior energy or about 1000 seconds with no prior energy. The TOV would decay over time, and the inrush is expected to decay within 100 seconds. Therefore, the TOV duty is within the capability of this arrester. The TOV capability of the actual surge arresters procured should be confirmed.

Another potential concern regarding low-order harmonic distortion is the duty of the Branford filters, since the band-pass filters are tuned at 3rd and 5th harmonics. The capacitor voltages of the Branford filters were plotted in selected cases based on the highest voltages observed at Branford 115 kV. Figure 6-8 shows the voltages for the case above with a stub fault and clearing at Singer 345 kV. It is recommended that the filter component ratings be reviewed at Branford.

Surge arrester energy was evaluated by simulating a single-pole restrike during cable de-energization. Figure 6-9 shows an energy duty simulation case for the surge arresters on the East Shore-Devon cable, with one shunt reactor out of service. In this case, the cable is de-energized by opening breakers at East Shore and Devon, and a restrike occurs at Devon causing voltage and current flow to be re-established in one phase. Despite some optimistic claims, no breaker is restrike free, and surge arresters should be rated to survive the energy duty in such cases. After the restrike on one phase, the arrester conducts with an energy duty of about 400 kiloJoules (kJ) with a peak current of 1.9 kA. Based on the GE Tranquell guide, the energy capability of the 294 kV rated arrester is 1800 kJ with a peak current of 2 kA. The current and energy capabilities of the actual surge arresters procured should be confirmed.

115 kV Equipment Considerations

High transient voltages at 115 kV buses were observed in various cases primarily at Rocky River, as in previous studies, and also at Sackett and others. For example, with a stub fault and clear at East Shore, a transient voltage of 2.5 pu was observed at Rocky River 115 kV. There is a widely-documented phenomenon, called voltage magnification, where oscillations between two coupled resonant circuits can result in magnified voltage oscillations in the second circuit due to oscillations in the first. Magnification is most severe when the driving circuit (the 345 kV system in this case) has a much larger capacitance than the driven system (115 kV capacitor bank). This phenomenon is most commonly reported as the result of switching a large capacitor bank in the vicinity of a smaller capacitor bank nearby on a lower-voltage system. However, as seen in this and previous studies of the cable projects, the 345 kV fault oscillations appear to instigate this magnification phenomenon. A surge arrester at Rocky River would limit the transient voltage, but would discharge significant current in this case. Fault clearing events also resulted in temporary overvoltages on the 115 kV system. It is recommended that arrester energy and TOV duty be evaluated in the 115 kV system.

