



ENGINEERING SERVICES

**TRANSIENTS / HARMONICS
STUDY REVIEW**

**SOUTHWESTERN
CONNECTICUT
RELIABILITY PROJECT**

FINAL REPORT

15 JUNE 2004

***PB* PB POWER**
100 YEARS

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EXECUTIVE SUMMARY

General

The Connecticut Light and Power Company and The United Illuminating Company are proposing to augment supplies to south western Connecticut by a project that extends the 345 kV transmission system. The project is to be constructed in two phases:

- Phase 1 consists of a 345 kV connection between the existing Plumtree 345 kV substation and a new Norwalk 345 kV substation. We understand that the Configuration X' is a firm approved proposal.
- Phase 2 extends the 345 kV system from Norwalk 345 kV substation to Beseck 345 kV substation via two intermediate 345 kV substations at Bridgeport (Singer) and East Devon.

A review of transient and harmonic studies performed by General Electric (GE) associated with the project has been undertaken. This has included a review of the following reports:

1. Connecticut Cable Transient and Harmonic Feasibility Study, Final Report, March 2003.
2. Connecticut Cable Transient and Harmonic Design Study for Phase 1, Summary Report, May 2003.
3. Connecticut Cable Transient and Harmonic Design Study for Phase 1, Part 1. Pre-insertion Resistor Size Analysis, Part 2. Effect of Phase 2 Additions on Phase 1, Final Report, October 2003.
4. Connecticut Cable Transient and Harmonic Study for Phase 2, Final Report, November 2003.
5. Connecticut Cable Transient and Harmonic Study for Middletown to Norwalk Project, East Devon-Beseck 40-mile Cable Option (M/N-P1), Final Report, November 2003.
6. Connecticut Cable Transient and Harmonic Study for Middletown to Norwalk Project, East Devon-Beseck 20-mile Cable Option (M/N-P2), Final Report, December 2003.
7. Connecticut Cable Transient and Harmonic Study for East Shore Alternatives, Final Report, April 5, 2004.

Conclusions and Recommendations

The studies performed by GE were aimed at examining the feasibility and preliminary engineering of a number of alternatives with respect to the type and range of voltage disturbances that may be expected as a result of the installation of significant lengths of HPFF cable. It must be pointed out that, whilst the results appear reasonable for this type of analyses, specific modelling details were not included within the reports and, therefore, their accuracy could not be verified.

We would however make the following recommendations in respect of the studies reviewed:

1. **Sub third harmonics and associated system resonances** - Resonant frequencies occurring below the third harmonic are undesirable and therefore there is a trade-off to be made between
 - I. the implementation of a simple and inherently reliable solution that maximises use of overhead line and thereby minimises complexity and sub-third harmonic resonances and
 - II. the implementation of a complex system to meet pressures associated with visual amenity that results in higher costs and degraded supply reliability.
2. **Connection technology** – To shift the low harmonic order resonant frequencies (2nd and 3rd) consideration should be given to minimising the additional connected capacitance by maximising the use of overhead line. Where undergrounding is essential to avoid serious environmental or security problems the use of alternative technologies, such as XLPE cable or Gas Insulated Line (GIL) installed in tunnels, could be considered as an alternative to HPFF cable.
3. **Operational switching and its relationship with system security** – As the complexity of the system increases the effects of individual switching actions under different operating conditions may be difficult to predict and some sequences may need to be avoided. In the extreme, automatic switching control equipment may be required.
4. **Higher order harmonic filters** – Subject to changes that may arise from changes to the connection technology, it would be prudent for the design to make provision for harmonic filtering but to ensure efficient capital spending harmonic measurements should be taken. Should harmonic measurements indicate distortion above standard requirements, mitigating measures through filtering should be implemented.
5. **Pre-insertion resistors** – The benefits of avoiding and/or limiting the application of pre-insertion resistors should be considered. The increased complexity of the circuit breaker with pre-insertion resistors has led to

manufacturers of SF6 circuit breakers preferring to offer POW control of the circuit breaker. The availability of circuit breakers with pre-insertion resistors may be limited.

6. **Point-On-Wave (POW) switching** – It is generally agreed that the switchgear must be capable of performing the duty required in the event of failure of the POW controller and it is recommended that this philosophy be adopted if it has not already been.
7. **Current chopping studies during circuit-de-energisation** – It is unclear if GE has considered current chopping scenarios within their analysis. These should be considered if they have not already been.
8. **Statistical switching studies** – During the detailed engineering phases of the project it is recommended that full Monte Carlo analysis of circuit breaker pole operation, together with pole scatter, be considered.
9. **Additional Study** Studies should be performed to determine the maximum capacitance that may be added to the system relative to an all overhead plan without depressing system resonances below the third harmonic. When this is established, the proportion of overhead line and cable that is required on the system, taking into account practical constraints, may be determined. Details of the modeling should also be provided for review.

1. INTRODUCTION

1.1 General

The Connecticut Light and Power Company and The United Illuminating Company are proposing to augment supplies to south western Connecticut by a project that extends the 345 kV transmission system. The project is to be constructed in two phases:

- Phase 1 consists of a 345 kV connection between the existing Plumtree 345 kV substation and a new Norwalk 345 kV substation.
- Phase 2 extends the 345 kV system from Norwalk 345 kV substation to Beseck 345 kV substation via two intermediate 345 kV substations at Bridgeport (Singer) and East Devon.

The initial proposal for Phase 1 works was for an overhead circuit between the Plumtree and Norwalk 345 kV substations. However, as further consideration has been given to the project the electrical configuration has evolved such that this Phase 1 segment is comprised of interchanging cable and overhead line sections as shown in Figure 1.

Phase 2 works arrangement is proposed with cable circuits from Norwalk to East Devon via Singer with an overhead single 345kV circuit from East Devon to Beseck (also shown in Figure 1).

The following alternate proposals were also studied:

- a. Construction of the East Devon to Beseck connection as a 3 circuit 345 kV cable as shown in Figure 2.
- b. Construction of the East Devon to Beseck connection as a 345 kV cable / overhead line circuit as shown in Figure 3.
- c. Construction of the circuits leaving East Devon as a 345 kV cable / overhead line circuit to Scovill Rock via East Shore as shown in Figure 4.
- d. Construction of the circuits leaving East Devon as a 345 kV 3 cable circuit to Scovill Rock via East Shore as shown in Figure 5.

1.2 Objectives

As part of the feasibility and engineering of the project transient and harmonic studies have been performed by General Electric (GE). This has included the following reports:

1. Connecticut Cable Transient and Harmonic Feasibility Study, Final Report, March 2003.

2. Connecticut Cable Transient and Harmonic Design Study for Phase 1, Summary Report, May 2003.
3. Connecticut Cable Transient and Harmonic Design Study for Phase 1, Part 1. Pre-insertion Resistor Size Analysis, Part 2. Effect of Phase 2 Additions on Phase 1, Final Report, October 2003.
4. Connecticut Cable Transient and Harmonic Study for Phase 2, Final Report, November 2003.
5. Connecticut Cable Transient and Harmonic Study for Middletown to Norwalk Project, East Devon-Beseck 40-mile Cable Option (M/N-P1), Final Report, November 2003.
6. Connecticut Cable Transient and Harmonic Study for Middletown to Norwalk Project, East Devon-Beseck 20-mile Cable Option (M/N-P2), Final Report, December 2003.
7. Connecticut Cable Transient and Harmonic Study for East Shore Alternatives, Final Report, April 5, 2004.

