Power System Studies

Laois – Ballyragget Cable Feasibility Study

PE667-F0400-R300-001-003

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Contents

Executive Summary

The purpose of this study was to asses the technical implications of installing a 110kV overhead line or cable between Ballyragget 110kV substation and Laois 400kV substation. In order to asses the feasibility of the overhead line/cable circuit, power flow, short circuit, transient and harmonic studies were carried out. Results show that the installation of a cable circuit results in more onerous utilisation of the 110kV network. However, in no case did result show the installation of the cable exceed the limits used for the purposes of this study.

The power flow studies showed that the loading of the cable was greater than the overhead line for both minimum and maximum system loading. This was to be expected as the impedance of the cable is considerably less than the overhead line. It was also observed that the cable generated approximately 32MVARs at rated voltage. This resulted in an increase in the system bus voltages at Laois, Ballyragget and Kilkenny. The use of ancillary equipment with the cable was not investigated as the load flow solutions were within the voltage and flow limits for the system.

The short circuit studies showed that the UGC yielded higher values for the both the peak make and the total rms break current values. This is to be expected as the impedance of the UGC is significantly lower that that of the OHL. However, it should be noted that the short circuit results for both the OHL and UGC are within the transmission system design limits as specified in the transmission grid code. The use of ancillary equipment with the cable was not investigated as the short circuit results were below the ratings set out in the transmission grid code.

Electromagnetic transient studies were carried out to investigate transients caused by; charged switching, energisation, de-energisation, and faults. Results show that overvoltages associated with the cable circuit are significantly higher than the overhead line circuit. However it should be noted that the results for both overhead line and cable are below the 420kV limit provided by Eirgrid.

The harmonic studies

The harmonic study showed that the UGC tended to increase the magnitude of the resonant conditions which occurred near the lower harmonic frequencies. This is to be expected as the capacitive effect of the cable tends to shift resonant conditions towards the lower harmonic frequencies. It was observed that the capacitor bank at Kilkenny has a significant effect on the impedance – frequency plots. In the case of Kilkenny 110kV busbar, it was found that when the capacitor bank was in service, the only observable resonant condition was at the 7th harmonic (Summer and Winter Dispatches).

It should be noted that the impedance – frequency plot only reveals a small part of the overall picture in regards to harmonics. The cable would also have a significant impact on the flow of existing harmonics in the power system. The low impedance of a cable at harmonic frequencies will tend to attract additional harmonic current flow in the vicinity of the cable. This could have the potential to increase the harmonic distortion at the local busbars beyond the IEC limits.

The use of ancillary equipment with the cable was not investigated, however the problems highlighted may necessitate mitigative action upon the connection of a generator or load containing harmonic currents at any of the resonant frequencies.

Finally, it can be concluded that, in general, the cable would have a more detrimental effect on the harmonic distortion levels in the area.

1 Introduction

1.1 Objectives

In order to reinforce the network in the Laois – Kilkenny region, Eirgrid propose to construct a new circuit between the two counties. The proposed new transmission infrastructure will consist of a new 400/110kV substation situated to the south east of Portlaoise, a new 110kV substation located adjacent to the existing 38kV substation at Ballyragget and an 110kV circuit between the proposed 400/110kV substation and the proposed 110kV substation.

ESB International has been contracted by Eirgrid to assess the implications of installing the following equipment between the two proposed stations:

- 110kV Overhead Line (OHL)
- 110kV Underground Cable (UGC)
- 110kV Underground Cable and Ancillary Equipment

1.2 Studies Performed

A number of studies were performed in order to asses the implications of installing an OHL or UGC between Ballyragget and Laois. The studies performed were as follows:

- Power Flow Studies
- Short Circuit Studies
- Harmonic Studies
- Switching and Fault Analysis

2 Power Flow Study

2.1 Introduction

Load flow calculations were carried out for the following four cases: 2010 Winter Peak System Model (WP10), 2010 Summer Night Valley System Model (SNV10), 2016 Winter Peak System Model (SNV16) and 2016 Summer Night Valley System Model (SNV16).

Load flow studies were carried out on the WP10 and the SNV10 models without the inclusion of the proposed new network. The load flow results were compared with the results provided in Eirgrid's Transmission Forecast Statement 2010-2016 [1]. Slight differences were noticed between the power flow results given in [1] and the results calculated from the PSS/E models obtained from Eirgrid. However, the differences between the two sets of results were small enough not to warrant further investigation.

Load flow studies were carried out on the WP16 and the SNV16 scenarios without the inclusion of the proposed new network. Again the load flow results were compared with the results provided in [1]. Slight differences existed between the power flow results given in [1] and the results calculated from the PSS/E models obtained from Eirgrid. As before, the differences between the two sets of results were small enough not to warrant further investigation.

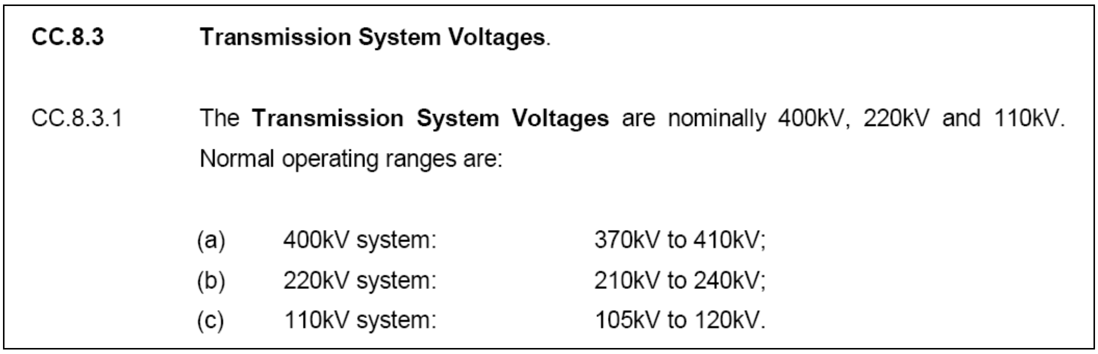
The comparison of the 2010 and 2016 power flow results with results given in [1] was done to ensure the validity of the PSSE models before commencing the power flow studies for the 110kV cable.

2.2 Load Flow Results – 110kV Overhead Line

Both the SNV16 and the WP16 PSSE models had an 110kV OHL between Laois and Ballyragget modelled. However, on guidance from Eirgrid, the line length was increased from 28km to 29.3km to match the length of the proposed UGC.

Load flow studies were carried out on both the SNV16 and the WP16 models. For the purposes of this study, the MVA rating of the OHL is assumed to be 190MVA. In the SNV16 model, the loading of the OHL was approximately 2% of the OHL rating and for the WP16 model the loading of the OHL was approximately 10%.

The voltage limits for the 400kV, 220kV and 110kV systems were also checked for both SNV16 and WP16 to ensure all bus voltages complied with the transmission system voltage limits set out in the Transmission Grid Code [2]. Figure 2.1 below shows the normal transmission system voltages outlined in section CC.8.3 of the code.



CC.8.3 **Transmission System Voltages**.

CC.8.3.1 The **Transmission System Voltages** are nominally 400kV, 220kV and 110kV. Normal operating ranges are:

(a) 400kV system: 370kV to 410kV;
(b) 220kV system: 210kV to 240kV;
(c) 110kV system: 105kV to 120kV.

Figure 2.1: Transmission System Voltages – Transmission Grid Code

No voltage limit violations were found for the 400kV, 220kV or the 110kV system for either the SNV16 or WP16 models. Also, no flow violations were found for the 400kV, 220kV or the 110kV system for either the SNV16 or WP16 models.

2.3 Load Flow Results – 110kV Cable

The 110kV OHL between Ballyragget and Laois was replaced with a 110kV cable as specified by Eirgrid. The cable chosen was a 1000mm^2 XLPE insulated single core cable composing of a copper conductor, copper screen, PE oversheath with laminated aluminium foil. For the purposes of this study it was necessary to make a number of assumptions in regards to the cable:

- 3 single core cables laid in trefoil
- 190MVA Cable Rating (Continuous Operation)
- Cable Length: 29.3km

It should be noted that a cable of this length would generate approximately 32MVARs of reactive power at rated voltage.

Load flow studies were carried out for both the SNV16 and the WP16 models. For the SNV16 model, the loading of the cable was approximately 11% of the cable rating and for the WP16 model the loading of the cable was approximately 25% of the cable rating.

As before, the voltage limits for the 400kV, 220kV and 110kV systems were checked for both SNV16 and WP16 models to ensure all bus voltages complied with the transmission system voltage limits. Again no voltage limit violations or flow violations were found for the 400kV, 220kV or the 110kV system for either the SNV16 or WP16 models.

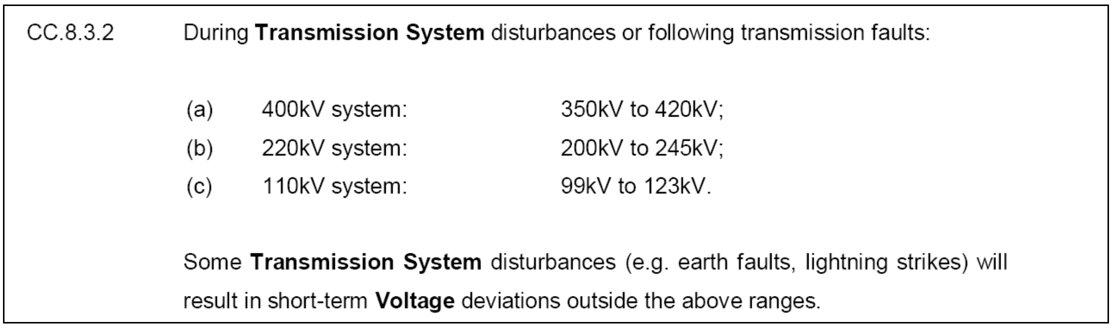
2.4 Load Flow: N-1 Contingency Analysis

For this study it was necessary to carryout N-1 Contingency Analysis for the 110kV OHL and the 110kV UGC modelled between Laois and Ballyragget. For the purposes of this study the following contingencies were considered.

- Loss of a Transformer
- Loss of a Line/Cable
- Loss of a Generator
- Loss of a Double Circuit Line

N-1 Contingency analysis was carried out for original SNV16 and WP16 models to identify existing problems on the system. Once the existing problems were identified, N-1 Contingency Analysis was carried out on the SNV16 and WP16 models for the OHL and the UGC. It should be noted that any problems existing in the original models were ignored in the analysis of both the UGC and the OHL as these are existing problems regardless of whether a UGC or OHL is built between Laois and Ballyragget.

For N-1 Contingency analysis, voltage limits during transmission system disturbances or following transmission faults were considered (Section CC.8.3.2 in [2]). Figure 2.2 shows the voltage limits outlined in section CC.8.3.2 of the grid code.



CC.8.3.2 During **Transmission System** disturbances or following transmission faults:

(a)	400kV system:	350kV to 420kV;
(b)	220kV system:	200kV to 245kV;
(c)	110kV system:	99kV to 123kV.

Some **Transmission System** disturbances (e.g. earth faults, lightning strikes) will result in short-term **Voltage** deviations outside the above ranges.

Figure 2.2: Transmission System Voltages – Transmission Grid Code

2.4.1 N-1 Contingency Analysis: Summer Night Valley 2016 Model

As previously stated, four types of contingencies were examined which were the loss of a transformer, loss of a line/cable, loss of a generator and loss of a double circuit line. All four types of contingencies were considered for the OHL and the UGC for the SNV16 system model.

Loss of a Transformer

For the SNV16 model, each transformer on the system was outaged and a power flow solution obtained. No additional problems were observed as a result of adding an OHL or UGC between Laois and Ballyragget.

Loss of a Line/Cable

For the SNV16 model, each line/cable on the system was outaged and a power flow solution obtained. No additional problems were observed as a result of adding an OHL or UGC between Laois and Ballyragget.

Loss of a Generator

For the SNV16 model, each generator on the system was outaged and a power flow solution obtained. No additional problems were observed as a result of adding an OHL or UGC between Laois and Ballyragget.

Loss of a Double Circuit Line

On the Irish system there are a number of locations were a tower is carrying two circuits of either equal or different voltages. While the loss of two circuits would be considered a double contingency, the fact that both circuits occupy the same tower structure means that loss of the tower (which is one contingency) would result in the loss of both circuits.

For the SNV16 model, each double circuit line on the system was outaged and a power flow solution obtained. No additional problems were observed as a result of adding an OHL or UGC between Laois and Ballyragget.

2.4.2 N-1 Contingency Analysis: Winter Peak 2016 Model

Again, four types of contingencies were examined which were the loss of a transformer, loss of a line/cable, loss of a generator and loss of a double circuit line. All four contingencies were considered for the OHL and the UGC for the WP16 model.

Loss of a Transformer

For the WP16 model, each transformer on the system was outaged and a power flow solution obtained. No additional problems were observed as a result of adding an OHL or UGC between Laois and Ballyragget.

Loss of a Line/Cable

For the WP16 model, each line on the system was outaged and a power flow solution obtained. No additional problems were observed as a result of adding an OHL or UGC between Laois and Ballyragget.

Loss of a Generator

For the WP16 model, each generator on the system was outaged and a power flow solution obtained. No additional problems were observed as a result of adding an OHL or UGC between Laois and Ballyragget.

Loss of a Double Circuit Line

For the WP16 model, each double circuit line on the system was outaged and a power flow solution obtained. No additional problems were observed as a result of adding an OHL or UGC between Laois and Ballyragget.

2.5 Load Flow Summary

The purpose of the load flow study is to identify possible issues between the installation of OHL and UGC between Laois and Ballyragget. For the SNV16 and WP16 models it was found that the loading of the UGC was greater than that of the OHL. Table 2.1 below shows a comparison of the loading of the UGC and the OHL for both SNV16 and WP16 models.

	SNV16	WP16
Overhead Line	2%	10%
Cable	11%	25%

Table 2.1: Comparison of MVA loading on OHL and UGC

During the course of the load flow study, a number of observations were made in regards to the installation of UGC. The UGC generated approximately 32MVARs at rated voltage which in turn had a number of effects on the system voltage. The 32MVARs of reactive power (at rated voltage) generated by the cable could provide voltage support for the system. This was observed for a number of cases during the N-1 contingency analysis. The cable also had the effect of raising the voltages at the local 110kV busbars for both the SNV16 and WP16 models. Both SNV16 and WP16 models (OHL and UGC) were within the normal voltage limits for the system as specified in the transmission grid code. However, it should be noted that for the WP16 model, the bus voltages at Kilkenny (119.3kV) and Ballyragget (118.9kV) 110kV busbars were approaching the upper voltage limits outlined in the transmission grid code.

Finally, the use of ancillary equipment with the cable was not investigated as the load flow solutions for both the SNV16 and WP16 models were within the voltage and flow limits for the system.

3 Short Circuit Study

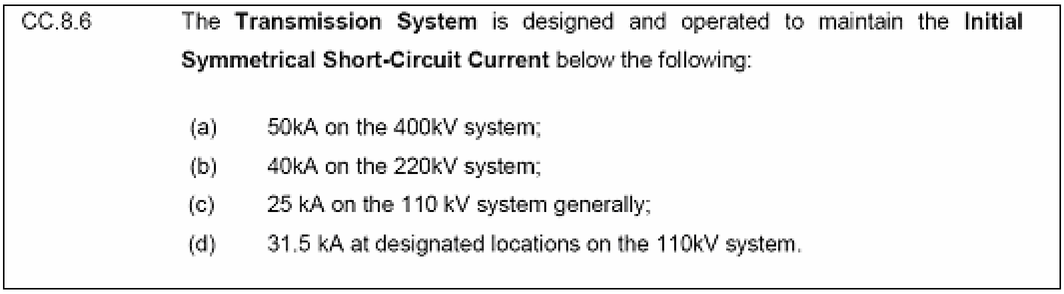
3.1 Short Circuit Currents

It was necessary to investigate the impact of both the OHL and the UGC on the short circuit levels at the stations surrounding the proposed network development. This was necessary as an excessive increase in short circuit levels means that equipment (Circuit Breakers, Switchgear etc.) may need to be replaced with higher-rated equipment.

All short circuit calculations are carried out using the Power System Simulator for Engineering software (PSS/E) Version 31, and according to the IEC standard 60909-0-2001 “Short circuit currents in three phase a.c. systems” [3].

For the purpose of this study it was necessary to make a number of assumptions in regards to the short circuit calculations:

- Generator Power Factor: 0.8
- Circuit Breaker Open Time (400kV Busbars): 50ms (Assumed)
- Circuit Breaker Open Time (220kV Busbars): 50ms[1]
- Circuit Breaker Open Time (110kV Busbars): 80ms[2]
- Initial Symmetrical Short Circuit Current Ratings as per Figure 3.1



CC.8.6 The **Transmission System** is designed and operated to maintain the **Initial Symmetrical Short-Circuit Current** below the following:

(a) 50kA on the 400kV system;
(b) 40kA on the 220kV system;
(c) 25 kA on the 110 kV system generally;
(d) 31.5 kA at designated locations on the 110kV system.

Figure 3.1: Initial Symmetrical Short Circuit Current – Transmission Grid Code

3.2 Short Circuit Results – 110kV Overhead Line

Three phase and Single Line to ground faults were placed at each of the busbars outlined in tables 3.1 and 3.2 and the short circuit results compared with the values given in [1]. It was observed that the results obtained were slightly higher (approx 5% – 7%) than the values supplied in [1]. This can be contributed to the slight differences in the methods used to obtain the short circuit results. Engineering Recommendation G74 (ER G74) which was used to calculate the short circuit levels in [1], defines a computer based method for calculation of short circuit currents which is more accurate than the methodology detailed in IEC60909. In short IEC60909 will yield more conservative results while ER G74 will yield slightly more accurate results.

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[1] Transmission Forecast Statement 2010 - 2016

[2] Transmission Forecast Statement 2010 - 2016

		Summer Valley 2016 Three Phase			Summer Valley 2016 Single Phase		
Substation	**Voltage (kV)**	**X/R**	**Peak Make (kA)**	**Tot. RMS Break (kA)**	**X/R**	**Peak Make (kA)**	**Tot. RMS Break (kA)**
Laois	110	6.6	26.8	12.4	9.6	35.0	15.0
Ballyragget	110	4.9	13.7	6.2	7.8	10.8	4.7
Kilkenny	110	3.9	13.9	6.7	10.5	13.7	6.2
Athy	110	3.5	13.6	6.7	6.7	12.0	5.6
Portlaoise	110	4.9	23.5	10.7	7.6	22.2	9.9
Laois	400	15.0	13.4	6.1	14.2	15.1	5.9

Table 3.1: Short Circuit Results: OHL Summer Night Valley 2016

		Winter Peak 2016 Three Phase			Winter Peak 2016 Single Phase		
Substation	**Voltage (kV)**	**X/R**	**Peak Make (kA)**	**Tot. RMS Break (kA)**	**X/R**	**Peak Make (kA)**	**Tot. RMS Break (kA)**
Laois	110	6.2	31.3	14.6	9.7	39.6	17.1
Ballyragget	110	5.5	16.7	7.5	7.8	11.8	5.1
Kilkenny	110	4.9	21.2	9.7	10.3	17.3	7.5
Athy	110	3.3	14.9	7.4	6.8	12.7	5.9
Portlaoise	110	4.5	26.5	12.3	7.6	23.8	10.6
Laois	400	15.5	17.0	7.7	13.6	18.0	7.1

Table 3.2: Short Circuit Results: OHL Winter Peak 2016

3.3 Short Circuit Results – 110kV Cable

Three phase and Single Line to ground faults were placed at each of the busbars outlined in tables 3.3 and 3.4 and the results obtained were compared with the short circuit results obtained for the OHL. It can be observed that the UGC resulted in significantly higher short circuit levels for Ballyragget and Kilkenny 110kV busbar compared with the results obtained for the OHL. However, it should be noted that the short circuit results for both the OHL and UGC are within the transmission system design limits as specified in the transmission grid code.

		Summer Valley 2016 Three Phase			**Summer Valley 2016 Single Phase**		
Substation	**Voltage (kV)**	**X/R**	**Peak Make (kA)**	**Tot. RMS Break (kA)**	**X/R**	**Peak Make (kA)**	**Tot. RMS Break (kA)**
Laois	110	6.4	27.4	12.6	9.2	35.6	15.3
Ballyragget	110	4.5	18.7	8.7	0.8	16.7	9.4
Kilkenny	110	4.0	15.7	7.5	6.2	15.2	7.0
Athy	110	3.5	13.6	6.7	6.7	12.0	5.6
Portlaoise	110	4.8	23.7	10.8	7.6	22.4	9.9
Laois	400	15.0	13.4	6.1	14.2	15.2	6.0

Table 3.3: Short Circuit Results: Cable Summer Night Valley 2016

		Winter Peak 2016 Three Phase			**Winter Peak 2016 Single Phase**		
Substation	**Voltage (kV)**	**X/R**	**Peak Make (kA)**	**Tot. RMS Break (kA)**	**X/R**	**Peak Make (kA)**	**Tot. RMS Break (kA)**
Laois	110	6.1	32.5	15.1	9.2	41.0	17.8
Ballyragget	110	4.6	22.5	10.4	0.8	18.5	10.5
Kilkenny	110	4.8	23.1	10.6	6.1	18.9	8.5
Athy	110	3.3	14.9	7.5	6.8	12.7	6.0
Portlaoise	110	4.4	26.8	12.5	7.6	24.0	10.7
Laois	400	15.6	17.1	7.7	13.6	18.0	7.1

Table 3.4: Short Circuit Results: Cable Winter Peak 2016

3.4 Short Circuit Summary

A number of observations were made in regards to the results obtained for the UGC and the OHL. It was observed that the UGC yielded higher values for the both the peak make and the total rms break current values. This is to be expected as the impedance of the UGC is significantly lower that that of the OHL. However, it should be noted that the short circuit results for both the OHL and UGC are within the transmission system design limits as specified in the transmission grid code.

Finally, the use of ancillary equipment with the cable was not investigated as the short circuit results for both the SNV16 and WP16 models (OHL and UGC) were within the limits set out in the transmission grid code.

4 Electromagnetic Transient Studies

4.1 Introduction

Electromagnetic transient studies were carried out to investigate transients caused by:

- Charged Switching
- Energisation
- De-energisation
- Faults

In order to carry out the necessary transient studies, EMTP ATP software was used. All results of the studies preformed are presented in peak voltage.

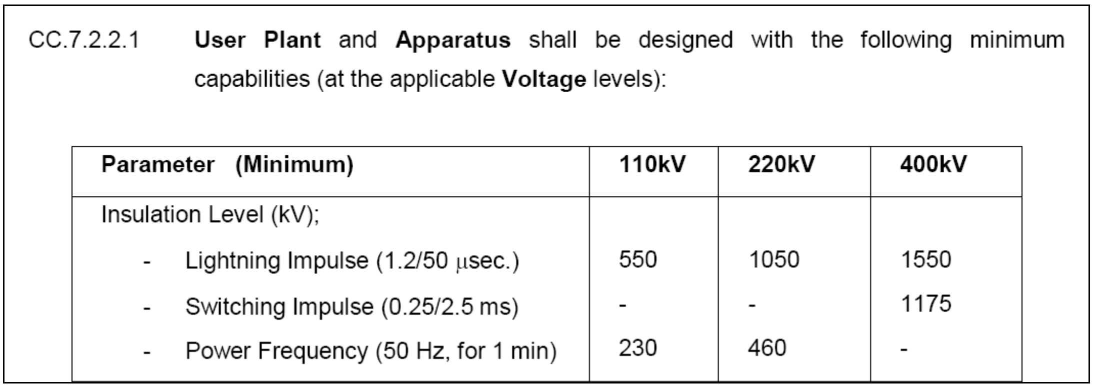
4.2 Modelling Assumptions

In order to carry out the required switching studies, it was necessary to make a number of assumptions.

4.2.1 General Assumptions

The following general assumptions were made:

- All Voltage Per Unit Values are expressed on a Voltage base of 89.81kV
    - $\left(\left(110kV/\sqrt{3}\right)*\sqrt{2}\right)=89.81kV$
- Time Step: $1x10^{-6} Seconds$
- Switching Impulse Insulation Level for 110kV: 420kV (Supplied by Eirgrid)
- Insulation Level for Transmission System as per section CC.7.2.2.1 of [2]. As there is no defined insulation level for a switching impulse at 110kV, Eirgrid have specified that the level to be used for the purposes of this report is 420kV.



CC.7.2.2.1 **User Plant** and **Apparatus** shall be designed with the following minimum capabilities (at the applicable **Voltage** levels):

Parameter (Minimum)	**110kV**	**220kV**	**400kV**
Insulation Level (kV);			
- Lightning Impulse (1.2/50 μsec.)	550	1050	1550
- Switching Impulse (0.25/2.5 ms)	-	-	1175
- Power Frequency (50 Hz, for 1 min)	230	460	-

Table 4.1: Insulation Levels for Transmission System

4.2.2 Thevenin Impedances

Thevenin impedances were calculated for the following locations:

- Laois 110kV
- Kilkenny 110kV

The Thevenin impedances were derived from the 2016 PSSE Models supplied by Eirgrid. The Thevenin impedances were modelled as a resistance and reactance in series terminated by a voltage source. It should be noted that the Thevenin impedance contains both the positive and zero sequence information for the system.

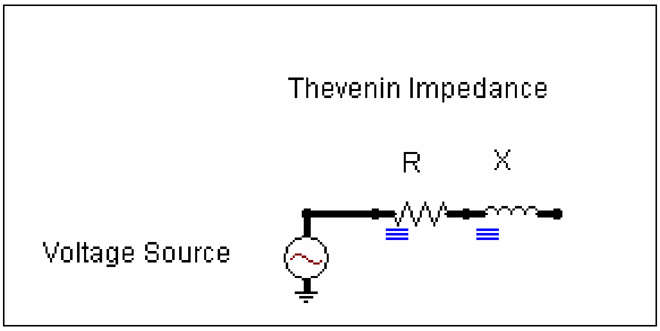
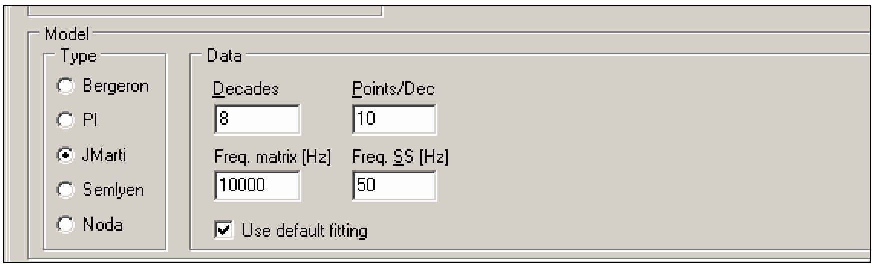


Figure 4.1: Thevenin Impedance Model

4.2.3 Overhead Line Assumptions

The following assumptions were made in regards to the overhead line:

- Over Head Line Data
    - R, X, B taken from [1] and scaled to 29.3km
    - Wooden Pole Structure (Figure 4.3)
- Leakage Resistance – Conductance of a Transmission Line: 3.25% of leakage capacitance [4]
- Velocity of a Travelling Wave on an OHL: ≈ 300,000km/s
- Surge Impedance Z_c of an OHL: 365Ω
- 110KV Overhead Line Tower Structure
    - Height of Phases above Ground: 16.2 Meters
    - Distance between Phases: 4.5 Meters
    - Maximum Sag: 2 Meters
- LCC Model: JMarti Model


Model

Type
○ Bergeron
○ PI
● JMarti
○ Semlyen
○ Noda

Data
Decades: 8
Points/Dec: 10
Freq. matrix [Hz]: 10000
Freq. SS [Hz]: 50
☑ Use default fitting

Figure 4.2: JMarti Model Parameters

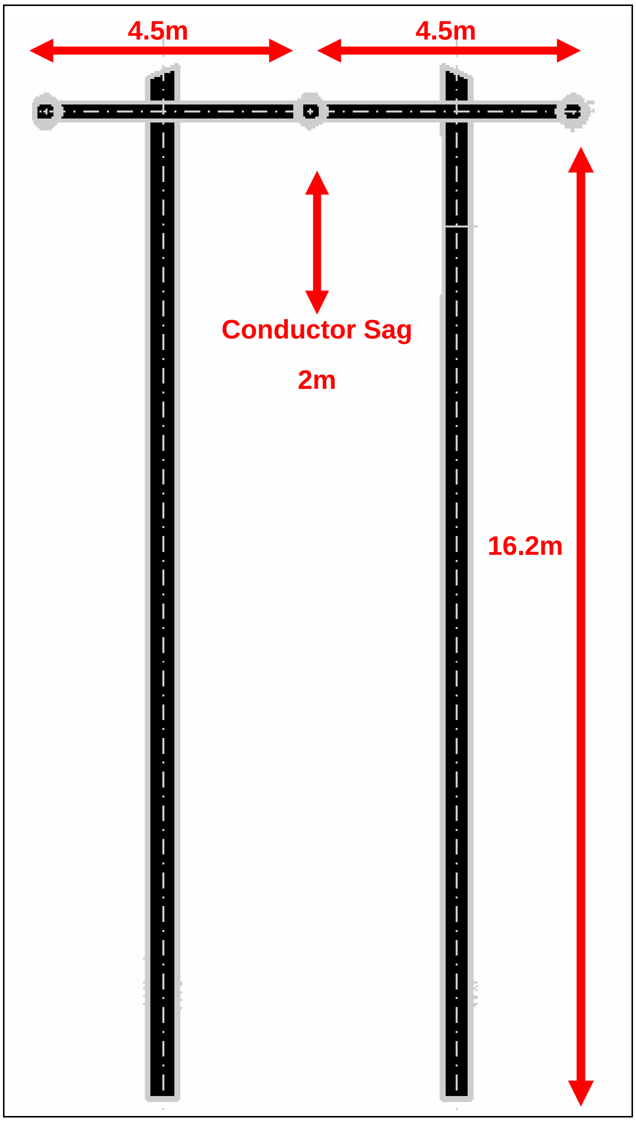
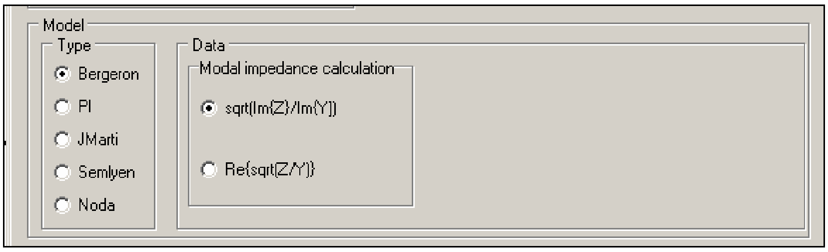


Figure 4.3: 110kV Wooden Pole Structure

4.2.4 Cable Assumptions

The following assumptions were made in regards to the Cable:

- Minimum Insulation Resistance for 1000mm^2 XLPE insulated single core cable: 1000MΩ km (As per Cable Spec. supplied by Eirgrid)
- 110kV Underground Cable Laid in Trefoil with d_{ab} = d_{bc} = d_{ac} =125mm
- Surge Impedance Z_c of an UGC: 37Ω
- LCC Model: Bergeron Model



Model

Type

● Bergeron
○ PI
○ JMarti
○ Semlyen
○ Noda

Data

Modal impedance calculation

● sqrt(Im{Z}/Im{Y})
○ Re{sqrt(Z/Y)}

Figure 4.4: Bergeron Model Parameters

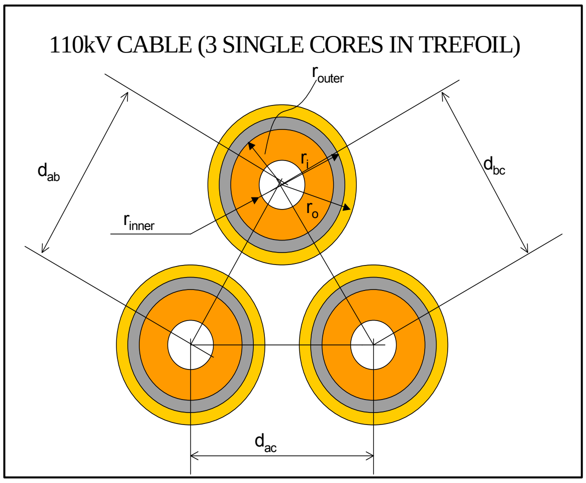


Figure 4.5: 110kV Cable Laid in Trefoil

4.2.5 Ballyragget 110kV Substation Loading

As no loading information has been given for Ballyragget 110kV substation, it is assumed that a load of 12.5MVA at a power factor of 0.8 will be connected to Ballyragget 110kV substation.

4.2.6 Detailed Transient ATP Model Vs Simplified ATP Transient Model

For the purpose of the Electromagnetic Transient Studies, a simplified transient model was built. While a detailed ATP model would yield more accurate results, the simplified ATP model still yields valid results. Appendix G shows a comparison of an OHL energisation using a simplified ATP model and a slightly more detailed ATP Model. It was found that the difference in the maximum overvoltages experienced in the detailed model and the simplified model was approximately 3-4%. Therefore, the use of a simplified ATP model for the switching study can be justified.

4.3 Ballyragget – Laois 110kV Cable Study

4.3.1 Charged Cable Switching

From a system perspective, the worse case switching action is the switching – in of a charged cable at opposite voltage polarity to the grid voltage. This would cause significant voltage and current distortion. A charged cable switching was carried out for both ends of the cable and the effects on the voltage and current at Ballyragget and Laois was observed.

In order to find the maximum overvoltages that could be experienced at Laois and Ballyragget, a statistical study was carried out. The assumptions for the statistical study are listed below:

Statistical Study Assumptions:

- 900 Simulations
- Time at Breaker Opening: 20ms
- Time at Breaker Closing: 50ms
- Standard Deviation for Closing Breaker: 10ms

4.3.1.1 Charged Cable Switching - Ballyragget

At t=0s it is assumed that the circuit breaker at Ballyragget is open and that the cable is energised from Laois 400kV substation. After 20ms, the circuit breaker at the Laois end of the cable opens. When the grid voltage reaches the opposite voltage polarity to the cable voltage, the circuit breaker at Ballyragget closes (50ms). Figures 4.6 and 4.7 show the worse case results obtained from the switching study for a charged cable switching at Ballyragget. The Laois end voltage graph shows the retained cable voltage before switching. It should be noted that the voltage graphs show significant voltage distortion for the first few cycles after the switching. A diagram of the model used for this case is shown in Appendix B Figure B1.

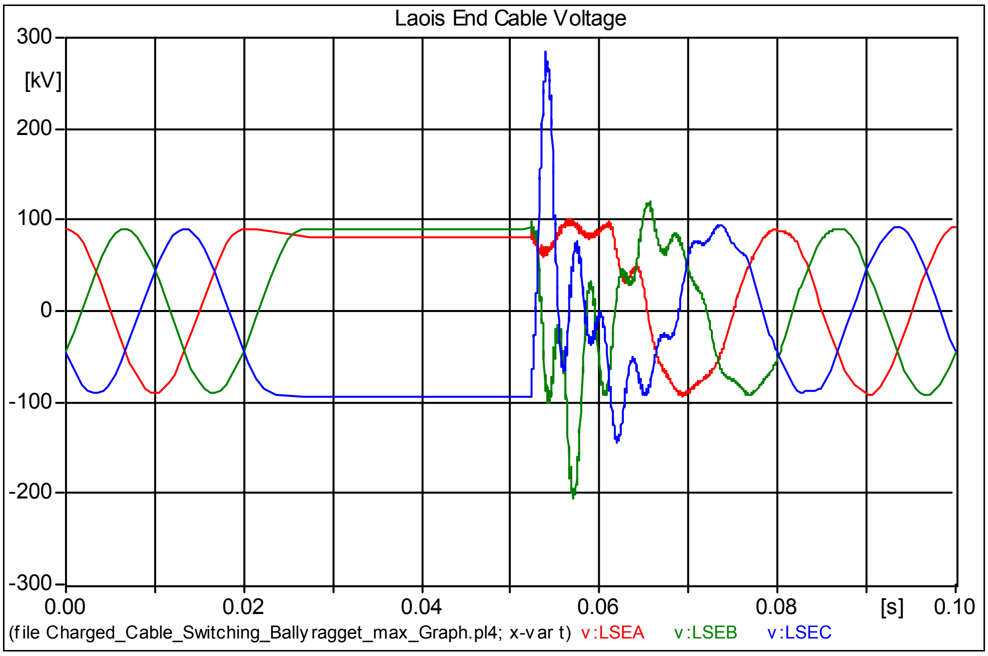


Figure 4.6: Laois Cable End Voltage for a Charged Switching at Ballyragget

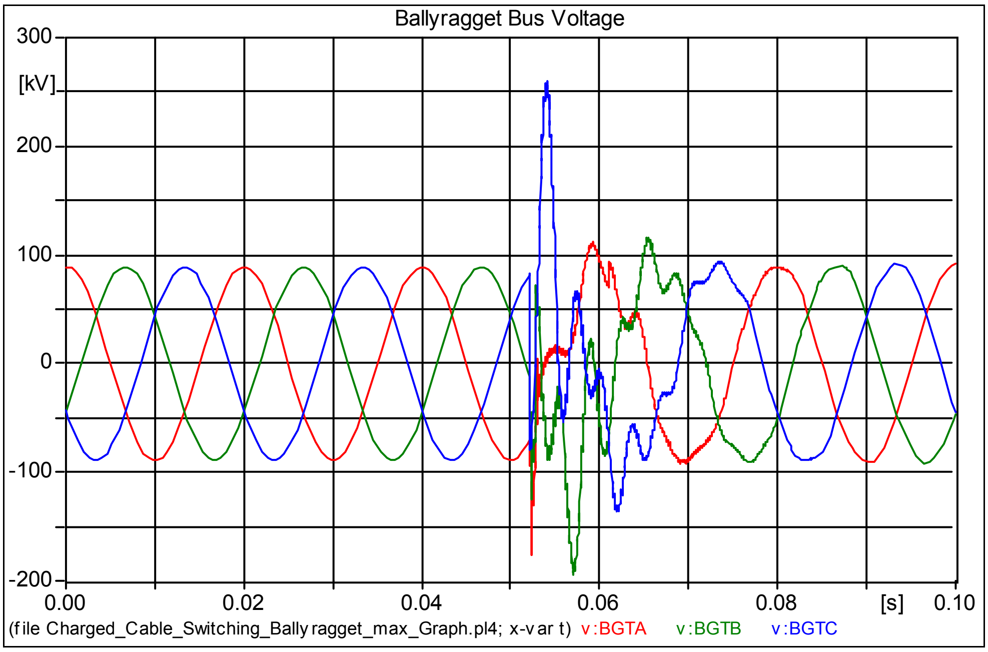


Figure 4.7: Ballyragget Bus Voltage for a Charged Switching at Ballyragget

Figure 4.8 shows the probability curve for peak overvoltages experienced at Ballyragget 110kV busbar. Table 4.2 shows the mean overvoltage, variance and standard deviation for overvoltages at Ballyragget. The average overvoltage which could be experienced at Ballyragget 110kV busbar for a charged cable switching at Ballyragget is 153kV (Peak L-G).

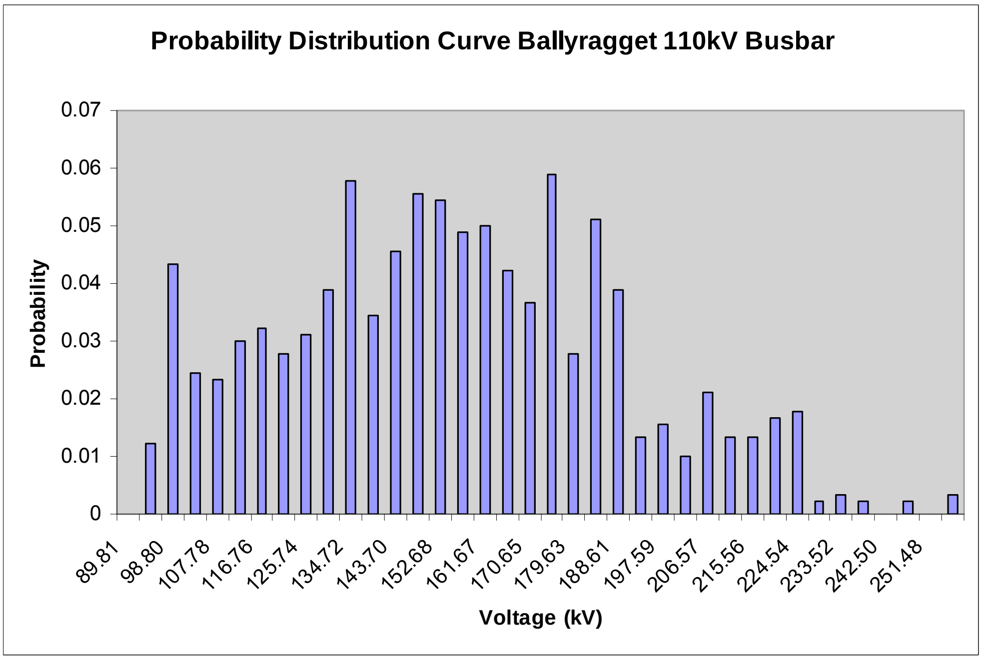


Figure 4.8: Probability Distribution Curve for Peak Overvoltages Experienced at Ballyragget 110kV Busbar

Mean Overvoltage	153kV
Variance	0.142
Standard Deviation	0.3766

Table 4.2: Mean/Variance/Standard Deviation

Figure 4.9 shows the probability curve for peak overvoltages experienced at the Laois end of the cable. Table 4.3 shows the mean overvoltage, variance and standard deviation for overvoltages at the Laois end of the cable. The average overvoltage which could be experienced at the Laois end of the cable for a charged cable switching at Ballyragget is 154kV (Peak L-G).