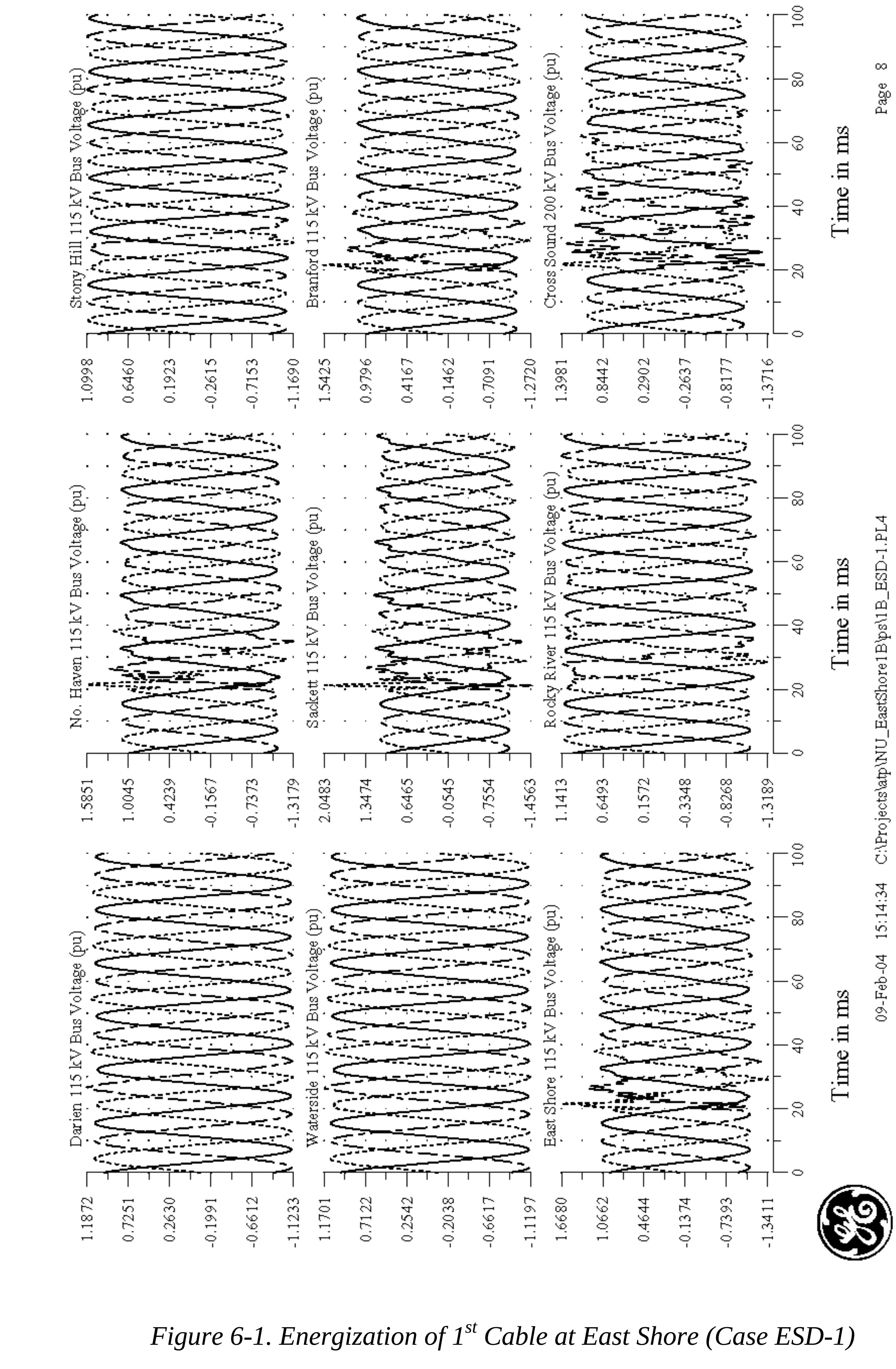

Figure 6-1. Energization of 1st Cable at East Shore (Case ESD-1)

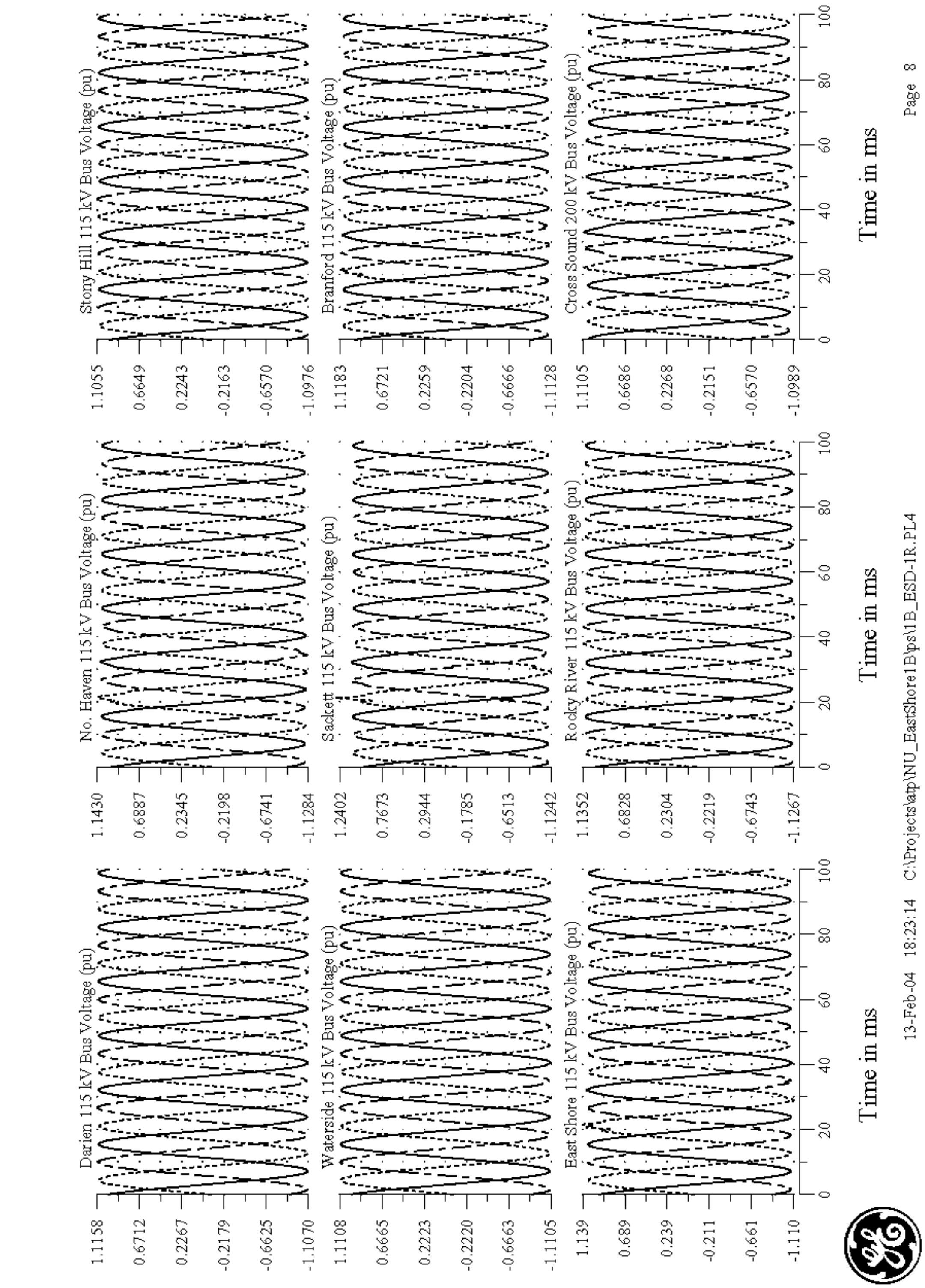

Figure 6-2. Energization of 1st Cable at East Shore, with Pre-Insertion Resistor (Case ESD-1R)