PB Power has been contracted to review these reports by ISO New England (ISO-NE), and where problems are identified propose mitigation measures together with budgetary costs. This Report details the review undertaken by PB Power.

1.3 Structure of Report

This Report is structured as follows:

- The **Executive Summary** is provided at the beginning of this Report.
- **Section 1** comprises this brief introduction.
- **Section 2** presents the review.
- **Section 3** concludes the Report and includes recommendations.

Diagrams are included as **Appendix A** to this Report.

2. REVIEW

2.1 Introduction

GE has undertaken a series of transient and harmonic studies to assess the impact of the proposed project and proposed variations on the south western Connecticut transmission system and identify preliminary equipment requirements. In the reports, conclusions have been drawn from the study results that indicate an increasing concern for the safe and reliable operation of the power system with regard to equipment ratings and power quality requirements, as the amount of underground power cable is increased. The objectives of this report are

- To establish if the extent and accuracy of the modelling is sufficient to have confidence in the results obtained.
- To examine the conclusions reached with a view to checking the soundness of the conclusions on the basis of the results provided.

The conclusions reached by GE in the series of reports are summarised below:

Connecticut Cable Transient and Harmonic Feasibility Study, Final Report, March 2003.

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

Connecticut Cable Transient and Harmonic Design Study for Phase 1, Summary Report, May 2003.

- Uncontrolled energisation of the cable would result in unacceptable power quality impact and overvoltages at other system locations.
- Harmonic measurements of the existing background voltage distortion would be helpful to predict the distortion that could be expected in Phase 1.
- With moderate existing distortion assumed, the additional cables may result in some individual harmonics exceeding IEEE 519 guidelines.

Connecticut Cable Transient and Harmonic Design Study for Phase 1, Part 1. Pre-insertion Resistor Size Analysis, Part 2. Effect of Phase 2 Additions on Phase 1, Final Report, October 2003.

- Switching transient evaluation of Phase 1 with the Phase 2 additions indicates that results are very similar to the Phase 1 design study, and the conclusions remain as before.
- Circuit breakers with 350 Ohm pre-insertion resistors are recommended.

- Higher rated surge arresters using metal oxide technology should replace the existing gapped arresters.
- Equipment performance should be reviewed with the switchgear, shunt reactor and cable manufacturers.

Connecticut Cable Transient and Harmonic Study for Phase 2, Final Report, November 2003.

- Controlled closing is essential to limit over voltages and voltage distortion but the use of point on wave switching is not effective in all situations.
- Controlled switching does not eliminate over voltages and voltage distortion due to fault clearing events.
- The design of surge arrester installations capable of discharging the energy levels resulting from disturbances needs careful consideration.

Connecticut Cable Transient and Harmonic Study for Middletown to Norwalk Project, East Devon-Beseck 40-mile Cable Option (MIN-P1), Final Report, November 2003.

- Designing a system configuration which results in an impedance resonance at 2nd harmonic is potentially very risky, could result in power system disturbances and is not recommended.
- Attempts to avoid the 2nd harmonic resonance by adding 2nd harmonic filters would not be practical.
- Changes in system configuration could easily move the resonance below 2nd harmonic.

Connecticut Cable Transient and Harmonic Study for Middletown to Norwalk Project, East Devon-Beseck 20-mile Cable Option (MIN-P2), Final Report, December 2003.

- The system resonances are just above 2nd and 3rd harmonics but system changes could move the resonances to 2nd and 3rd or below.
- Resonance effects could be additive resulting in a more severe distortion than with a single resonance.

Connecticut Cable Transient and Harmonic Study for East Shore Alternatives, Final Report, April 5, 2004.

- Controlled closing is recommended to limit over voltages and voltage distortion but the use of point on wave switching is not effective in all situations.
- Controlled switching does not eliminate over voltages and voltage distortion due to fault clearing events.

- Higher circuit breaker voltage ratings may be required.
- Higher rated surge arresters using metal oxide technology should replace the existing gapped arresters.
- Filter component ratings at Branford may be inadequate.
- The system resonances are just above 2nd and just below 3rd harmonic but system changes could move the resonances to 2nd and 3rd.
- Resonance effects could be additive resulting in a more severe distortion than with a single resonance.
- Other system contingencies need to be considered, to ensure that more severe overvoltages, which could result in major disturbances and equipment failures, are understood.

2.2 General

The introduction of additional capacitance into a power system can have significant implications for the operation of the power system. When introduced in a controlled way for a specific purpose (e.g. power factor correction) the anticipated performance and “side effects” can be modelled and the results interpreted with a high degree of certainty.

In the case of the south western Connecticut project the capacitance has been introduced as a result of the need for system reinforcement in the form of underground cables. Whilst the cables may be modelled as equivalent circuits the influence on the system operation is not readily modified by the introduction of additional components (inductors or resistors) to change their characteristics at harmonic frequencies. Whereas, shunt capacitor banks may be readily modified to create filters, the distributed nature of the cable capacitance means that other methods of avoiding system problems must be considered.

Having reviewed the reports provided, it is evident that changes to a relatively straightforward proposal have resulted in relatively complex alternatives incorporating significantly more equipment than was originally proposed. In itself, this increase in equipment required is a cause for concern in a number of areas; modelling, operation, maintenance, capital expenditure and operational expenditure.

Ideally, any capacitance required on the 345kV system should be added in a controlled way to meet the needs of the system and to ensure effective system operation. In an ideal world this would be achieved by the use of overhead lines that would add the minimum capacitance to the network, together with purpose designed capacitor banks (with detuning if necessary).

If capacitance in the form of underground circuits is to be added, the maximum amount of capacitance that the system can tolerate within the system design constraints should be

considered and hence the maximum amount of under-grounding achievable using cable technology or other underground alternatives may be established.

If the additional capacitance proposed exceeds the estimated maximum, other equipment, if practical, would have to be introduced to limit the system effects of the capacitance, inherently increasing the system complexity and introducing other system issues which must be considered.

2.2.1 Modelling

The studies forming part of this review have been undertaken using the Electromagnetic Transient Programme (EMTP) that, as indicated by GE, is considered an industry standard. **The data and modelling techniques used by GE within EMTP are fundamental to the analysis results and the conclusions drawn. For this reason, this data should have been made more transparent within the reports.**

The data and models used would include that used for 115 kV shunt capacitors, 345/115 kV transformers, cables, overhead lines, (equivalent) sources and earthing arrangements. For example, it is expected that:

- the transformer magnetising characteristic and the level of residual flux assumed in the model would have some influence on the switching study results.
- the shunt capacitor banks would normally include in-rush/de-tuning reactors and may influence any system resonant frequencies.

While the results seem reasonable, the data and modelling techniques need to be provided in more detail to ensure a high degree of confidence.

2.2.2 System Operating Conditions

Related to the data and modelling techniques above are the operating conditions considered within the studies. The operating conditions are not always transparent within the GE reports but there is a suggestion of a “base case” with “light load dispatch of generators and capacitor banks in service”¹. Whilst this may be a perfectly valid system condition, it is not discussed in adequate detail.

2.3 Transient Studies

2.3.1 General

The GE transient studies have included:

- Cable / overhead line energisation studies.
- Cable / overhead line de-energisation studies.

¹ Connecticut Cable Transient and Harmonic Design Study for Phase 1, Summary Report, May 2003.

- Transformer / shunt reactor energisation studies.
- Fault clearing studies.