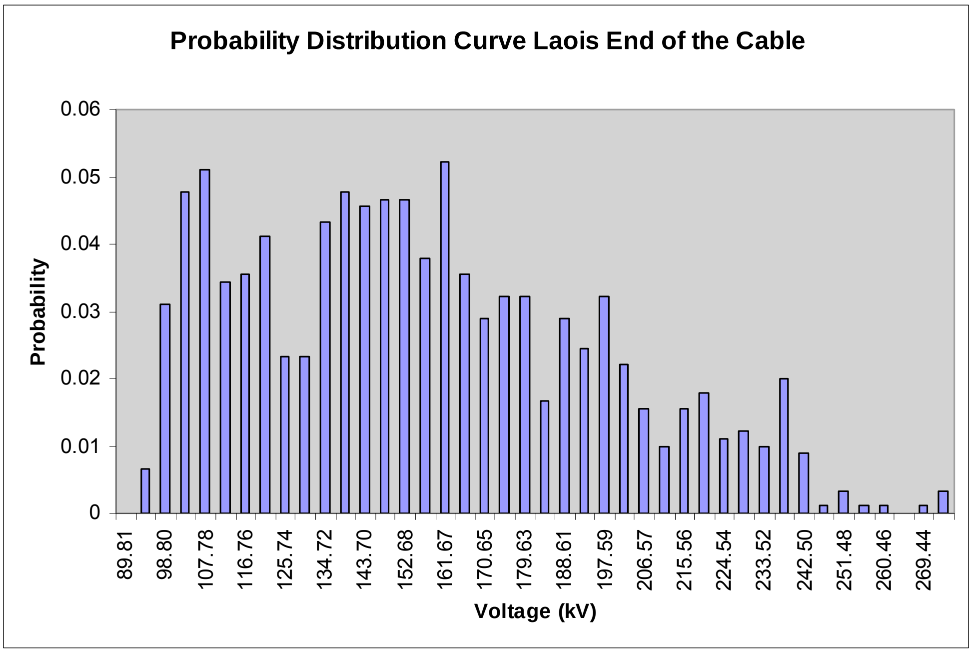


Figure 4.9: Probability Distribution Curve for Peak Overvoltages Experienced at Laois end of the Cable

Mean Overvoltage	154kV
Variance	0.1924
Standard Deviation	0.4386

Table 4.3: Mean/Variance/Standard Deviation

Figure 4.10 shows the probability curve for peak overvoltages experienced at both Laois and Ballyragget for a charged cable switching at Ballyragget. Table 4.4 shows the mean overvoltage, variance and standard deviation for the peak overvoltages. The average overvoltage which could be experienced for a charged cable switching at Ballyragget is 181.42kV (Peak L-G).

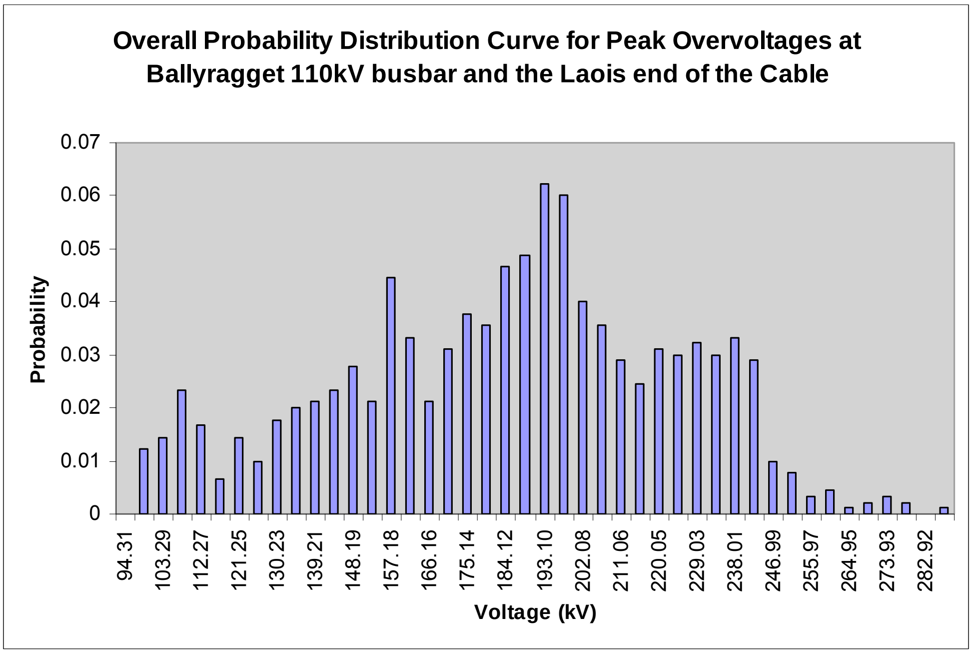


Figure 4.10: Probability Distribution Curve for Charged Cable Switching at Ballyragget

Mean Overvoltage	181.42kV
Variance	0.191
Standard Deviation	0.437

Table 4.4: Mean/Variance/Standard Deviation

Table 4.5 below shows both the mean and maximum overvoltages that could be experienced at Ballyragget 110kV busbar and at the Laois end of the 110kV cable.

	Ballyragget Bus Voltage (kV)		**Laois End Cable Voltage (kV)**	
	L-L	**L-G**	**L-L**	**L-G**
Maximum Overvoltage	350	259	372	270
Mean Overvoltage	-	153	-	154

Table 4.5: Charged Cable Switching Ballyragget Results

4.3.1.2 Charged Cable Switching – Laois

At t=0s it is assumed that the circuit breaker at Laois is open and that the cable is energised from Ballyragget 110kV substation. After 20ms, the circuit breaker at the Ballyragget end of the cable opens. When the grid voltage reaches the opposite voltage polarity to the cable voltage, the circuit breaker at Laois closes (50ms). Figures 4.11 and 4.12 show the worse case results obtained from the switching study for a charged cable switching at Laois. The Ballyragget end voltage graph shows the retained cable voltage before switching. It should be noted that the voltage graphs show significant voltage distortion for the first few cycles after the switching. It should also be noted that the voltage distortions are worse for a cable energisation from Laois 400kV substation. A diagram of the model used for this case is shown in Appendix B Figure B2

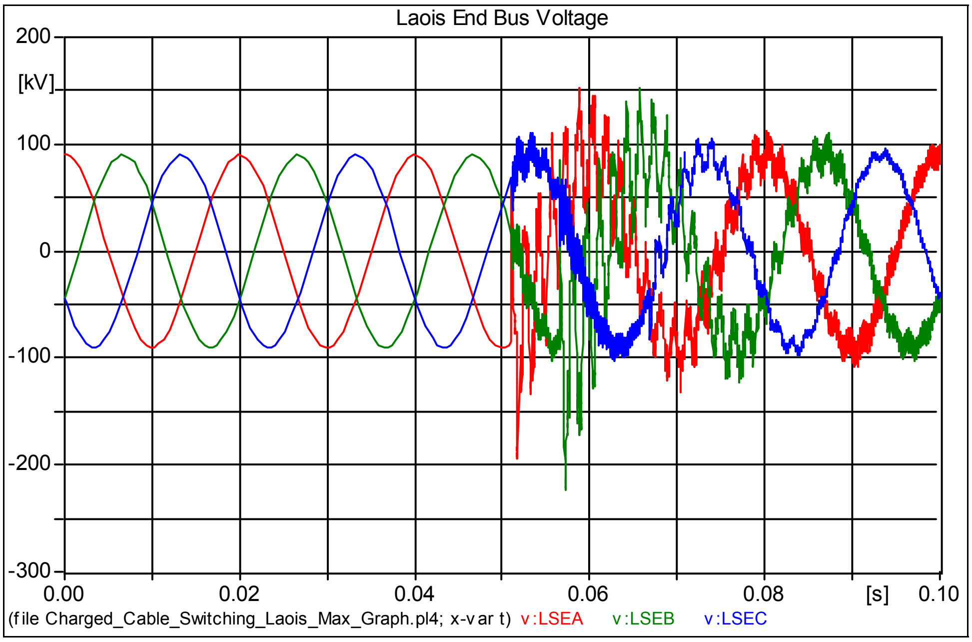


Figure 4.11: Laois Bus Voltage for a Charged Switching at Laois

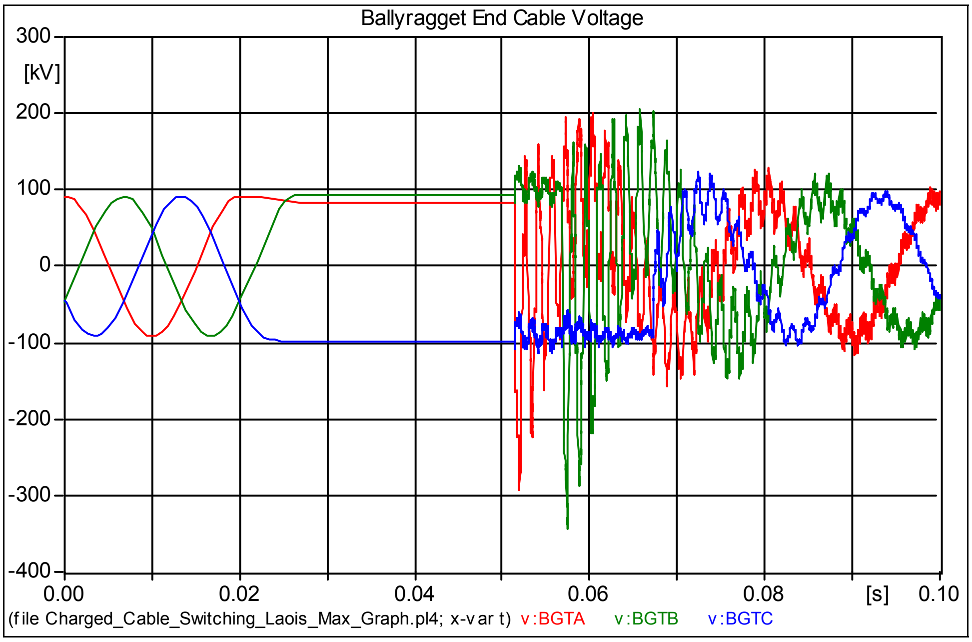


Figure 4.12: Ballyragget Cable End Voltage for a Charged Switching at Laois

Figure 4.13 shows the probability curve for peak overvoltages experienced at Laois 110kV busbar. Table 4.6 shows the mean overvoltage, variance and standard deviation for overvoltages at Laois. The average overvoltage which could be experienced at Laois 110kV busbar for a charged cable switching at Laois is 142kV (Peak L-G).

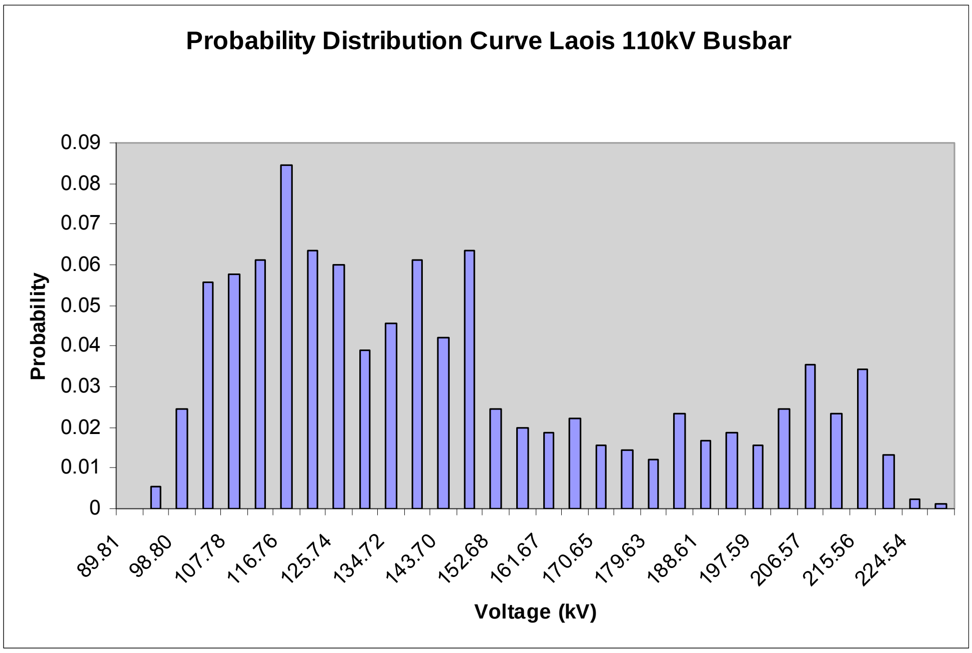


Figure 4.13: Probability Distribution Curve for Peak Overvoltages Experienced at Laois 110kV Busbar

Mean Overvoltage	142kV
Variance	0.1547
Standard Deviation	0.3932

Table 4.6: Mean/Variance/Standard Deviation

Figure 4.14 shows the probability curve for peak overvoltages experienced at the Ballyragget end of the cable. Table 4.7 shows the mean overvoltage, variance and standard deviation for overvoltages at the Ballyragget end of the cable. The average overvoltage which could be experienced at the Ballyragget end of the cable for a charged cable switching at Laois is 193kV (Peak L-G).

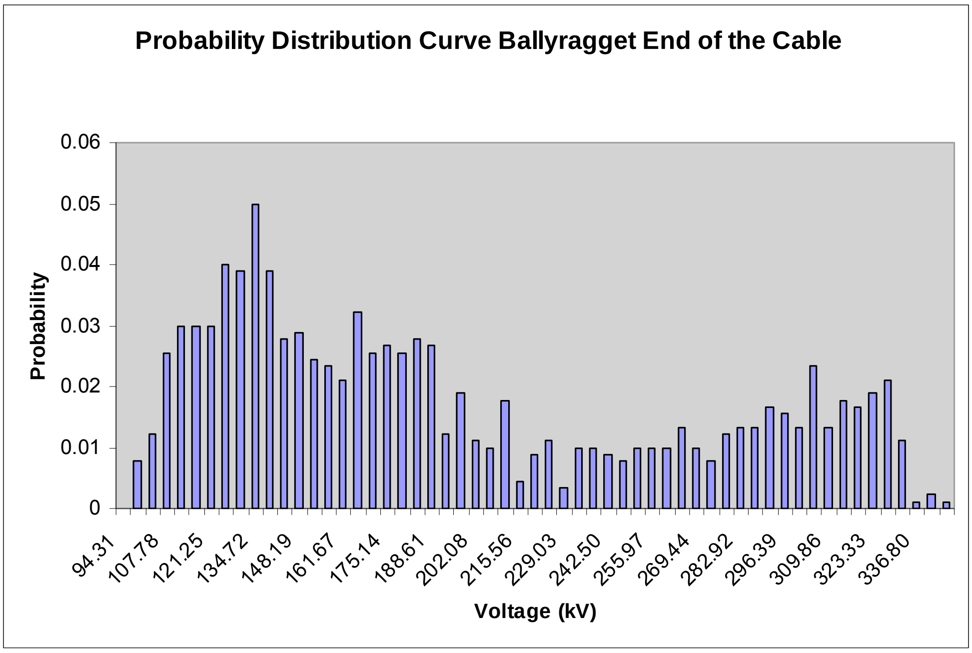


Figure 4.14: Probability Distribution Curve for Peak Overvoltages Experienced at Ballyragget end of the Cable

Mean Overvoltage	193kV
Variance	0.619
Standard Deviation	0.787

Table 4.7: Mean/Variance/Standard Deviation

Figure 4.15 shows the probability curve for peak overvoltages experienced at both Laois and Ballyragget for a charged cable switching at Ballyragget. Table 4.8 shows the mean overvoltage, variance and standard deviation for the peak overvoltages. The average overvoltage which could be experienced for a charged cable switching at Laois is 251.47kV (Peak L-G).

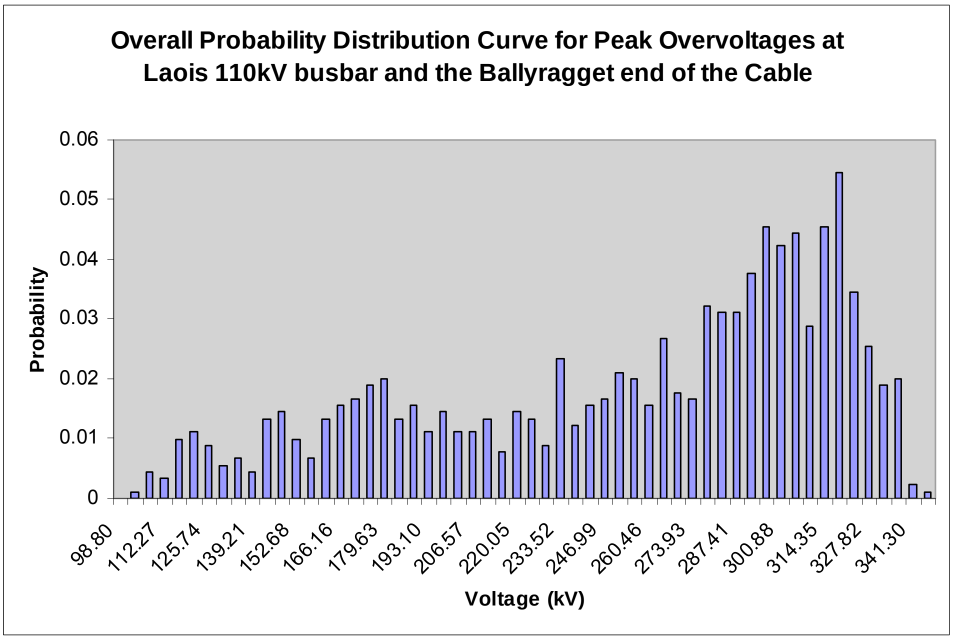


Figure 4.15: Probability Distribution Curve for Charged Cable Switching at Laois

Mean Overvoltage	251.47kV
Variance	0.483
Standard Deviation	0.694

Table 4.8: Mean/Variance/Standard Deviation

Table 4.9 below shows both the mean and maximum overvoltages that could be experienced at Laois 110kV busbar and at the Ballyragget end of the 110kV cable.

	Laois Bus Voltage (kV)		**Ballyragget End Cable Voltage (kV)**	
	L-L	**L-G**	**L-L**	**L-G**
Maximum Overvoltage	337	224	488	343
Mean Overvoltage	-	142	-	193

Table 4.9: Charged Cable Switching Laois Results

4.3.1.3 Charged Cable Switching Summary

A number of points were noted in regards to the charged cable switching study which are as follows:

- A charged cable switching at Laois caused significantly higher overvoltages compared to a charged cable switching at Ballyragget.
- The highest overvoltage measured was 488kV and was measured at the Ballyragget end of the cable for a charged cable switching at Laois.

4.3.2 Cable Energisation

The cable can be energised from either Ballyragget or Laois. The cable was energised from Laois and Ballyragget and the resultant voltages and currents were observed.

In order to find the maximum overvoltages that could be experienced at Laois and Ballyragget, a statistical study was carried out. The assumptions for the statistical study are listed below:

Statistical Study Assumptions:

- 900 Simulations
- Time of Breaker Closing: 40ms
- Standard Deviation for Closing Breaker: 10ms

4.3.2.1 Cable Energisation – Ballyragget

At t=0s it is assumed that both the Laois and Ballyragget circuit breakers are open. At t = 40ms, the breaker at Ballyragget is closed and the line is energised from Ballyragget. Figures 4.16 and 4.17 show the worse case overvoltages which were obtained form the statistical study. The first observation made is that the voltage distortions were lower than the voltage distortions observed for the charged switching event which is to be expected. It can be seen from figures 4.16 and 4.17 that significant voltage distortion exists for the first few cycles after the switching event. Also it can be observed that a significant energisation current is experienced with the energisation of the cable. A diagram of the model used for this case is shown in Appendix B Figure B3

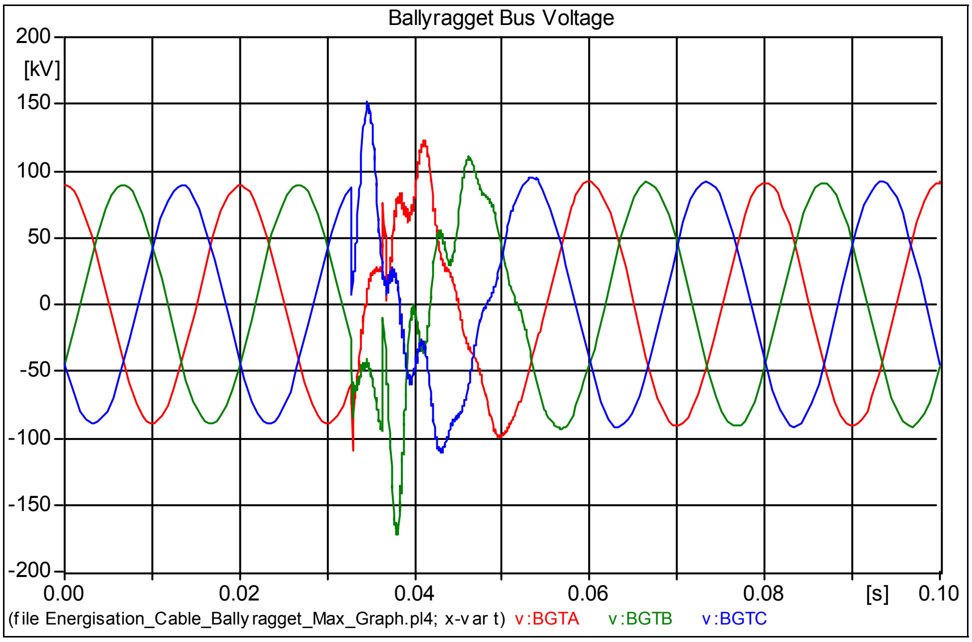


Figure 4.16: Ballyragget Bus Voltage for Cable Energisation from Ballyragget

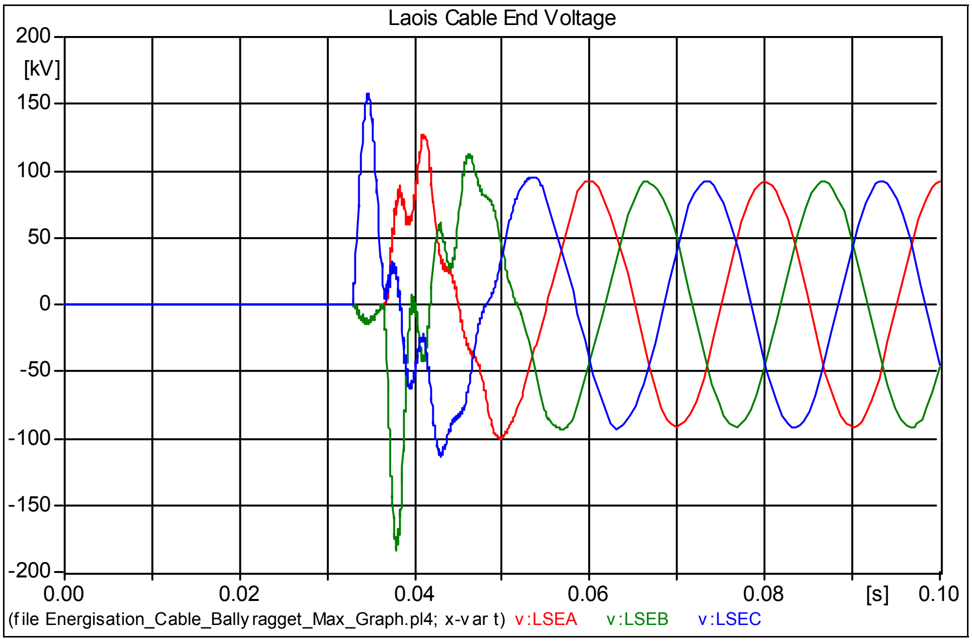


Figure 4.17: Laois Cable End Voltage for Cable Energisation from Ballyragget

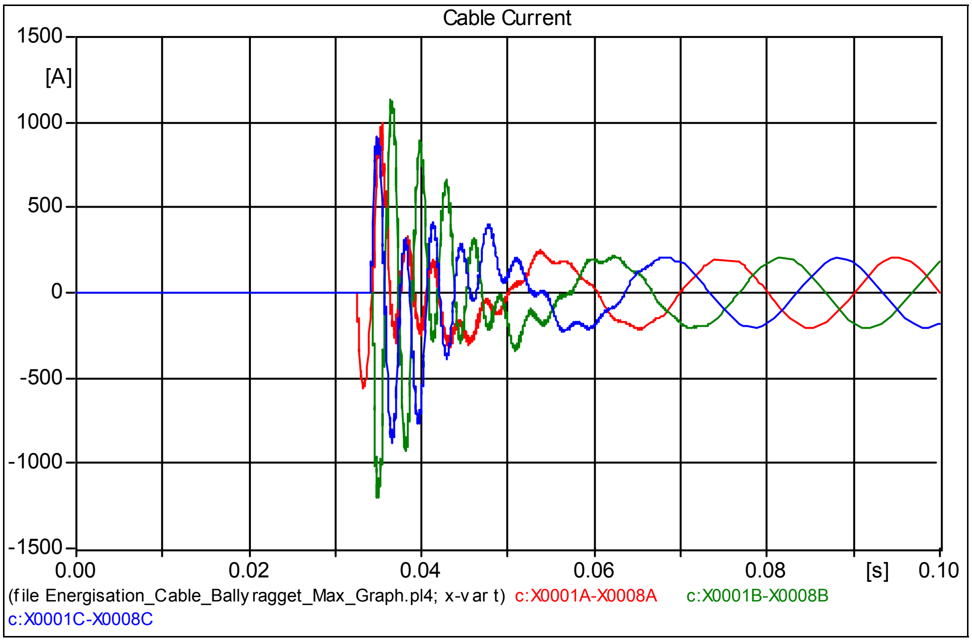


Figure 4.18: Cable Current for Cable Energisation from Ballyragget

Figure 4.19 shows the probability curve for peak overvoltages experienced at Ballyragget 110kV busbar. Table 4.10 shows the mean overvoltage, variance and standard deviation for overvoltages at Ballyragget. The average overvoltage which could be experienced at Ballyragget 110kV busbar for a cable energisation at Ballyragget is 123kV (Peak L-G).

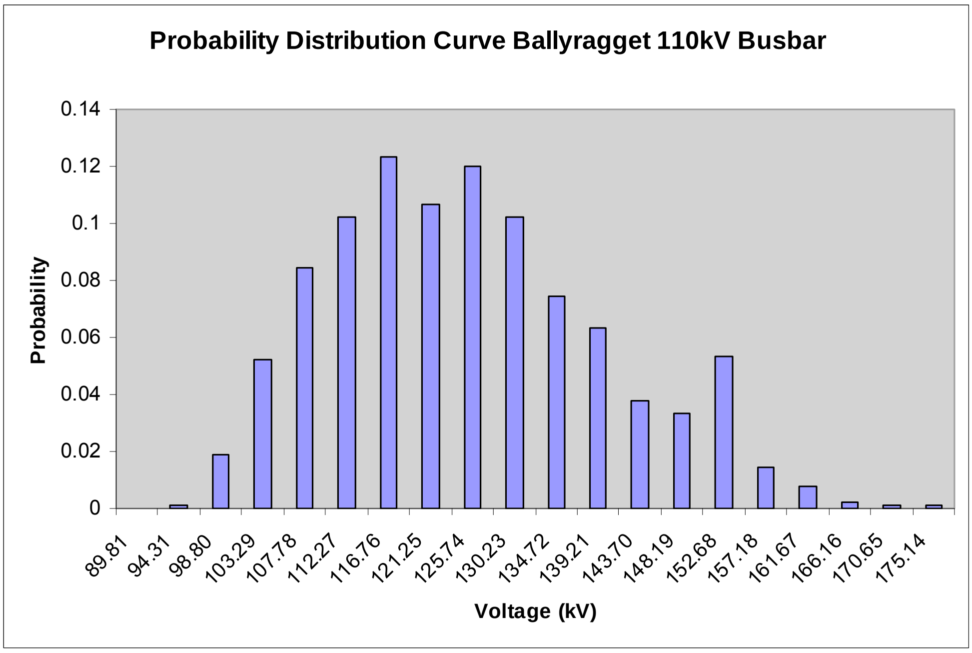


Figure 4.19: Probability Distribution Curve for Peak Overvoltages Experienced at Ballyragget 110kV Busbar

Mean Overvoltage	123kV
Variance	0.027
Standard Deviation	0.164

Table 4.10: Mean/Variance/Standard Deviation

Figure 4.20 shows the probability curve for peak overvoltages experienced at the Laois end of the cable. Table 4.11 shows the mean overvoltage, variance and standard deviation for overvoltages at the Laois end of the cable. The average overvoltage which could be experienced at the Laois end of the cable for a cable energisation at Ballyragget is 125kV (Peak L-G).

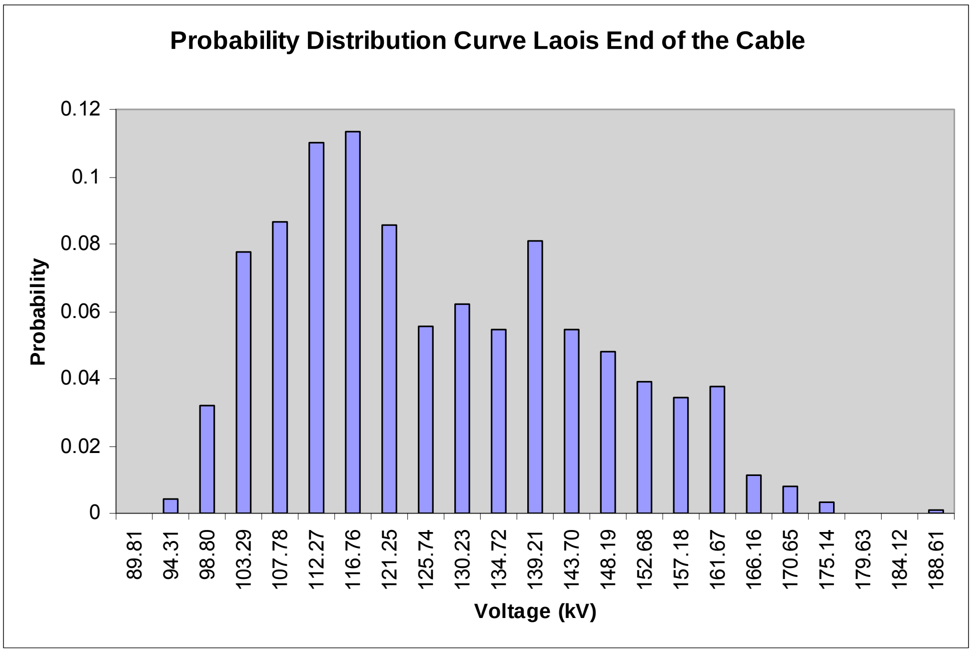


Figure 4.20: Probability Distribution Curve for Peak Overvoltages Experienced at Laois end of the Cable

Mean Overvoltage	125kV
Variance	0.0426
Standard Deviation	0.206

Table 4.11: Mean/Variance/Standard Deviation

Figure 4.21 shows the probability curve for peak overvoltages experienced at both Laois and Ballyragget for a cable energisation at Ballyragget. Table 4.12 shows the mean overvoltage, variance and standard deviation for the peak overvoltages. The average overvoltage which could be experienced for a charged cable switching at Ballyragget is 141kV (Peak L-G).

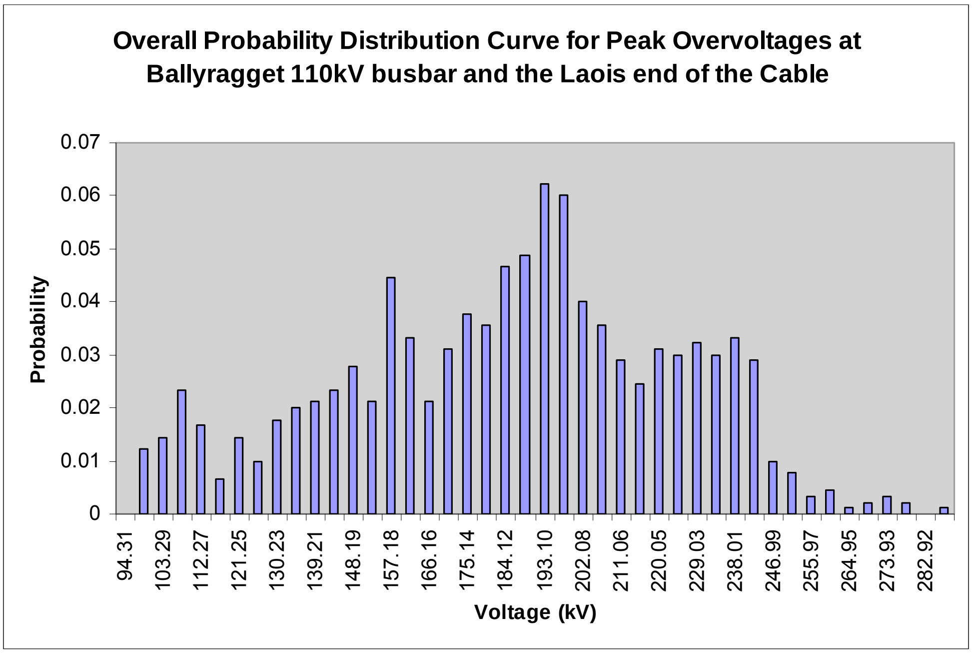


Figure 4.21: Probability Distribution Curve for Cable Energisation at Ballyragget

Mean Overvoltage	141.00kV
Variance	0.0275
Standard Deviation	0.166

Table 4.12: Mean/Variance/Standard Deviation

Table 4.13 below shows both the mean and maximum overvoltages that could be experienced at Laois 110kV busbar and at the Ballyragget end of the 110kV cable.

	Ballyragget Bus Voltage (kV)		**Laois End Cable Voltage (kV)**	
	L-L	**L-G**	**L-L**	**L-G**
Maximum Overvoltage	270	173	300	184
Mean Overvoltage	-	123	-	125

Table 4.13: Cable Energisation Ballyragget Results

4.3.2.2 Cable Energisation – Laois

At t=0s it is assumed that both the Laois and Ballyragget circuit breakers are open. At t = 40ms, the breaker at Laois is closed and the line is energised from Laois. Figures 4.22 and 4.23 show the worse case overvoltages which were obtained form the statistical study. It can be seen that significant voltage distortion exists for the first few cycles after the switching event. Also it can be observed that a significant energisation current is experienced with the energisation of the cable. A diagram of the model used for this case is shown in Appendix B Figure B4

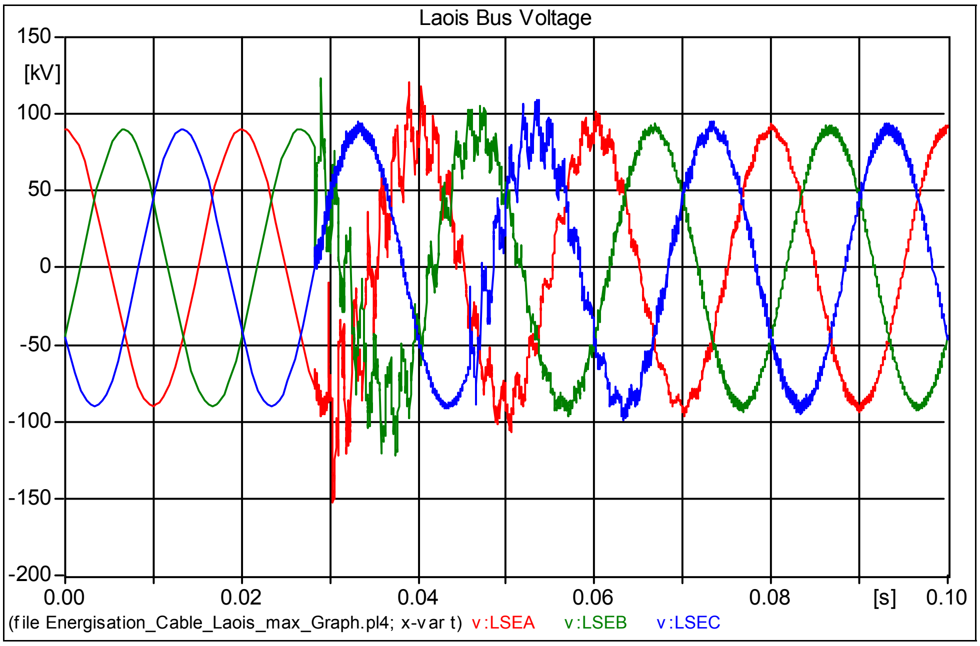


Figure 4.22: Laois Bus Voltage for Cable Energisation from Laois

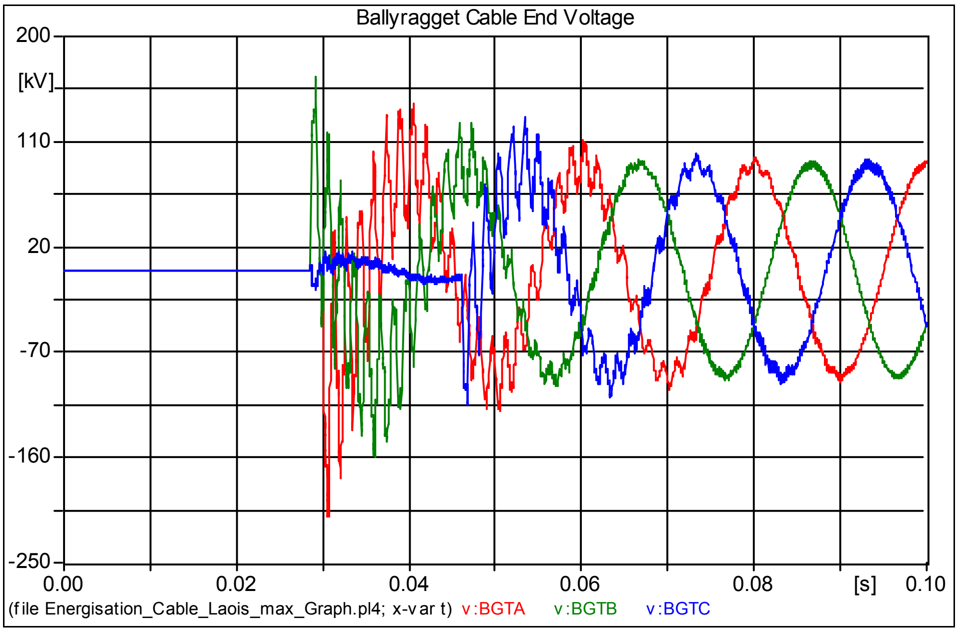


Figure 4.23: Ballyragget Cable End Voltage for Cable Energisation from Laois

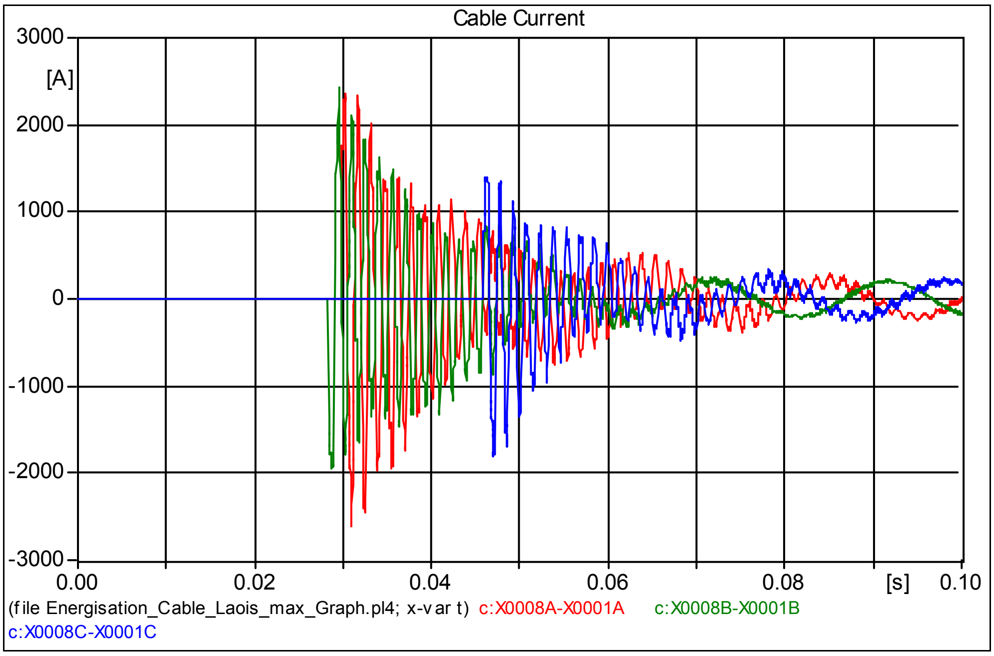


Figure 4.24: Cable Current for Cable Energisation from Laois

Figure 4.25 shows the probability curve for peak overvoltages experienced at Laois 110kV busbar. Table 4.14 shows the mean overvoltage, variance and standard deviation for overvoltages at Laois. The average overvoltage which could be experienced at Laois 110kV busbar for a cable energisation at Laois is 120kV (Peak L-G).