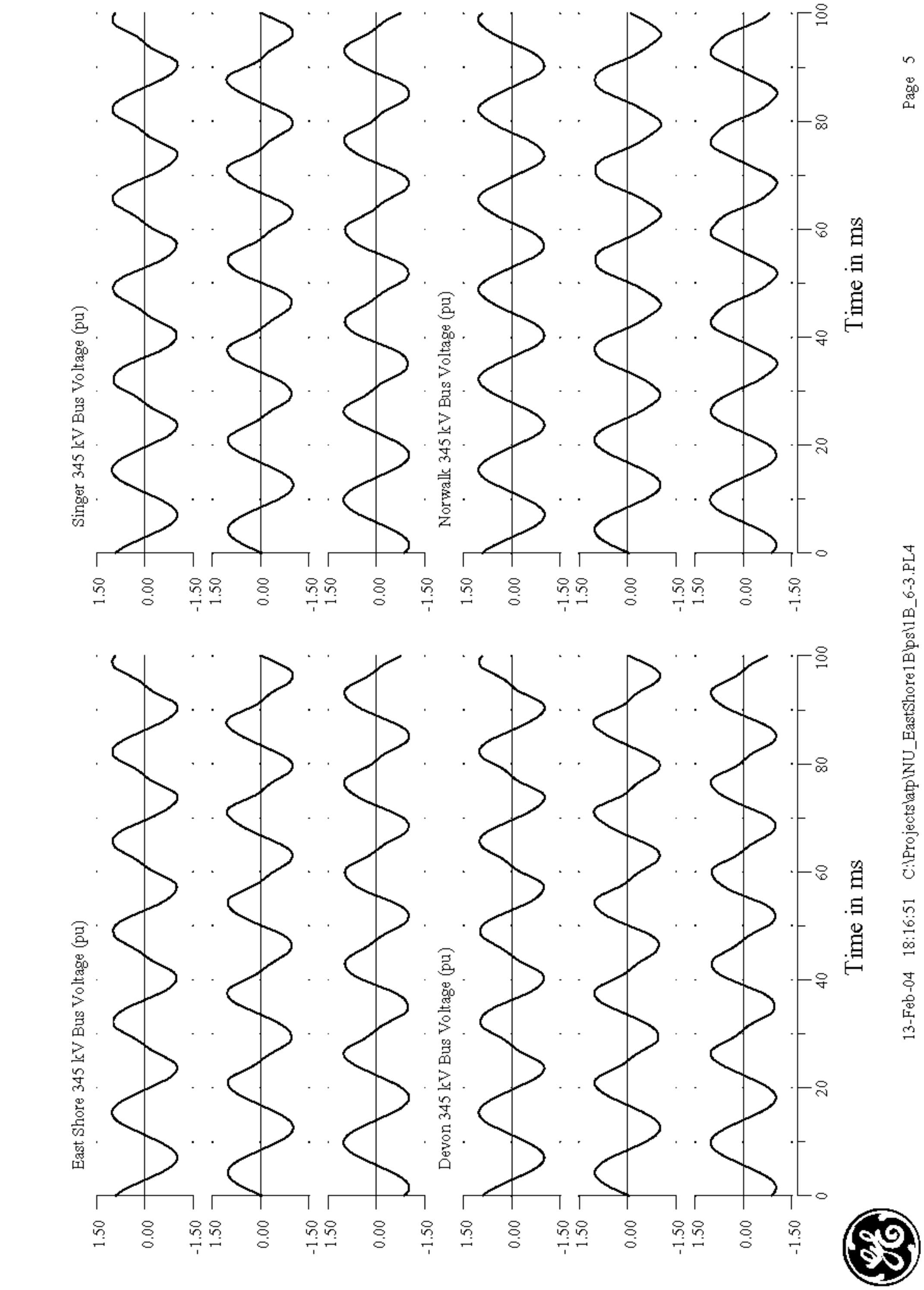

Figure 6-3. Energization of Devon Transformer, with Norwalk-Singer Open (Case 6-3)