In undertaking the studies consideration has been given to:

- Means of switching transient suppression including Point-On-Wave (POW) switching and pre-insertion resistors.
- The rating of equipment and requirements of surge arrestors.

The transient studies undertaken by GE cover those studies that we would expect to be undertaken during the feasibility and preliminary engineering of a project such as this.

The following points are however of note.

2.3.2 Statistical switching studies

GE have correctly indicated that the magnitude of transients on the system is sensitive to the exact time on the 60 Hz waveform that switching occurs. GE has restricted their analysis by assuming point-on-wave switching that approximates to worst-case scenarios. **During the detailed engineering phases of the project it is recommended that full Monte Carlo analysis of circuit breaker pole operation, together with pole scatter, be considered to assure that worst case scenarios have been tested**

2.3.3 Current chopping during circuit-de-energisation

During circuit de-energisation it is possible for interruption to occur at non-zero values of current – a phenomenon known as current chopping. When current chopping takes place, it is possible for the magnitude of transients to be greater than those that occur when interruption takes place at the current zero. **It is unclear if GE has considered current chopping scenarios within their analysis.**

2.3.4 Point-On-Wave (POW) switching

GE has correctly indicated that the selection of the optimum point for POW closure of the circuit breaker is dependent on the characteristics of the circuit being switched. Hence any circuit breaker that may be required to switch circuits with significantly different characteristics will require different settings. Many utilities are applying POW switching to reduce overvoltages and thereby reduce the severity of transients on equipment to minimise maintenance requirements, maximise equipment asset life and improve power quality to consumers. **Most agree that the switchgear must be capable of performing the duty required in the event of failure of the POW controller and it is recommended that this philosophy be adopted if it has not already been.**

2.3.5 Pre-insertion resistors

Pre-insertion resistors are a method of limiting switching overvoltages and have been used for many years. However, their use adds mechanical complexity to the circuit breaker and there has been experience in the past of the resistors themselves failing due to both thermal and electrical transients. The widespread use of pre-insertion resistors may have an effect on system availability. The availability of suitable circuit breakers will need to be investigated, particularly if any of the installations are to utilise metal clad Gas Insulated Switchgear, as it may be difficult to procure suitable equipment.

In recent years there has been a preference to avoid the use of pre-insertion resistors and control overvoltages through other means including the use of high-energy dissipation surge arrestors wherever possible.

Alternatively consideration may be given to enhancing the withstand rating of equipment to accommodate transient effects but it must be remembered that this is effective in ensuring the security of the enhanced equipment and may have no (or a detrimental) effect on the system transient performance. **It is considered that the potential of avoiding and/or limiting pre-insertion resistors be considered.**

2.3.6 Surge arrestors

The careful selection of surge arrestors is essential whatever their specific purpose but in this application, particularly recognising proposals for use of pre-insertion resistors, the energy discharge rating is a major consideration. Multiple arrestors in parallel may be required to achieve the required rating.

2.4 Harmonic Studies

2.4.1 General

GE has undertaken a series of harmonic studies to determine harmonic levels. In addition, GE has calculated impedance/frequency characteristics at substations to graphically illustrate resonant frequencies of the system.

The harmonic studies undertaken by GE cover those studies that we would expect to be undertaken during the feasibility and preliminary engineering of a project such as this.

The following points are however of note.

2.4.2 Approach

The analysis performed by GE assumes the injection of harmonic currents to a level resulting in limiting harmonic distortion levels in accordance with IEEE 519². Whilst this provides a limiting case the harmonics do not necessarily exist. This is reinforced by the fact

² IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, 1992.

that the analysis suggests that the existing system (i.e.: the system prior to implementation of this project) is not compliant with IEEE 519 that is presumably not the case. **It is therefore considered prudent for the design to make provision for harmonic mitigation measures but to ensure efficient capital spending harmonic measurements should be taken. Should harmonic measurements indicate distortion, mitigating measures should be implemented.**

2.4.3 System design

The analysis performed by GE indicates resonant frequencies on the system as shown in Table 1 for the different reports.

Table 1 Resonant frequencies for different studies

Study	Existing configuration	Phase 1	Phase 2
Connecticut Cable Transient and Harmonic Feasibility Study, Final Report	-	-	3 rd , 7 th and 11 th
Connecticut Cable Transient and Harmonic Design Study for Phase 1, Summary Report, Part 2. Effects of phase 2 additions on phase 1, Final Report	9 th and 11 th	without 115 kV capacitor banks: 3 rd and 4 th , with 115 kV capacitor banks: 3 rd and 5 th	-
Connecticut Cable Transient and Harmonic Design Study for Phase 1, Part 1. Pre –insertion resistor size analysis, Part 2	-	with 115 kV capacitor banks: 3 rd and 5 th	below 3 rd , 5 th and 11 th
Connecticut Cable Transient and Harmonic Design Study for Phase 2, Final Report	-	-	below 3 rd , 5 th , 7 th and 11 th
Connecticut Cable Transient and Harmonic for Middletown to Norwalk Project, East Devon – Beseck 40 mile cable option (MIN-P1), Final Report	-	-	2 nd , 7 th and 11 th
Connecticut Cable Transient and Harmonic for Middletown to Norwalk Project, East Devon – Beseck 20 mile cable option (MIN-P2), Final Report	-	-	between 2 nd and 3 rd , 7 th and 11 th

Connecticut Cable Transient and Harmonic Design Study for East Shore Alternatives, Final Report	-	-	between 2 nd and 3 rd , 7 th and 11 th
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The different configurations include resonances associated with the 2nd, 3rd, 4th, 5th, 7th and 11th harmonic.

Resonances below 3rd order harmonic

As indicated by GE, harmonics below the 3rd harmonic are difficult to mitigate as they result in impractical complex and large filter design. **It is therefore considered that other options be considered** which will reduce the capacitance on the system and are therefore likely to increase the frequency at which resonance occurs to higher order harmonics at which, if necessary, more effective harmonic filters can be applied. Alternative underground transmission circuits are discussed in the next section.

Resonances above 3rd order harmonic

Dependent on resolving the above, and assuming harmonics such as the 4th, 5th, 7th and 11th harmonic are still problematic, appropriate filters can be designed.

2.4.4 Summary

Most power systems exhibit impedance resonance at several frequencies for any given configuration, the phenomenon is unavoidable and impedance resonance in itself is not a problem.

The value of the impedance at each system resonant frequency affects the level of disturbance resulting from any given harmonic current injection and in general the value reduces with increasing fault level.

It is the potential for connected loads or system switching events to inject currents at frequencies (harmonics) at or close to the system resonant frequencies that creates problems.

In general harmonic current levels injected into a power system decrease with frequency (harmonic number). Low order harmonic currents are associated with system switching activities but these may be suppressed by the adoption of controlled switching, however the clearance of system faults may result in unsuppressed low order harmonics.

The higher order harmonic currents normally produced by “dirty” loads are normally absorbed at source by effective filters

Therefore as a working principle it is most efficient to avoid a system configuration that exhibits low order harmonic impedance resonance and is subject to low order harmonic current injection, as the product of the two characteristics results in poor power quality and

the potential for equipment damage. It is therefore desirable to minimise one of the components of the product and the options may be summarised as follows:

- Low order harmonic impedance resonance may be avoided by maintaining a high ratio of system fault level to the connected capacitance level.
- Low order harmonic current injection may be controlled by the use of more complex switching devices and control systems. The use of such devices may need to be so extensive as to become impractical.
- In order to minimise the risk of equipment damage where low order harmonic current injection cannot be eliminated, it is necessary to add more equipment (usually high energy surge arresters) to protect the system and equipment on those occasions where controlled switching is ineffective (fault recovery). The operation of surge arresters will not eliminate the power quality aspects associated with the event.