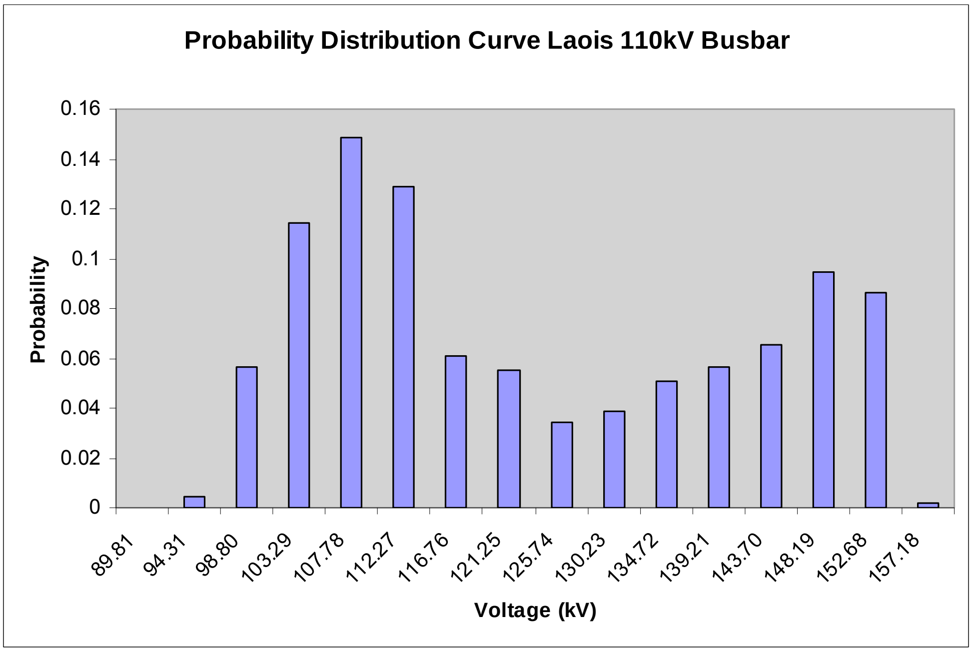


Figure 4.25: Probability Distribution Curve for Peak Overvoltages Experienced at Laois 110kV Busbar

Mean Overvoltage	120kV
Variance	0.0402
Standard Deviation	0.2006

Table 4.14: Mean/Variance/Standard Deviation

Figure 4.26 shows the probability curve for peak overvoltages experienced at the Laois end of the cable. Table 4.15 shows the mean overvoltage, variance and standard deviation for overvoltages at the Laois end of the cable. The average overvoltage which could be experienced at the Ballyragget end of the cable for a cable energisation at Laois is 150kV (Peak L-G).

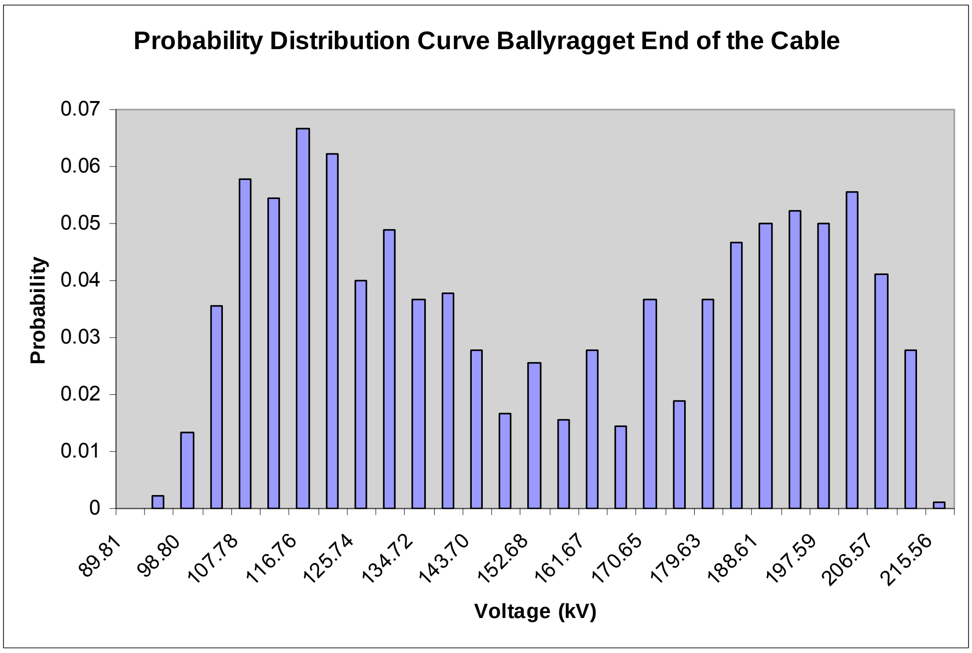


Figure 4.26: Probability Distribution Curve for Peak Overvoltages Experienced at Ballyragget end of the Cable

Mean Overvoltage	150kV
Variance	0.1519
Standard Deviation	0.3897

Table 4.15: Mean/Variance/Standard Deviation

Figure 4.27 shows the probability curve for peak overvoltages experienced at both Laois and Ballyragget for a cable energisation at Laois. Table 4.16 shows the mean overvoltage, variance and standard deviation for the peak overvoltages. The average overvoltage which could be experienced for a cable energisation at Laois is 182kV (Peak L-G).

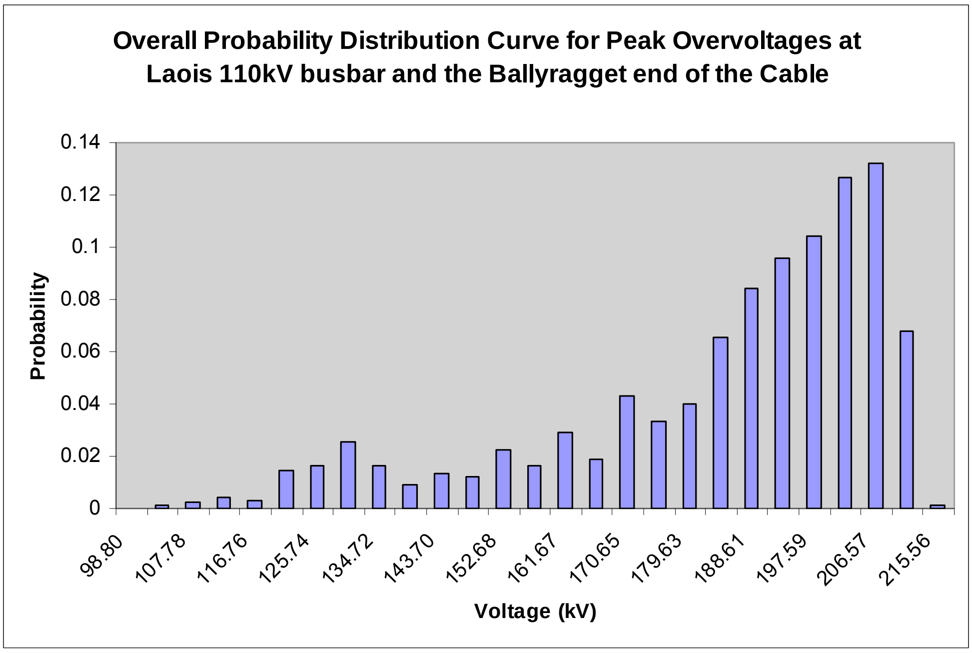


Figure 4.27: Probability Distribution Curve for Cable Energisation at Laois

Mean Overvoltage	182kV
Variance	0.0738
Standard Deviation	0.271

Table 4.16: Mean/Variance/Standard Deviation

Table 4.17 below shows both the mean and maximum overvoltages that could be experienced at Laois 110kV busbar and at the Ballyragget end of the 110kV cable.

	Laois Bus Voltage (kV)		**Ballyragget End Cable Voltage (kV)**	
	L-L	**L-G**	**L-L**	**L-G**
Maximum Overvoltage	215	153	328	211
Mean Overvoltage	-	120	-	150

Table 4.17: Cable Energisation Laois Results

4.3.2.3 Cable Energisation Summary

A number of points were noted in regards to the cable energisation study which are as follows:

- Energising the cable from Laois caused higher overvoltages compared with energising the cable from Ballyragget.
- The highest overvoltage measured was 328kV and was measured at the Ballyragget end of the cable for a cable energisation from Laois.

4.3.3 Cable De-Energisation

The de-energisation of the cable from either end did not cause any significant overvoltage therefore a number of cases where restriking on the circuit breakers was considered.

When de-energising a cable from near end, it appears as a shunt capacitance to ground from the far end, and a large transient recovery voltage (TRV) appears across the circuit breaker contacts. There may also be a high rate of rise of restrike voltage (RRRV). The RRRV or the TRV can cause an arc across the circuit breaker contact, known as restrike. Circuit breaker manufactures typically insist that their circuit breakers are restrike free. However, if the TRV or RRRV is high enough it will cause restrike. The occurrence of a restrike will depend on the TRV and RRRV and on and the nature of the circuit breaker itself.

As there is not sufficient data in order to access the probability of restrike occurring, a simplified case where restrike does occur has been considered. In order to simulate the effect of restrike, the contacts of the circuit breaker are assumed to arc when the voltage between them reaches 2 pu. These cases are for the purposes of illustration only

4.3.3.1 Cable De-Energisation – (no restrike)

At t=0s it is assumed that the circuit breaker at the Laois end of the cable has already opened and that the circuit breaker at Ballyragget is waiting for zero crossings of the current. Voltage profiles are shown in Figures 4.28 – 4.31.

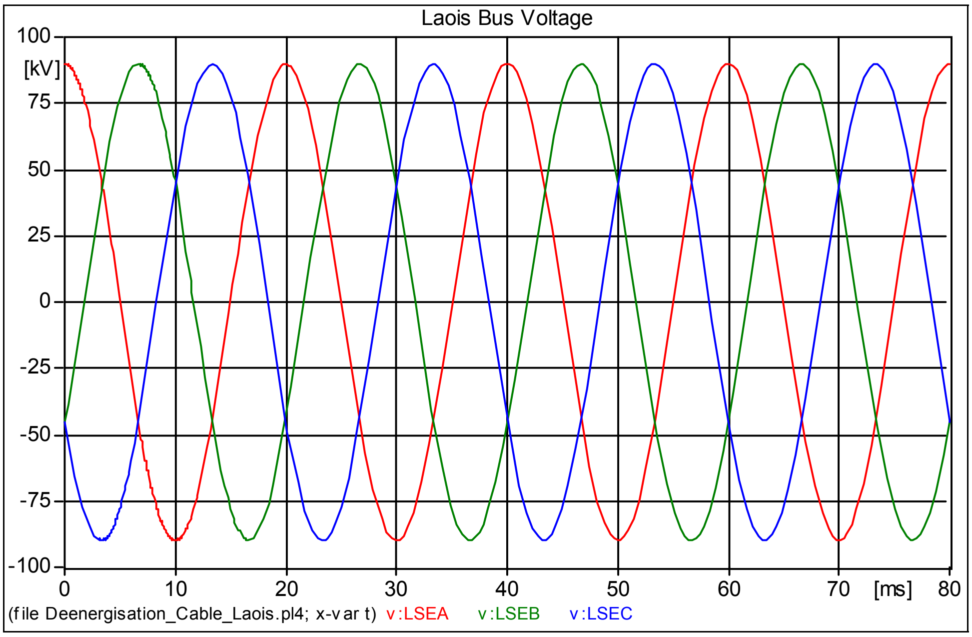


Figure 4.28: Laois Bus Voltage (No-Restrike)

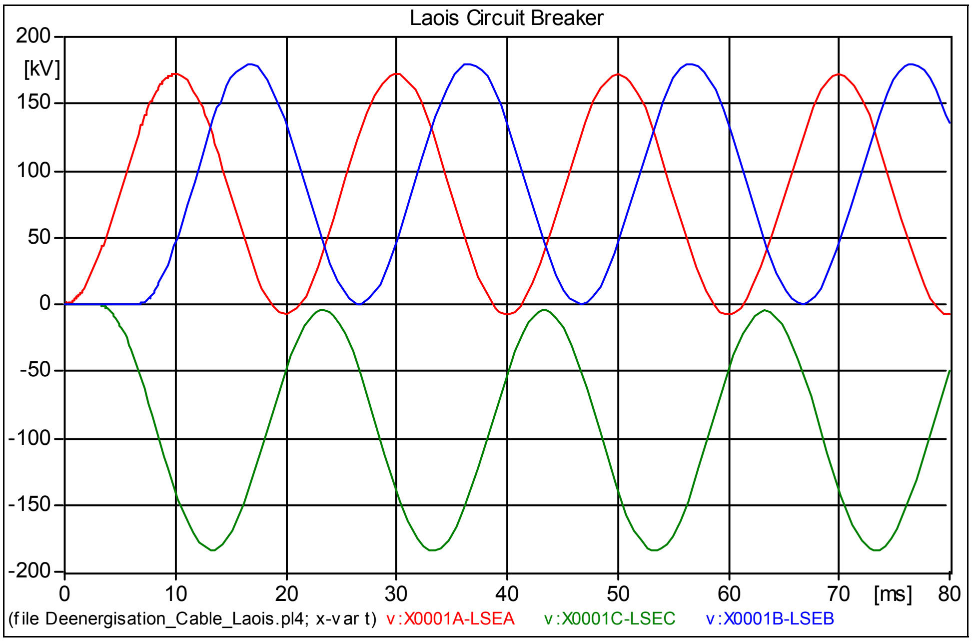


Figure 4.29: Laois Circuit Breaker (No-Restrike)

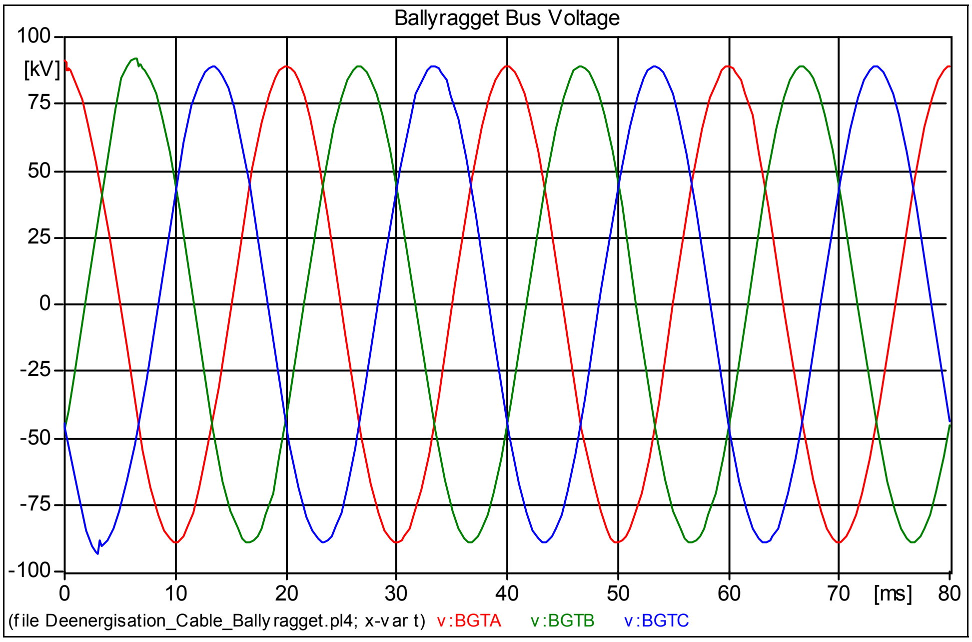


Figure 4.30: Ballyragget Bus Voltage (No-Restrike)

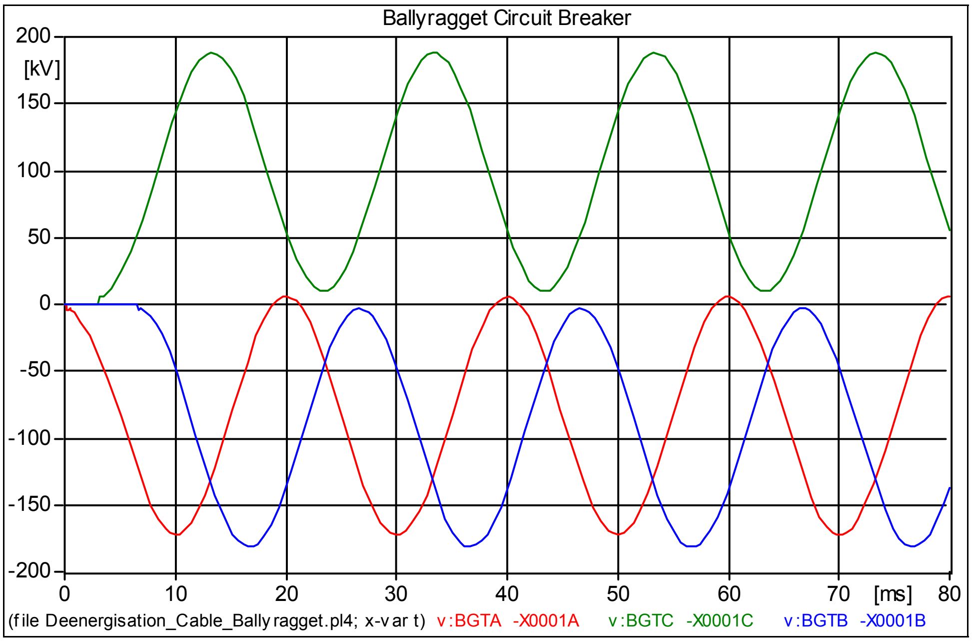


Figure 4.31: Ballyragget Bus Voltage (No-Restrike)

Table 4.18 below shows the overvoltages that could be experienced at Laois and Ballyragget.

Laois End Cable Voltage (kV)		**Ballyragget Bus Voltage (kV)**	
L-L	**L-G**	**L-L**	**L-G**
191	98	184	93

Table 4.18: Cable De-Energisation (no-restrike)

4.3.3.2 Cable De-Energisation – Ballyragget (restrike)

At t=0s it is assumed that the circuit breaker at the Laois end of the cable has already opened and that the circuit breaker at Ballyragget is waiting for zero crossings of the current. The cable remains charged and a TRV builds up across the circuit breaker contacts (Figure 4.34). For the purposes of this study it is assumed that restrike occurs at a voltage across the breaker of 2pu. This restrike causes large voltage transients at Ballyragget 110kV substation (Figure 4.33). The circuit breaker is opened again at a later zero crossings. It is assumed that no further restriking occurs. A diagram of the model used for this case is shown in Appendix B Figure B5.

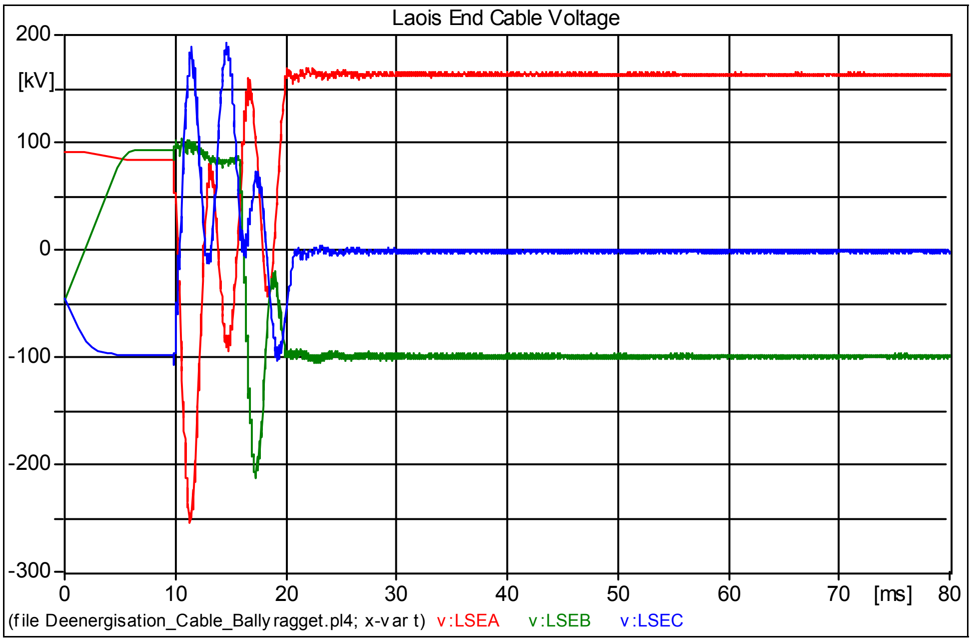


Figure 4.32: Laois End Cable Voltage for Cable De-Energisation from Ballyragget

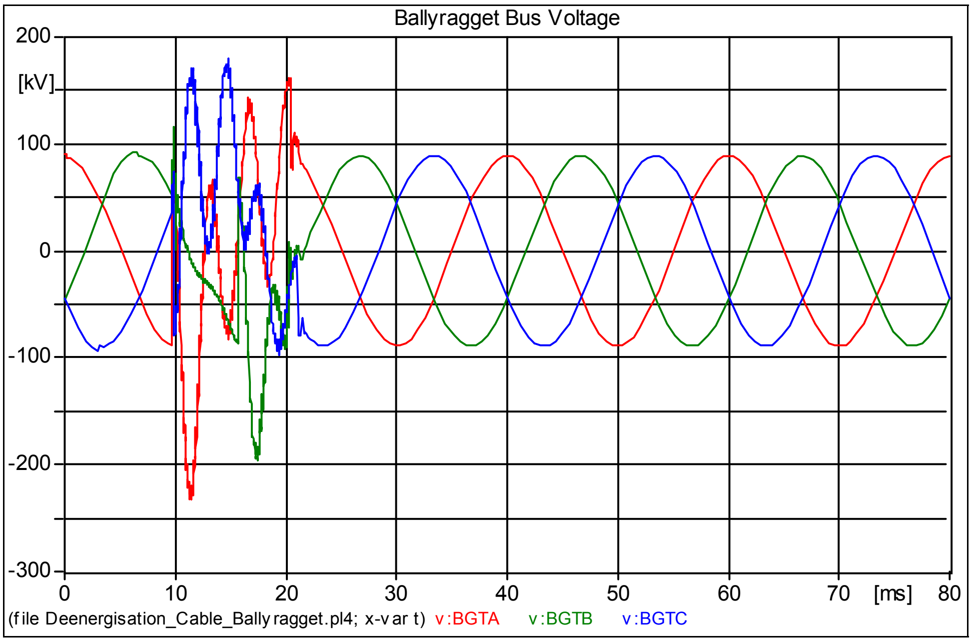


Figure 4.33: Ballyragget Bus Voltage for Cable De-Energisation from Ballyragget

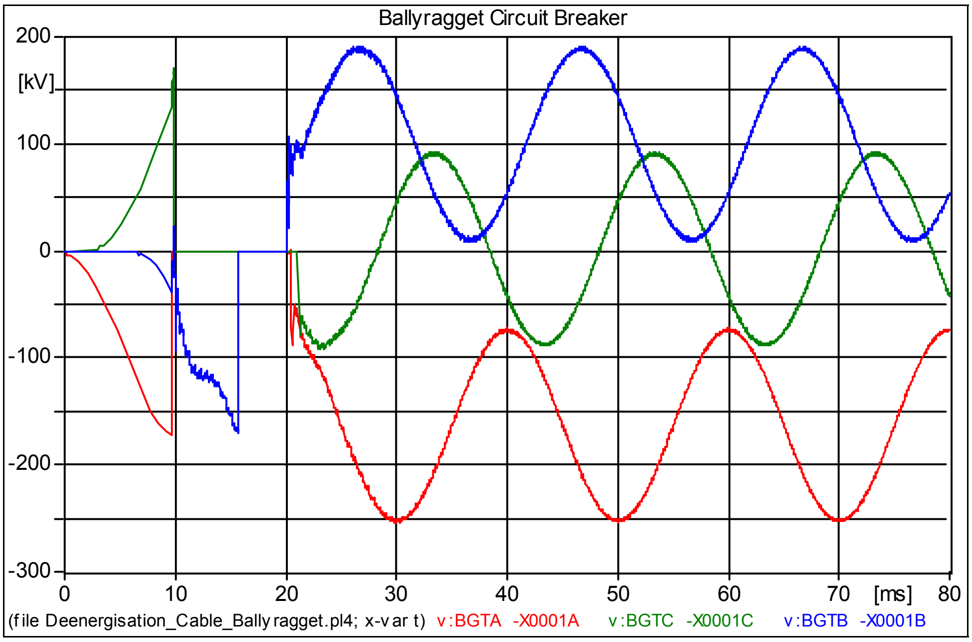


Figure 4.34: Ballyragget Circuit Breaker Voltages for Cable De-Energisation from Ballyragget

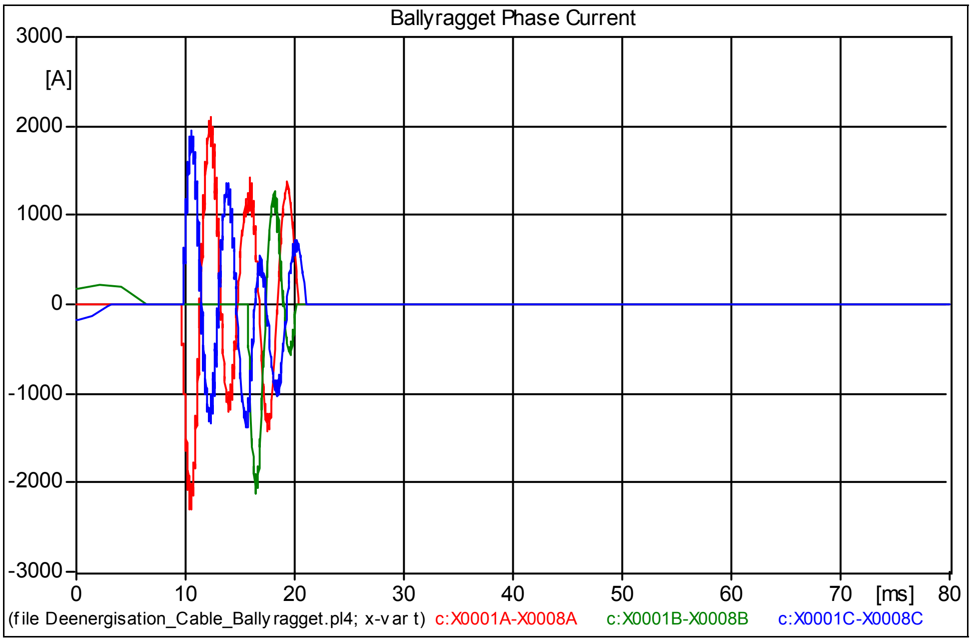


Figure 4.35: Ballyragget Phase Current for Cable De-Energisation from Ballyragget

Table 4.19 below shows the overvoltages that could be experienced at Laois and Ballyragget.

Laois End Cable Voltage (kV)		**Ballyragget Bus Voltage (kV)**	
L-L	**L-G**	**L-L**	**L-G**
435	254	400	233

Table 4.19: Cable De-Energisation from Ballyragget

4.3.3.3 Cable De-Energisation – Laois (restrike)

At t=0s it is assumed that the circuit breaker at the Ballyragget end of the cable has already opened and that the circuit breaker at Laois is waiting for zero crossings of the current. The cable remains charged and a TRV builds up across the circuit breaker contacts (Figure 4.38). For the purposes of this study it is assumed that restrike occurs at a voltage across the breaker of 2pu. This causes large voltage transients at Laois 400kV substation (Figure 4.37). The circuit breaker is opened again at a later zero crossings. Again, it is assumed that no further restriking occurs. It can be observed that the voltage distortions are significantly worse for de-energising the cable (with restrike) from Laois 400kV substation. A diagram of the model used for this case is shown in Appendix B Figure B6.

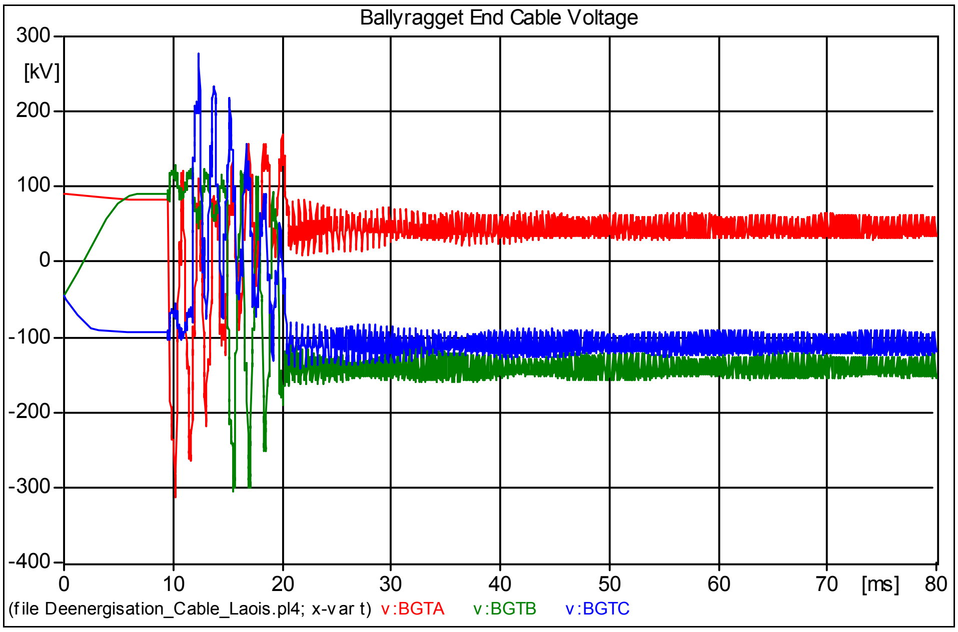


Figure 4.36: Ballyragget End Cable Voltage for Cable De-Energisation from Laois

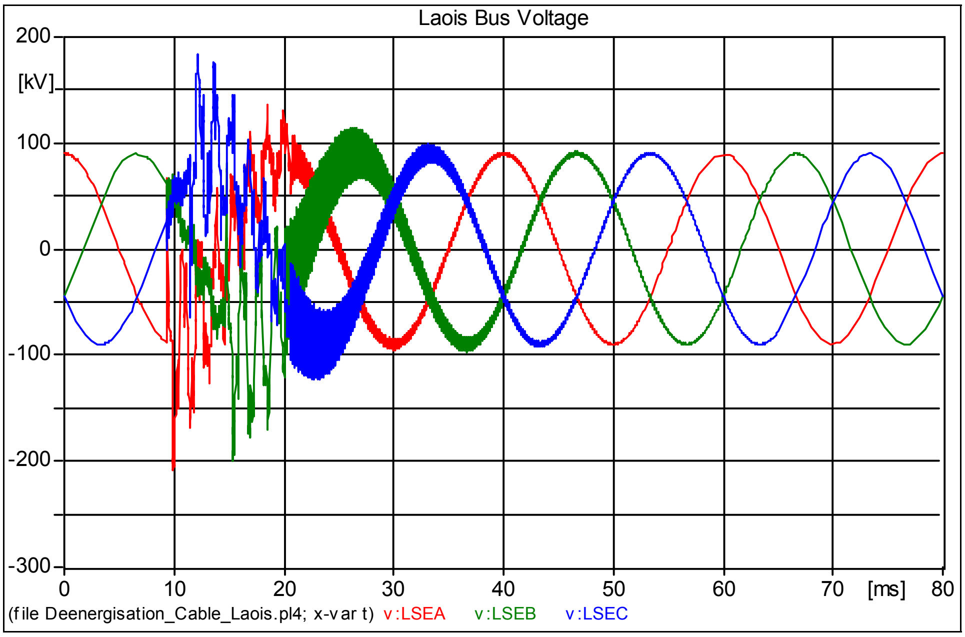


Figure 4.37: Laois Bus Voltage for Cable De-Energisation from Laois

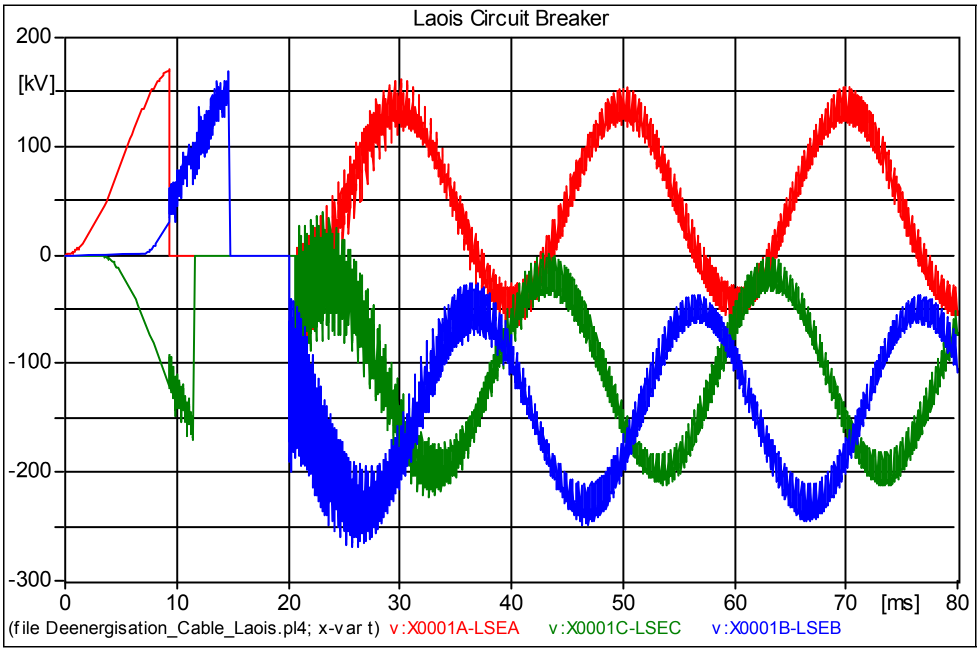


Figure 4.38: Laois Circuit Breaker Voltages for Cable De-Energisation from Laois

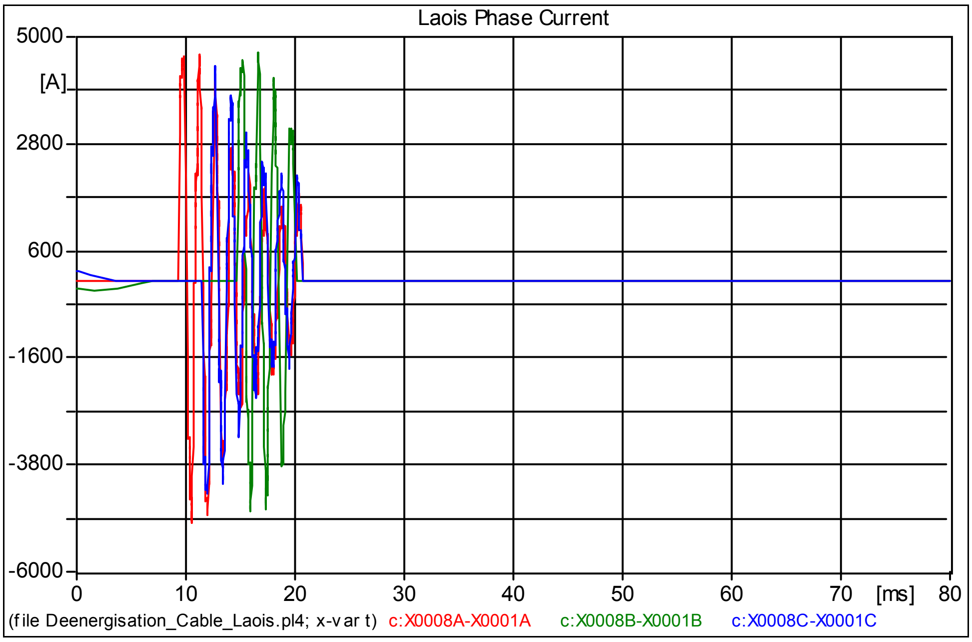


Figure 4.39: Laois Phase Current for Cable De-Energisation from Laois

Table 4.20 below shows the overvoltages that could be experienced at Laois and Ballyragget.

Laois Bus Voltage (kV)		**Ballyragget End Cable Voltage (kV)**	
L-L	**L-G**	**L-L**	**L-G**
324	208	440	315

Table 4.20: Cable De-Energisation from Laois

4.3.3.4 Cable De-Energisation Summary

A number of points were noted in regards to the cable de-energisation study which are as follows:

- De-energising the cable from Laois caused higher overvoltages compared with de-energising the cable from Ballyragget.
- It should be noted that the voltage distortions for de-energisation from Laois are primarily due to restrike. If the circuit breaker is restrike free then there should be no problems with de-energising the cable from Laois. (see Fig 4.28 & 4.30)

4.3.4 Cable Single Line to Ground Faults

When a single line to ground fault occurs on a cable, it is necessary to open the circuit breakers at both ends of the cable. Primary protection for cables is provided by unit protection with impedance protection providing backup to the unit protection.

For this study, the following assumptions were made:

- Fault Inception: 10ms
- Time of opening of Local Breaker: 70ms
- Time of opening of Remote Breaker Opening Time: 90ms

The effects of restrike were also examined as part of this study. When switching a cable from near end, it appears as a shunt capacitance to ground from the far end, and a large transient recovery voltage (TRV) appears across the circuit breaker contacts. There may also be a high rate of rise of restrike voltage (RRRV). The RRRV or the TRV can cause an arc across the circuit breaker contact, known as restrike. Circuit breaker manufactures typically insist that their circuit breakers are restrike free. However, if the TRV or RRRV is high enough it will cause restrike. The occurrence of a restrike will depend on the TRV and RRRV and on and the nature of the circuit breaker itself.

As there is not sufficient data in order to access the probability of restrike occurring, a simplified case where restrike does occur has been considered. In order to simulate the effect of restrike, the contacts of the circuit breaker are assumed to arc when the voltage between them reaches 2 pu. These cases are for the purposes of illustration only

4.3.4.1 Cable Single Line to Ground Fault – Ballyragget

At t=0s it assumed that the transmission system is healthy and the bus voltages at Ballyragget and Laois are within the operating limits of the system. At t=10ms it is then assumed that a single line to ground fault occurs on the Ballyragget end of the cable. At t=70ms the circuit breaker at Ballyragget opens. At t=90ms the breaker at Laois opens and the fault on the cable is cleared. It can be observed from figure 4.41 that significant voltage distortion occurs at the 110kV busbar at Laois compared with the distortion voltage distortion observed at Ballyragget 110kV substation (figure 4.40). A diagram of the model used for this case is shown in Appendix B Figure B7

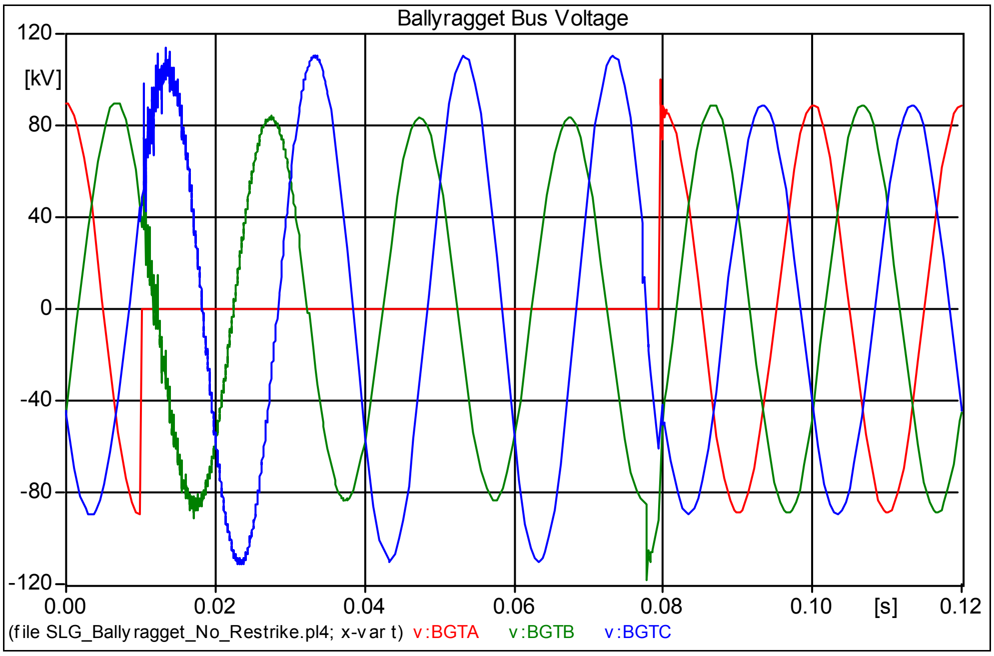


Figure 4.40: Ballyragget Bus Voltage for SLG at Ballyragget Cable End

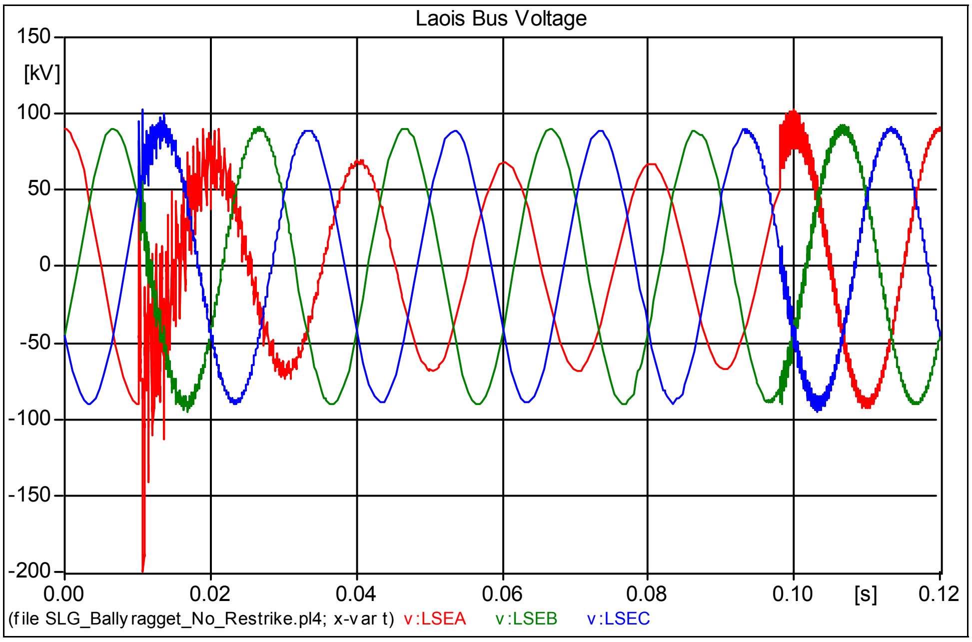


Figure 4.41: Laois Bus Voltage for SLG at Ballyragget Cable End

Table 4.21 below shows the overvoltages that could be experienced at Laois and Ballyragget.