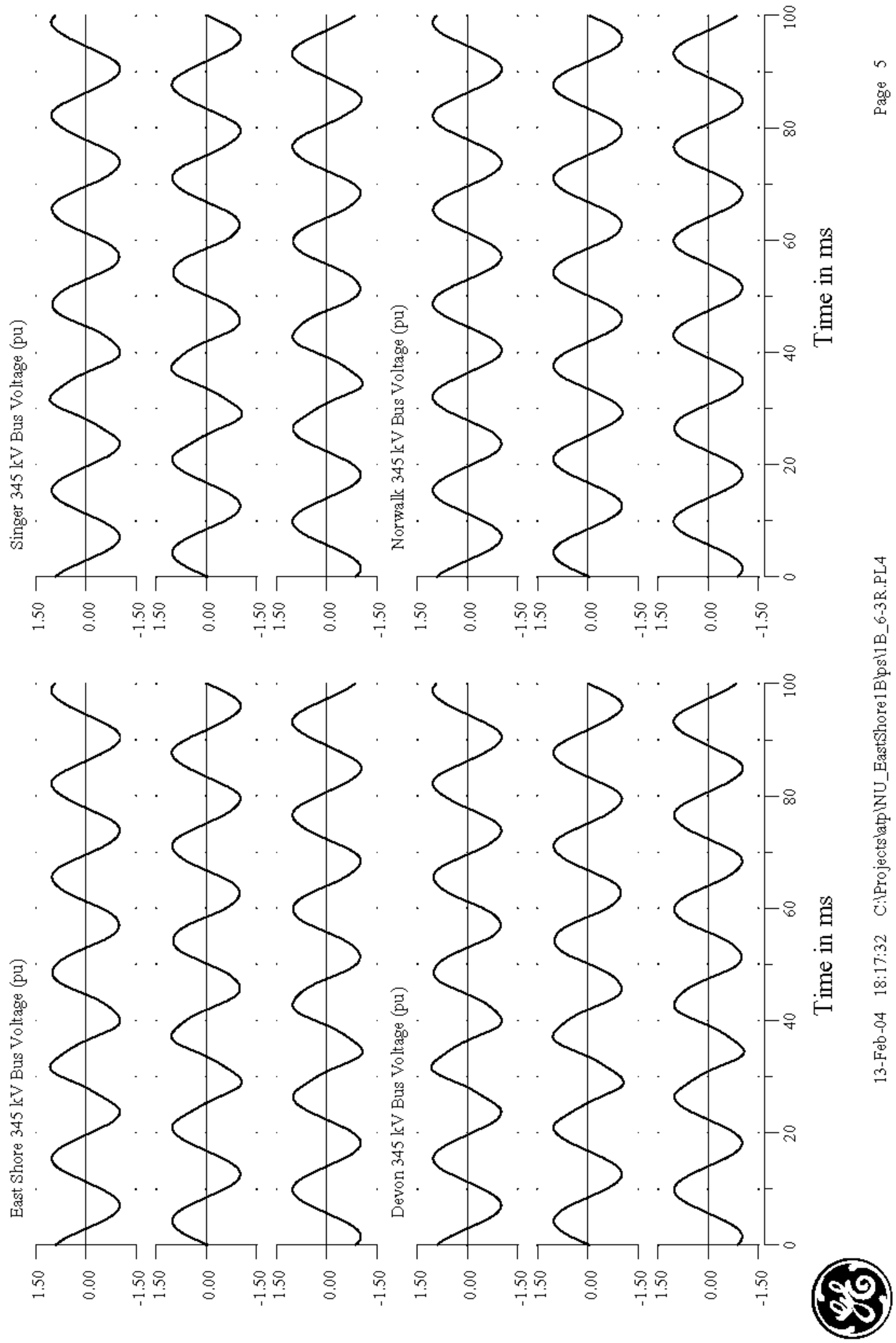

Figure 6-4. Energization of Devon Transformer, with Norwalk-Singer Open and with PIR (Case 6-3R)

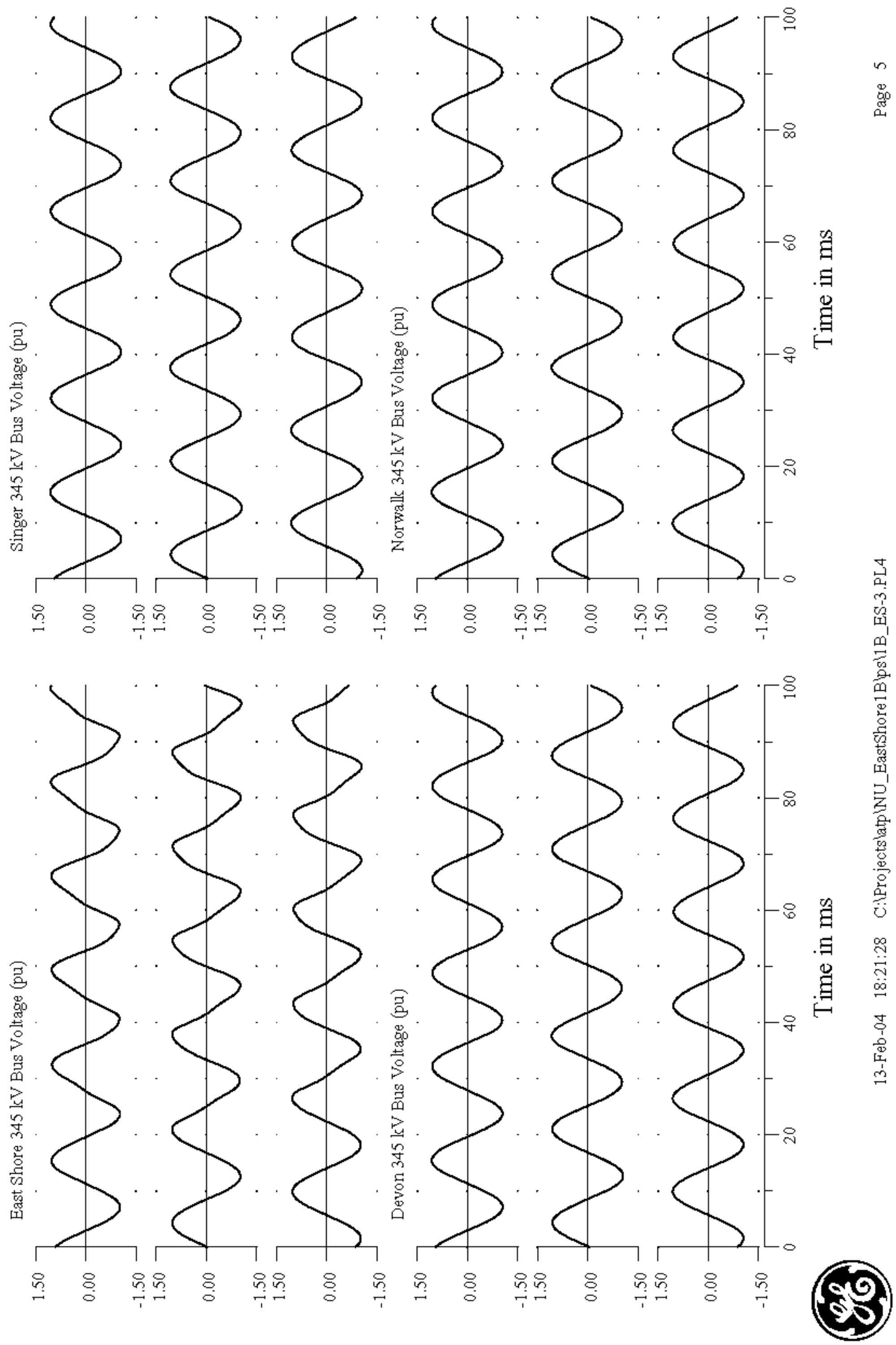

Figure 6-5. Energization of East Shore Transformer, with Devon-East Shore Cable Open at Devon (Case ES-3)