For the reasons given above we conclude that it is more efficient and effective to move potential system resonances away from the second and third harmonic region than to attempt to control the multiple sources of current injection by the addition of more sophisticated equipment at multiple locations.

2.5 Transmission Cable Model

Figure 2 illustrates the worst-case scenario in terms of quantity of cable required.

The following principal observations may be made on the GE transmission cable model:

- XLPE insulated cable has been selected for short route lengths only and HPFF pipe-type cable has been selected for all other routes.
- Three parallel cable circuits are routed between Beseck and East Devon.
- The cable circuits between Beseck and East Devon are interrupted at 10 mile intervals in order to connect shunt reactors.

In the following sections, the assumptions underlying these observations are analysed and consideration is given to potential advantages of other cable types.

2.5.1 Cable technology: choices and limitations

Cable Types

The following cable types (based on cable dielectric) are available at 345 kV:

- LDPE – Low density polyethylene.
- XLPE –Cross-linked polyethylene. This dielectric is essentially an LDPE cable that has been cross-linked in order to raise the maximum operating temperature of the dielectric from 70°C to 90°C.

- HPFF – High pressure fluid-filled paper insulated pipe type cable. The predominant type of cable used in North America at 345 kV. Three unsheathed, paper-insulated cores are pulled into a single steel pipe, which is then filled with an insulating fluid (previously termed oil).
- SCFF – Self-contained fluid-filled paper insulated cable. This type of cable utilises essentially the same type of paper and insulating fluid as an HPFF cable to form the cable dielectric. However, instead of being pulled into a steel pipe, a flexible extruded metallic sheath is applied to each individual core. The cables are thus self-contained and can be laid directly into the ground.
- SCFF (PPL) - Self-contained fluid-filled paper-polypropylene laminate (PPL) insulated cable. This type of cable is a variation on the SCFF cable. The paper tapes used in the SCFF cable are replaced with PPL tapes. The PPL tapes have the same appearance and approximately the same dimensions as the paper tapes but actually consist of two layers of paper, with a layer of polypropylene in between. The benefit of this construction is that the dielectric losses are significantly reduced. Capacitance is also reduced.

Salient design data (per phase) for these cable types is tabulated below in Table 2, based on maximum cable size available for each cable type.

Table 2 Design data for cable types available at 345kV (largest size)

Cable Type	Rating (A)	Capacitance (nF/mi)	Charging Current (A/mi)	Susceptance (µmho/mi)
XLPE	1775	355	27.8	133.8
LDPE	1526	355	27.8	133.8
SCFF	1504	748	57.4	282.0
SCFF(PPL)	1745	603	46.4	227.0
HPFF	1000	442	33.23	166.6

To facilitate comparison between the cable types (except HPFF), a common cable design and common installation conditions were assumed in compiling the above table.

The cable design for each cable type (except HPFF) was assumed to include the following:

- single core

- un-armoured
- 2500mm² segmental type copper conductor (hollow for SCFF and SCFF (PPL) cables and solid for all other cable types)
- cable dielectric thickness in accordance with established industry practice (11.5kV/mm for LDPE/XLPE, 15kV/mm for SCFF / SCFF (PPL) / HPFF)
- lead sheath
- medium density polyethylene (MDPE) oversheath

The principal difference with HPFF cables was that a maximum conductor size of 1250mm² (2500kcmil) was assumed to be available. Additionally HPFF cable design includes a copper tape shield and skid wire instead of a lead sheath and MDPE oversheath.

The common installation conditions (except for HPFF cable) were assumed to be as follows:

- ground temperature of 15°C
- ground thermal resistivity of 1.2Km/W
- cables configured in a flat spaced arrangement, 300mm between phases
- cable sheaths cross-bonded.
- Depth to the top of the cable of 900mm.

The principal difference with HPFF cables is that HPFF cables are constrained within a steel pipe and thus the cables' cores are in contact with each other. Cross-bonding cannot be employed with pipe-type cables although circulating shield currents are largely cancelled as the cable shields are in contact with each other.

We understand that due to local authority requirements it may be necessary to install cables at a depth of 2400mm (8 feet). This will have a detrimental effect on the continuous current rating of the cable when compared with the results set out above. It is anticipated that the values in Table 2 would be reduced by approximately 10%.

Cable Ratings

The following observations may be made on the data contained in Table 2:

- The best ratings are obtained from XLPE insulated cables and SCFF (PPL) insulated cables due to the lower dielectric losses exhibited by these cables. However, when charging current is factored into the rating equations (for long cable circuits), it can be seen that XLPE would have an advantage over SCFF (PPL).

- In contrast, the worst ratings are obtained from the HPFF type cable. This is principally due to the limitation on conductor size available with this type of cable.
- The three circuits shown in the GE model between Beseck and East Devon could be replaced by two circuits if an alternative cable type to the HPFF cable was used.

Table 3 below illustrates the effect on MVAR's generated between Beseck and East Devon through the use of different cable types.

Table 3 Comparison of MVAR generation between Beseck and East Devon for different cable types and configurations

Cable Circuits required for 3000A	MVAR's generated over 40 mile route
3xHPFF (1250mm ² , 2500kcmil)	2382
2xSCFF (2500mm ²)	2744
2xSCFF(PPL) (2500mm ²)	2218*
2xXLPE (2500mm ²)	1329*
MVAR reduction HPFF - XLPE	1053

* These figures are likely to reduce by 10%, as a 2500mm² conductor is larger than required for a 3000A rating. Reducing the conductor size will reduce the cable capacitance.

Rating of cable circuits (Beseck to East Devon)

Selection of an alternative cable type to HPFF for the GE model would give benefits in terms of cable ratings and the level of MVAR's generated by the transmission network. However in the context of the application the firm rating would need to be considered, hence three HPFF circuits would provide a firm rating of 2 x 1000A and the best of the alternatives (XLPE) configured as two circuits would provide 1 x 1775A.

When considering the capacitance of the cables and hence the total MVAR generation it can be seen that only the XLPE cable offers any real advantage over the other technologies.

Table 4 Comparison of MVA_r generation between Singer and East Devon for different cable types and configurations

Cable Circuits required	MVA_r's generated over 8.2 mile route
2xHPFF (1250mm ² , 2500kcmil)	325
2xXLPE (800mm ²)	161*
MVA _r reduction	164

* This figure is based on the selection of an XLPE cable size that will provide an equivalent rating to the 2500kcmil HPFF cable.

Rating of cable circuits (Norwalk to East Devon)

The cable size selected for the XLPE alternative is 800mm² that provides a direct replacement for the HPFF 2500kcmil cable. If the selection of two cables was made on the basis of a rating requirement higher than 1000A but less than 1775A a single 2500mm² cable could be used. This would give a reactive generation of 274MVA_r, which is greater than 2 x 800mm² cables

Table 5 Comparison of MVA_r generation between Norwalk and Singer for different cable types and configurations

Cable Circuits required	MVA_r's generated over 15.5 mile route
2xHPFF (1250mm ² , 2500kcmil)	616
2xXLPE (2500mm ²)	304*
MVA _r reduction	312

* This figure is based on the selection of an XLPE cable size, which will provide an equivalent rating to the 2500kcmil HPFF cable.