Laois Bus Voltage (kV)		**Ballyragget Bus Voltage (kV)**	
L-L	**L-G**	**L-L**	**L-G**
280	200	167	118

Table 4.21: Single Line to Ground Fault at Ballyragget (No - Restrike)

4.3.4.2 Cable Single Line to Ground Fault – Laois

At t=0s it assumed that the transmission system is healthy and the bus voltages at Ballyragget and Laois are within the operating limits of the system. At t=10ms it is then assumed that a single line to ground fault occurs on the Laois end of the cable. At t=70ms the circuit breaker at Laois opens. At t=90ms the breaker at Ballyragget opens and the fault on the cable is cleared. It can be observed from figure 4.43 that significant voltage distortion occurs at the 110kV busbar at Laois compared with the distortion voltage distortion observed at Ballyragget 110kV substation (figure 4.42). A diagram of the model used for this case is shown in Appendix B Figure B9

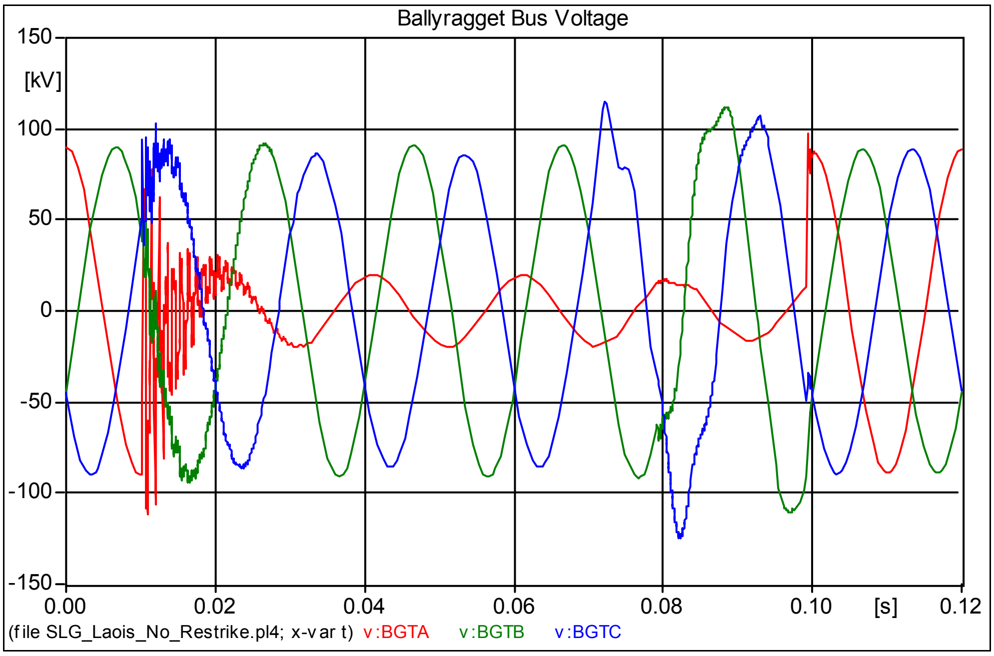


Figure 4.42: Ballyragget Bus Voltage for SLG at Laois Cable End

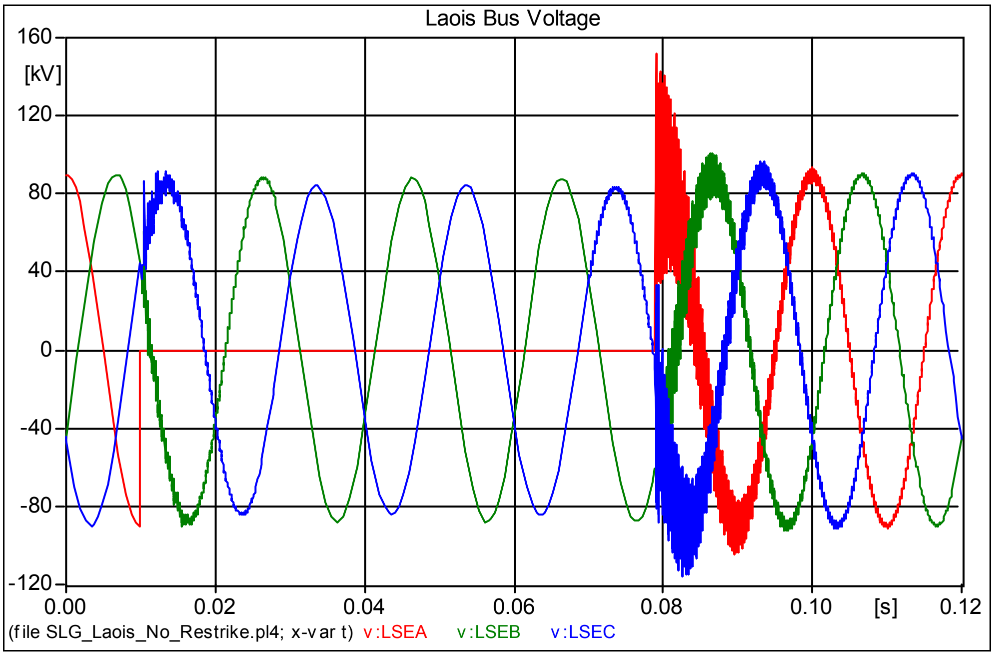


Figure 4.43: Laois Bus Voltage for SLG at Laois Cable End

Table 4.22 below shows the overvoltages that could be experienced at Laois and Ballyragget.

Laois Bus Voltage (kV)		**Ballyragget Bus Voltage (kV)**	
L-L	**L-G**	**L-L**	**L-G**
215	150	193	125

Table 4.22: Single Line to Ground Fault at Laois (No-Restrike)

4.3.4.3 Cable Single Line to Ground Fault – Ballyragget (Restrike)

At t=0s it assumed that the transmission system is healthy and the bus voltages at Ballyragget and Laois are within the operating limits of the system. At t=10ms it is then assumed that a single line to ground fault occurs on the Ballyragget end of the cable. At t=70ms the circuit breaker at Ballyragget opens. At t=90ms the breaker at Laois opens. For the purposes of this study it is assumed that restrike occurs at a voltage across the breaker of 2pu. The restrike results in large voltage transients at Laois 400kV substation (Figure 4.47) which are similar in nature to the transients observed for de-energisation. It is then assumed that the breaker re-opens at a later zero crossing and no further restriking occurs. A diagram of the model used for this case is shown in Appendix B Figure B8.

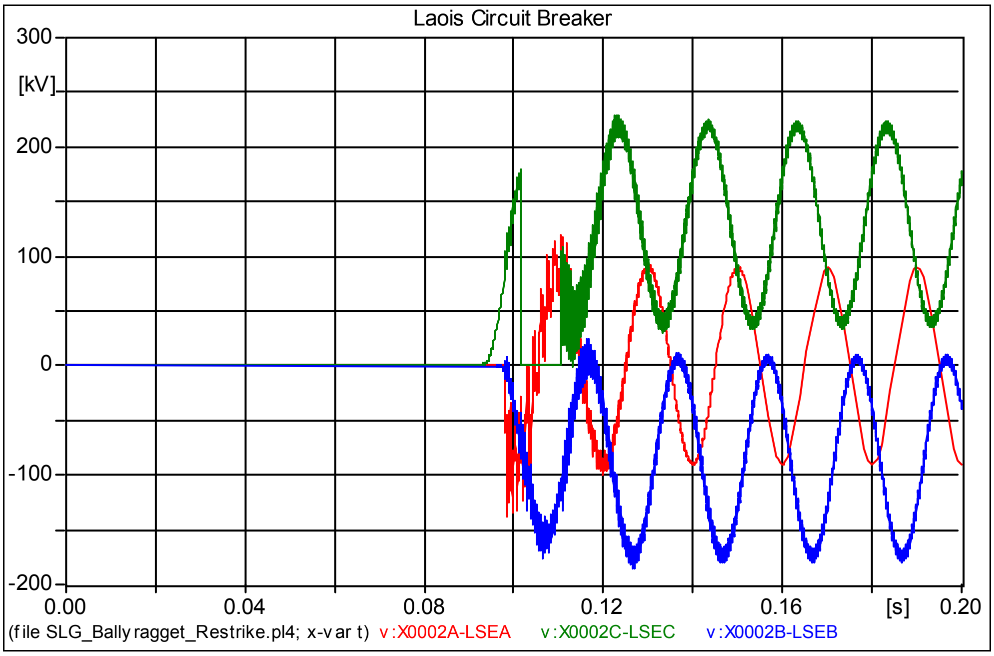


Figure 4.44: Laois Circuit Breaker for SLG at Ballyragget Cable End (Restrike)

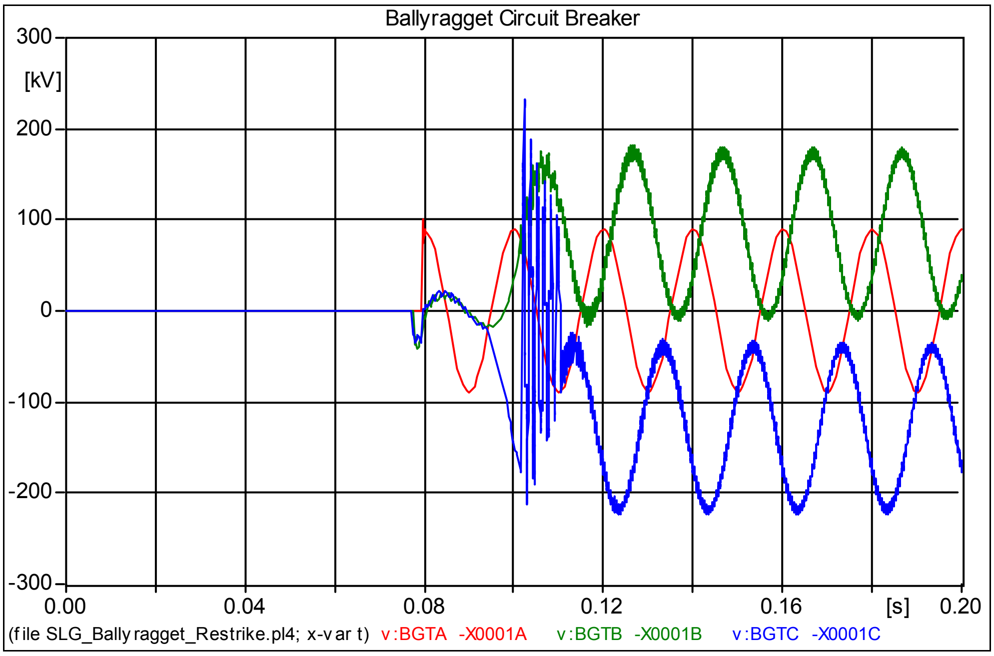


Figure 4.45: Ballyragget Circuit Breaker for SLG at Ballyragget Cable End (Restrike)

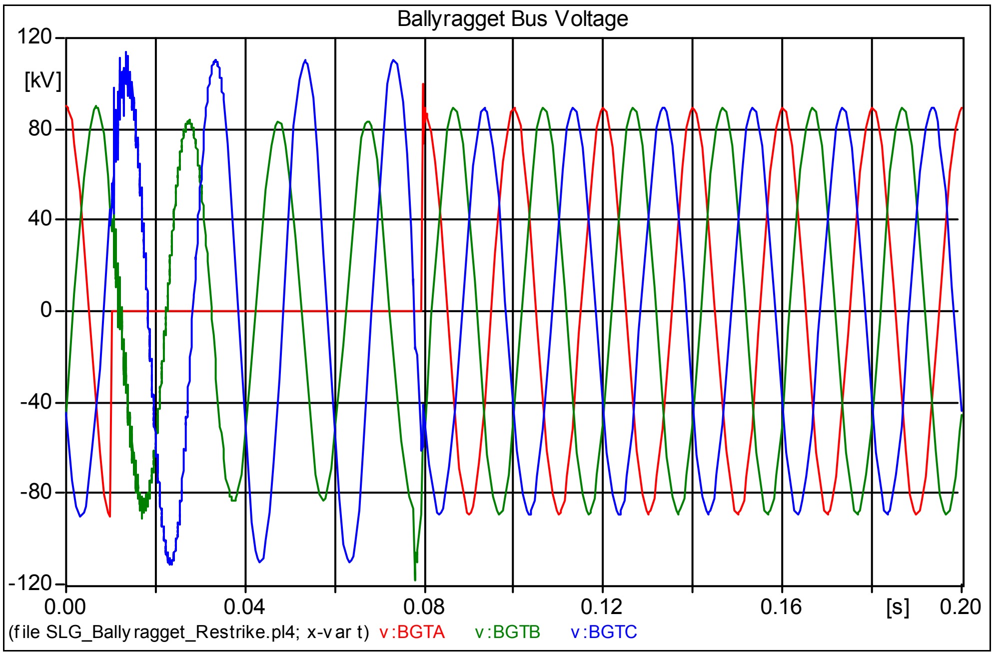


Figure 4.46: Ballyragget Bus Voltage for SLG at Ballyragget Cable End (Restrike)

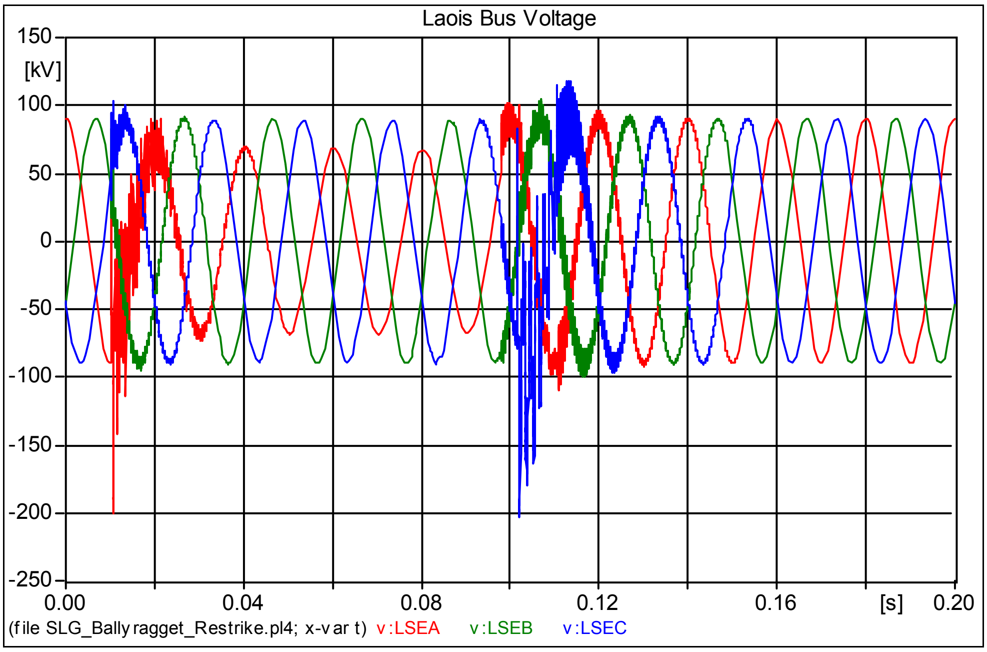


Figure 4.47: Laois Bus Voltage for SLG at Ballyragget Cable End (Restrike)

Table 4.23 below shows the overvoltages that could be experienced at Laois and Ballyragget.

Laois Bus Voltage (kV)		**Ballyragget Bus Voltage (kV)**	
L-L	**L-G**	**L-L**	**L-G**
300	202	167	118

Table 4.23: Single Line to Ground Fault at Ballyragget (Restrike)

4.3.4.4 Cable Single Line to Ground Fault – Laois (Restrike)

At t=0s it assumed that the transmission system is healthy and the bus voltages at Ballyragget and Laois are within the operating limits of the system. At t=10ms it is then assumed that a single line to ground fault occurs on the Laois end of the cable. At t=70ms the circuit breaker at Laois opens. At t=90ms the breaker at Ballyragget opens. For the purposes of this study it is assumed that restrike occurs at a voltage across the breaker of 2pu. The restrike results in large voltage transients at Ballyragget 110kV substation (Figure 4.49) which are similar in nature to the transients observed for de-energisation. It is then assumed that the breaker re-opens at a later zero crossing and no further restriking occurs. A diagram of the model used for this case is shown in Appendix B Figure B10.

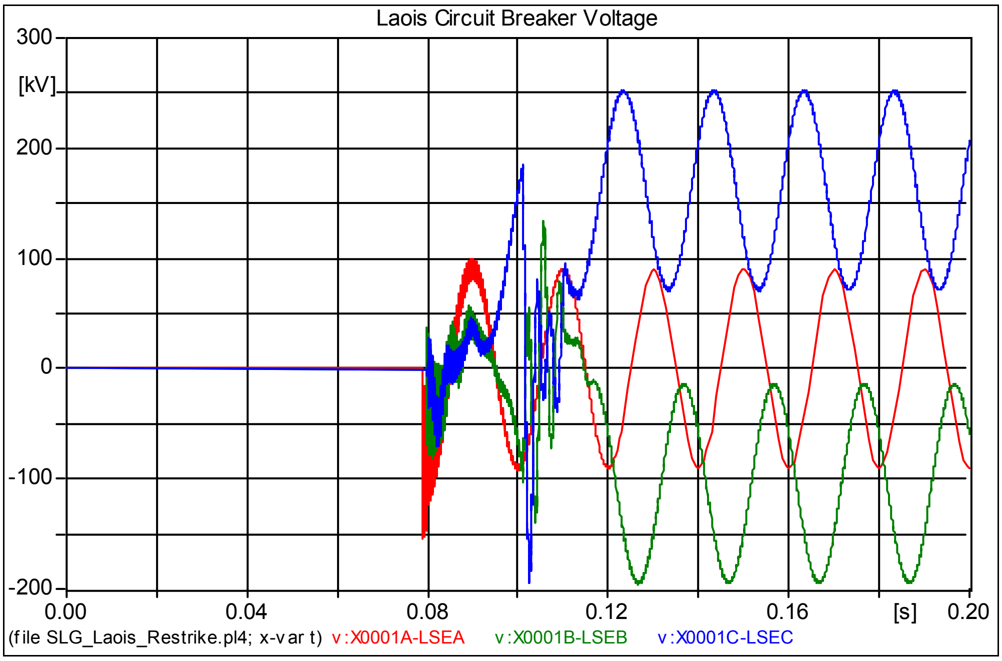


Figure 4.48: Laois Circuit Breaker for SLG at Laois Cable End (Restrike)

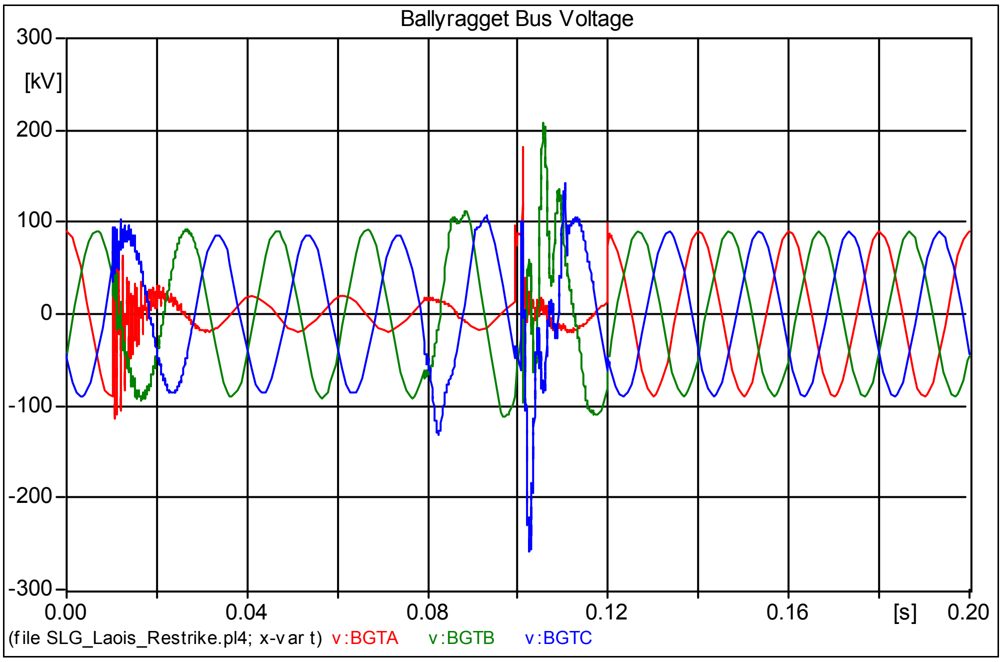


Figure 4.49: Ballyragget Bus Voltage for SLG at Laois Cable End (Restrike)

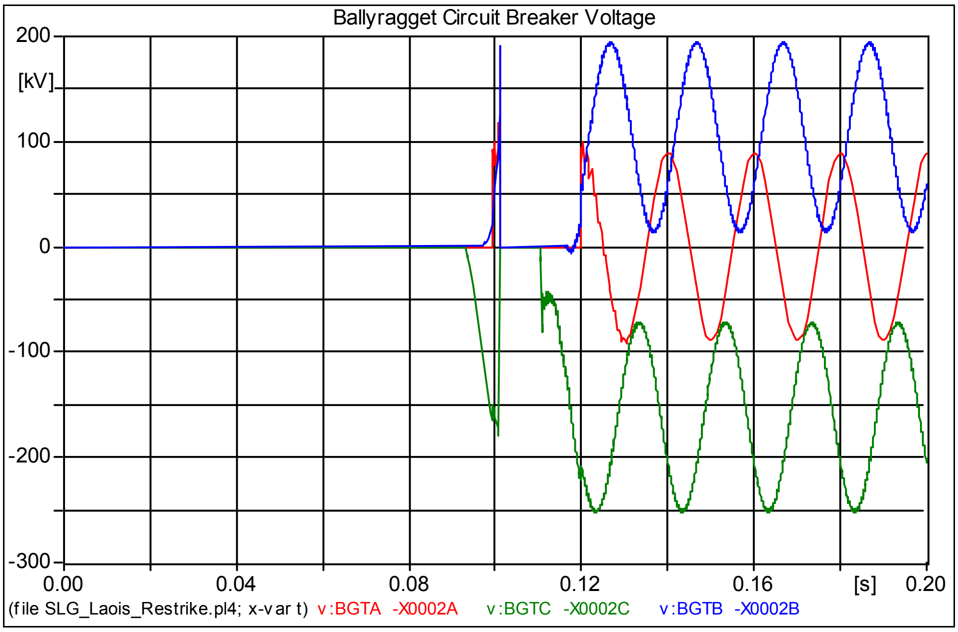


Figure 4.50: Ballyragget Circuit Breaker for SLG at Laois Cable End (Restrike)

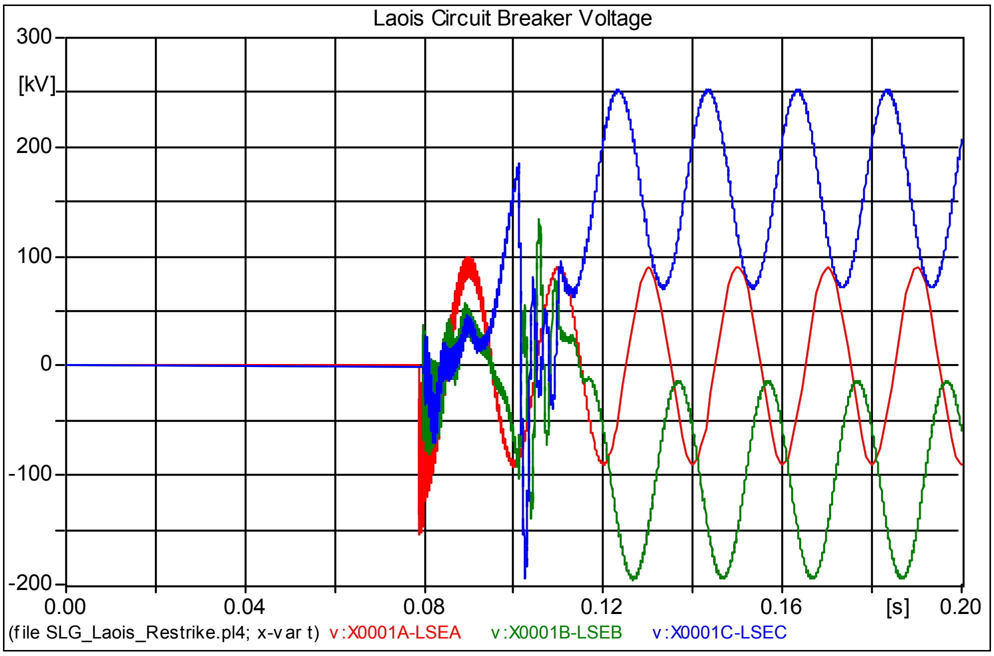


Figure 4.51: Laois Bus Voltage for SLG at Laois Cable End (Restrike)

Table 4.24 below shows the overvoltages that could be experienced at Laois and Ballyragget.

Laois Bus Voltage (kV)		**Ballyragget Bus Voltage (kV)**	
L-L	**L-G**	**L-L**	**L-G**
217	154	310	260

Table 4.24: Single Line to Ground Fault at Laois (Restrike)

4.3.4.5 Single Line to Ground Fault Summary

A number of points were noted in regards to the cable single line to ground fault study which are as follows:

- Single Line to Ground Faults at Laois and Ballyragget ends of the cable were observed to be benign events when no restriking occurred.
- Single Line to Ground Faults at either the Laois or Ballyragget ends of the cable resulted in significant voltage distortions at the Laois 110kV busbar.
- Restriking resulted in significant voltage distortions at both the Laois and Ballyragget 110kV busbars. However, the voltage distortions were significantly worse for restriking of the Laois 110kV circuit breaker.

4.4 Ballyragget – Laois 110kV Overhead Line Study

4.4.1 Overhead Line Energisation

The OHL can be energised from either Ballyragget or Laois. The OHL was energised from Laois and Ballyragget and the resultant voltages and currents were observed.

In order to find the maximum overvoltages that could be experienced at Laois and Ballyragget, a statistical study was carried out. The assumptions for the statistical study are listed below:

Statistical Study Assumptions:

- 900 Simulations
- Time of Breaker Closing: 40ms
- Standard Deviation for Closing Breaker: 10ms

4.4.2 Energisation – Ballyragget

At t=0s it is assumed that both the Laois and Ballyragget circuit breakers are open. At t = 40ms, the breaker at Ballyragget is closed and the line is energised from Ballyragget. Figures 4.52 and 4.53 show the worse case overvoltages which were obtained form the statistical study. The first observation made is that the voltage distortions were lower than the voltage distortions observed for the charged switching event which is to be expected. It can be seen from figures 4.52 and 4.53 that voltage distortion exists for the first cycle after the switching event. However, the distortions are less severe than those observed for the cable energisation. A diagram of the model used for this case is shown in Appendix C Figure C1.

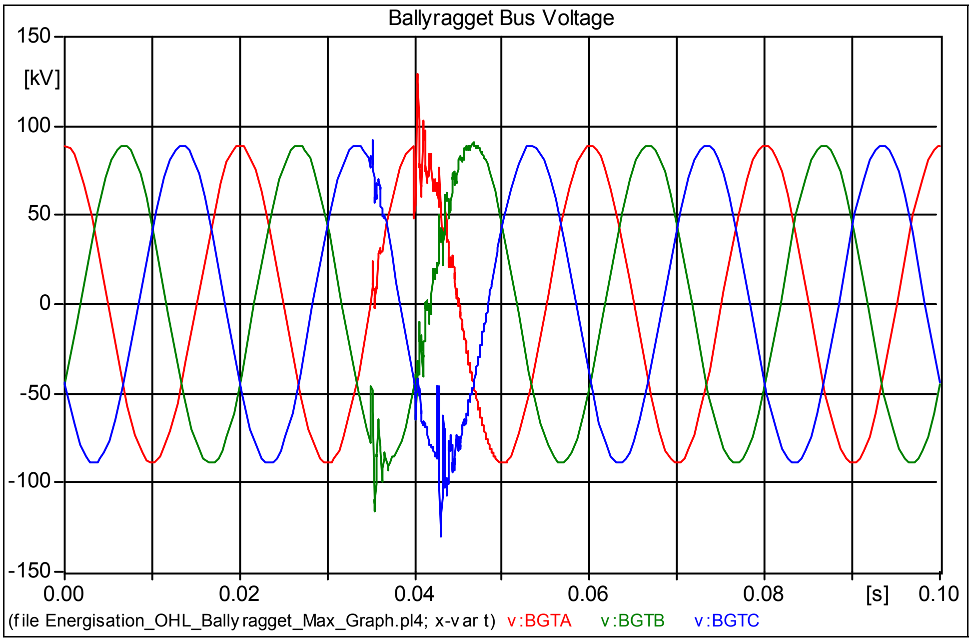


Figure 4.52: Ballyragget Bus Voltage for OHL Energisation from Ballyragget

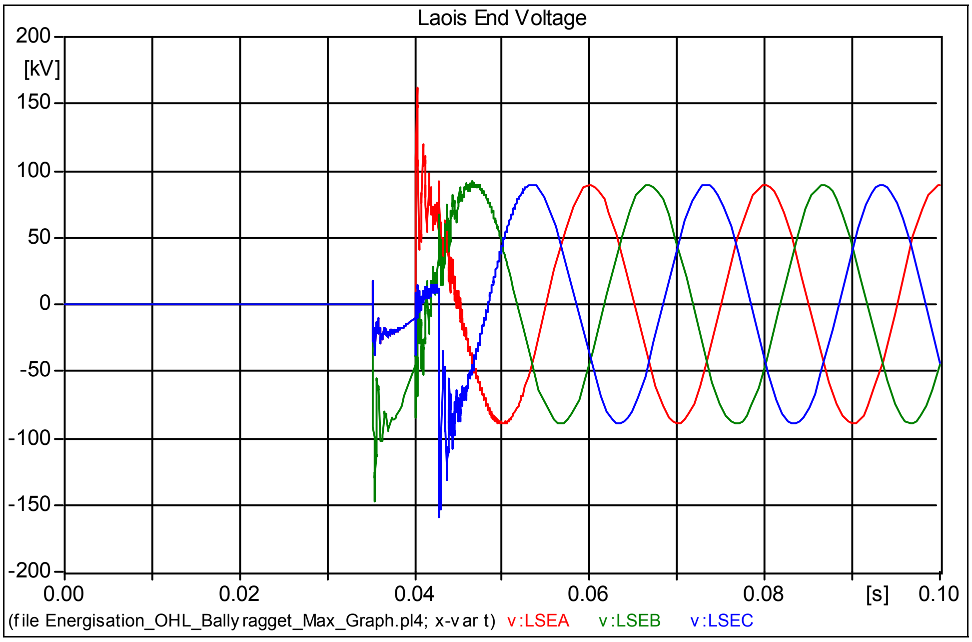


Figure 4.53: Laois End Voltage for OHL Energisation from Ballyragget

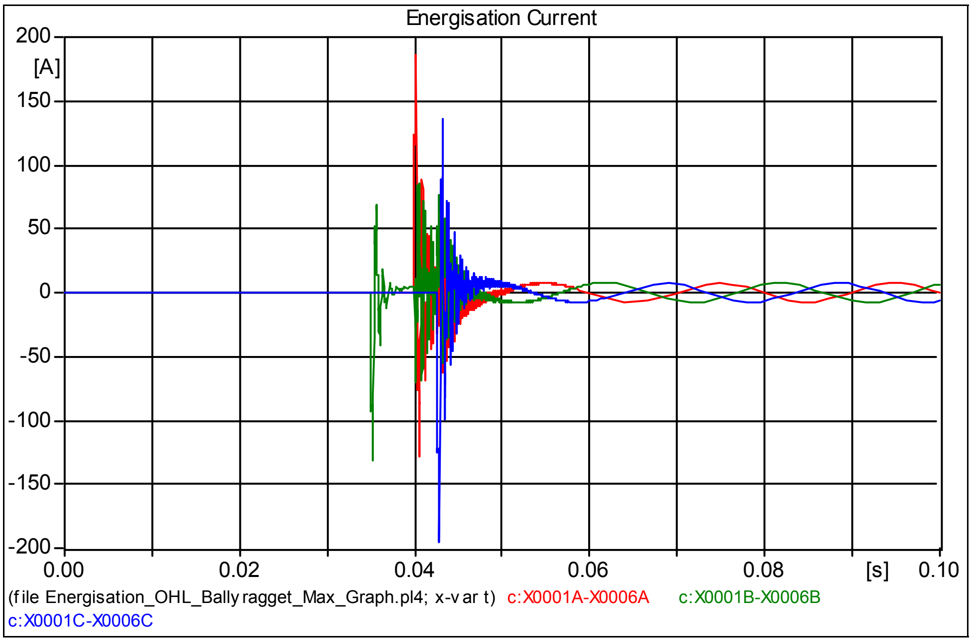


Figure 4.54: Energisation Current for OHL Energisation from Ballyragget

Figure 4.55 shows the probability curve for peak overvoltages experienced at Ballyragget 110kV busbar. Table 4.25 shows the mean overvoltage, variance and standard deviation for overvoltages at Ballyragget. The average overvoltage which could be experienced at Ballyragget 110kV busbar for a OHL energisation at Ballyragget is 105kV (Peak L-G).

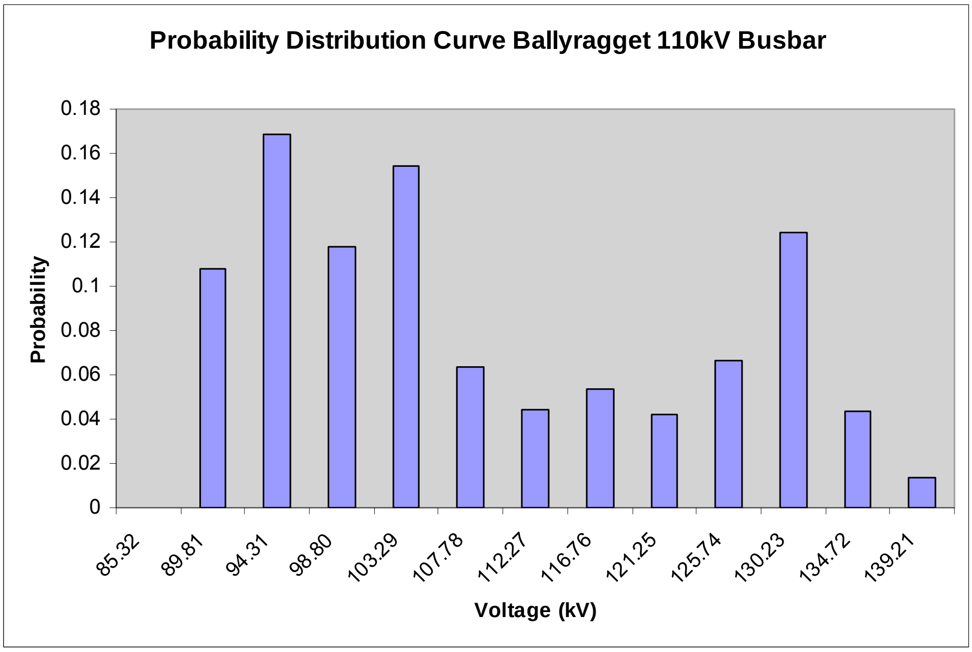


Figure 4.55: Probability Distribution Curve for Peak Overvoltages Experienced at Ballyragget 110kV Busbar

Mean Overvoltage	105kV
Variance	0.0272
Standard Deviation	0.1648

Table 4.25: Mean/Variance/Standard Deviation

Figure 4.56 shows the probability curve for peak overvoltages experienced at the Laois end of the OHL. Table 4.26 shows the mean overvoltage, variance and standard deviation for overvoltages at the Laois end of the OHL. The average overvoltage which could be experienced at the Laois end of the OHL for a OHL energisation at Ballyragget is 126kV (Peak L-G).

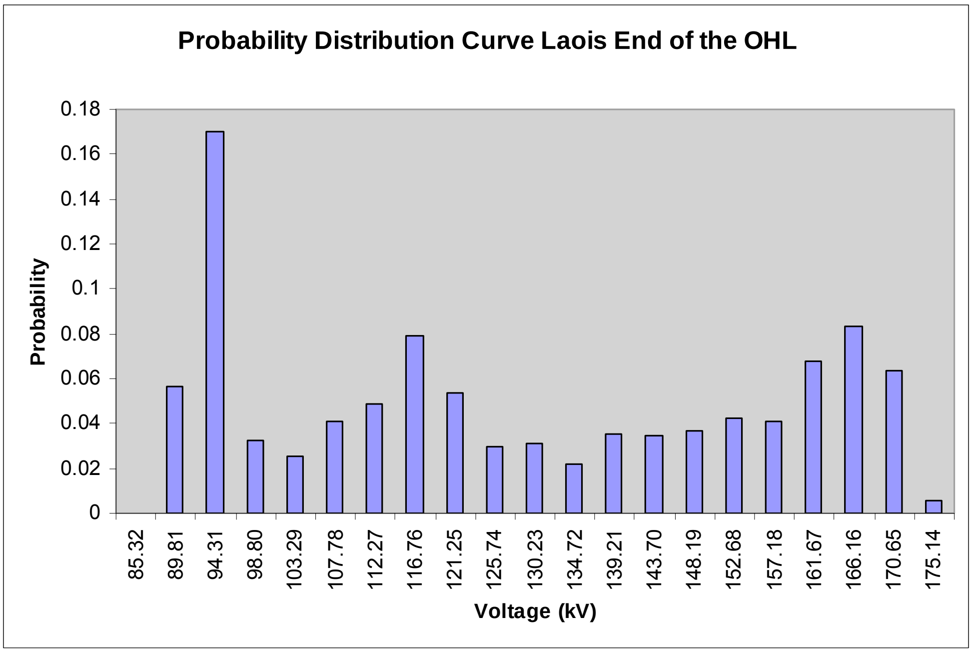


Figure 4.56: Probability Distribution Curve for Peak Overvoltages Experienced at Laois end of the OHL

Mean Overvoltage	126kV
Variance	0.0967
Standard Deviation	0.310

Table 4.26: Mean/Variance/Standard Deviation

Figure 4.57 shows the probability curve for peak overvoltages experienced at both Laois and Ballyragget for a OHL energisation at Ballyragget. Table 4.27 shows the mean overvoltage, variance and standard deviation for the peak overvoltages. The average overvoltage which could be experienced for a OHL energisation at Ballyragget is 141kV (Peak L-G).