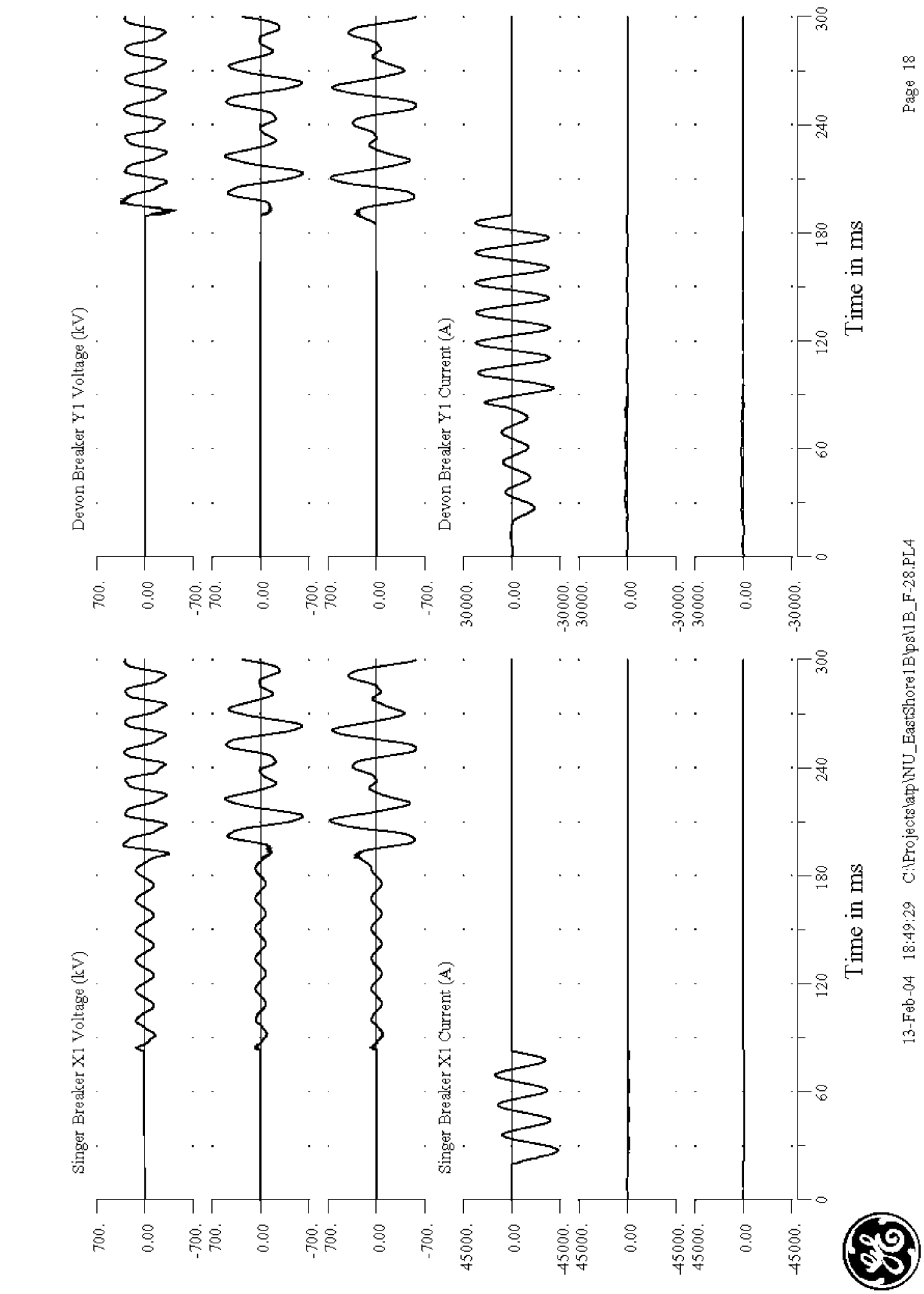

Figure 6-6. Fault & Clear Singer-Devon Cable (Case F-28)