Table 6 Comparison of MVA_r generation between Norwalk Junction and Archers Lane for different cable types and configurations

Cable Circuits required	MVA_r's generated over 9.7 mile route
2xHPFF (1250mm ² , 2500kcmil)	385
2xXLPE (800mm ²)	191*
MVA _r reduction	194

* This figure is based on the selection of an XLPE cable size, which will provide an equivalent rating to the 2500kcmil HPFF cable.

Effect of replacing all HPFF cables proposed in M/N – P1 by XLPE cables sized to achieve thermal ratings

The total reduction in charging MVAR which would be achieved by replacing all HPFF cables in the completely under-grounded Phase 2 proposal M/N – P1 would be:

Beseck – East Devon	1053
East Devon – Singer	164
Singer – Norwalk	308
Norwalk Junction – Archers Lane	194
Total	1719

The results indicate that approximately 1700MVAR of charging could be avoided by the use of XLPE cable which would help in raising the resonant frequency but it is not sufficient to return the resonant harmonic above the third.

Service Experience and Reliability

Although there is little data available in the public domain on cable failure rates, the following qualitative comments may be made.

At first inspection, XLPE insulated cables would appear to be the most advantageous cable type, offering the best ratings and the minimum MVAR generation. However although the cable extrusion technology is relatively mature, the development of joints (splices) is considered to be less well established. Long EHV XLPE cable circuits, containing multiple joints have been in operation since 1998 with generally reliable service. However whilst some utilities have complete confidence in XLPE, others have exhibited caution and it is considered unlikely that XLPE would be utilised for all of the cable requirements for this project.

Although a much greater proportion of XLPE cable could be considered for this project, it would be prudent to install any long length EHV XLPE cable circuits in a tunnel in order to:

- a. facilitate ready access to the cable circuits in the event of remedial work being required.
- b. improve sensitivity of partial discharge (PD) measurements during commissioning. [Note - For XLPE cable systems, unlike oil-filled paper cable systems, it is considered to be 'best practice' to conduct partial discharge measurements on the installed cable system during the HV commissioning test. These measurements are very sensitive to external interference, which is significantly reduced when the cables are installed in a tunnel instead of conventional underground burial.]

- c. maximise section lengths between joints by improving access for large cable drums and reducing pulling tensions by virtue of minimising severe route deviations.

SCFF type cable on the other hand has a service record at least equivalent to the HPFF type cable. Using the data from Table 2 however it can be seen that although two SCFF type cables could meet the rating of three HPFF type cable circuits, the two SCFF type cable circuits would generate more MVAR's than the three HPFF circuits. SCFF cable circuits therefore offer no advantage to this project other than a lower capital cost of the cables which is offset however by a higher reactive compensation costs.

The final type of cable to be considered is, the SCFF (PPL) cable. This cable essentially combines the benefits of the XLPE cable (i.e. low dielectric losses) and of the SCFF type cable (i.e. robust electrical design based on the principle of pressurised insulating fluid fully impregnating all parts of the cable system at all times). However, although the ratings of the SCFF (PPL) type cable are significantly better than the HPFF type cable, allowing two circuits instead of three, the saving in MVAR generation is minimal.

Summary

Consideration has been given to the use of other cable types for the south western Connecticut project in order to:

- a. reduce the number of cable circuits between Beseck and East Devon from three to two and,
- b. reduce the amount of MVAR generated by the cable circuits.

Four alternative cable types were identified for use at 345kV. Each of these cable types may result in a reduction in the number of cable circuits from three to two (subject to clarification of the N-1 rating required) however only two types, LDPE and XLPE, would have a significant effect on the level of MVAR generation.

It is noted however that long length EHV XLPE/LDPE cable circuits are still considered to be a developing technology with the operation of such circuits commencing in 1998. The quantity of cable required for the south western Connecticut project as proposed would make the project the second largest (2 miles short of the longest) AC cable project ever undertaken anywhere in the world. A much greater proportion of XLPE cable could be implemented, but for reasons outlined previously we believe that it would be industry 'best practice' to install such circuits in an underground tunnel, as was done in the aforementioned project. It would therefore be difficult to present engineering justification for the implementation of all of the cable circuits using XLPE insulated cables.

The use of HPFF cable as proposed is a reasonable choice from considerations of inherent reliability and service experience but is much less attractive from system operation consideration (MVAR generation).

A minor detail that is probably explained by the difference between three-phase and single-phase values, is the value of susceptance used for HPFF cable in the GE study, which seems to be significantly higher than the value identified in our report. The cable parameter values listed in the table 2 of the PB Power report are single phase values.

It should be noted that there are also two further options for underground transmission circuits that might be considered as alternatives to the AC cable options described in the preceding sections and used in the GE model. These are:

- a. Gas insulated line (GIL) and
- b. HVDC cable.

GIL has been extensively used worldwide for short connections (up to 1 mile), principally between power stations and primary substations. However, although GIL has been proposed for long length transmission circuits by GIL manufacturers, it has never been implemented. The principal constraints on long length GIL is cost and difficulty in installation. GIL is not ideally suited for direct buried application and installation in a specially designed tunnel is recommended for long lengths. The very high thermo-mechanical forces generated by GIL however require specially reinforced tunnel walls beyond what would be required for conventional cable circuits. It is this requirement that further escalates the cost of a long GIL circuit beyond that of a cable circuit installed in tunnels. Cost implications aside, however, it should be noted that the GIL does offer a technical solution for this project where AC underground transmission is absolutely necessary but circuit capacitance must be minimised.

HVDC cable systems, while theoretically a proven option for long distance underground power transmission are fundamentally different, come at a high cost, and may not address other issues of concern in southwest Connecticut. Its contribution to system strength and corresponding improvement in harmonic improvement are questionable.

2.6 Complexity

The level of complexity in certain of the options (Figure 4 – Figure 5), particularly for the East Devon – Beseck section, has increased considerably as compared to the proposed plan.

As an example, the proposal in East Devon – Beseck 40 Mile Cable Option (M/N-P1) introduces the following additional equipment as compared with the Phase 2 Final Report (November 2003) for the section between East Devon and Beseck.

M/N-P1	Phase 2 Final report Nov 2003 basis (Proposed Plan)
3 - Intermediate switching station sites	0 - Intermediate switching station sites

2 - Additional busbar sections at Beseck and East Devon	0 - Additional busbar sections at Beseck and East Devon
6 - Feeder circuit breakers (closing resistors)	2 - Feeder circuit breakers (closing resistors)
18 - Shunt Reactors	0 - Shunt Reactors
18 - Shunt reactor circuit breakers (closing resistors)	0 - Shunt reactor circuit breakers (closing resistors)
72 - High voltage cable terminations	0 - High voltage cable terminations
72 - Surge arresters	6 - Surge arresters

3. CONCLUSIONS

The studies performed by GE were aimed at examining the feasibility and preliminary engineering of a number of alternatives with respect to the type and range of voltage disturbances that may be expected as a result of the installation of significant lengths of HPFF cable. It must be pointed out that, whilst the results appear reasonable for this type of analyses, specific modelling details were not included within the reports and, therefore, their accuracy could not be verified.