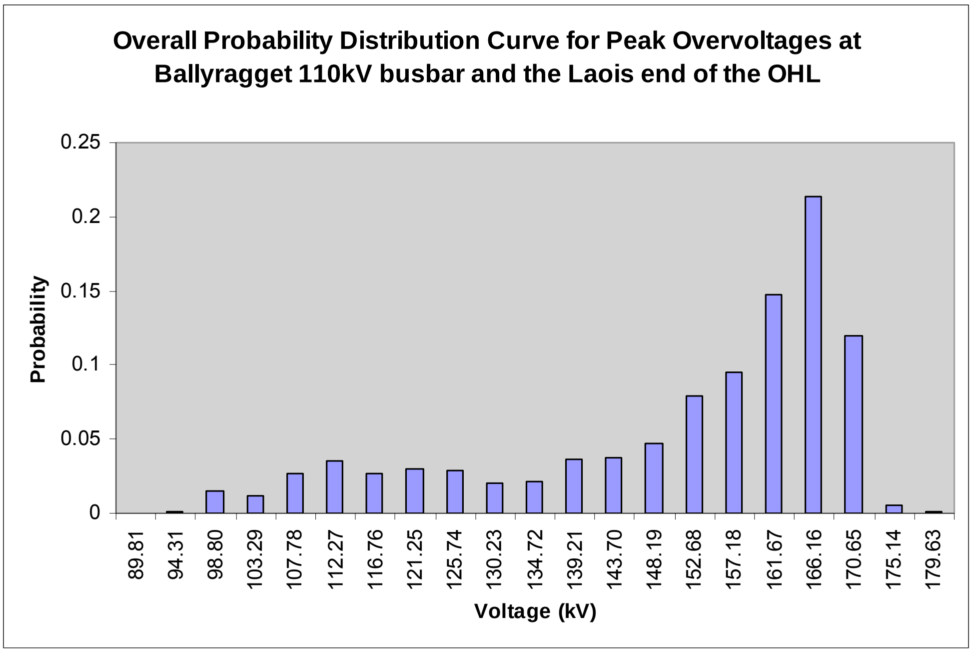


Figure 4.57: Probability Distribution Curve for Cable Energisation at Ballyragget

Mean Overvoltage	141kV
Variance	0.0275
Standard Deviation	0.166

Table 4.27: Mean/Variance/Standard Deviation

Table 4.28 below shows both the mean and maximum overvoltages that could be experienced at Laois 110kV busbar and at the Ballyragget end of the 110kV OHL.

	Ballyragget Bus Voltage (kV)		**Laois End Voltage (kV)**	
	L-L	**L-G**	**L-L**	**L-G**
Maximum Overvoltage	187	130	239	161
Mean Overvoltage	-	105	-	126

Table 4.28: OHL Energisation Ballyragget Results

4.4.3 Energisation – Laois

At t=0s it is assumed that both the Laois and Ballyragget circuit breakers are open. At t = 40ms, the breaker at Laois is closed and the line is energised from Laois. Figures 4.58 and 4.59 show the worse case overvoltages which were obtained form the statistical study. It can be seen that voltage distortion exists for the first few cycles after the switching event. A diagram of the model used for this case is shown in Appendix C Figure C2.

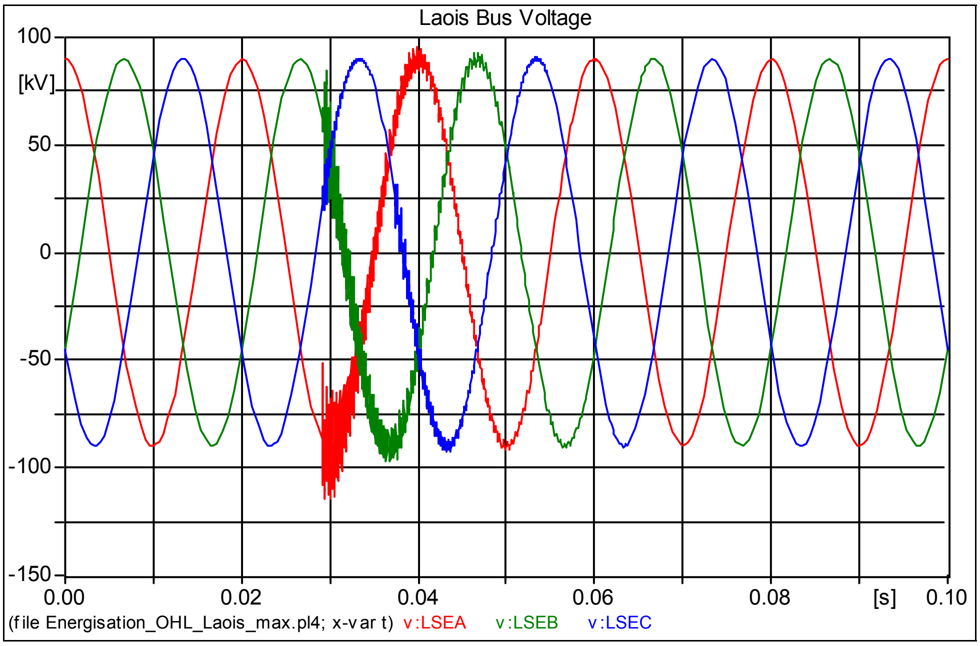


Figure 4.58: Laois Bus Voltage for OHL Energisation from Laois

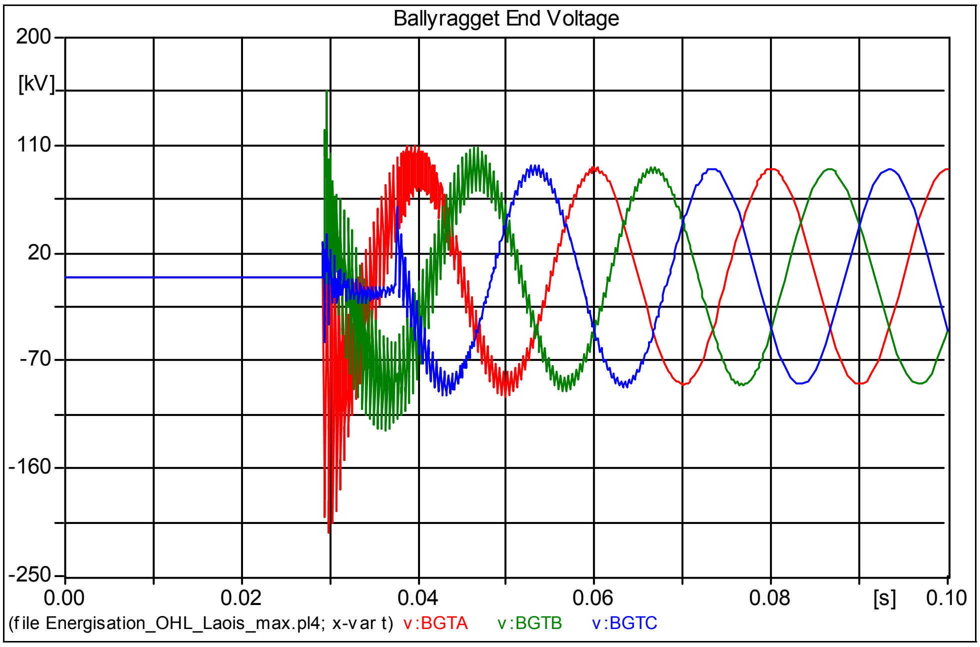


Figure 4.59: Ballyragget End Voltage for OHL Energisation from Laois

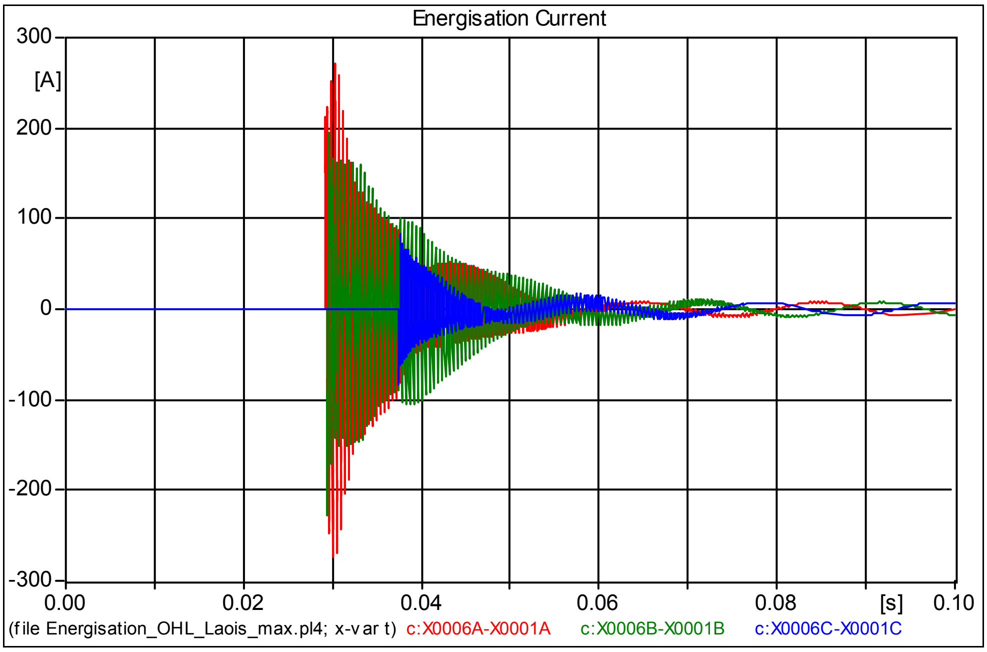


Figure 4.60: Energisation Current for OHL Energisation from Laois

Figure 4.61 shows the probability curve for peak overvoltages experienced at Laois 110kV busbar. Table 4.29 shows the mean overvoltage, variance and standard deviation for overvoltages at Laois. The average overvoltage which could be experienced at Laois 110kV busbar for a OHL energisation at Laois is 107kV (Peak L-G).

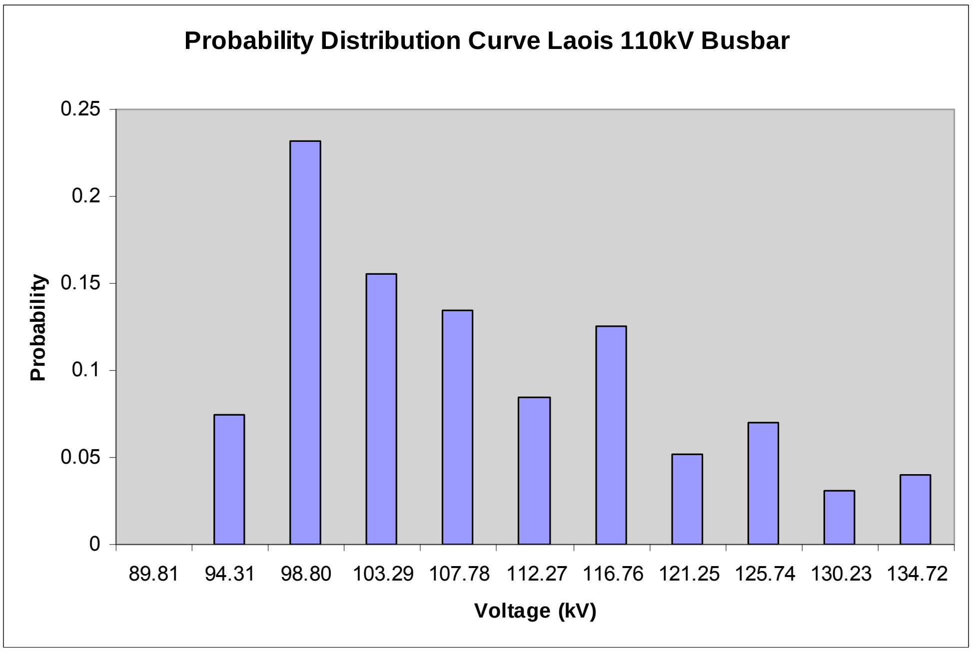


Figure 4.61: Probability Distribution Curve for Peak Overvoltages Experienced at Laois 110kV Busbar

Mean Overvoltage	107kV
Variance	0.0151
Standard Deviation	0.123

Table 4.29: Mean/Variance/Standard Deviation

Figure 4.62 shows the probability curve for peak overvoltages experienced at the Laois end of the OHL. Table 4.30 shows the mean overvoltage, variance and standard deviation for overvoltages at the Laois end of the OHL. The average overvoltage which could be experienced at the Ballyragget end of the OHL for a OHL energisation at Laois is 152kV (Peak L-G).

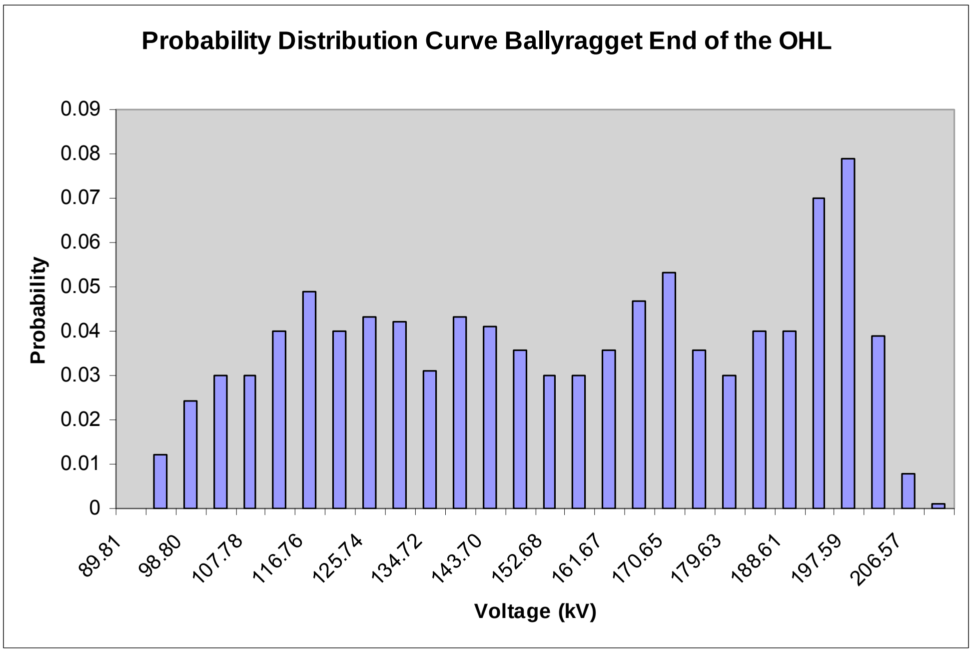


Figure 4.62: Probability Distribution Curve for Peak Overvoltages Experienced at Ballyragget end of the OHL

Mean Overvoltage	152kV
Variance	0.129
Standard Deviation	0.359

Table 4.30: Mean/Variance/Standard Deviation

Figure 4.63 shows the probability curve for peak overvoltages experienced at both Laois and Ballyragget for a OHL energisation at Laois. Table 4.31 shows the mean overvoltage, variance and standard deviation for the peak overvoltages. The average overvoltage which could be experienced for a OHL energisation at Laois is 176kV (Peak L-G).

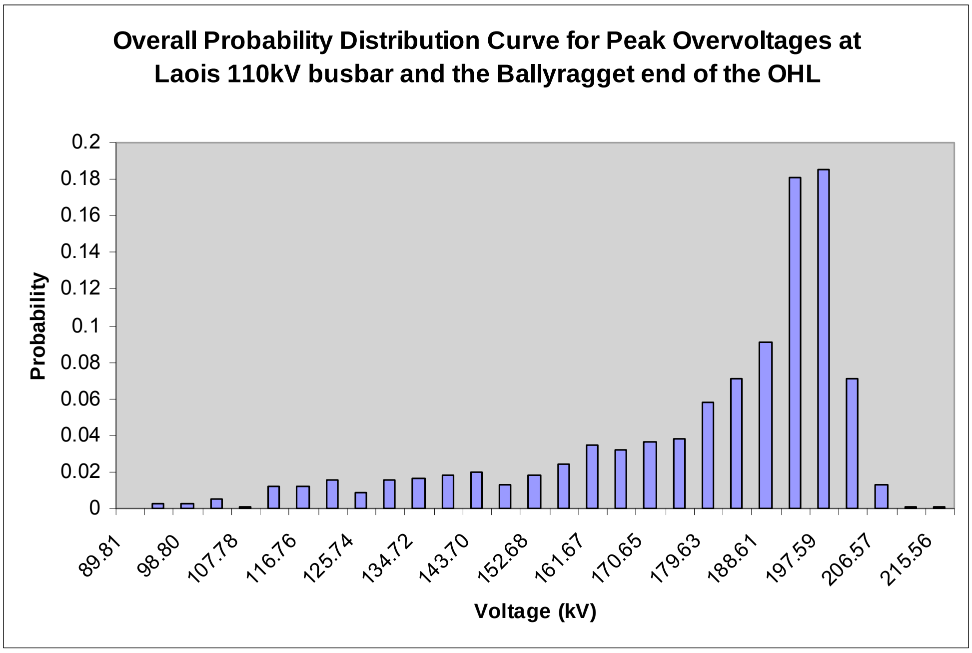


Figure 4.63: Probability Distribution Curve for OHL Energisation at Laois

Mean Overvoltage	176kV
Variance	0.0726
Standard Deviation	0.269

Table 4.31: Mean/Variance/Standard Deviation

Table 4.32 below shows both the mean and maximum overvoltages that could be experienced at Laois 110kV busbar and at the Ballyragget end of the 110kV OHL.

	Laois Bus Voltage (kV)		**Ballyragget End Voltage (kV)**	
	L-L	**L-G**	**L-L**	**L-G**
Maximum Overvoltage	185	116	313	214
Mean Overvoltage	-	107	-	152

Table 4.32: OHL Energisation Laois Results

4.4.3.1 OHL Energisation Summary

A number of points were noted in regards to the OHL energisation study which are as follows:

- Energising the OHL from Laois caused higher overvoltages compared with energising the OHL from Ballyragget.
- The highest overvoltage measured was 313kV and was measured at the Ballyragget end of the OHL for an OHL energisation from Laois.

4.4.4 Overhead Line Single Line to Ground Faults

When a single line to ground fault occurs on a OHL, it is necessary to open the circuit breakers at both ends of the OHL.

For this study, the following assumptions were made:

- Fault Inception: 10ms
- Time of opening of Local Breaker: 70ms
- Time of opening of Remote Breaker Opening Time: 90ms

The effects of restrike were also examined as part of this study. The clearing of the fault on the overhead line from either end did not cause any significant overvoltage therefore a number of cases where restriking on the circuit breakers was considered.

When de-energising a cable from near end, it appears as a shunt capacitance to ground from the far end, and a large transient recovery voltage (TRV) appears across the circuit breaker contacts. There may also be a high rate of rise of restrike voltage (RRRV). The RRRV or the TRV can cause an arc across the circuit breaker contact, known as restrike. Circuit breaker manufactures typically insist that their circuit breakers are restrike free. However, if the TRV or RRRV is high enough it will cause restrike. The occurrence of a restrike will depend on the TRV and RRRV and on and the nature of the circuit breaker itself.

As there is not sufficient data in order to access the probability of restrike occurring, a simplified case where restrike does occur has been considered. In order to simulate the effect of restrike, the contacts of the circuit breaker are assumed to arc when the voltage between them reaches 2 pu. These cases are for the purposes of illustration only

4.4.4.1 Single Line to Ground Fault – Ballyragget (no-restrike)

At t=0s it assumed that the transmission system is healthy and the bus voltages at Ballyragget and Laois are within the operating limits of the system. At t=10ms it is then assumed that a single line to ground fault occurs on the Ballyragget end of the OHL. At t=70ms the circuit breaker at Ballyragget opens. At t=90ms the breaker at Laois opens and the fault on the cable is cleared.

It can be observed from figure 4.64 and 4.65 that very little voltage transients occurs for the single line to ground fault at the Ballyragget end of the OHL compared with the results obtained for the cable. A diagram of the model used for this case is shown in Appendix C Figure C3.

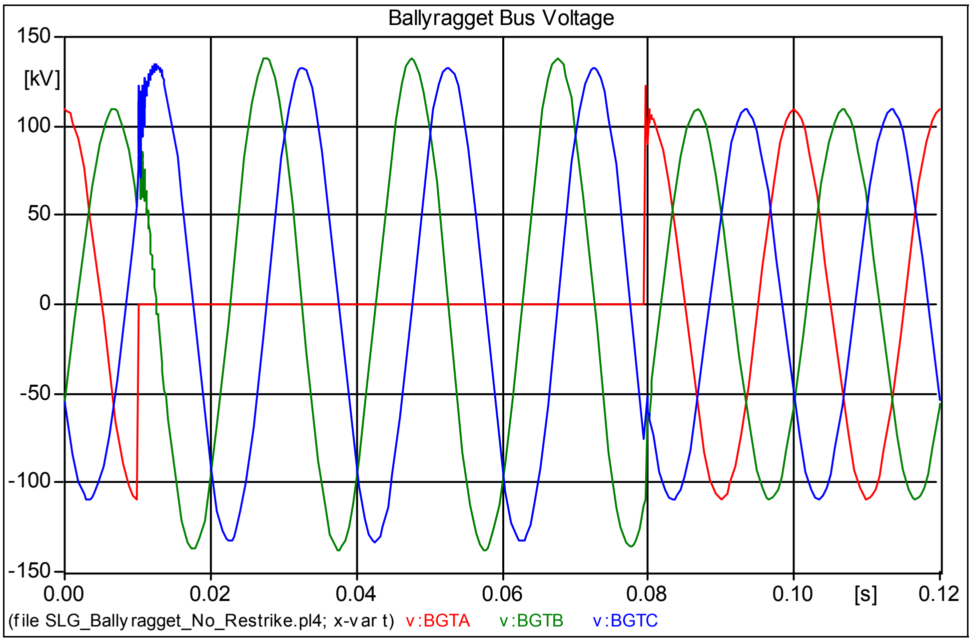


Figure 4.64: Ballyragget Bus Voltage for SLG at Ballyragget

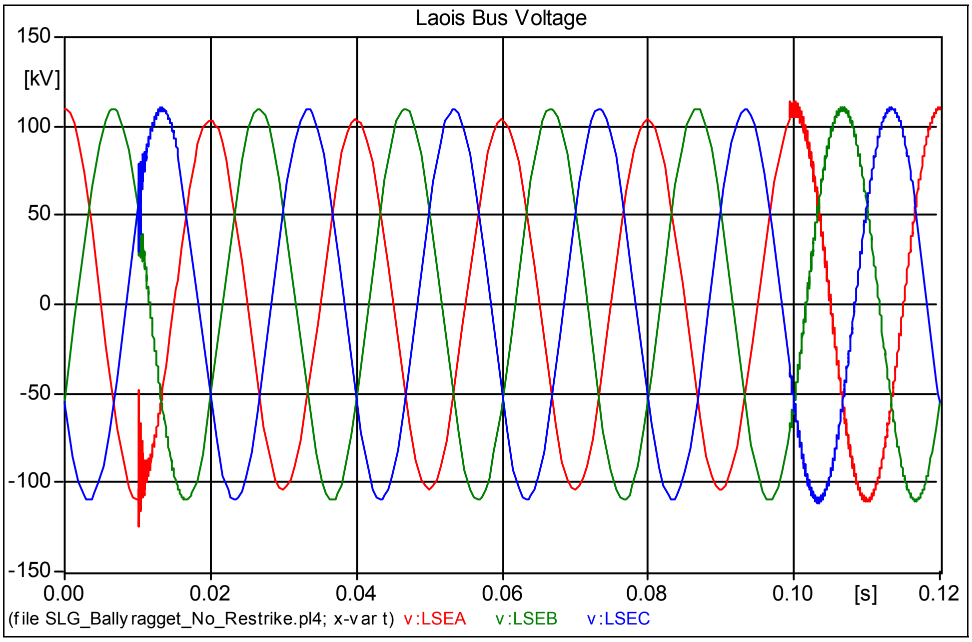


Figure 4.65: Laois Bus Voltage for SLG at Ballyragget

Table 4.33 below shows the overvoltages that could be experienced at Laois and Ballyragget.

Laois Bus Voltage (kV)		**Ballyragget Bus Voltage (kV)**	
L-L	**L-G**	**L-L**	**L-G**
198	126	205	138

Table 4.33: Single Line to Ground Fault at Ballyragget (No - Restrike)

4.4.4.2 Single Line to Ground Fault – Laois (no-restrike)

At t=0s it assumed that the transmission system is healthy and the bus voltages at Ballyragget and Laois are within the operating limits of the system. At t=10ms it is then assumed that a single line to ground fault occurs on the Laois end of the OHL. At t=70ms the circuit breaker at Laois opens. At t=90ms the breaker at Ballyragget opens and the fault on the cable is cleared.

It can be observed from figure 4.66 and 4.67 that very little voltage transients occurs for the single line to ground fault at the Laois end of the OHL compared with the results obtained for the cable. A diagram of the model used for this case is shown in Appendix C Figure C4.

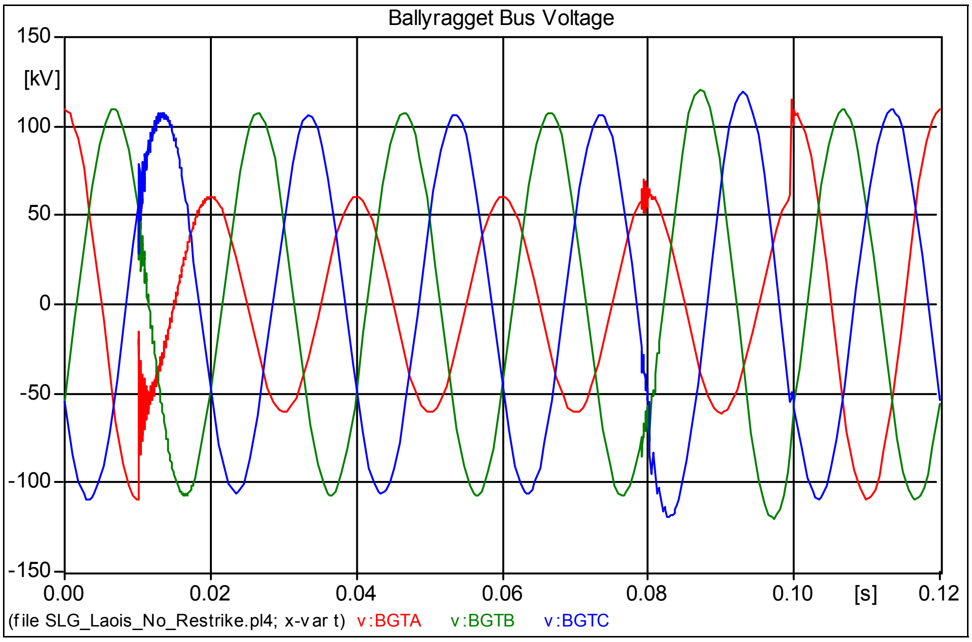


Figure 4.66: Ballyragget Bus Voltage for SLG at Laois

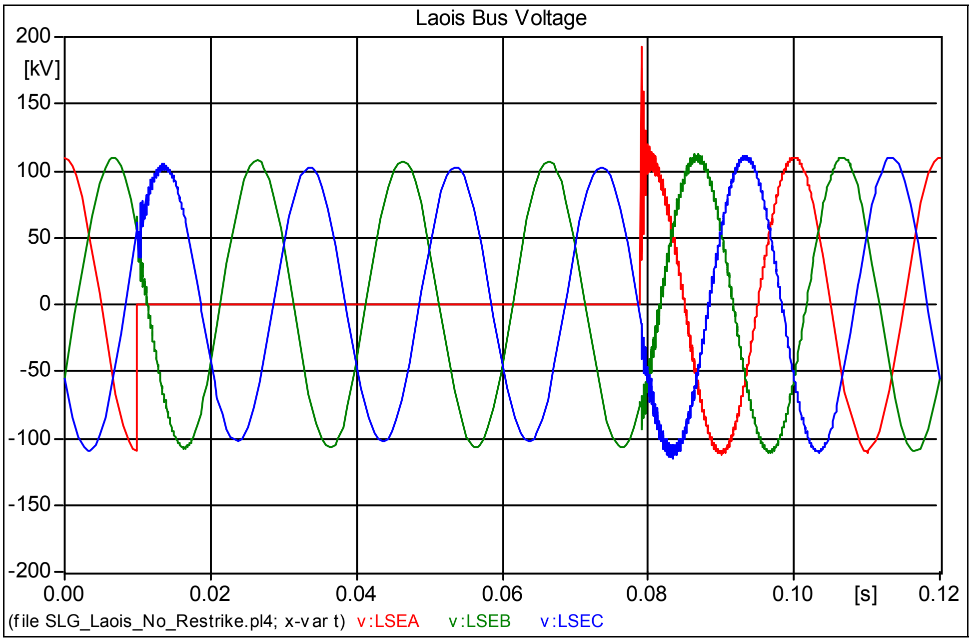


Figure 4.67: Laois Bus Voltage for SLG at Laois

Table 4.34 below shows the overvoltages that could be experienced at Laois and Ballyragget.

Laois Bus Voltage (kV)		**Ballyragget Bus Voltage (kV)**	
L-L	**L-G**	**L-L**	**L-G**
285	194	190	120

Table 4.34: Single Line to Ground Fault at Laois (No-Restrike)

4.4.4.3 Single Line to Ground Fault Summary

A number of points were noted in regards to the OHL single line to ground fault study which are as follows:

- Single Line to Ground Faults at Laois and Ballyragget ends of the OHL were observed to be benign events when no restriking occurred.
- Single Line to Ground Faults at either the Laois or Ballyragget ends of the OHL resulted in voltage distortions at the Laois 110kV busbar.
- The transients caused by single line to ground faults on the OHL were significantly lower that the transients observed for single line to ground faults on the Cable

4.4.5 Overhead Line Three Phase Faults

When a three phase fault occurs on a OHL, it is necessary to open the circuit breakers at both ends of the OHL.

For this study, the following assumptions were made:

- Fault Inception: 10ms
- Local Breaker Operating Time: 60ms
- Remote Breaker Operating Time: 80ms

The effects of restrike were not produced in this case do to the low level of TRV.

4.4.5.1 Three Phase Fault – Ballyragget

At t=0s it assumed that the transmission system is healthy and the bus voltages at Ballyragget and Laois are within the operating limits of the system. At t=10ms it is then assumed that a three phase fault occurs on the Ballyragget end of the cable. At t=70ms the circuit breaker at Ballyragget opens. At t=90ms the breaker at Laois opens and the fault on the OHL is cleared. It can be observed from figure 4.68 that significant voltage distortion occurs at the 110kV busbar at Laois compared with the distortion voltage distortion observed at Ballyragget 110kV substation (figure 4.69). The voltage distortions observed could cause problems for rate of change of frequency (ROCOF) relays, which are installed at distribution system wind farms. A diagram of the model used for this case is shown in Appendix C Figure C5.

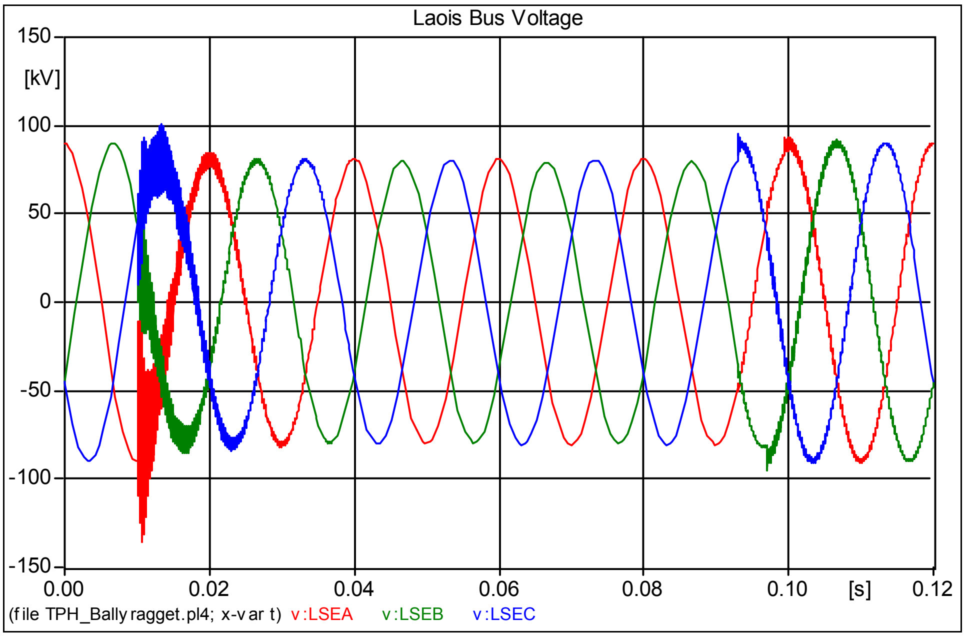


Figure 4.68: Laois Bus Voltage for TPH Fault at Ballyragget

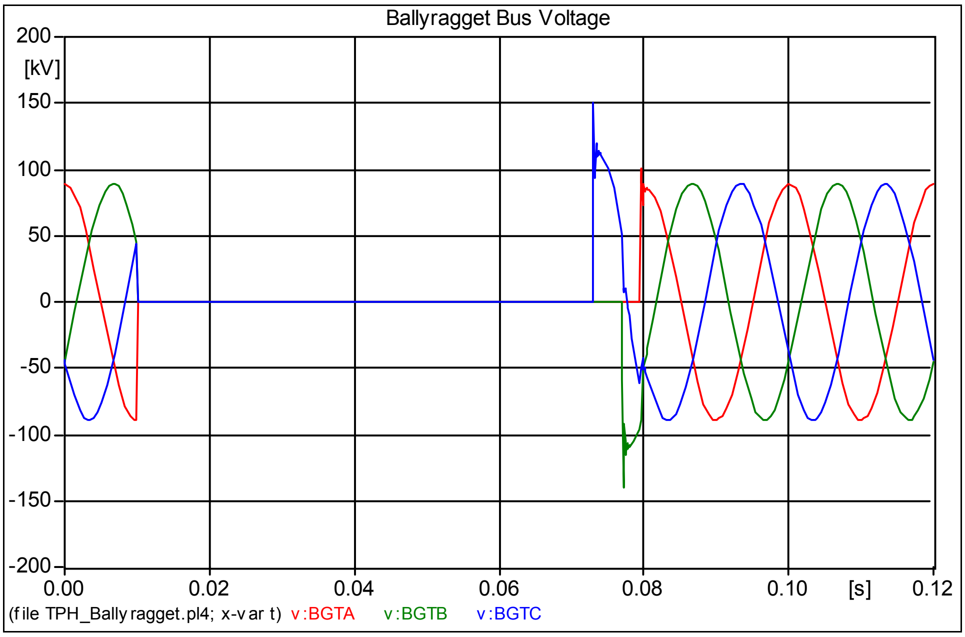


Figure 4.69: Ballyragget Bus Voltage for TPH Fault at Ballyragget

Table 4.35 below shows the overvoltages that could be experienced at Laois and Ballyragget.

Laois Bus Voltage (kV)		**Ballyragget Bus Voltage (kV)**	
L-L	**L-G**	**L-L**	**L-G**
235	141	165	151

Table 4.35: Three Phase Fault at Ballyragget

4.4.5.2 Three Phase Faults - Laois

At t=0s it assumed that the transmission system is healthy and the bus voltages at Ballyragget and Laois are within the operating limits of the system. At t=10ms it is then assumed that a three phase fault occurs on the Laois end of the OHL. At t=70ms the circuit breaker at Laois opens. At t=90ms the breaker at Ballyragget opens and the fault on the OHL is cleared. It can be observed from figure 4.70 that significant voltage distortion occurs at the 110kV busbar at Laois compared with the distortion voltage distortion observed at Ballyragget 110kV substation (figure 4.71). The voltage distortions observed show numerous spurious zero crossing which could cause problems for rate of change of frequency (ROCOF) relays, which are installed at distribution system wind farms. A diagram of the model used for this case is shown in Appendix C Figure C6.

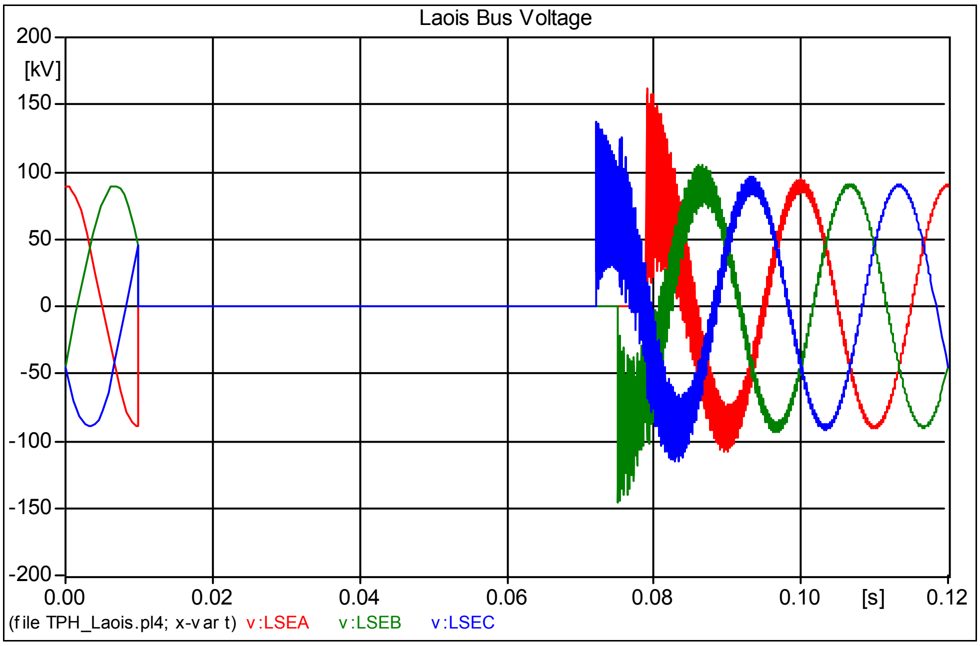


Figure 4.70: Laois Bus Voltage for TPH Fault at Laois

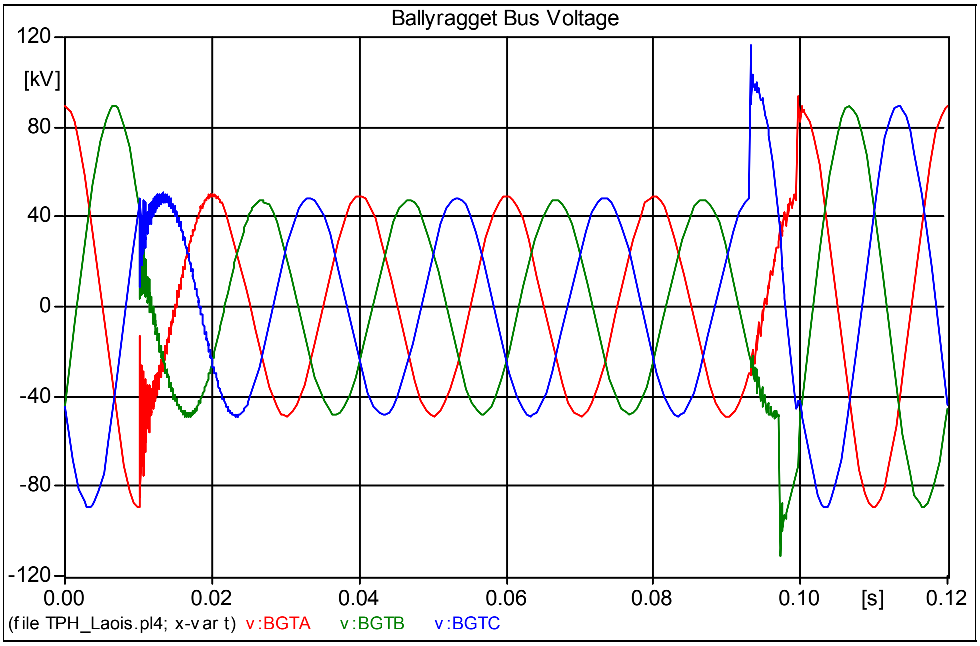


Figure 4.71: Ballyragget Bus Voltage for TPH Fault at Laois

Table 4.36 below shows the overvoltages that could be experienced at Laois and Ballyragget.

Laois Bus Voltage (kV)		**Ballyragget Bus Voltage (kV)**	
L-L	**L-G**	**L-L**	**L-G**
264	181	155	117

Table 4.36: Three Phase Fault at Laois

4.4.5.3 Overhead Line Three Phase Faults Summary

A number of points were noted in regards to the OHL three phase fault study which are as follows:

- Three phase Faults at either the Laois or Ballyragget ends of the cable resulted in significant voltage distortions at the Laois 110kV busbar.
- The voltage distortions observed for three phase faults on the cable were more severe that the voltage distortions observed for the OHL

4.5 Transformer Energisation Study

At the 110kV bus at Laois, there will be a 250MVA transformer connecting to the 400kV system. When this transformer is energised, saturation of its magnetising reactance will lead to inrush currents. An energisation of this transformer was simulated in order to observe the effects it energisation would have on the system. Since this transformer has not yet been built, nor is there a similar sized transformer with the same HV and LV ratings on the system, a number of assumptions were made.

4.5.1 Transformer Energisation Study Assumptions

The following assumptions were made for the proposed 400/110kV transformer which is to be installed at Laois 400kV substation.