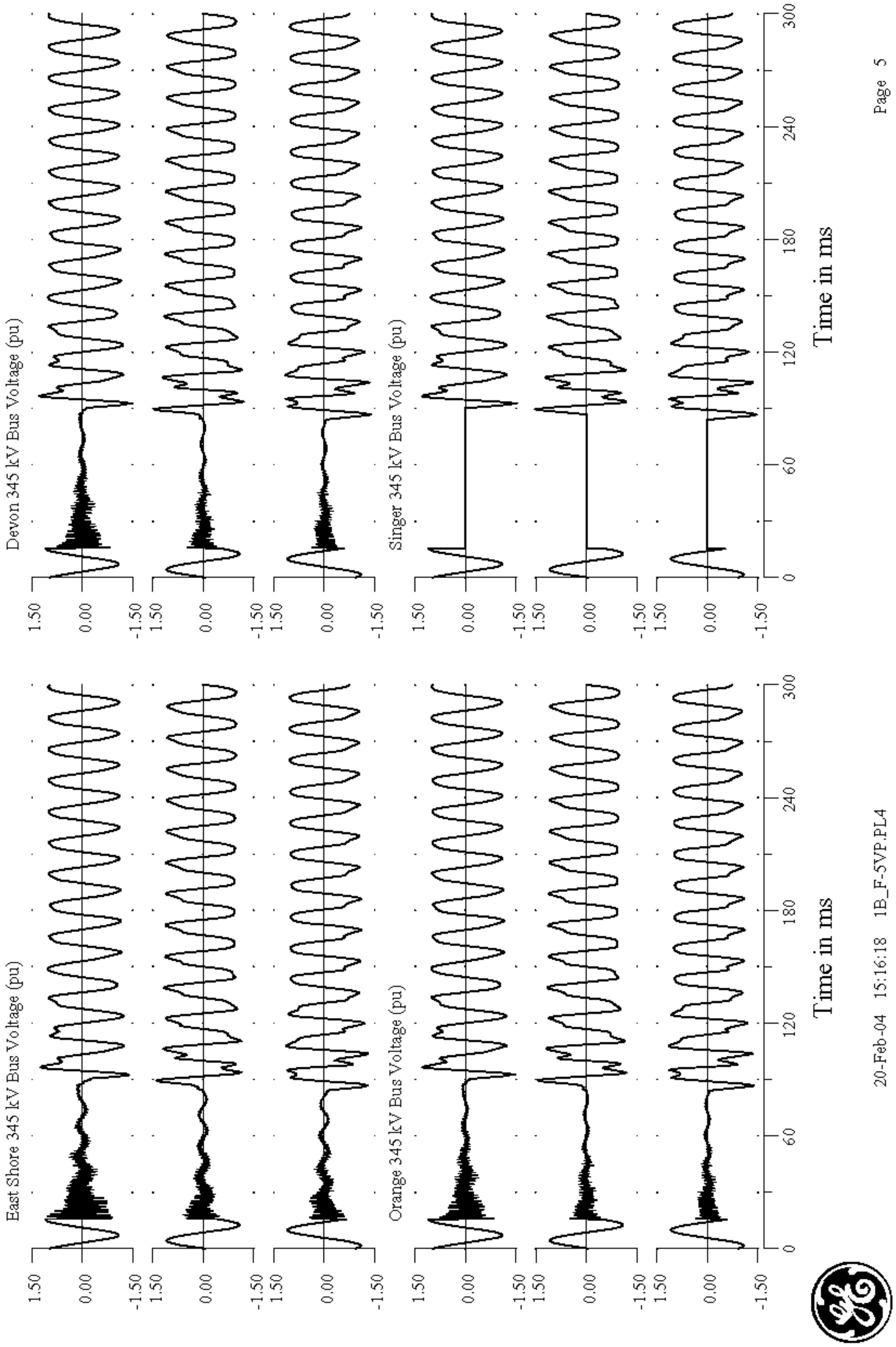

Figure 6-7. Stub Fault & Clear at Singer – Bus Voltages (Case F-5_VP)