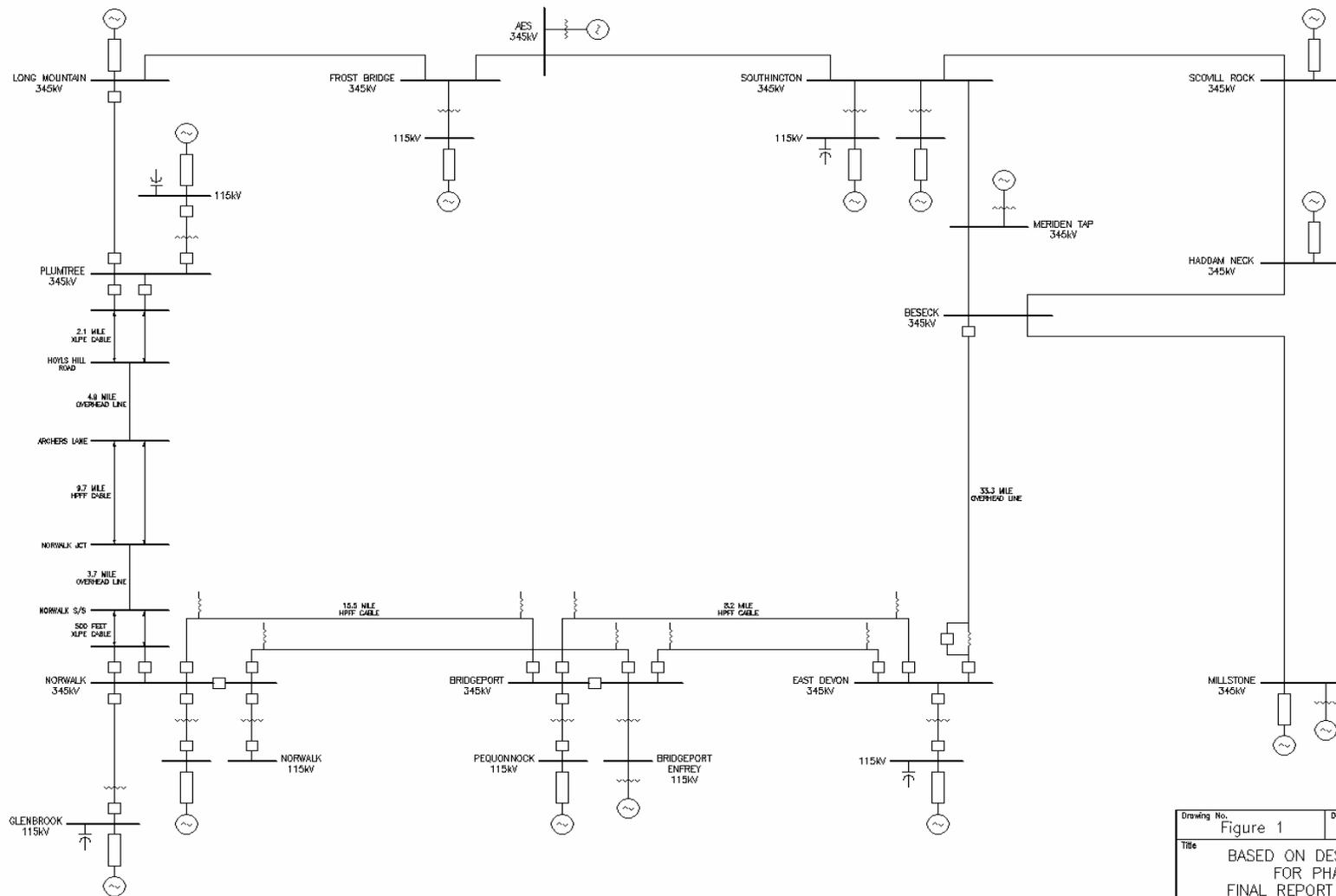
We would however make the following recommendations in respect of the studies reviewed:

1. **Sub third harmonics and associated system resonances** - Resonant frequencies occurring below the third harmonic are undesirable and therefore there is a trade-off to be made between
 - the implementation of a simple and inherently reliable solution that maximises use of overhead line and thereby minimises complexity and sub-third harmonic resonances and
 - the implementation of a complex system to meet pressures associated with visual amenity that results in higher costs and degraded supply reliability.
2. **Connection technology** – To shift the low harmonic order resonant frequencies (2nd and 3rd) consideration should be given to minimising the additional connected capacitance by maximising the use of overhead line. Where undergrounding is essential to avoid serious environmental or security problems the use of alternative technologies, such as XLPE cable or Gas Insulated Line (GIL) installed in tunnels, could be considered as an alternative to HPFF cable.
3. **Operational switching and its relationship with system security** – As the complexity of the system increases the effects of individual switching actions under different operating conditions may be difficult to predict and some sequences may need to be avoided. In the extreme, automatic switching control equipment may be required.
4. **Higher order harmonic filters** – Subject to changes that may arise from changes to the connection technology, it would be prudent for the design to make provision for harmonic filtering but to ensure efficient capital spending harmonic measurements should be taken. Should harmonic measurements indicate distortion above standard requirements, mitigating measures through filtering should be implemented.
5. **Pre-insertion resistors** – The benefits of avoiding and/or limiting the application of pre-insertion resistors should be considered. The increased complexity of the circuit breaker with pre-insertion resistors has led to

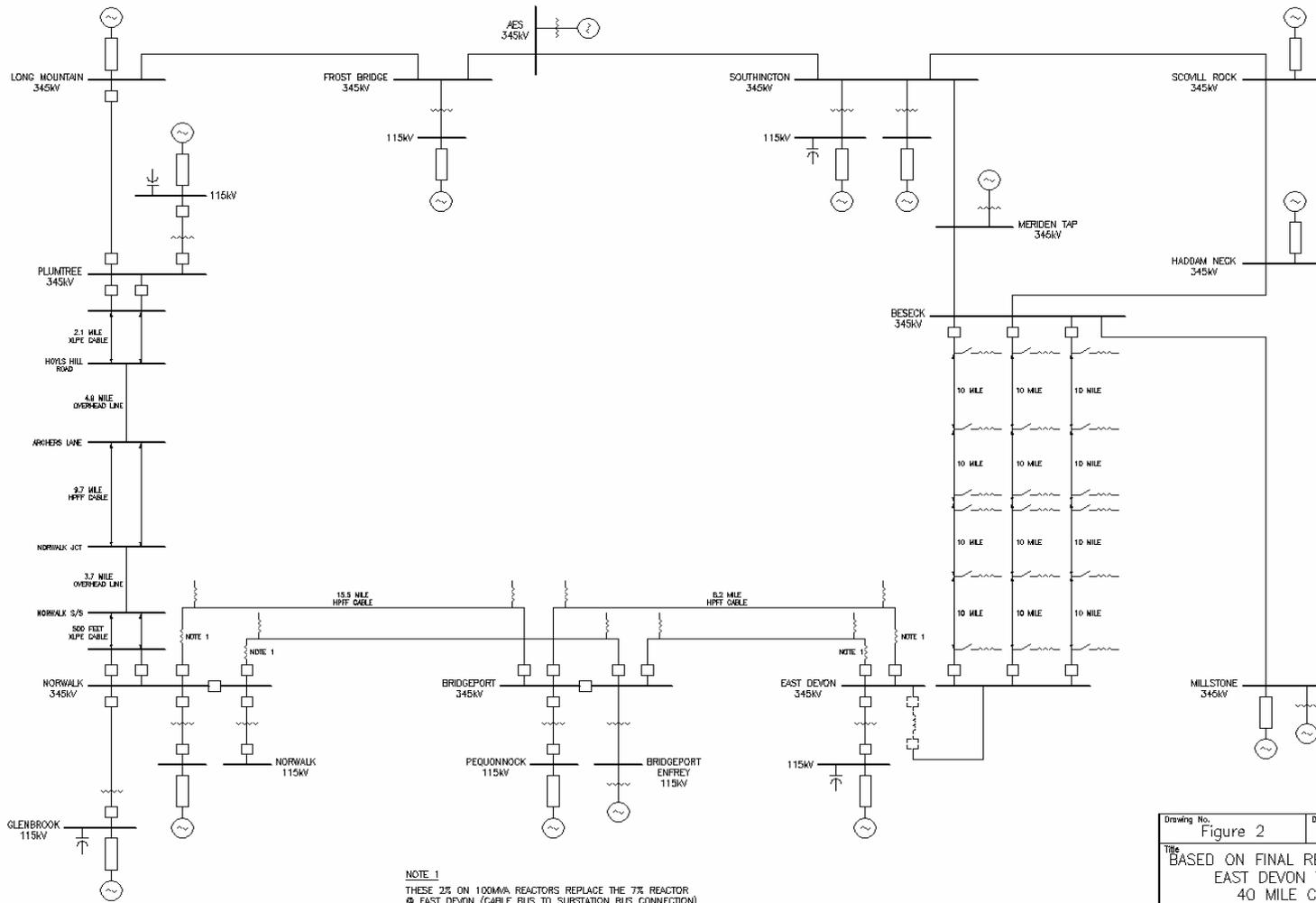
manufacturers of SF6 circuit breakers preferring to offer POW control of the circuit breaker. The availability of CBs with pre-insertion resistors may be limited.