- The transformer will be energised from the 400kV system as the local 110kV system may not be strong enough. This assumption was made on the guidance of Eirgrid.
- The Winding Capacitance were taken from a 220/110kV 250MVA transformer (See Appendix D Figure D1)
- The positive sequence impedance for the transformer was taken from the 2016 PSSE Models provided by Eirgrid.
- The Excitation Losses, Excitation Current and short Circuit losses were taken from factory test data for a 400/132/18kV power transformer (See Appendix D Table D1). This data was taken from a worked example supplied in the Application Examples Section of the ATP handbook for advanced usage [5].
- The Saturation curve was taken form the above example [5]. (See Appendix D Graph D1)

4.5.2 Transformer Energisation Results

Figures 4.72 and 4.73 show the inrush current and the voltage on the 400kV side of the transformer. It can be observed that energising the transformer from the 400kV side resulted in a slight dip in the voltage (figure 4.73) on the 400kV side of the transformer. This is to be expected as energising a transformer of this size would result in large inrush currents of the magnitude of 5 – 10 times nominal current which in turn would result in a voltage dip on the system.

As the transformer is energised from the 400kV side, the installation of either OHL or Cable between Ballyragget and Laois would have no effect on the voltage distortion caused be energisation of the transformer.

It should be noted that the transformer energisation study was carried out using assumed data for the transformer. As such, the results obtained should only be used for indicative purposes only. This study should be carried out using actual data for the transformer which is to be installed once the data is made available. A diagram of the model used for this case is shown in Appendix D Figure D2.

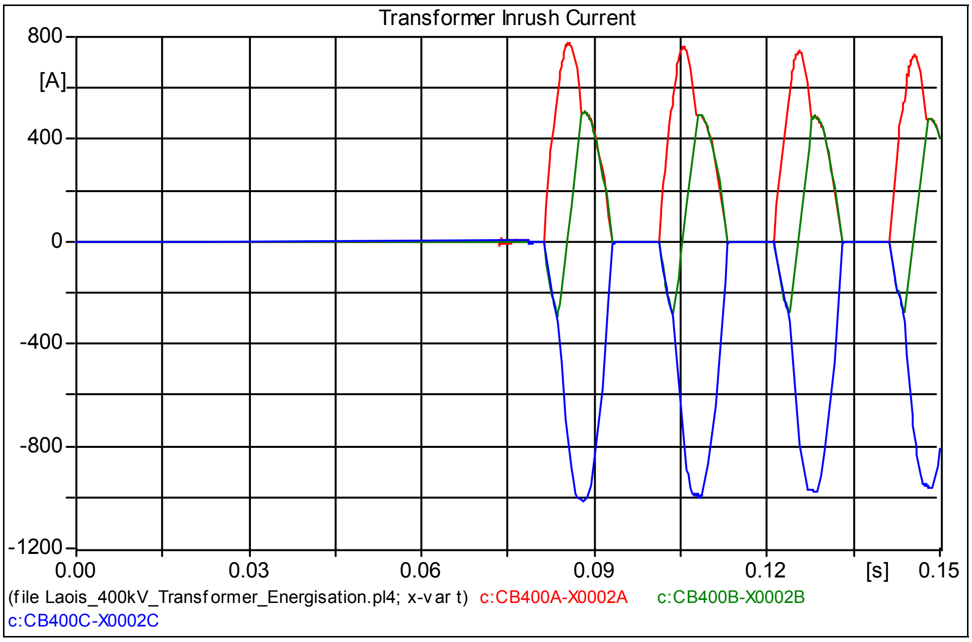


Figure 4.72: Transformer Inrush Current

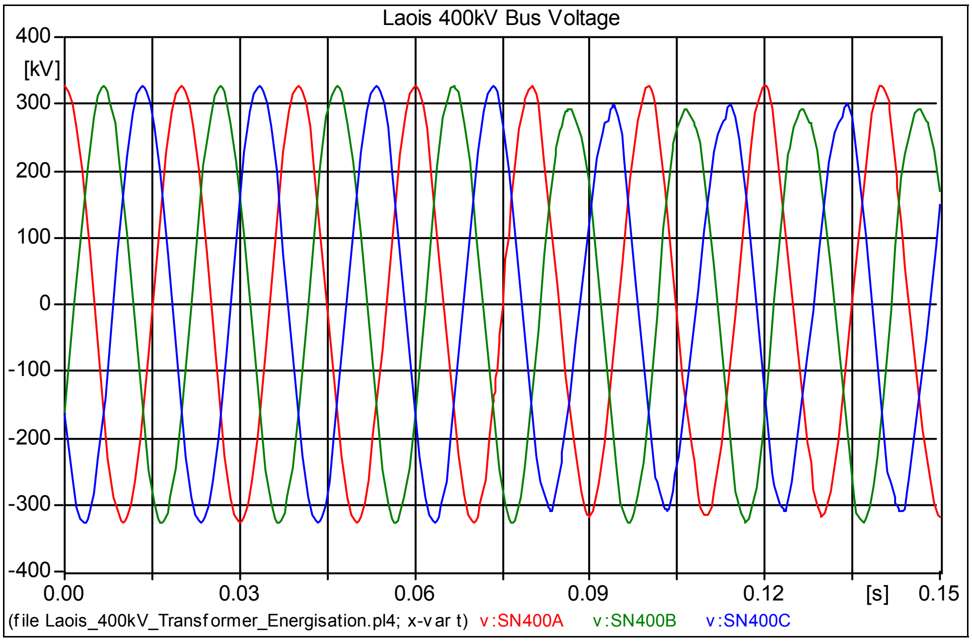


Figure 4.73: Laois 400kV Bus Voltage

4.6 Transient Study Summary

Electromagnetic studies have been carried out in order to investigate a number of phenomena for both overhead line and cable options. Results shown in Section 5 and in Appendix E tables E-1 and E-2 show that overvoltages associated with the cable solution are on average 13% higher than the OHL option, and in one instance the overvoltage associated with the cable option are 68% higher than the OHL option. Results show that in no calculation considered did the line to ground voltage exceed the 420kV limit supplied by Eirgrid. The highest calculated line to ground voltage for the cable solution is 343kV, and for the OHL solution is 320kV. Results show that in one case for both OHL and cable solutions, the line to line voltage does exceed the 420kV limit.

When simplified restike scenarios, as outlined, were considered the line to ground voltage did not exceed the 420kV insulation level. However, the line to line voltage did exceed the insulation level of 420kV in one case for the OHL solution, and two cases for the cable option. These cases are provided for illustration purposes only, as sufficient circuit breaker data in order to model this phenomena accurately were not provided.

The following observations were made as part of this study:

- The 110kV cable generates approximately 205A of charging current. The OHL on the other hand generates approximately 3-5A of charging current.
- Due to the capacitive effects of the cable, the chances of restrike are a greater risk compared with the OHL. However, restrike should not be an issue as most manufacturers advertise their circuit breakers to be restrike free. Therefore, if careful consideration is given to the choice of circuit breaker, then restrike should not be an issue if the cable were to be implemented.
- Voltage distortions associated with the cable switching could cause problems for rate of change of frequency (ROCOF) relays installed at distribution windfarms. However, due to insufficient complexity in the model it cannot be confirmed that the voltage distortions associated with the cable switching would cause problems for ROCOF relays at distribution windfarms.
- A charged cable switching yielded higher overvoltages compared to a charged switching of the overhead line. A charged cable switching at Laois yielded higher overvoltages compared to a charged cable switching at Ballyragget.
- Energisation of the Cable or OHL from either Ballyragget or Laois had little effect on the power system. However, the inrush current associated with the cable is significantly larger than the inrush current associated with the OHL.
- De-Energisation of either the cable or OHL had little effect on the power system. However, de-energisation of the cable with restrike caused significant voltage distortion. If the circuit breakers chosen are restrike free, then de-energisation should not be a problem.

5 Harmonics Study

5.1 Introduction

A harmonic study was carried out to determine the frequency dependent driving point impedance for selected locations on the system. These impedance - frequency plots are calculated for both a 110kV cable circuit and an 110kV OHL circuit between Laois and Ballyragget. The switching in/out of the capacitor bank at Kilkenny 110kV busbar was also investigated for both the cable and the OHL. The main purpose of impedance - frequency plots is to identify both the frequency and relative magnitude of the various parallel and series resonances expected for a particular location in the system. While the existence of a resonance – either very low or very high impedance – is an indicator of possible harmonic issues, it is not sufficient for determining the severity of the associated harmonic currents and voltages.

5.2 Impedance – Frequency Plots

To determine the possible existence of dangerous resonant conditions due to installation of a cable or OHL between Laois and Ballyragget, a number of impedance – frequency plots were carried out. In order to carry out the necessary impedance - frequency plots, four system models were built in ATP which are as follows:

- Summer Night Valley 2016 Cable ATP Model
- Summer Night Valley 2016 OHL ATP Model
- Winter peak 2016 Cable ATP Model
- Winter peak 2016 OHL ATP Model

5.2.1 Model Assumptions

A number of assumptions were made in regards to the ATP models created for the impedance - frequency plots.

5.2.1.1 Thevenin Impedances

Thevenin impedances were calculated for the following locations:

Bus	Voltage (kV)
LANESBORO	110
SHANNONBRIDGE	110
CORDUFF	110
MONEYPOINT	380
KILLONAN	110
KNOCKRAHA	110
GREAT ISLAND	110
GREAT ISLAND	220
DUNSTOWN	220
LANESBORO	110
SHANNONBRIDGE	110
WEXFORD	110

Table 5.1: Thevenin Impedances

The Thevenin impedances were derived from the 2016 PSSE Models (SNV16 and WP16) supplied by Eirgrid. The Thevenin impedances were modelled as a resistance and reactance in series terminated by a voltage source.

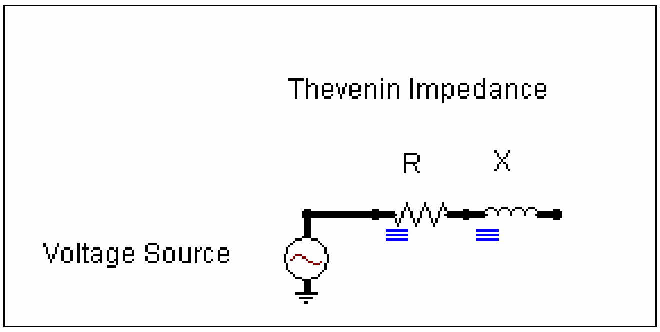


Figure 5.1: Thevenin Impedance Model

5.2.1.2 Load Modelling

The following assumptions were made in regards to the modelling of load:

- Summer Night Valley System Loading as per [1]
- Winter Peak System Loading as per [1]
- Load modelled as a Resistor and Inductor in series (Figure 5.2)

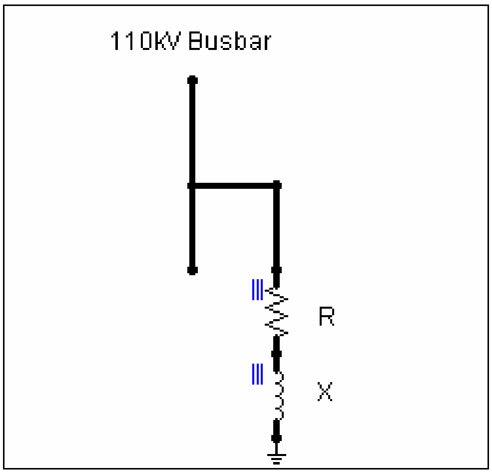


Figure 5.2: Thevenin Impedance Model

5.2.1.3 Generator Models

All Generators were modelled as a Thevenin impedance terminated by a voltage source.

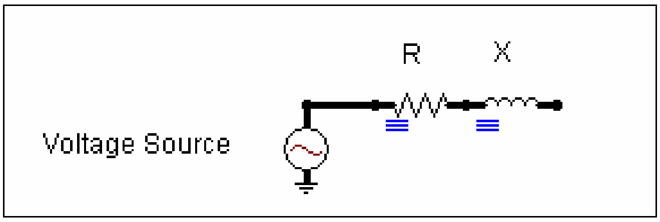


Figure 5.3: Generator Model

5.2.1.4 Line/Cable/Transformer Information

- Line/Cable/Transformer Information as per [1]

5.2.1.5 Line/Cable Modelling

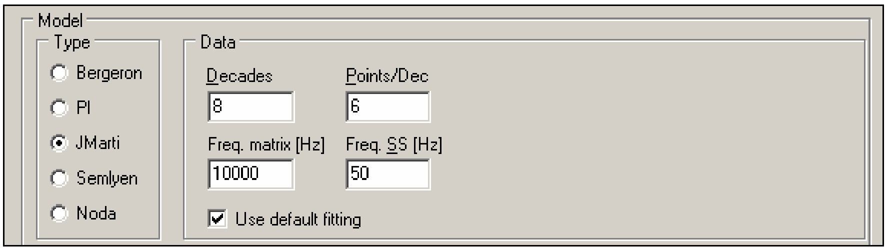
For all lines/underground cables modelled, the following guidelines were used:

- One Pi-Section for every 10km of 110kV/220kV/400kV OHL Modelled [6,9,10]
- Distributed Pi Model used for underground cable [6]

5.2.1.6 Benchmarking

To validate the use of multi pi sections for overhead lines, the 110kV line between Kilkenny and Ballyragget was modelled by 4 different methods which were:

- Multi Pi Sections
- Multi Pi Sections (Alternative – single capacitor between pi sections))
- Single Pi Section
- Frequency Dependent Model (JMarti)



Model

Type

○ Bergeron

○ PI

● JMarti

○ Semlyen

○ Noda

Data

Decades: 8

Points/Dec: 6

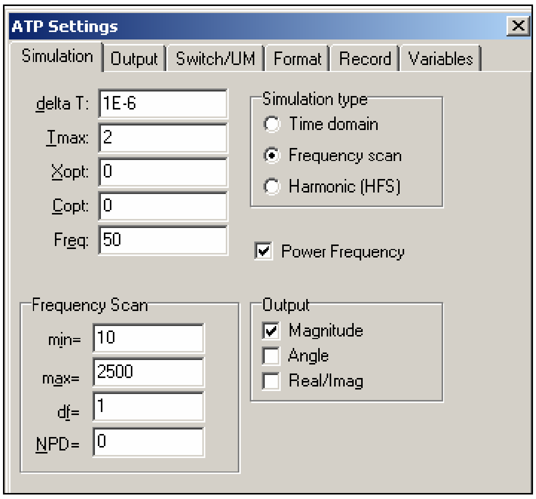
Freq. matrix [Hz]: 10000

Freq. SS [Hz]: 50

☑ Use default fitting

Figure 5.4: JMarti Model Setup

Each line model was terminated by the same load and each circuit driven by a 1A current source (Figure 5.6). An impedance - frequency scan was carried out over the 10-2500Hz frequency range (Figure 5.5). Figure 5.7 shows the results of the impedance - frequency scan for the 4 line models. It was observed that the impedance plots for all 4 line models were identical. Therefore the use of multi pi sections for overhead lines is valid.



delta T: 1E-6

Tmax: 2

Xopt: 0

Copt: 0

Freq: 50

Simulation type

○ Time domain

● Frequency scan

○ Harmonic (HFS)

☑ Power Frequency

Frequency Scan

min= 10

max= 2500

df= 1

NPD= 0

Output

☑ Magnitude

☐ Angle

☐ Real/Imag

Figure 5.5: JMarti Model Setup

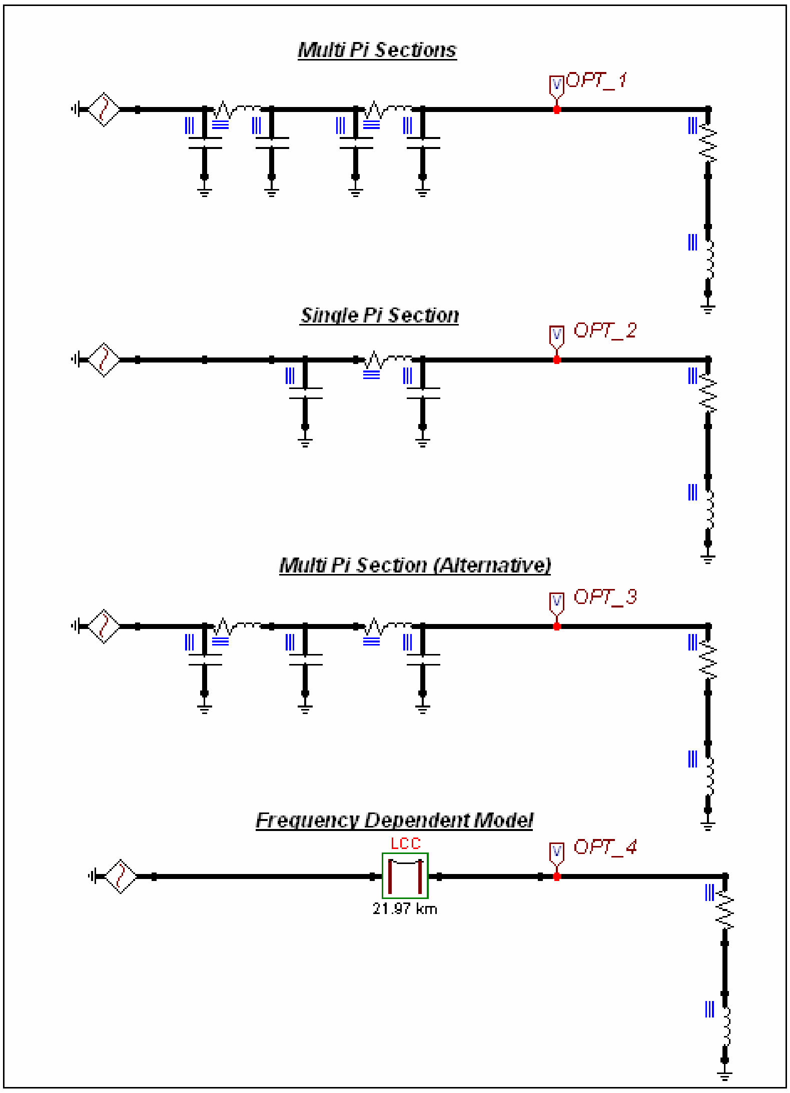


Figure 5.5: Overhead Line Models

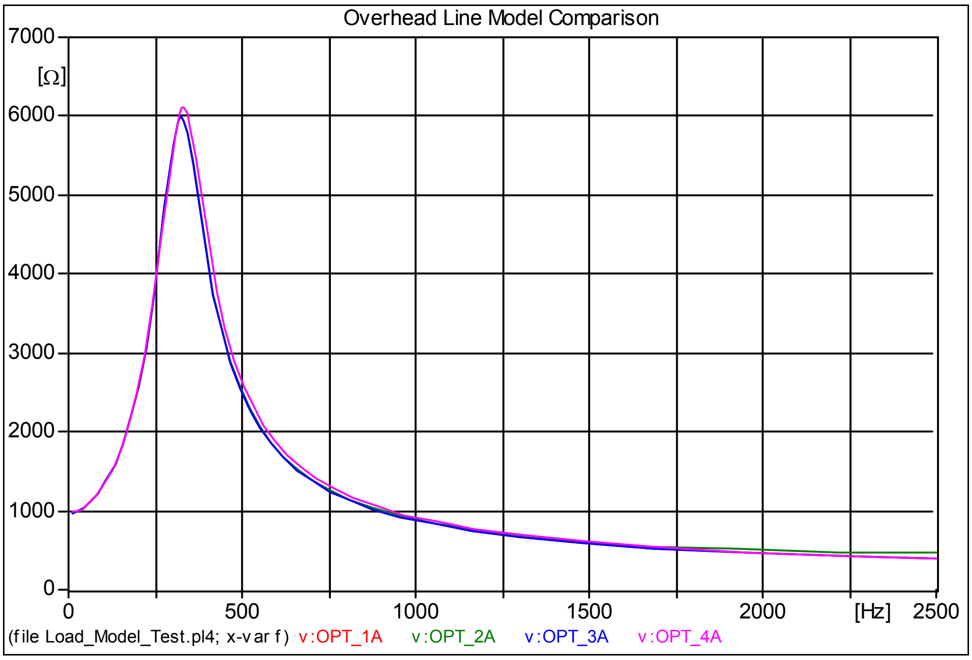


Figure 5.6: Overhead Line Model Comparison

5.2.2 Summer Night Valley – Impedance - Frequency Plots

Impedance - Frequency Plots were carried out at the following buses:

- Portlaoise 110kV Busbar
- Laois 110kV Busbar
- Ballyragget 110kV Busbar
- Kilkenny 110kV Busbar

Impedance - Frequency Plots were carried out at the above buses for the following conditions

- Overhead Line with the proposed 30MVAR Capacitor at Kilkenny 110kV Busbar in service
- Overhead Line with the proposed 30MVAR Capacitor at Kilkenny 110kV Busbar out of service
- Cable with the proposed 30MVAR Capacitor at Kilkenny 110kV Busbar in service
- Cable with the proposed 30MVAR Capacitor at Kilkenny 110kV Busbar out of service

5.2.2.1 Summer Night Valley – Portlaoise 110kV Busbar

OHL

Figure 5.7 shows the impedance - frequency plot at Portlaoise 110kV busbar for the case where the 30MVAR capacitor at Kilkenny 110kV busbar is both in & out of service. It can be seen that resonant conditions occur near the 22nd, 30th, 36th, 38th and 46th harmonic frequencies for the capacitor bank in & out of service at Kilkenny. It can also be seen that resonant conditions of smaller magnitude occur near the 15th, 26th and 35th harmonic frequencies for the capacitor bank in & out of service at Kilkenny. It was also observed that the resonant condition which occurs near the 46th harmonic frequency shifts towards the 47th harmonic frequency when the capacitor at Kilkenny is out of service.

Cable

Figure 5.8 shows the impedance - frequency plot at Portlaoise 110kV busbar for the case where the 30MVAR capacitor at Kilkenny 110kV busbar is both in & out of service. It can be seen that resonant conditions occur near the 22nd, 30th, 36th, 38th and 46th harmonic frequencies for the capacitor bank in & out of service at Kilkenny. It can also be seen that resonant conditions of smaller magnitude occur near the 15th, 26th and 35th harmonic frequencies for the capacitor bank in & out of service at Kilkenny. It was also observed that the resonant condition which occurs near the 46th harmonic frequency increased in magnitude in the case of the cable compared with the OHL.

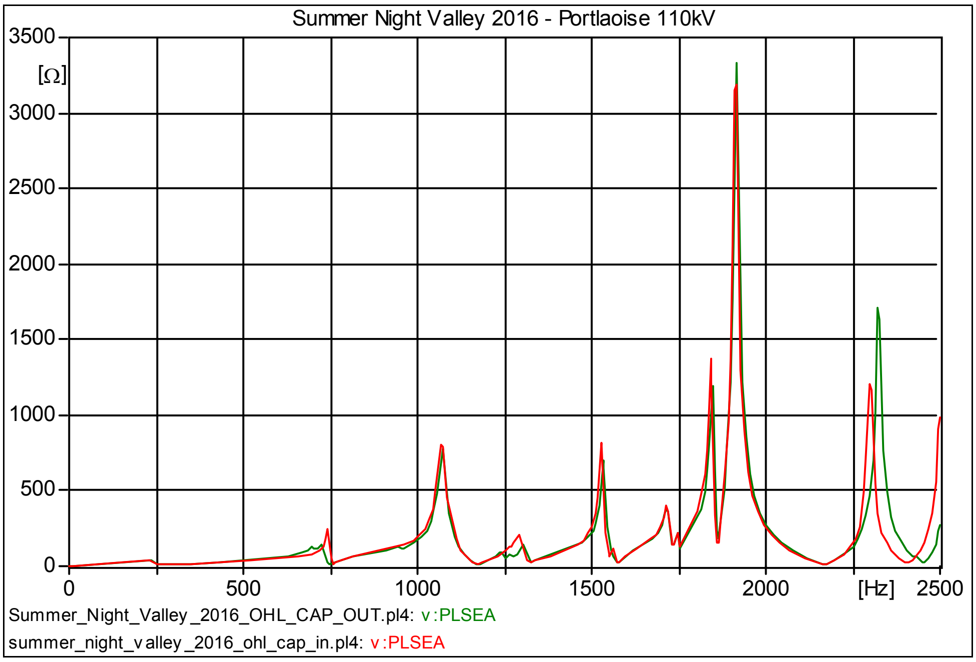


Figure 5.7: Portlaoise 110kV Busbar (OHL)

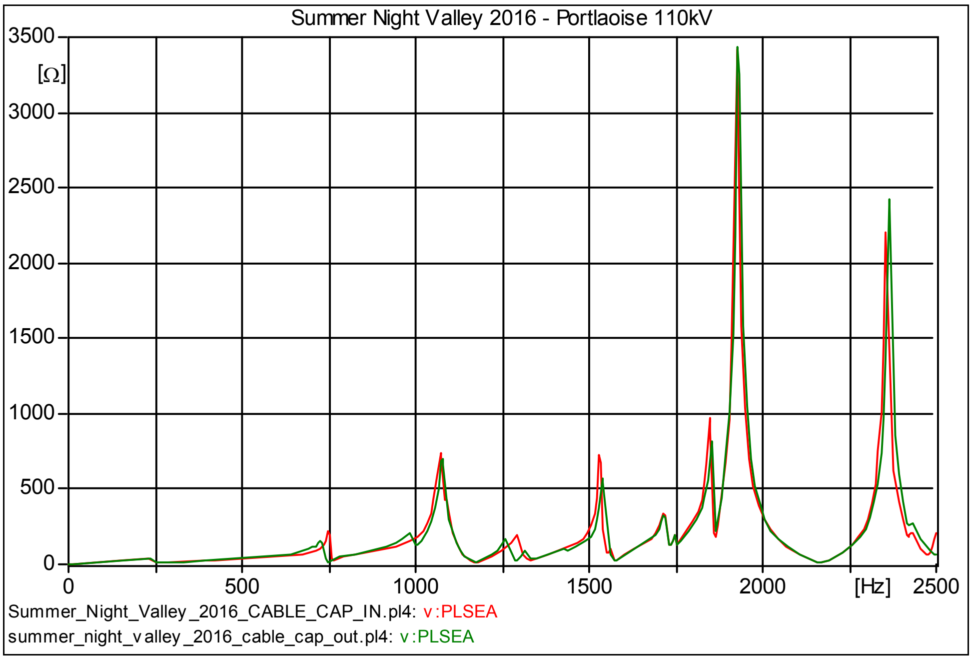


Figure 5.8: Portlaoise 110kV Busbar (CABLE)

5.2.2.2 Summer Night Valley – Laois 110kV Busbar

OHL

Figure 5.9 shows the impedance - frequency plot at Laois 110kV busbar for the case where the 30MVAR capacitor at Kilkenny 110kV busbar is both in & out of service. It can be seen that resonant conditions occur near the 15th, 31st, 36th, 38th and 46th harmonic frequencies for the capacitor bank in & out of service at Kilkenny. It can also be observed that the resonant condition which occurs near the 46th harmonic frequency shifts towards the 47th harmonic frequency when the capacitor at Kilkenny is out of service.

Cable

Figure 5.10 shows the impedance - frequency plot at Laois 110kV busbar for the case where the 30MVAR capacitor at Kilkenny 110kV busbar is both in & out of service. It can be seen that resonant conditions occur near the 15th, 31st, 36th, 38th and 46th harmonic frequencies for the capacitor bank in & out of service at Kilkenny.

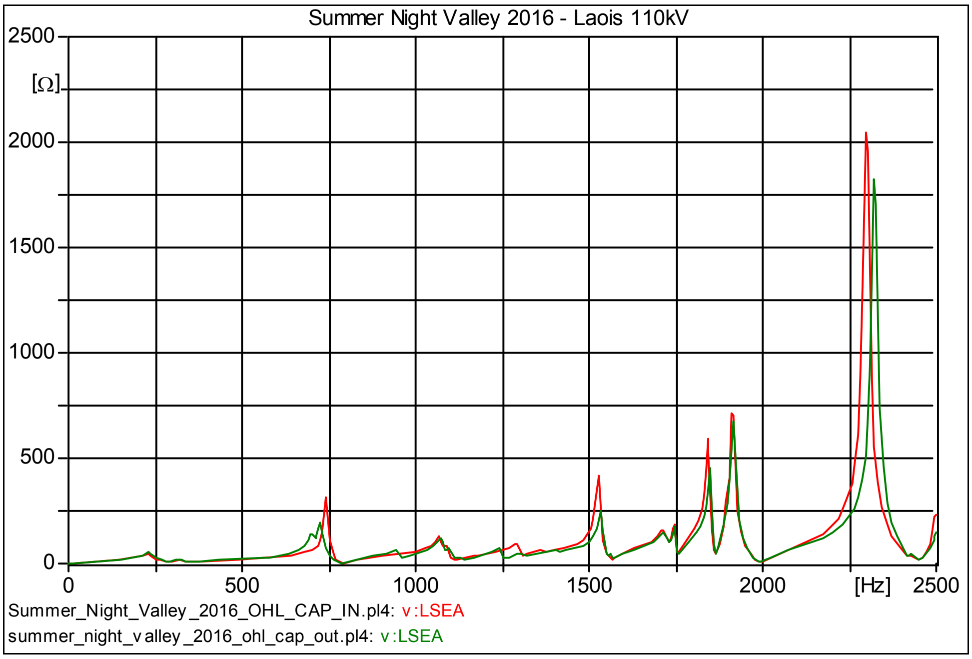


Figure 5.9: Laois 110kV Busbar (OHL)

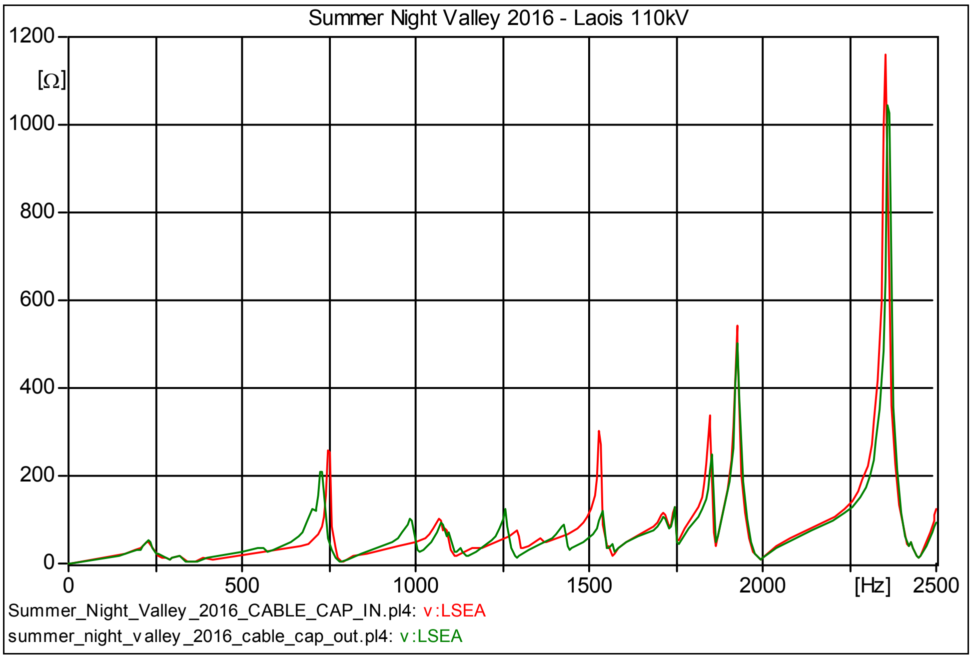


Figure 5.10: Laois 110kV Busbar (CABLE)

5.2.2.3 Summer Night Valley – Ballyragget 110kV Busbar

OHL

Figure 5.11 shows the impedance - frequency plot at Ballyragget 110kV busbar for the case where the 30MVAR capacitor at Kilkenny 110kV busbar is both in & out of service. It can be seen that resonant conditions occur near the 18th, 25th, 28th and 46th harmonic frequencies when the capacitor bank is out of service. When the capacitor bank is in service, the resonant conditions near the 18th, 25th and 28th harmonic frequencies are no longer prominent. However, the resonant condition near the 46th harmonic frequency increased in magnitude with the capacitor bank in service.

Cable

Figure 5.12 shows the impedance - frequency plot at Ballyragget 110kV busbar for the case where the 30MVAR capacitor at Kilkenny 110kV busbar is both in & out of service. It can be seen that resonant conditions occur near the 15th, 20th, 25th, 28th, 38th and 47th harmonic frequencies when the capacitor bank is out of service. When the capacitor bank is in service, the resonant conditions near the 15th, 20th 25th and 28th harmonic frequencies are no longer prominent. When the capacitor bank is in service, resonant conditions occur near the 30th, 37th and 47th harmonic frequencies. However, the resonant condition near the 47th harmonic frequency increased in magnitude with the capacitor bank in service.

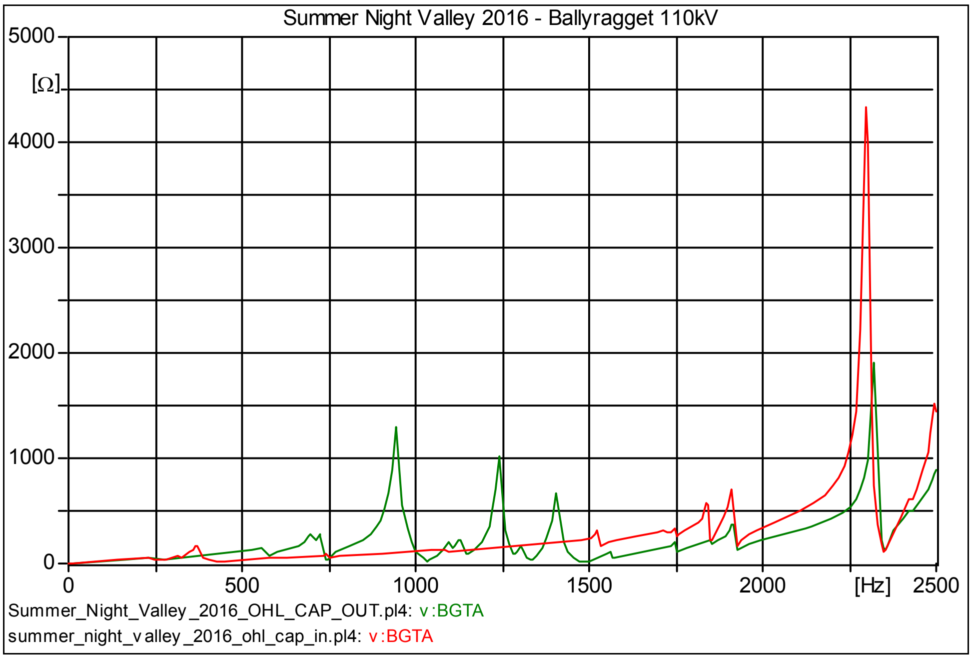


Figure 5.11: Ballyragget 110kV Busbar (OHL)

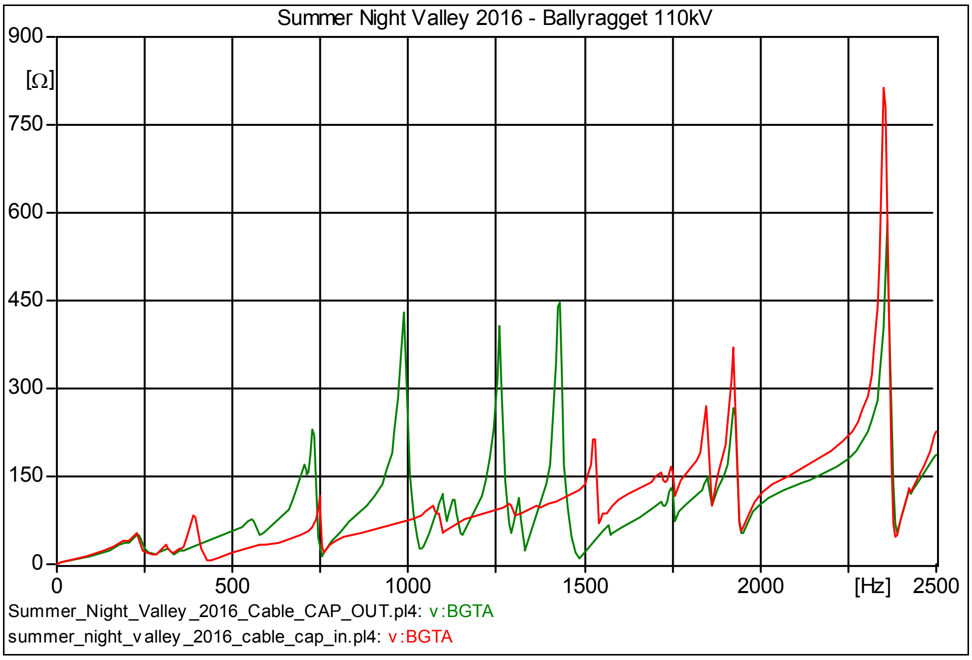


Figure 5.12: Ballyragget 110kV Busbar (CABLE)

5.2.2.4 Summer Night Valley – Kilkenny 110kV Busbar

OHL

Figure 5.13 shows the impedance - frequency plot at Kilkenny 110kV busbar for the case where the 30MVAR capacitor at Kilkenny 110kV busbar is both in & out of service. It can be seen that resonant conditions occur near the 18th, 25th and 28th harmonic frequencies when the capacitor bank is out of service. Resonant conditions which are smaller in magnitude occur near the 11th, 14th, 22nd, 27th, 31st and 46th harmonic frequencies. When the capacitor bank is in service, a resonant condition occurs near the 7th harmonic frequency only.

Cable

Figure 5.14 shows the impedance - frequency plot at Kilkenny 110kV busbar for the case where the 30MVAR capacitor at Kilkenny 110kV busbar is both in & out of service. It can be seen that resonant conditions occur near the 20th, 25th, 27th, 28th and 32nd harmonic frequencies when the capacitor bank is out of service. Resonant conditions which are smaller in magnitude occur near the 11th, 14th, 22nd, 36th and 46th harmonic frequencies. When the capacitor bank is in service, a resonant condition occurs near the 7th harmonic frequency only.

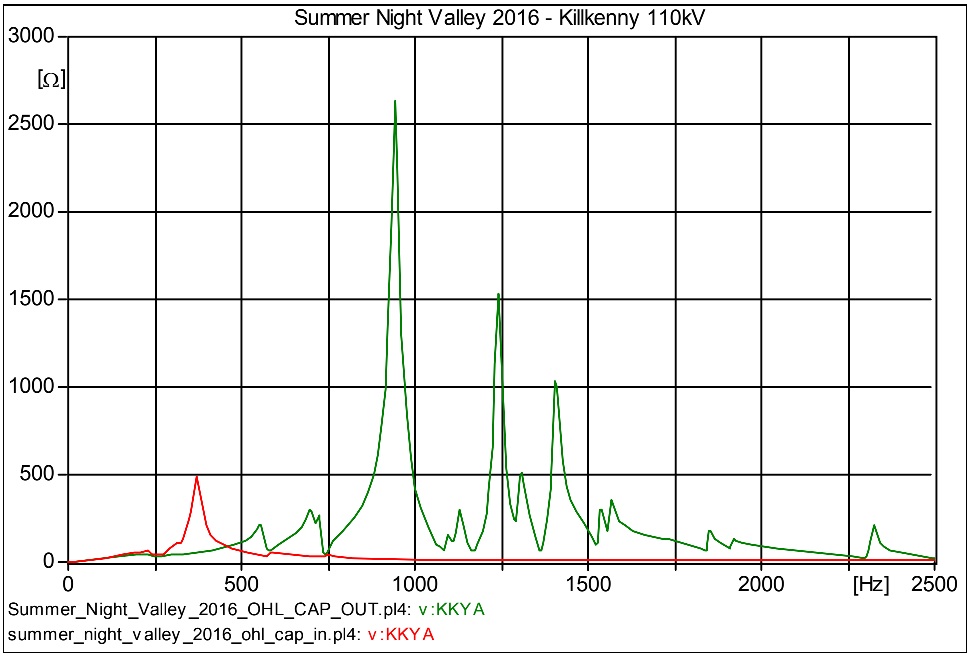


Figure 5.13: Kilkenny 110kV Busbar (OHL)

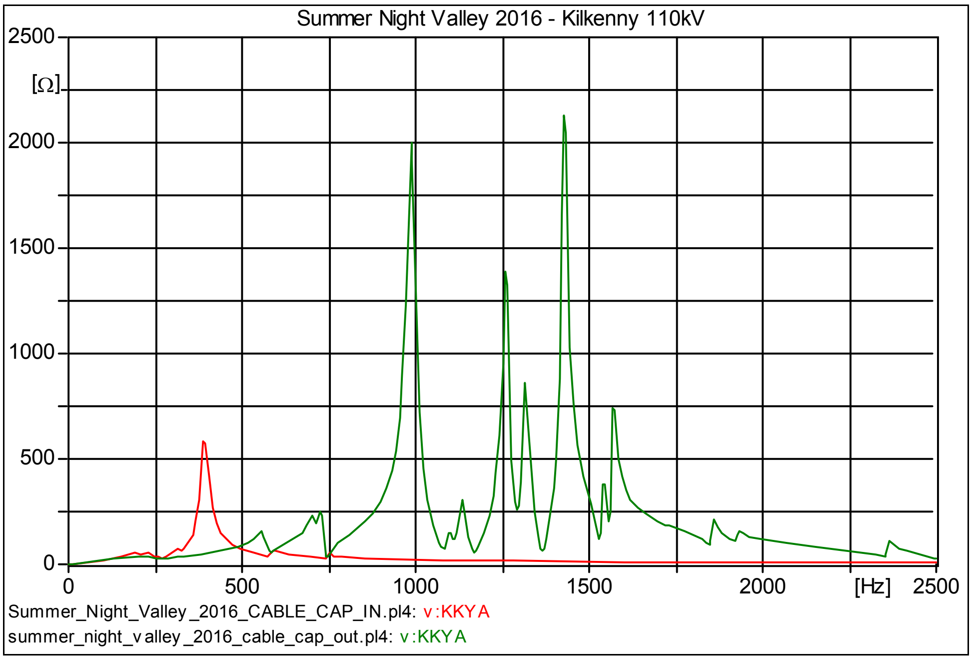


Figure 5.14: Kilkenny 110kV Busbar (CABLE)

5.2.3 Winter Peak – Impedance - Frequency Plots

Impedance - Frequency Plots were carried out at the following buses:

- Portlaoise 110kV Busbar
- Laois 110kV Busbar
- Ballyragget 110kV Busbar
- Kilkenny 110kV Busbar

Impedance - Frequency Plots were carried out at the above buses for the following conditions

- Overhead Line with the proposed 30MVAR Capacitor at Kilkenny 110kV Busbar in service
- Overhead Line with the proposed 30MVAR Capacitor at Kilkenny 110kV Busbar out of service
- Cable with the proposed 30MVAR Capacitor at Kilkenny 110kV Busbar in service
- Cable with the proposed 30MVAR Capacitor at Kilkenny 110kV Busbar out of service

5.2.3.1 Winter Peak – Portlaoise 110kV Busbar

OHL

Figure 5.15 shows the impedance - frequency plot at Portlaoise 110kV busbar for the case where the 30MVAR capacitor at Kilkenny 110kV busbar is both in & out of service. It can be seen that resonant conditions occur near the 15th, 23rd, 30th, 37th, 39th and 46th harmonic frequencies for the capacitor bank in & out of service at Kilkenny. It was also observed that the resonant condition which occurs near the 46th harmonic frequency shifts towards the 47th harmonic frequency when the capacitor at Kilkenny is out of service.