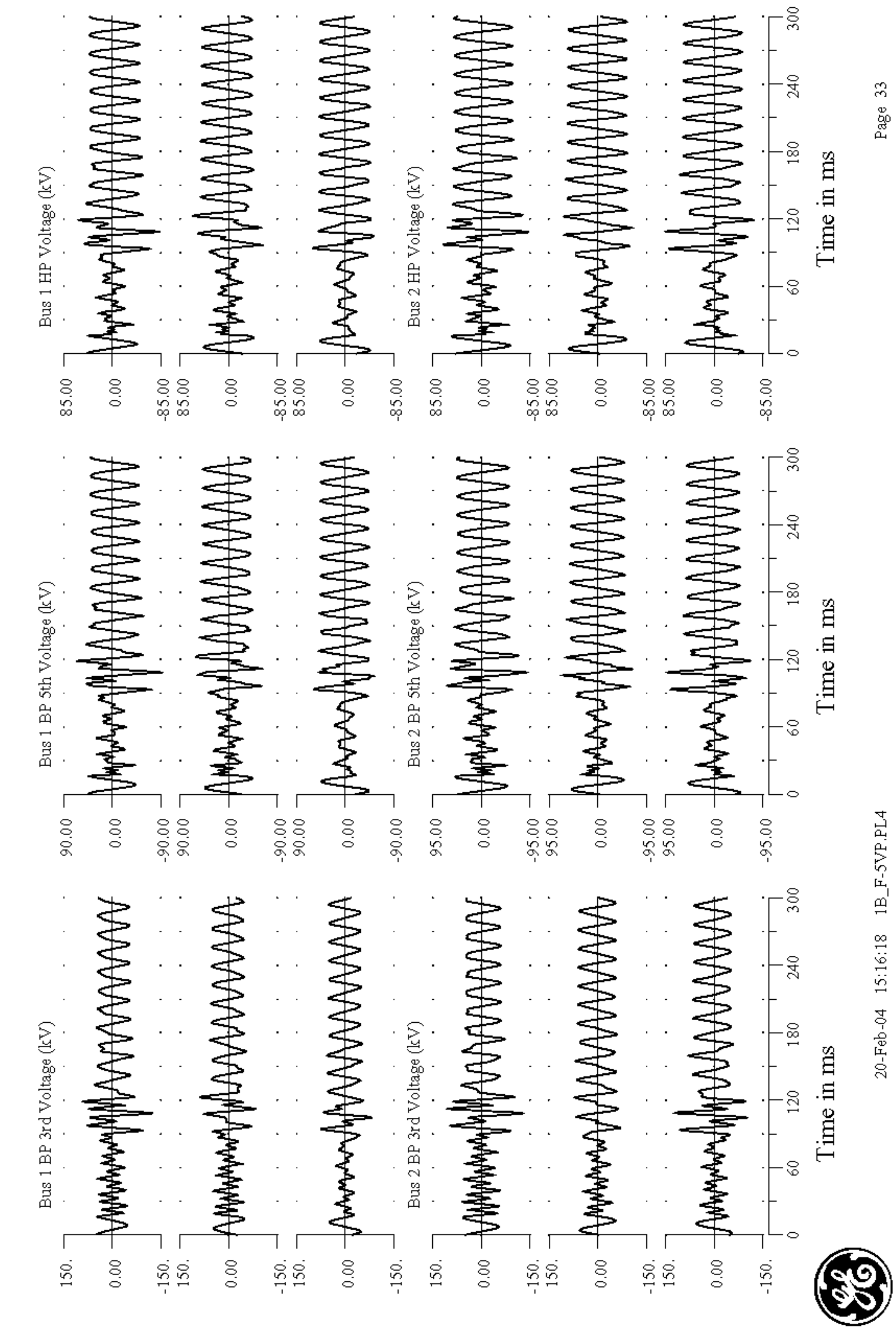

Figure 6-8. Stub Fault & Clear at Singer – Branford Filter Capacitors (Case F-5_VP)

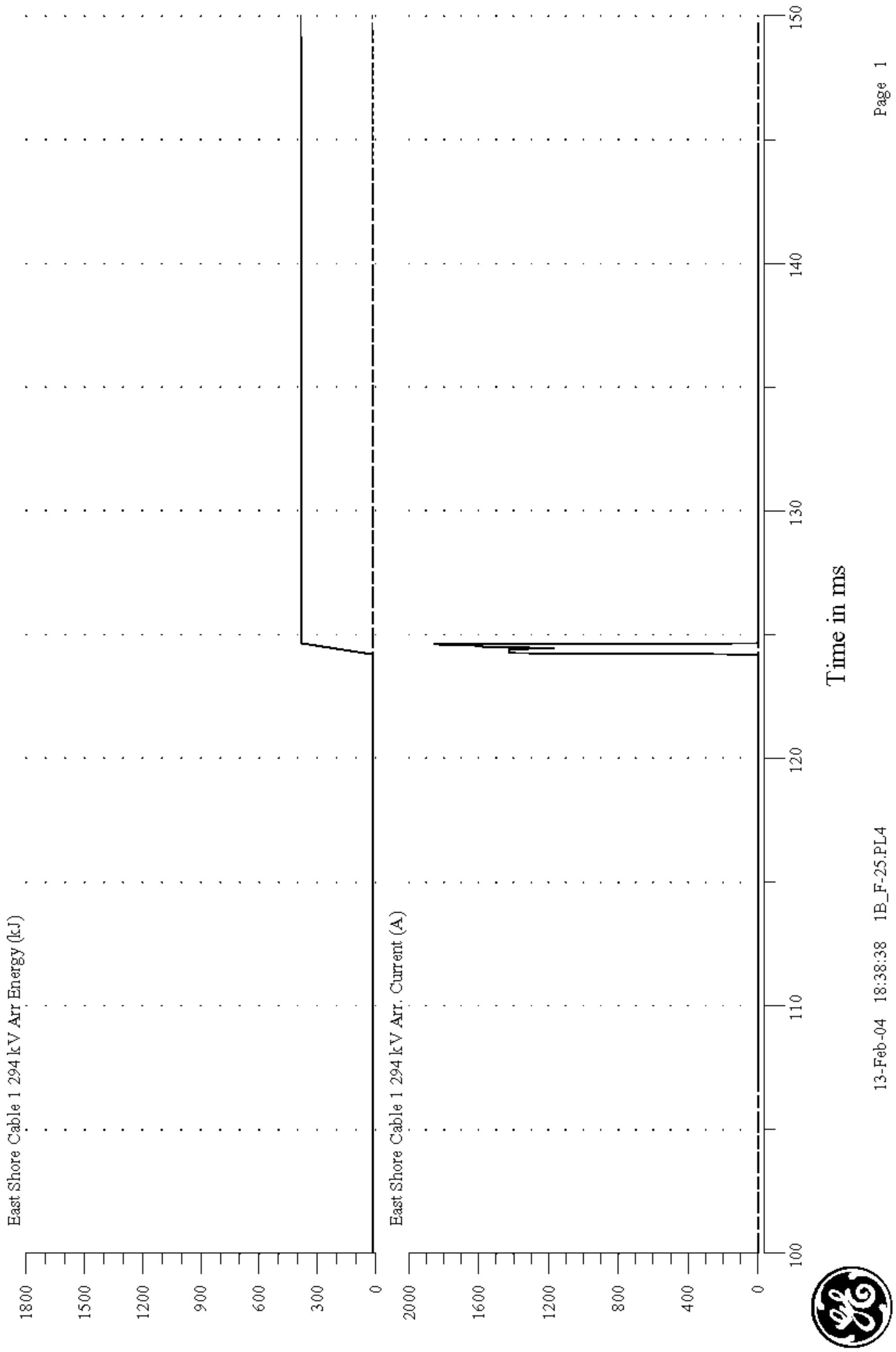

Figure 6-9. De-Energize and Restrike East Shore Cable (Case F-25)

7. Conclusions and Recommendations

Harmonic and switching transient evaluation of the ES-1A and ES-1B configurations did not identify any overtly fatal flaws, and switching transient results were similar to those of the M/N configuration. Therefore, it is concluded that with the appropriate selection of equipment and implementation of operating practices, the ES-1A and ES-1B configurations could be feasible alternatives to the M/N configuration from a switching transients and harmonics perspective. However, since the harmonic characteristics of ES-1A and ES-1B are of significant concern, a more comprehensive study would be required to further evaluate the ES-1A and ES-1B configurations.