6. **Point-On-Wave (POW) switching** – it is generally agreed that the switchgear must be capable of performing the duty required in the event of failure of the POW controller and it is recommended that this philosophy be adopted if it has not already been.
7. **Current chopping studies during circuit-de-energisation** – It is unclear if GE has considered current chopping scenarios within their analysis. These should be considered if they have not already been.
8. **Statistical switching studies** – During the detailed engineering phases of the project it is recommended that full Monte Carlo analysis of circuit breaker pole operation, together with pole scatter, be considered.
9. **Additional Study** - Studies should be performed to determine the maximum capacitance that may be added to the system relative to an all overhead plan without depressing system resonances below the third harmonic. When this is established, the proportion of overhead line and cable that is required on the system, taking into account practical constraints, may be determined. Details of the modeling should also be provided for review.

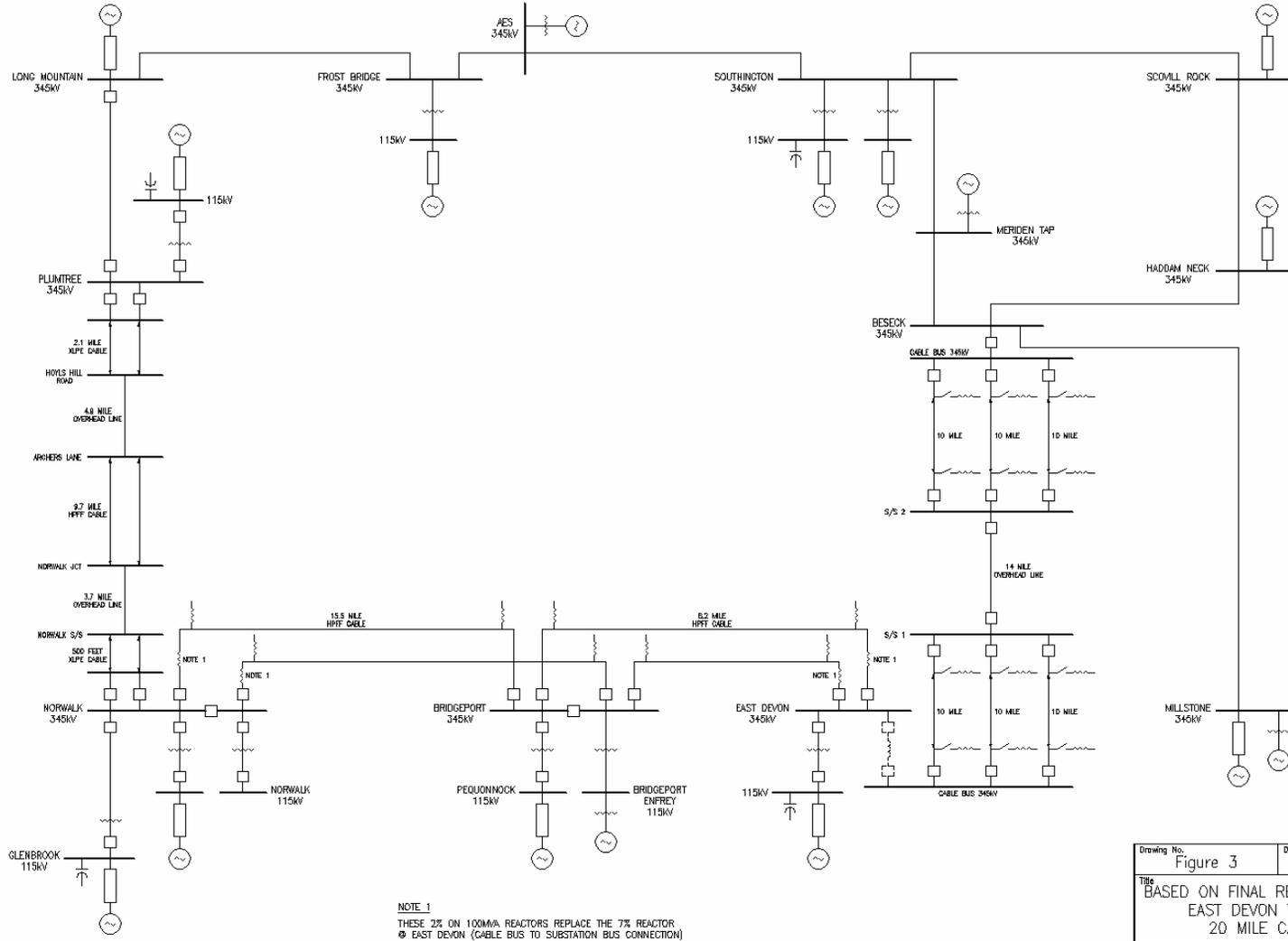
APPENDIX A- DIAGRAMS



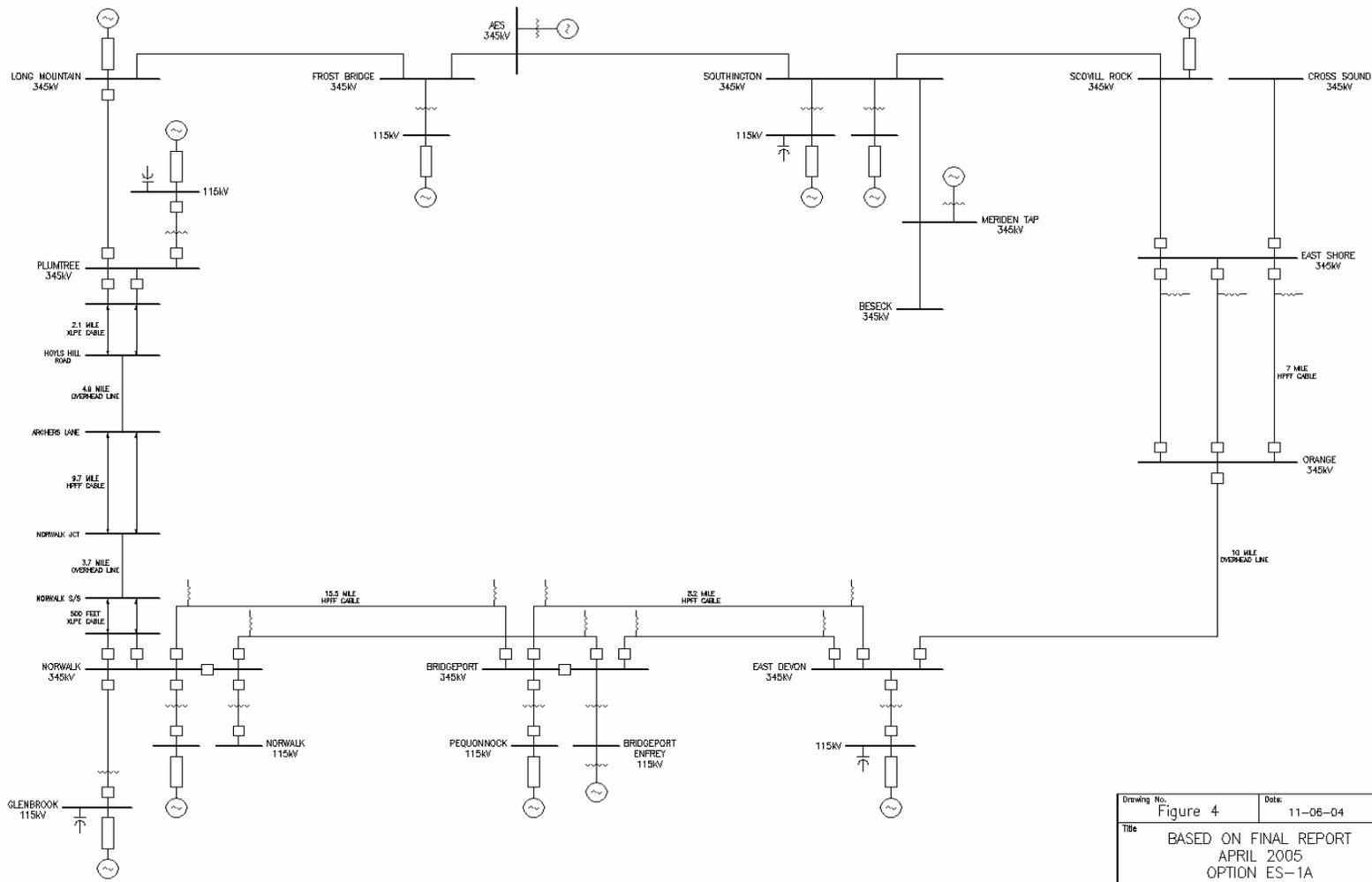
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Title	BASED ON DESIGN STUDY FOR PHASE 2 FINAL REPORT NOV. 2003		
Report Number	33.00/PP01:62049A		



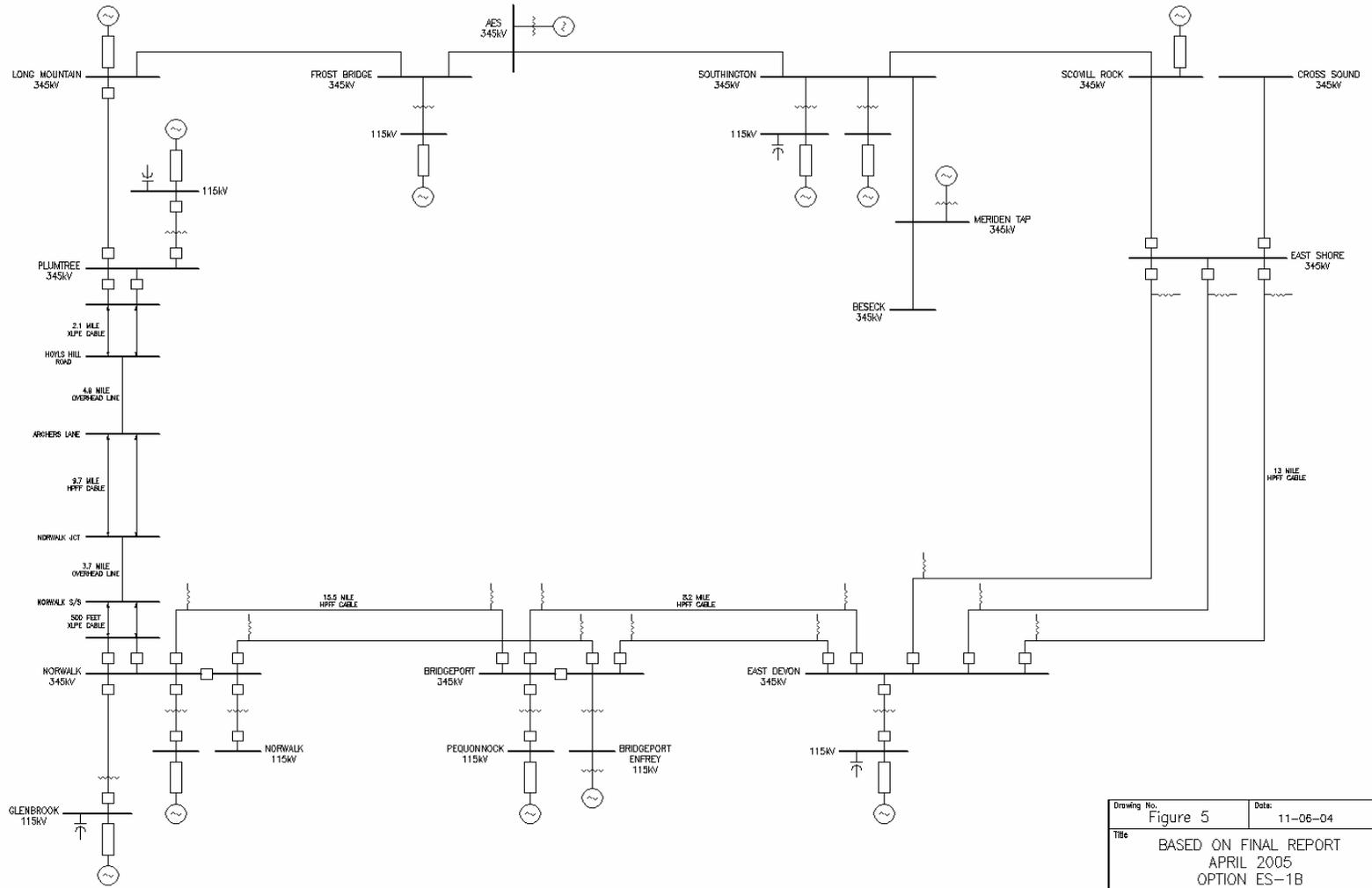
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Title			
BASED ON FINAL REPORT NOV 2003 EAST DEVON TO BESECK 40 MILE CABLE P1			
Report Number			
33.00/PP01:62049A			



Drawing No. Figure 3	Date 11-06-04
Title BASED ON FINAL REPORT DEC 2003 EAST DEVON TO BESECK 20 MILE CABLE P2	
Report Number 33.00/PP01:62049A	



Drawing No.	Figure 4	Date:	11-06-04
Title	BASED ON FINAL REPORT APRIL 2005 OPTION ES-1A		
Report Number	33.00/PP01:62049A		



Drawing No.	Date:
Figure 5	11-06-04
Title	
BASED ON FINAL REPORT APRIL 2005 OPTION ES-1B	
Report Number	
33.00/PP01:62049A	