Cable

Figure 5.16 shows the impedance - frequency plot at Portlaoise 110kV busbar for the case where the 30MVAR capacitor at Kilkenny 110kV busbar is both in & out of service. It can be seen that resonant conditions occur near the 15th, 23rd, 30th, 37th, 39th and 46th harmonic frequencies for the capacitor bank in & out of service at Kilkenny. It was also observed that the resonant condition which occurs near the 46th harmonic frequency increased in magnitude in the case of the cable compared with the OHL.

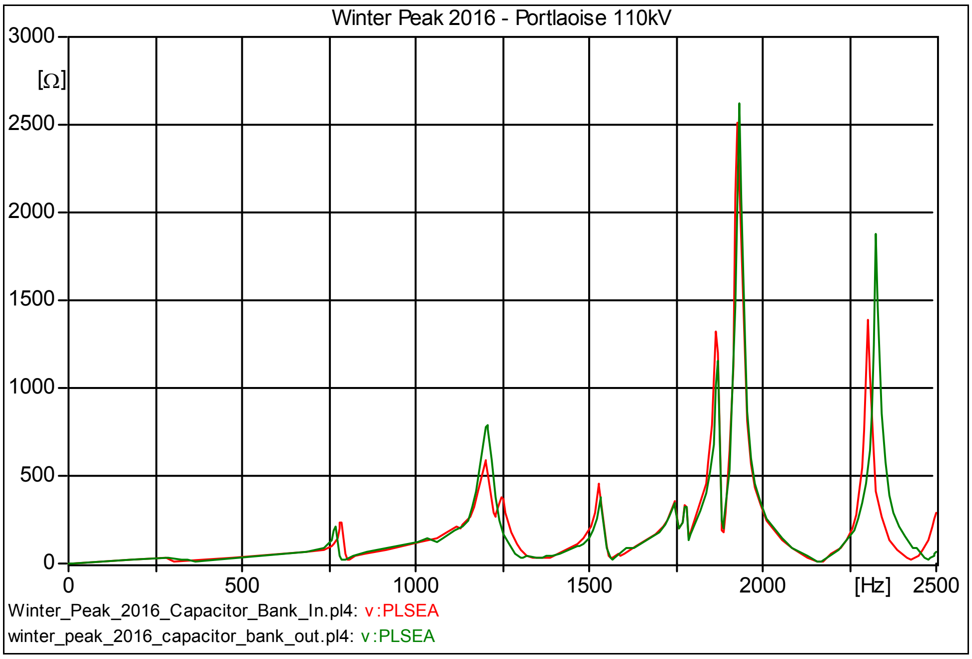


Figure 5.15: Portlaoise 110kV Busbar (OHL)

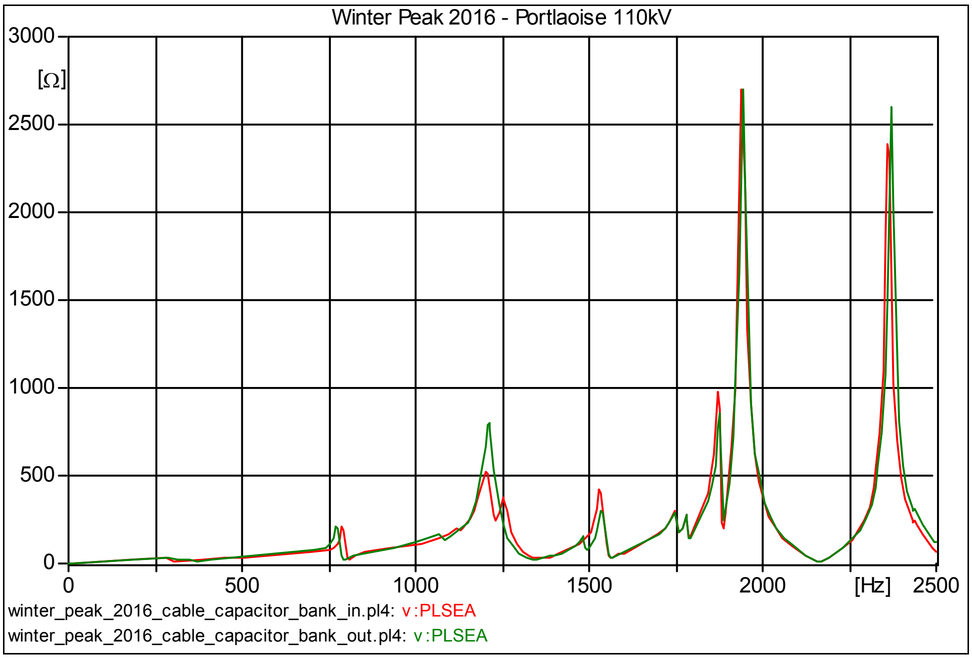


Figure 5.16: Portlaoise 110kV Busbar (CABLE)

5.2.3.2 Winter Peak – Laois 110kV Busbar

OHL

Figure 5.17 shows the impedance - frequency plot at Laois 110kV busbar for the case where the 30MVAR capacitor at Kilkenny 110kV busbar is both in & out of service. It can be seen that resonant conditions occur near the 15th, 24th, 31st, 32nd, 37th, 39th and 46th harmonic frequencies for the capacitor bank in & out of service at Kilkenny. It can also be observed that the resonant condition which occurs near the 46th harmonic frequency shifts towards the 47th harmonic frequency when the capacitor at Kilkenny is out of service.

Cable

Figure 5.18 shows the impedance - frequency plot at Laois 110kV busbar for the case where the 30MVAR capacitor at Kilkenny 110kV busbar is both in & out of service. It can be seen that resonant conditions occur near the 15th, 24th, 31st, 32nd, 37th, 39th and 46th harmonic frequencies for the capacitor bank in & out of service at Kilkenny.

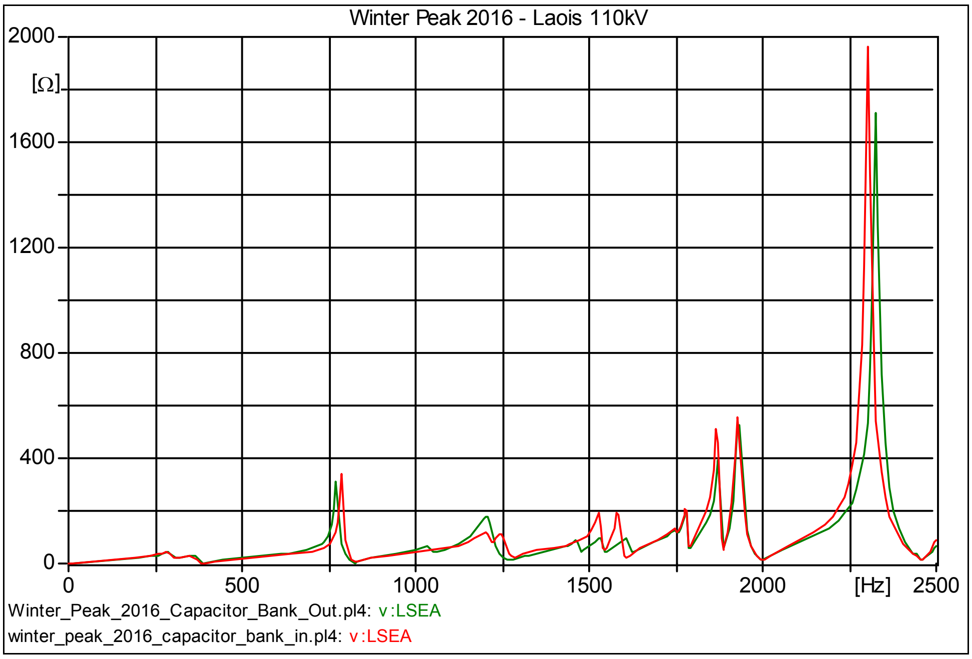


Figure 5.17: Laois 110kV Busbar (OHL)

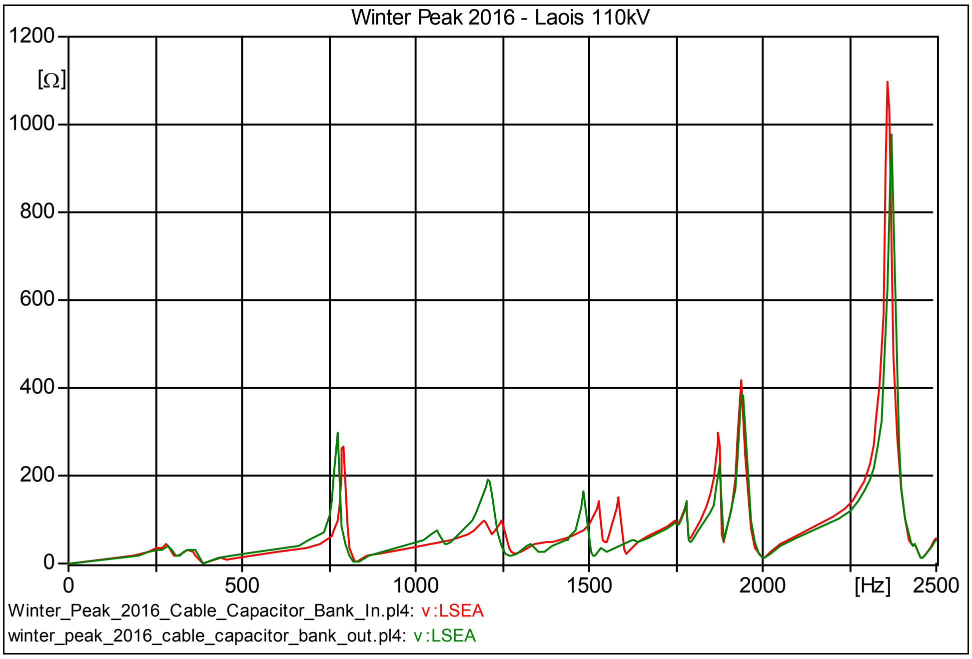


Figure 5.18: Laois 110kV Busbar (CABLE)

5.2.3.3 Winter Peak – Ballyragget 110kV Busbar

OHL

Figure 5.19 shows the impedance - frequency plot at Ballyragget 110kV busbar for the case where the 30MVAR capacitor at Kilkenny 110kV busbar is both in & out of service. It can be seen that resonant conditions occur near the 15th, 20th, 24th, 26th, 28th, 32nd and 46th harmonic frequencies when the capacitor bank is out of service. When the capacitor bank is in service, the resonant conditions at the 15th, 20th, 24th, 26th and 28th harmonic frequencies are no longer prominent. When the capacitor bank is in service, resonant conditions occur near the 37th, 39th and 46th harmonic frequencies. However, the resonant condition near the 46th harmonic frequency increased in magnitude with the capacitor bank in service.

Cable

Figure 5.20 shows the impedance - frequency plot at Ballyragget 110kV busbar for the case where the 30MVAR capacitor at Kilkenny 110kV busbar is both in & out of service. It can be seen that resonant conditions occur near the 15th, 20th, 24th, 26th, 28th, 32nd, 39th and 46th harmonic frequencies. When the capacitor bank is in service, the resonant conditions at the 15th, 20th 24th, 26th and 28th harmonic frequencies are no longer as prominent. However, the resonant conditions near the 8th, 37th, 39th and 46th harmonic frequencies have become more prominent with the capacitor bank in service.

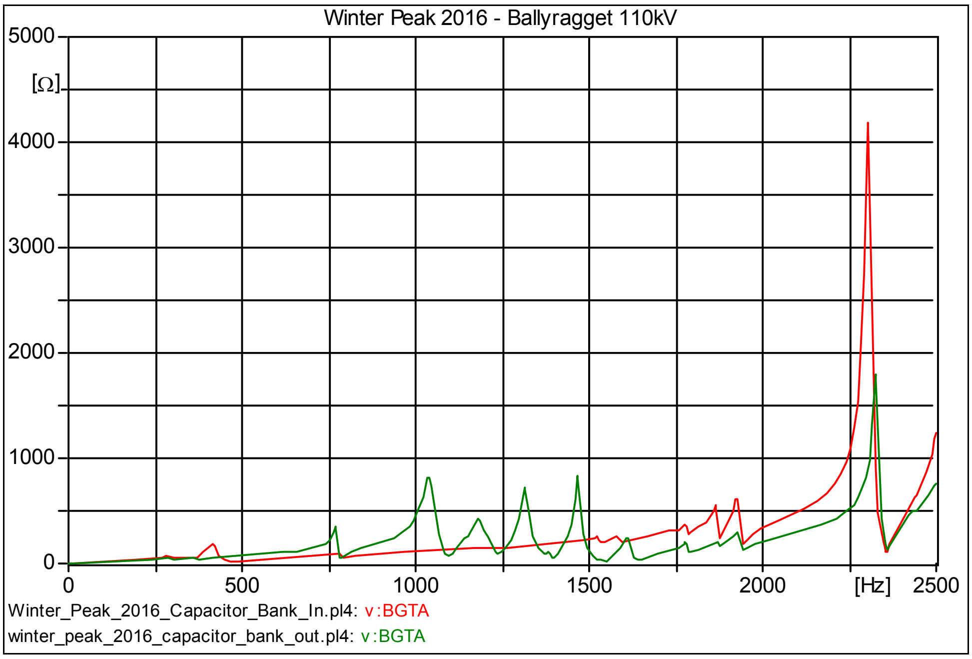


Figure 5.19: Ballyragget 110kV Busbar (OHL)

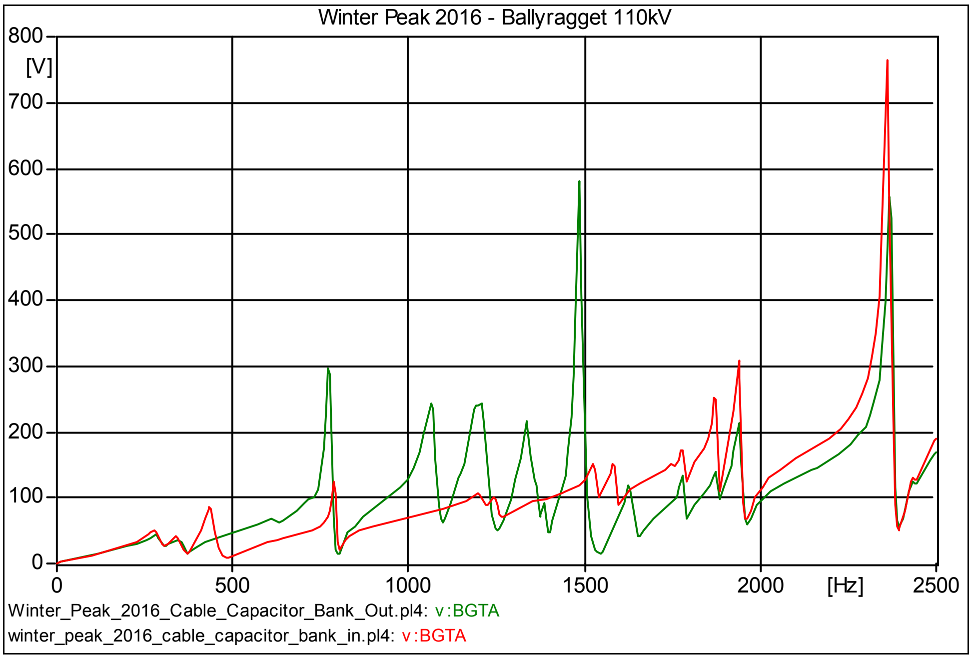


Figure 5.20: Ballyragget 110kV Busbar (CABLE)

5.2.3.4 Winter Peak – Kilkenny110kV Busbar

OHL

Figure 5.21 shows the impedance - frequency plot at Kilkenny 110kV busbar for the case where the 30MVAR capacitor at Kilkenny 110kV busbar is both in & out of service. It can be seen that resonant conditions occur near the 15th, 21st, 24th, 26th, 29th, 32nd and 46th harmonic frequencies when the capacitor bank is out of service. When the capacitor bank is in service, a resonant condition occurs near the 7th harmonic frequency only.

Cable

Figure 5.22 shows the impedance - frequency plot at Kilkenny 110kV busbar for the case where the 30MVAR capacitor at Kilkenny 110kV busbar is both in & out of service. It can be seen that resonant conditions occur near the 15th, 20th, 24th, 26th, 29th and 32nd harmonic frequencies when the capacitor bank is out of service. When the capacitor bank is in service, a resonant condition occurs near the 7th harmonic frequency only.

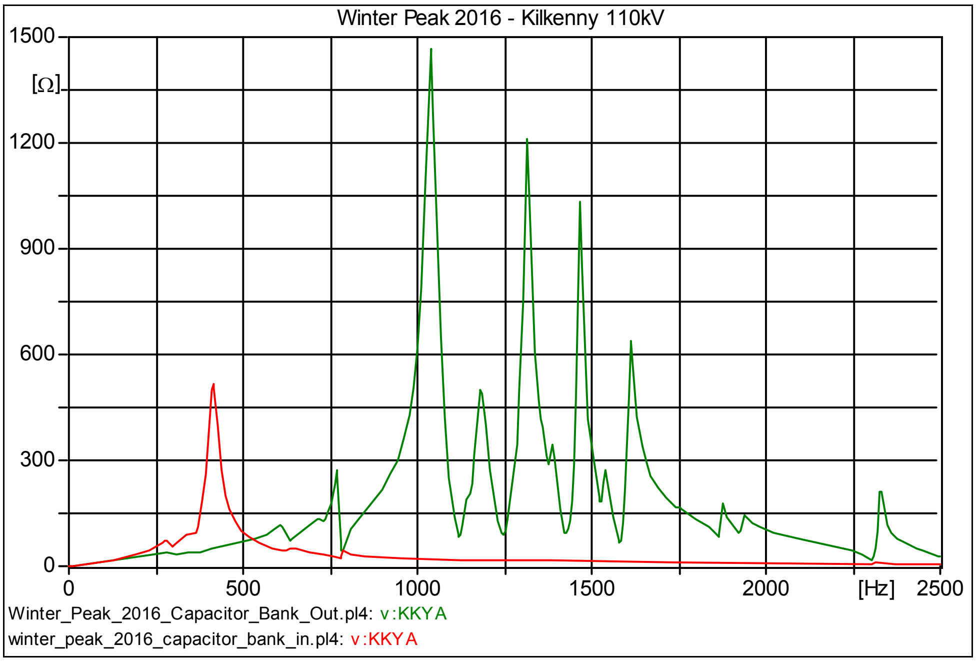


Figure 5.21: Kilkenny 110kV Busbar (OHL)

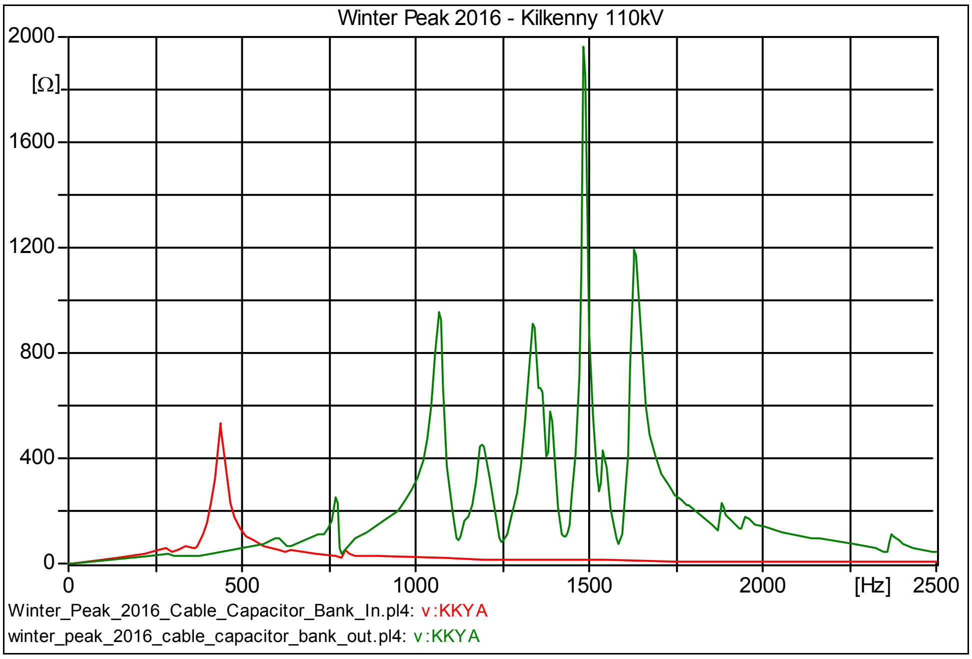


Figure 5.22: Kilkenny 110kV Busbar (CABLE)

5.3 Harmonics Summary

The purpose of the harmonic study was to determine the affect that the installation of both a 110kV cable circuit and a 110kV OHL circuit between Laois and Ballyragget would have on the frequency dependent driving point impedance at selected locations on the network. The locations chosen for the impedance - frequency plots where Kilkenny, Ballyragget, Laois and Portlaoise 110kV busbars. Impedance - Frequency Plots were carried out for the summer night valley and winter peak 2016 dispatches. The effect of switching the capacitor at Kilkenny in & out of service was also considered.

5.3.1 Summer Night Valley – Impedance - Frequency Plots

In the case of the impedance - frequency plot for Portlaoise, the main resonant conditions which occurred for both the cable and the OHL were near the 22nd, 30th, between the 36-38th and the 46th harmonic frequencies. The effect of the capacitor to shift the resonant conditions towards the lower harmonic frequencies was also observed. It was also observed that the cable resulted in the magnitude of the resonant condition which occurred near the 46th harmonic frequency to increase in magnitude.

In the case of the impedance - frequency plot for Laois, the main resonant conditions which occurred for both the cable and the OHL were near the 15th, 31st, between the 36-38th and the 46th harmonic frequencies. The effect of the capacitor to shift the resonant conditions towards the lower harmonic frequencies was also observed.

In the case of the impedance - frequency plot for Ballyragget, the main resonant conditions which occurred for the OHL (with Kilkenny Capacitor Bank out of service) were near the 18th, 25th, 28th and 46th harmonic frequencies. When the capacitor bank is in service, the resonant conditions at the 18th, 25th and 28th harmonic frequencies are no longer prominent. However, the resonant condition near the 46th harmonic frequency increased in magnitude with the capacitor bank in service. In the case of the cable it was observed that resonant conditions occurred near the 15th, 20th, 25th, 28th, 38th and 47th harmonic frequencies when the capacitor bank is out of service. When the capacitor bank is in service, the resonant conditions near the 15th, 20th 25th and 28th harmonic frequencies are no longer prominent. When the capacitor bank is in service, resonant conditions occur near the 30th, 37th and 47th harmonic frequencies. However, the resonant condition near the 47th harmonic frequency increased in magnitude with the capacitor bank in service.

In the case of the impedance - frequency plot for Kilkenny, the main resonant conditions which occurred for the OHL were near the 18th, 25th and 28th harmonic frequencies when the capacitor bank is out of service. Resonant conditions which are smaller in magnitude occur near the 11th, 14th, 22nd, 27th, 31st and 46th harmonic frequencies. When the capacitor bank is in service, a resonant condition occurs near the 7th harmonic frequency only. In the case of the cable it was observed that resonant conditions occurred near the 20th, 25th, 27th, 28th and 32nd harmonic frequencies when the capacitor bank is out of service. Resonant conditions which are smaller in magnitude occur near the 11th, 14th, 22nd, 36th and 46th harmonic frequencies. When the capacitor bank is in service, a resonant condition occurs near the 7th harmonic frequency only.

5.3.2 Winter Peak – Impedance - Frequency Plots

In the case of the impedance - frequency plot for Portlaoise, the main resonant conditions which occurred for both the cable and the OHL were near the 15th, 23rd, 30th, between the 37th, 39th and the 46th harmonic frequencies. The effect of the capacitor to shift the resonant conditions towards the lower harmonic frequencies was also observed. It was also observed that the cable resulted in the magnitude of the resonant condition which occurred near the 46th harmonic frequency to increase in magnitude.

In the case of the impedance - frequency plot for Laois, the main resonant conditions which occurred for the OHL were near the 15th, 24th, 31st, 32nd, 37th, 39th and 46th harmonic frequencies. It can also be observed that the resonant condition which occurs near the 46th harmonic frequency shifts towards the 47th harmonic frequency when the capacitor at Kilkenny is out of service. In the case of the cable it was observed that resonant conditions occurred near the 15th, 24th, 31st, 32nd, 37th, 39th and 46th harmonic frequencies for the capacitor bank in & out of service at Kilkenny.

In the case of the impedance - frequency plot for Ballyragget, the main resonant conditions which occurred for the OHL were near the 15th, 20th, 24th, 26th, 28th, 32nd and 46th harmonic frequencies when the capacitor bank is out of service. When the capacitor bank is in service, the resonant conditions at the 15th, 20th, 24th, 26th and 28th harmonic frequencies are no longer prominent. However, the resonant condition near the 46th harmonic frequency increased in magnitude with the capacitor bank in service. In the case of the cable it was observed that resonant conditions occurred near the 15th, 20th, 24th, 26th, 28th, 32nd, 39th and 46th harmonic frequencies. When the capacitor bank is in service, the resonant conditions at the 15th, 20th 24th, 26th and 28th harmonic frequencies are no longer as prominent. However, the resonant conditions near the 37th, 39th harmonic frequencies have become more prominent with the capacitor bank in service.

In the case of the impedance - frequency plot for Kilkenny, the main resonant conditions which occurred for the OHL were near the 15th, 20th, 24th, 26th, 29th, 32nd and 46th harmonic frequencies when the capacitor bank is out of service. When the capacitor bank is in service, a resonant condition occurs near the 7th harmonic frequency only. In the case of the cable it was observed that resonant conditions occurred near the 15th, 20th, 24th, 26th, 29th, 32nd and 46th harmonic frequencies when the capacitor bank is out of service. When the capacitor bank is in service, a resonant condition occurs near the 7th harmonic frequency only.

5.3.3 Conclusions

It was observed that the capacitor bank at Kilkenny has a significant effect on the impedance - frequency plots. This is to be expected as capacitive devices (Cables, Capacitor banks, SVC's etc) tend to have a large effect on resonant conditions. For a number of the Impedance - Frequency Plots it could be observed that the resonant conditions which occurred when the capacitor was out of service shifted towards the lower harmonic frequencies when the capacitor was in service. In the case of Kilkenny 110kV busbar, it was found that when the capacitor bank was in service, the only observable resonant condition was at the 7th harmonic (Summer and Winter Dispatches).

A number of general comments can be made in regards to the effect of HV underground cables on Harmonics. HV underground cables tend to have a relatively larger shunt capacitance compared to overhead lines which make them able to participate more in resonant scenarios [7]. Furthermore, as cables have a larger capacitance than OHLs, the resonance frequencies will be at lower frequencies than in OHL based grids, and thus more likely to be a problem for the grid [8]. Inserting a long AC cable into the transmission system can also change the characteristic of the impedance of the network because of the large capacitance of cable.

It should be noted that the impedance - frequency plot only reveals a small part of the overall picture in regards to harmonics. The cable would also have a significant impact on the flow of existing harmonics in the power system. The low impedance of a cable at harmonic frequencies will tend to attract additional harmonic current flow in the vicinity of the cable. This could have the potential to increase the harmonic distortion at the local busbars beyond the IEC limits. In order to determine if the proposed Laois – Ballyragget UGC would increase the harmonic distortion at the local busbars beyond IEC limits, a harmonic load flow should be carried out. Harmonic load flow calculations were not performed in this report.

The use of ancillary equipment with the cable was not investigated, however the problems highlighted may necessitate mitigative action upon the connection of a generator or load containing harmonic currents at any of the aforementioned resonant frequencies.

Finally, it can be concluded that, in general, the cable would have a more detrimental effect on the harmonic distortion levels in the area.

6 Conclusions

6.1 Power Flow Studies

The power flow studies showed that the loading of the cable was greater than the overhead line for both minimum and maximum system loading. This was to be expected as the impedance of the cable is considerably less than the overhead line. It was also observed that the cable generated approximately 32MVARs at rated voltage. This resulted in an increase in the system bus voltages at Laois, Ballyragget and Kilkenny.

6.2 Short Circuit Studies

The short circuit study showed that the UGC yielded higher values for the both the peak make and the total rms break current values. This is to be expected as the impedance of the UGC is significantly lower that that of the OHL. However, it should be noted that the short circuit results for both the OHL and UGC are within the transmission system design limits as specified in the transmission grid code.

6.3 Electromagnetic Studies

Studies have shown that overvoltage associated with the cable circuit are significantly higher than the overhead line circuit. However it should be noted that the results for both overhead line and cable are within the limits provided by Eirgrid (420kV peak line to ground).

6.4 Harmonic Study

The harmonic study showed that the UGC tended to increase the magnitude of the resonant conditions which occurred near the lower harmonic frequencies. This is to be expected as the capacitive effect of the cable tends to shift resonant conditions towards the lower harmonic frequencies. It was observed that the capacitor bank at Kilkenny has a significant effect on the impedance scans. In the case of Kilkenny 110kV busbar, it was found that when the capacitor bank was in service, the only observable resonant condition was at the 7th harmonic (Summer and Winter Dispatches).

It should be noted that the impedance - frequency plot only reveals a small part of the overall picture in regards to harmonics. The cable would also have a significant impact on the flow of existing harmonics in the power system. The low impedance of a cable at harmonic frequencies will tend to attract additional harmonic current flow in the vicinity of the cable. This could have the potential to increase the harmonic distortion at the local busbars beyond the IEC limits.

The use of ancillary equipment with the cable was not investigated, however the problems highlighted may necessitate mitigative action upon the connection of a generator or load containing harmonic currents at any of the aforementioned resonant frequencies. As the cable increases the size of these resonant conditions and shifts them to the lower harmonic frequencies. It can be concluded that, in general, the cable would have a more detrimental effect on the harmonic distortion levels in the area.

References

[1] Eirgrid Transmission Forecast Statement 2010 – 2016

[2] Eirgrid Grid Code V3.4, October 16th 2009

[3] IEC standard 60909-0-2001 “Short circuit currents in three phase a.c. systems”

[4] R. Willhem, M. Watters, “Neutral Grounding in High Voltage Transmission” Elsevier, 1956, *pg 294*

[5] L.Prickler “Electromagnetic Transient Program ATP-EMTP, ATP Draw for Insulation Co-ordination Studies”, Feb 2008

[6] S Papathanassiou, M.Papadopoulos, “A Study Case On Harmonic Distortion Created by Wind Turbines”

[7] S. Rahimi, *Student Member, IEEE*, W. Wiechowski, M. Randrup, J. Østergaard and A. H. Nielsen, “Identification of Problems when Using Long High Voltage AC Cable in Transmission System II: Resonance & Harmonic Resonance

[8] F. Faria da Silva, Claus L. Bak, Wojciech T. Wiechowski, “Study of High Voltage AC Underground Cable Systems”

[9] IEEE Task Force on Harmonic Modeling and Simulation, “Modeling and Simulation of the Propogation of Harmonics in Electric Power Networks, Part I: Concepts, Models, and Simulation Techniques”

[10] IEEE Task Force on Harmonic Modeling and Simulation, “Modeling and Simulation of the Propogation of Harmonics in Electric Power Networks, Part II: Sample Systems and Examples”

Appendices

Appendix A Short Circuit Results

Summer Night Valley 2016 Overhead Line

```
 PSS(tm)E IEC 60909 SHORT CIRCUIT CURRENTS          MON, AUG 30 2010  19:42
             / CASE: 2016;  SUMMER 01/07/2016; FORECAST STATEMENT 2010 -
             / FS10_NOV 09 - MEMO  GALLERY_T;  20:55:22  MONDAY, DECEMBER
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP      DEG       AMP       AMP       AMP       AMP       AMP
  4481 [PORTLAOI    110.00] 3PH    2042.43   10720.0   -78.41   23495.2   23791.2     379.3   10719.9   10726.6
                             LG    1878.21    9858.0   -79.99   22265.6   22496.6     -        9858.0     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.009147+j0.069623, 7.611365  Z+: 0.010817+j0.052760, 4.877349  Z-: 0.010578+j0.050641, 4.787556
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP      DEG       AMP       AMP       AMP       AMP       AMP
  3551 [LAOIS       110.00] 3PH    2202.61   11560.7   -81.34   26824.6   27531.1    4456.3   11560.5   12389.6
                             LG    2853.60   14977.5   -81.66   34974.5   35769.2     -       14977.5     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.001810+j0.017465, 9.647957  Z+: 0.007516+j0.049372, 6.569309  Z-: 0.007454+j0.047582, 6.383550
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP      DEG       AMP       AMP       AMP       AMP       AMP
  1431 [BALLYRAG    110.00] 3PH    1175.29    6168.7   -78.58   13561.5   13724.9     218.8    6168.7    6172.5
                             LG     893.15    4687.8   -80.57   10709.4   10784.6     -        4687.8     -
THEVENIN IMPEDANCE (PU), X/R

Z0: 0.023570+j0.183063, 7.766822  Z+: 0.018536+j0.091740, 4.949406  Z-: 0.018439+j0.089682, 4.863717
```

```
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA       AMP      DEG       AMP       AMP       AMP       AMP       AMP
  1221 [ATHY        110.00] 3PH    1272.66    6679.7   -74.08   13570.3   13762.3      34.8    6679.5    6679.6
                             LG    1063.17    5580.2   -77.37   11997.4   12131.6     -        5580.2     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.020619+j0.138637, 6.723699  Z+: 0.023705+j0.083119, 3.506382  Z-: 0.023561+j0.081121, 3.443065
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA       AMP      DEG       AMP       AMP       AMP       AMP       AMP
  3261 [KILKENNY    110.00] 3PH    1270.23    6667.0   -75.51   13873.2   14146.2      89.5    6666.9    6667.5
                             LG    1173.79    6160.8   -78.99   13648.8   13871.4     -        6160.8     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.010529+j0.110663, 10.510307  Z+: 0.021665+j0.083845, 3.870038  Z-: 0.021521+j0.081454, 3.784911
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.050000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA       AMP      DEG       AMP       AMP       AMP       AMP       AMP
  3554 [LAOIS       380.00] 3PH    3474.69    5279.2   -86.19   13438.8   13647.2    2978.0    5279.2    6061.2
                             LG    3910.71    5941.7   -86.12   15125.1   15385.6     -        5941.7     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.001571+j0.022255, 14.169531  Z+: 0.002103+j0.031588, 15.022322  Z-: 0.002032+j0.030348, 14.933805
---------------------------------------------------------------------------------------------------------------
```

Summer Night Valley 2016 Cable

```
       PSS(tm)E IEC 60909 SHORT CIRCUIT CURRENTS          MON, AUG 30 2010  19:50
              / CASE: 2016;  SUMMER 01/07/2016; FORECAST STATEMENT 2010 -
              / FS10_NOV 09 - MEMO  GALLERY_T;  20:55:22  MONDAY, DECEMBER
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP      DEG       AMP       AMP       AMP       AMP       AMP
  3551 [LAOIS       110.00] 3PH    2255.11   11836.3   -81.16   27359.1   28067.4    4438.6   11836.0   12640.9
                             LG    2919.84   15325.2   -81.45   35632.2   36436.7     -       15325.2     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.001874+j0.017163, 9.160549  Z+: 0.007500+j0.048198, 6.426414  Z-: 0.007439+j0.046402, 6.237918
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP      DEG       AMP       AMP       AMP       AMP       AMP
  1431 [BALLYRAG    110.00] 3PH    1649.98    8660.1   -77.48   18658.7   18954.1     310.1    8660.0    8665.6
                             LG    1785.69    9372.4   -64.90   16705.0   17806.8     -        9372.4     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.049598+j0.039068, 0.787694  Z+: 0.014448+j0.065083, 4.504634  Z-: 0.014361+j0.063195, 4.400425
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP      DEG       AMP       AMP       AMP       AMP       AMP
  3261 [KILKENNY    110.00] 3PH    1424.67    7477.6   -75.88   15657.7   15915.7      99.8    7477.4    7478.1
                             LG    1339.80    7032.1   -77.69   15209.3   15535.1     -        7032.1     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.014936+j0.093127, 6.235013  Z+: 0.018842+j0.074877, 3.974008  Z-: 0.018716+j0.072642, 3.881227
```

```
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP     DEG       AMP       AMP       AMP       AMP       AMP
  1221 [ATHY        110.00] 3PH    1273.57    6684.5   -74.07   13576.5   13768.9      34.8    6684.3    6684.4
                             LG    1063.66    5582.8   -77.36   12001.1   12135.5     -         5582.8     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.020621+j0.138617, 6.722240  Z+: 0.023711+j0.083053, 3.502701  Z-: 0.023566+j0.081060, 3.439707
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP     DEG       AMP       AMP       AMP       AMP       AMP
  4481 [PORTLAOI    110.00] 3PH    2064.30   10834.8   -78.23   23664.1   23968.0     374.6   10834.7   10841.2
                             LG    1891.19    9926.2   -79.87   22368.9   22605.8     -         9926.2     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.009171+j0.069553, 7.584043  Z+: 0.010874+j0.052166, 4.797487  Z-: 0.010636+j0.050056, 4.706322
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.050000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP     DEG       AMP       AMP       AMP       AMP       AMP
  3554 [LAOIS       380.00] 3PH    3484.41    5294.0   -86.19   13476.4   13684.2    2980.5    5294.0    6075.3
                             LG    3918.34    5953.3   -86.12   15154.6   15415.0     -         5953.3     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.001570+j0.022259, 14.176305  Z+: 0.002097+j0.031499, 15.022681  Z-: 0.002026+j0.030268, 14.937483
---------------------------------------------------------------------------------------------------------------
```