Controlled closing is recommended for energization of the East Shore cables and transformers. Implementation of controlled closing by applying circuit breakers with resistor preinsertion provides a universal and robust solution.

The use of circuit breakers with synchronous closing is potentially risky for cable energization due to the potential for persistent direct current offset, without sufficient ac component to cause natural current zeros. This can occur when a highly compensated (near 100% compensation) cable is energized at voltage zero, without resistor preinsertion. Existing ac circuit breaker standards do not address the ability to interrupt direct current. Because voltage-zero energization is the objective of synchronous breakers used for cable switching, this can be a significant issue if synchronous closing technology is applied. Therefore, it is essential that, if synchronous closing breakers are to be considered, the ability of the breakers to interrupt several hundred Amperes of direct current must be confirmed with the breaker manufacturer.

Critical fault clearing cases with sustained voltage across the breaker contacts above 750 kV exceed test values defined in ANSI C37.06 and would require review with the breaker manufacturer. These cases indicate the need for a higher temporary overvoltage and transient recovery voltage capability required for the breaker or could possibly be a driver for a higher circuit breaker voltage rating if the manufacturer cannot provide the capability with a 362 kV breaker.

While controlled closing nearly eliminates overvoltage and severe voltage distortion resulting from cable and transformer switching, it cannot eliminate overvoltages and distortion resulting from faults and equipment failure, such as circuit breaker restrikes during interruption. For such events, the criterion is that consequential equipment damage or misoperation should not occur. Faults and restrikes cause both transient and temporary overvoltages which appear both locally and sometimes at remote locations in the system. Transient overvoltages observed on the 345 kV system are limited by 294 kV-rated surge arresters, without exposing these arresters to energy duty in excess of the typical capability of such an arrester. Temporary overvoltages observed after fault clearing are within the typical withstand capability of this arrester rating.

Fault and restrike events also tend to create overvoltages at locations remote from the fault on the 115 kV system, particularly at capacitor bank locations. Some very high overvoltages were observed in this study's simulations, resulting from the oscillatory transient introduced by application of a 345 kV system fault. The natural-frequency oscillations of the 345 kV cable system appear to interact with the resonance of the 115 kV capacitor banks, greatly amplifying the transient. In the actual system, surge arresters located on the 115 kV system will limit these overvoltages.[1] Evaluation of the energy duty imposed on the 115 kV arresters was not within the scope of this study, but should be considered during system design to determine if arresters with greater energy rating should be applied. Fault clearing events also result in temporary overvoltages on the 115 kV system. The study results should be compared with the temporary overvoltage capability of existing surge arresters, to determine if arresters should be replaced with a higher voltage rating. The older silicon carbide arrester technology is ill-suited for application near large capacitances, and it is recommended that NU review the use of SiC arresters at 115 kV and 345 kV substations located near East Shore. NU should consider replacement of these arresters with metal-oxide surge arresters, especially at shunt capacitor bank locations. It is also recommended that NU review the filter component ratings at Branford due to the low-order harmonic distortion observed in the band-pass filters, which are tuned at 3rd and 5th harmonics.

With regard to harmonic characteristics, the ES-1A and ES-1B configurations resulted in impedance resonances marginally above the 2nd harmonic and marginally below the 3rd harmonic. Changes in system configuration could easily move the resonances to 2nd or 3rd harmonic. In the M/N configuration, there was a single impedance resonance between 2nd and 3rd harmonics, but in the ES-1A and ES-1B configurations there are two impedance resonances between 2nd and 3rd harmonics, all with similar magnitudes. Consequently, there are concerns regarding power system events involving transformer exciting current, such as energization and inrush due to fault clearing. With resonances near both 2nd and 3rd harmonics, the harmonic currents due to inrush could have an additive effect to produce more severe results than those with resonances at either harmonic.

Additional system contingencies could lead to more severe sustained overvoltage situations than observed in this study. A reasonable effort was made in this study to include first-contingency events likely to initiate a critical system response. However, higher-level contingencies, beyond routine planning criteria, may result in much more severe consequences to utility and consumer equipment. Extreme contingencies could result, for example, from a major regional disturbance such as a blackout. Equipment failures resulting from extreme resonant conditions during system breakup could greatly hinder power restoration efforts.

There are also concerns about being close to 2nd harmonic. Although the resonance is above 2nd harmonic, it is very close, and defining a design with a minimum safe margin above 2nd harmonic is a subjective call. There is significant concern in regard to the harmonic characteristics of the ES-1A and ES-1B configurations.

In summary, with the ES-1A and ES-1B configurations, it is expected that the system would be very sensitive to future upgrades and would require careful engineering to study changes

[1] Also, damping of the system at the relatively high frequency of this interaction (600 Hz – 1 kHz) may be greater than represented in the simulation model, due to skin effects in the transmission cables and overhead 1ines.

in the transmission system, even at somewhat remote areas. With resonances near both 2nd and 3rd harmonics, power system events involving transformer exciting current could be more severe with system configuration changes. Careful consideration would be required for specifying equipment to withstand transient and temporary overvoltages observed during switching events. A more comprehensive study is recommended further evaluate the East Shore alternatives.

Appendix A – Driving-Point Impedance Plots

Appendix B – Switching Simulation Case Plots for ES-1A

Appendix C – Switching Simulation Case Plots for ES-1B