Winter Peak 2016 Overhead Line

```
       PSS(tm)E IEC 60909 SHORT CIRCUIT CURRENTS          MON, AUG 30 2010  19:55
              / CASE: 2016/2017;  WINTER 01/12/2016; FORECAST STATEMENT 20
              / FS10_NOV 09 - MEMO  GALLERY_T;  16:44:29  FRIDAY, DECEMBER
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP      DEG       AMP       AMP       AMP       AMP       AMP
  3551 [LAOIS       110.00] 3PH    2593.70   13613.4   -80.89   31301.6   32212.6    5165.6   13613.4   14560.5
                             LG    3249.60   17055.9   -81.38   39600.2   40564.8     -       17055.9     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.001809+j0.017461, 9.652670  Z+: 0.006713+j0.041876, 6.238325  Z-: 0.006707+j0.041066, 6.123051
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP      DEG       AMP       AMP       AMP       AMP       AMP
  1431 [BALLYRAG    110.00] 3PH    1415.71    7430.6   -79.61   16660.4   16904.6     617.1    7430.6    7456.2
                             LG     971.12    5097.1   -81.24   11802.5   11893.7     -        5097.1     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.023705+j0.183792, 7.753133  Z+: 0.014010+j0.076426, 5.455034  Z-: 0.014019+j0.075636, 5.395116
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP      DEG       AMP       AMP       AMP       AMP       AMP
  3261 [KILKENNY    110.00] 3PH    1840.51    9660.2   -78.36   21151.1   21847.7    2180.1    9434.3    9682.9
                             LG    1424.57    7477.0   -81.30   17332.9   17700.0     -        7477.0     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.010931+j0.112800, 10.318878  Z+: 0.012059+j0.058537, 4.854139  Z-: 0.012056+j0.057646, 4.781548
---------------------------------------------------------------------------------------------------------------
```

```
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                 /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA       AMP      DEG       AMP       AMP       AMP       AMP       AMP
  1221 [ATHY        110.00] 3PH    1417.15    7438.1   -73.01   14852.0   15045.8      21.5    7438.0    7438.0
                             LG    1131.46    5938.6   -77.05   12695.4   12831.0     -         5938.6     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.020023+j0.136558, 6.820114  Z+: 0.022679+j0.074234, 3.273280  Z-: 0.022659+j0.073448, 3.241524
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                 /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA       AMP      DEG       AMP       AMP       AMP       AMP       AMP
  4481 [PORTLAOI    110.00] 3PH    2342.54   12295.2   -77.40   26450.4   26786.3     266.6   12295.2   12298.0
                             LG    2021.80   10611.7   -79.56   23771.2   24015.6     -        10611.7     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.009179+j0.069907, 7.615747  Z+: 0.010243+j0.045827, 4.473831  Z-: 0.010141+j0.044788, 4.416355
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.050000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                 /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA       AMP      DEG       AMP       AMP       AMP       AMP       AMP
  3554 [LAOIS       380.00] 3PH    4403.00    6689.7   -86.31   17029.1   17330.4    3810.6    6689.7    7698.9
                             LG    4644.08    7056.0   -86.13   17961.5   18273.5     -         7056.0     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.001603+j0.021766, 13.582290  Z+: 0.001609+j0.024931, 15.494043  Z-: 0.001583+j0.024199, 15.284502
---------------------------------------------------------------------------------------------------------------
```

Winter Peak 2016 Cable

```
       PSS(tm)E IEC 60909 SHORT CIRCUIT CURRENTS          MON, AUG 30 2010  19:58
              / CASE: 2016/2017;  WINTER 01/12/2016; FORECAST STATEMENT 20
              / FS10_NOV 09 - MEMO  GALLERY_T;  16:44:29  FRIDAY, DECEMBER
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP      DEG       AMP       AMP       AMP       AMP       AMP
  3551 [LAOIS       110.00] 3PH    2706.81   14207.1   -80.75   32572.8   33485.7    5178.9   14206.9   15121.4
                             LG    3376.58   17722.4   -81.21   41010.4   41980.8     -       17722.4     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.001871+j0.017162, 9.171493  Z+: 0.006533+j0.040110, 6.139617  Z-: 0.006530+j0.039313, 6.020434
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP      DEG       AMP       AMP       AMP       AMP       AMP
  1431 [BALLYRAG    110.00] 3PH    1976.82   10375.6   -77.81   22486.4   22940.3     697.1   10375.6   10399.0
                             LG    2009.00   10544.5   -63.54   18493.1   19861.7     -       10544.5     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.049683+j0.039048, 0.785941  Z+: 0.011754+j0.054389, 4.627440  Z-: 0.011761+j0.053612, 4.558361
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP      DEG       AMP       AMP       AMP       AMP       AMP
  3261 [KILKENNY    110.00] 3PH    2016.69   10584.9   -78.28   23142.0   23810.9    2100.5   10358.9   10569.8
                             LG    1617.14    8487.8   -79.39   18949.1   19483.3     -        8487.8     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.015420+j0.094610, 6.135419  Z+: 0.011079+j0.053408, 4.820630  Z-: 0.011079+j0.052557, 4.743652
---------------------------------------------------------------------------------------------------------------
```

```
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP      DEG       AMP       AMP       AMP       AMP       AMP
  1221 [ATHY        110.00] 3PH    1422.56    7466.5   -72.99   14902.9   15095.4      20.9    7466.4    7466.4
                             LG    1133.84    5951.1   -77.04   12720.7   12855.7     -        5951.1     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.020024+j0.136539, 6.818733  Z+: 0.022624+j0.073942, 3.268340  Z-: 0.022604+j0.073157, 3.236423
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.080000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP      DEG       AMP       AMP       AMP       AMP       AMP
  4481 [PORTLAOI    110.00] 3PH    2386.13   12524.0   -77.15   26822.7   27160.9     255.1   12524.0   12526.5
                             LG    2044.03   10728.4   -79.43   23972.4   24219.3     -       10728.4     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.009202+j0.069837, 7.589073  Z+: 0.010250+j0.044946, 4.384913  Z-: 0.010151+j0.043926, 4.327218
---------------------------------------------------------------------------------------------------------------
                                  BREAKING CURRENT AT TIME =   0.050000 SECONDS
                                  <-SCMVA-> <-Sym I''k rms--> <-ip(B)-> <-ip(C)-> <-DC Ib-> <Sym Ib-> <Asym Ib>
                                                /I/    AN(I)      /I/       /I/       /I/       /I/       /I/
X---------- BUS ----------X          MVA        AMP      DEG       AMP       AMP       AMP       AMP       AMP
  3554 [LAOIS       380.00] 3PH    4425.72    6724.2   -86.34   17117.0   17430.7    3844.9    6724.2    7745.8
                             LG    4660.89    7081.5   -86.15   18026.5   18347.2     -        7081.5     -
THEVENIN IMPEDANCE (PU), X/R
Z0: 0.001603+j0.021763, 13.580129  Z+: 0.001585+j0.024804, 15.644783  Z-: 0.001561+j0.024075, 15.425342
---------------------------------------------------------------------------------------------------------------
```

Appendix B Cable Switching Study Models

Figure B1 Charged Cable Switching – Ballyragget

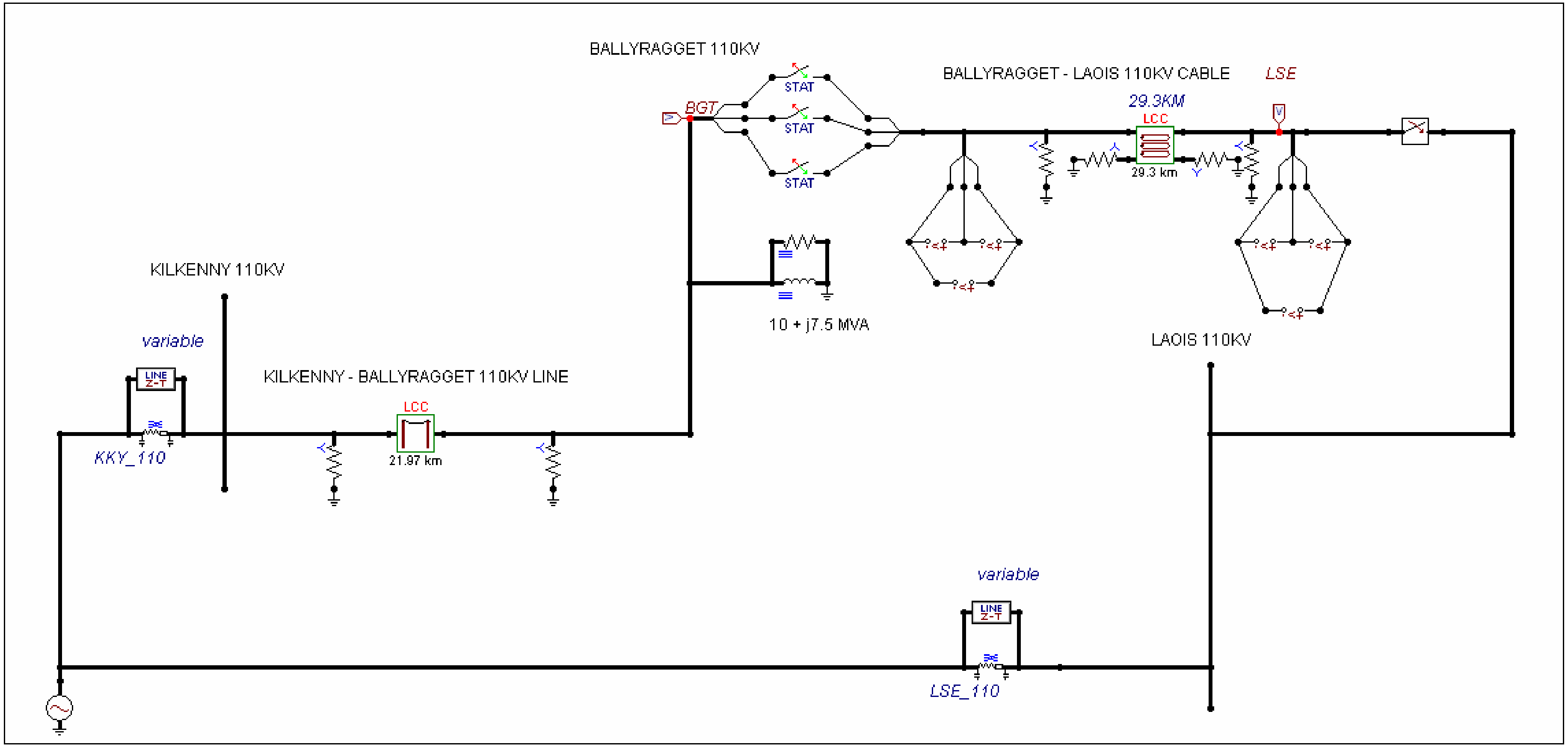


Figure B2 Charged Cable Switching – Laois

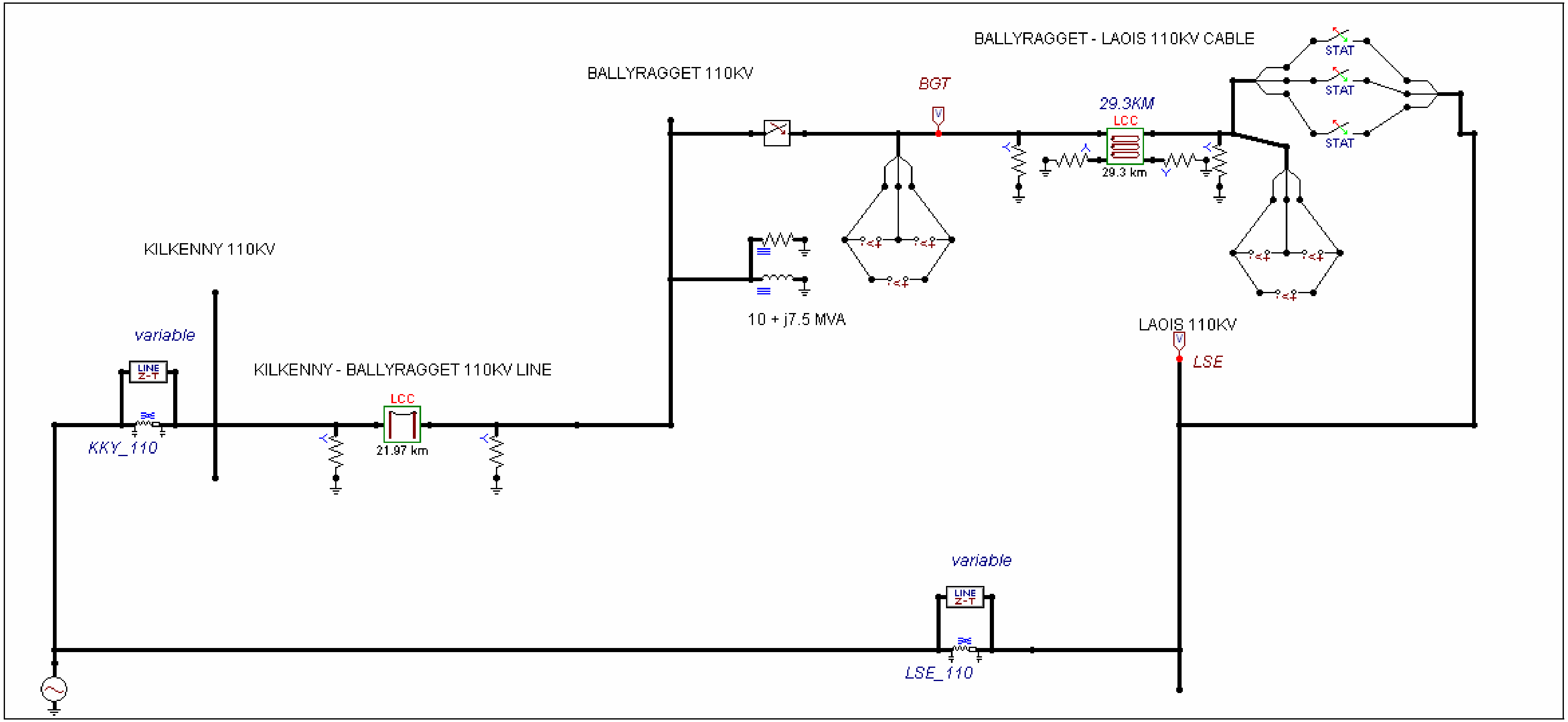


Figure B3 Cable Energisation - Ballyragget

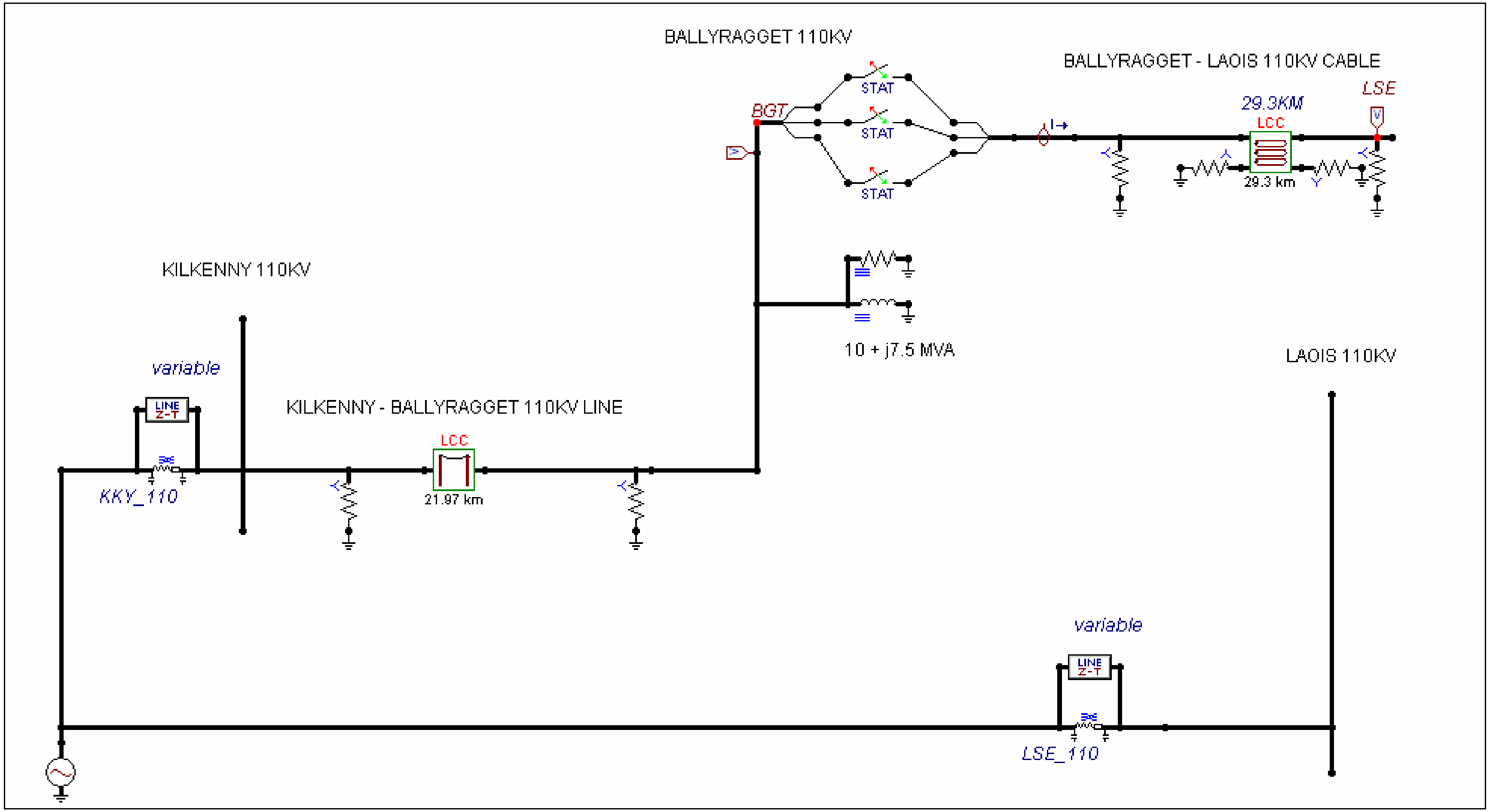


Figure B4 Cable Energisation – Laois

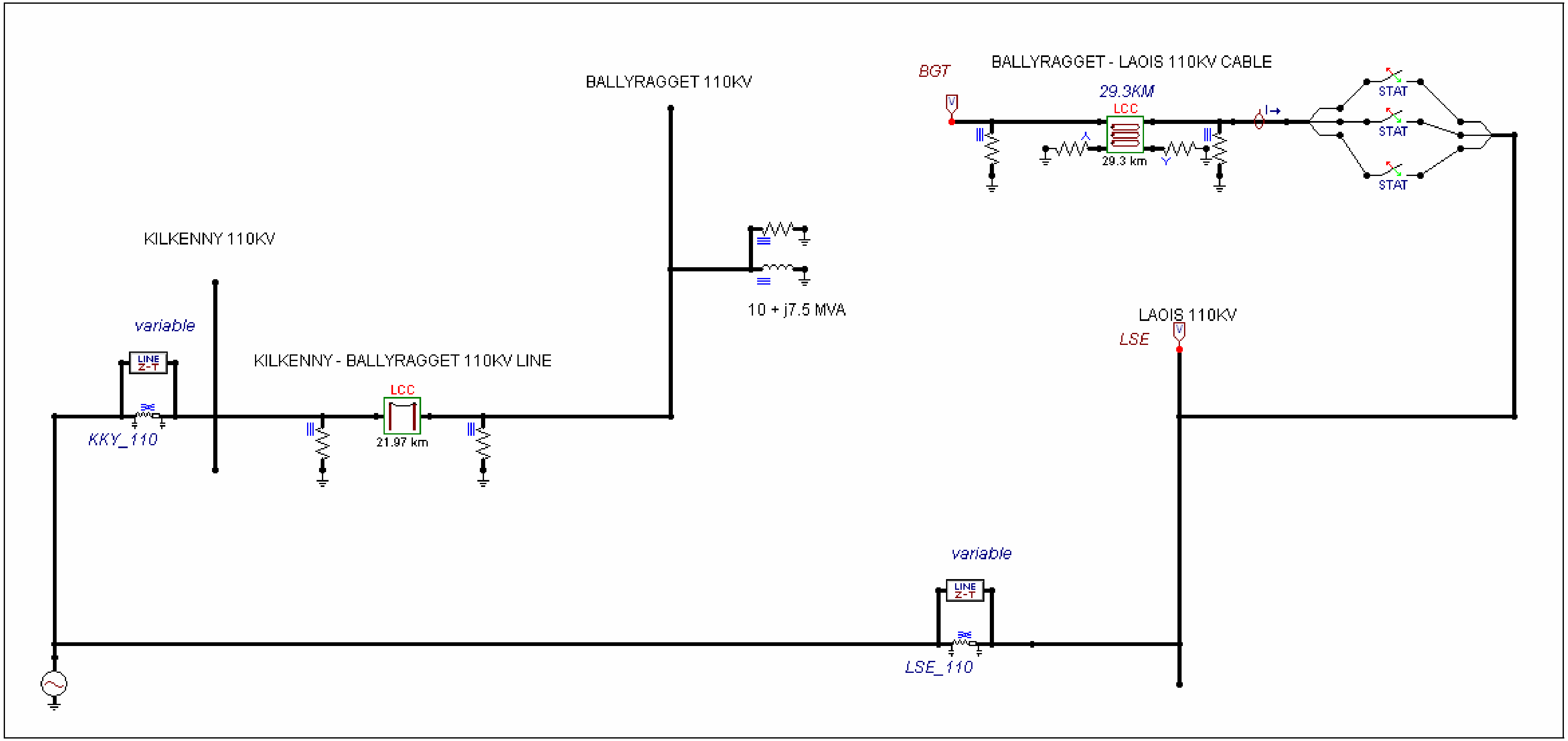


Figure B5 Cable De-Energisation - Ballyragget

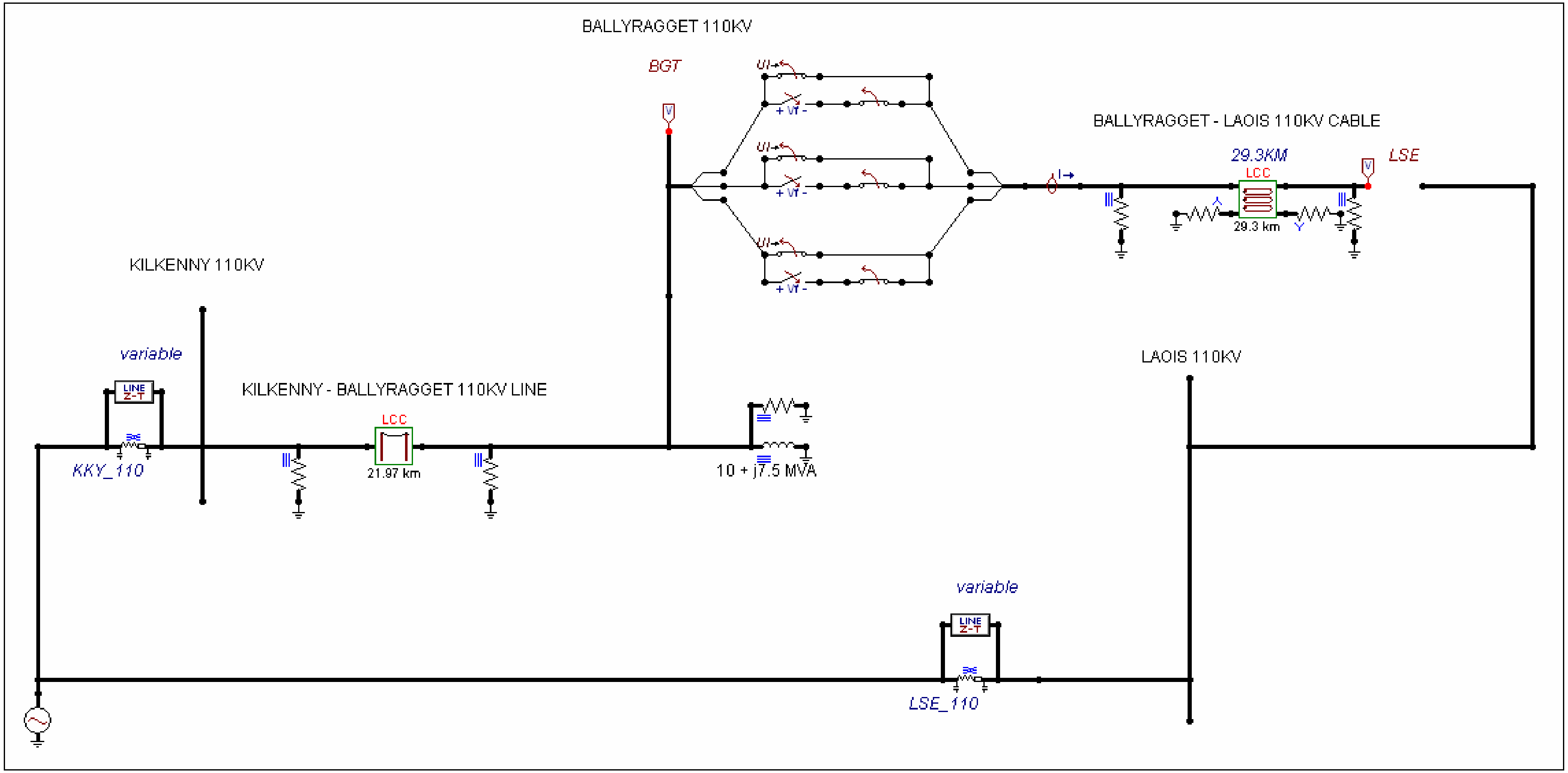


Figure B6 Cable De-Energisation – Laois

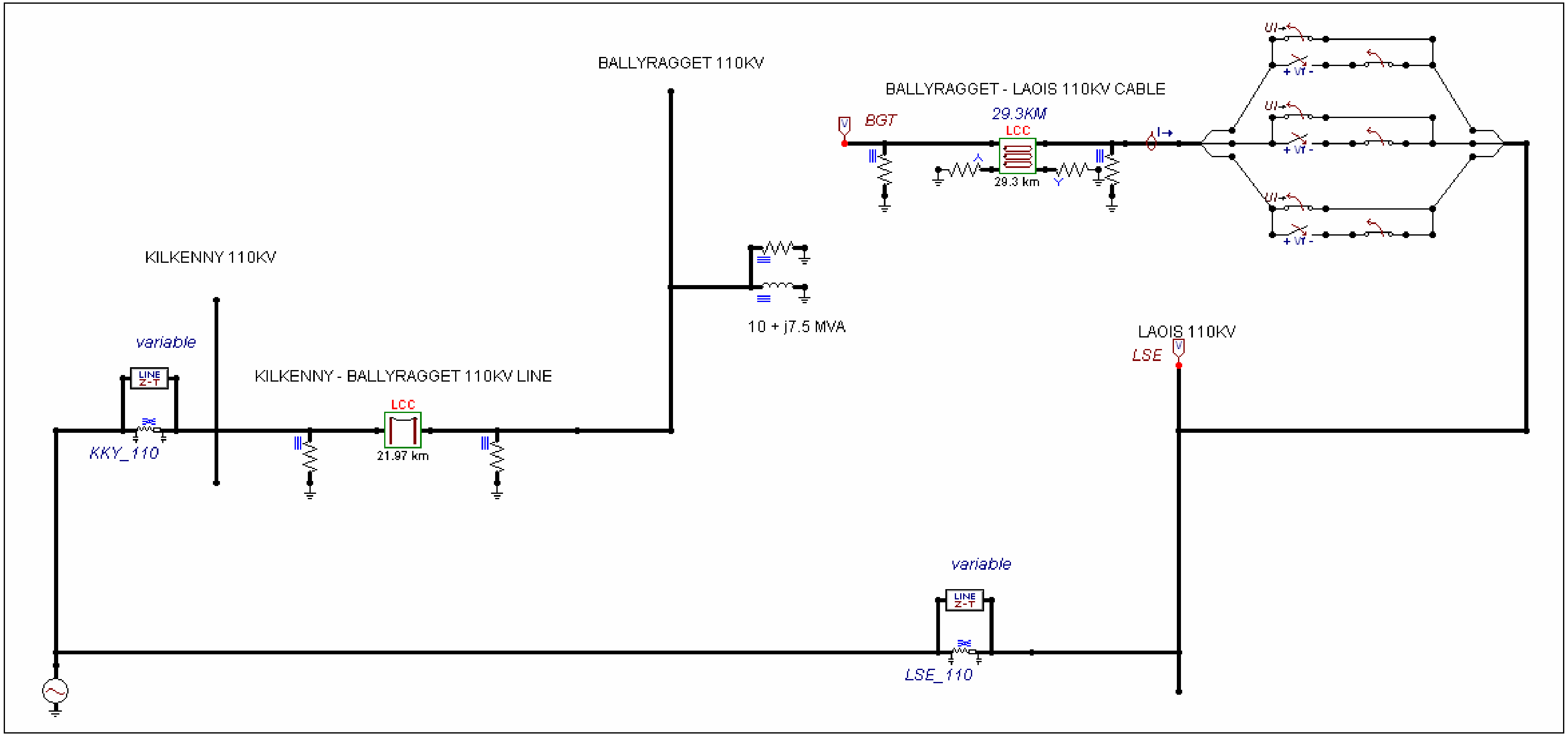


Figure B7 Cable Single Line to Ground Fault – Ballyragget

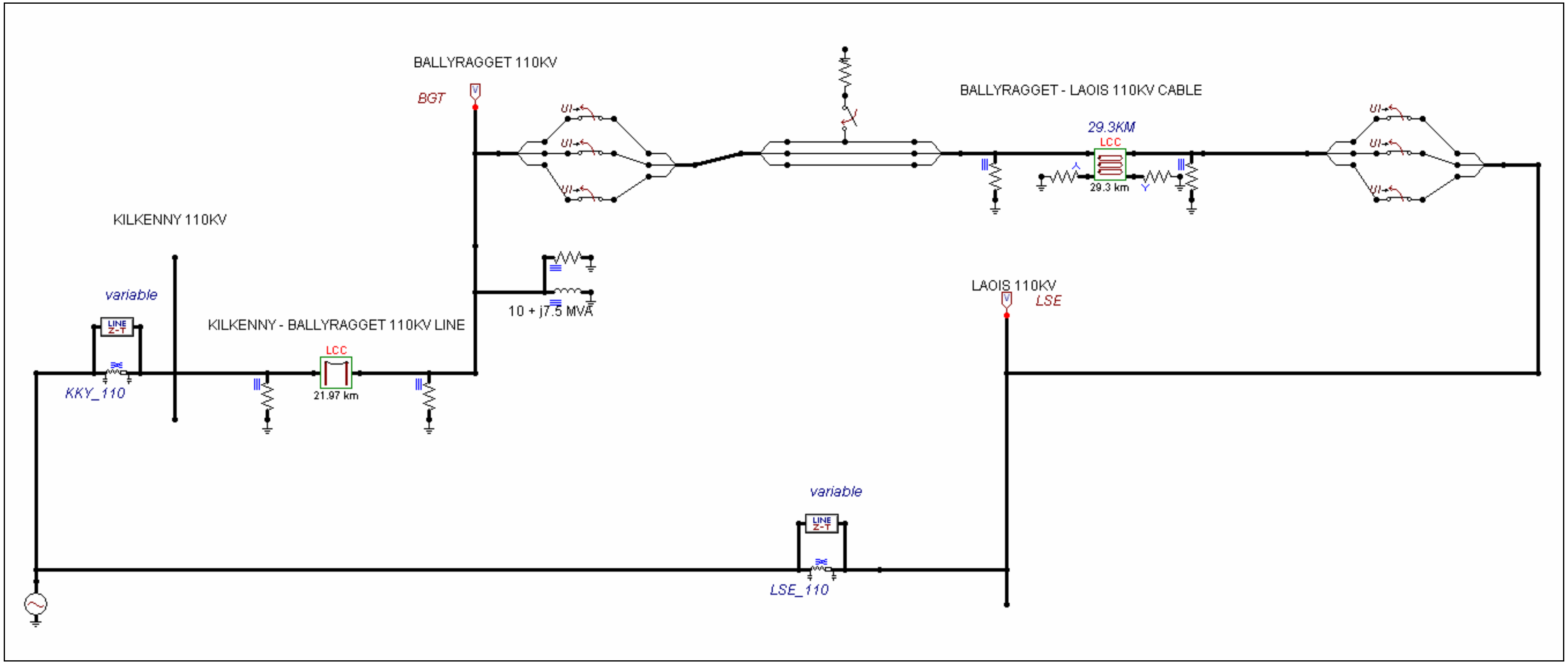


Figure B8 Cable Single Line to Ground Fault – Ballyragget (Restrike)

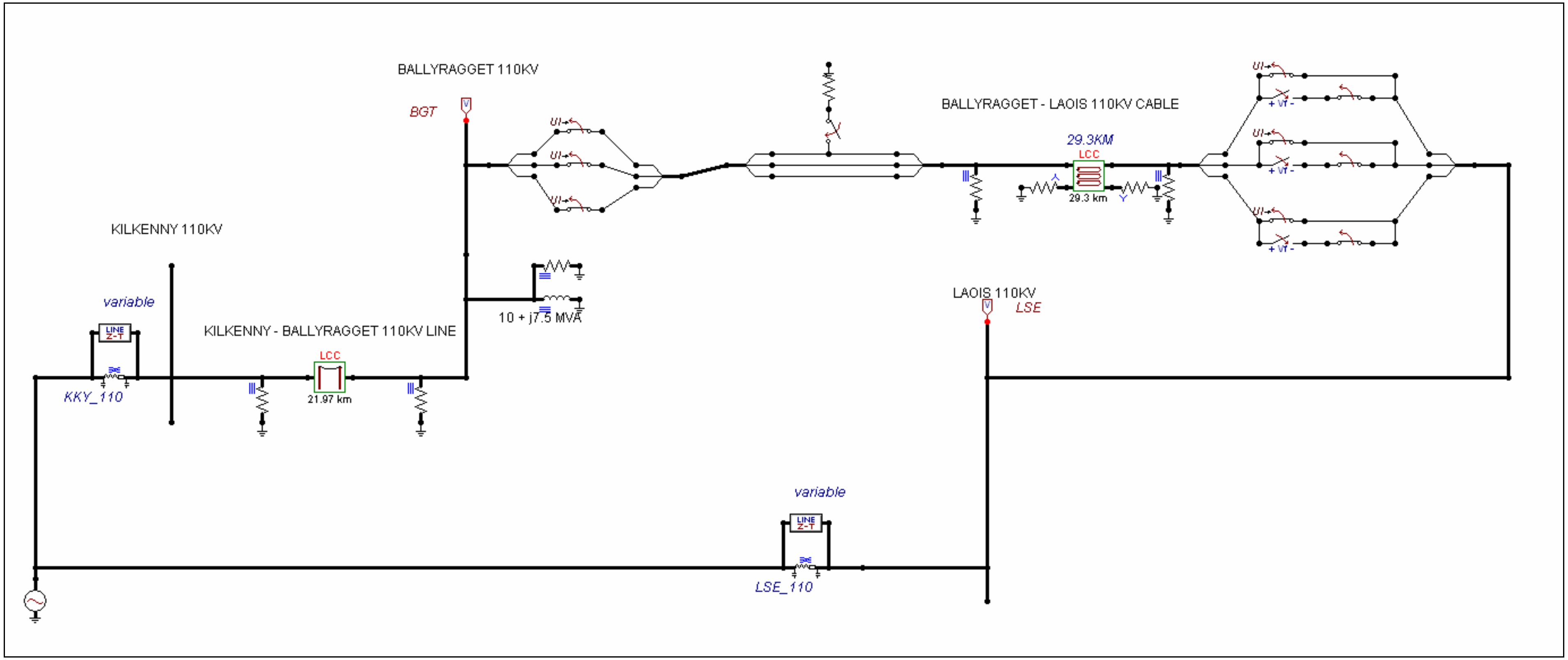


Figure B9 Cable Single Line to Ground Fault – Laois

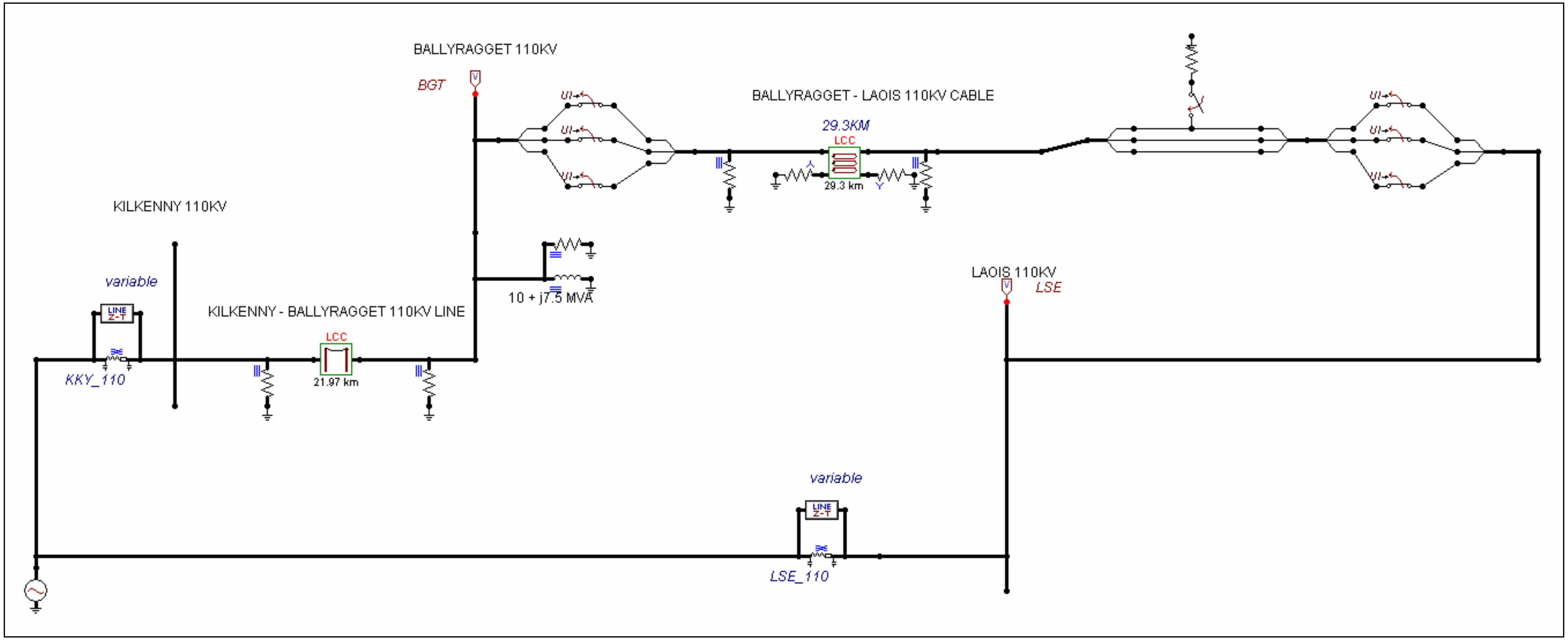
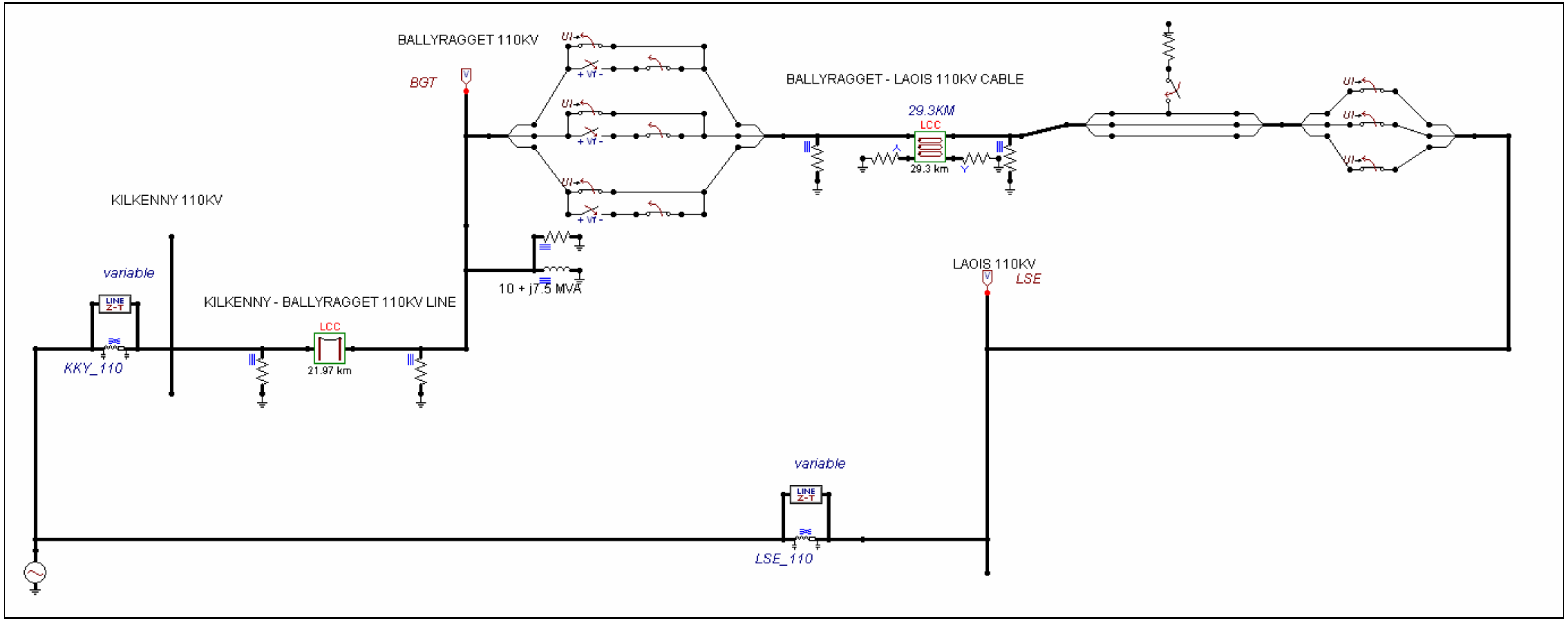


Figure B10 Cable Single Line to Ground Fault – Laois (Restrike)



Appendix C Overhead Line Switching Study Models

Figure C1 Energisation - Ballyragget

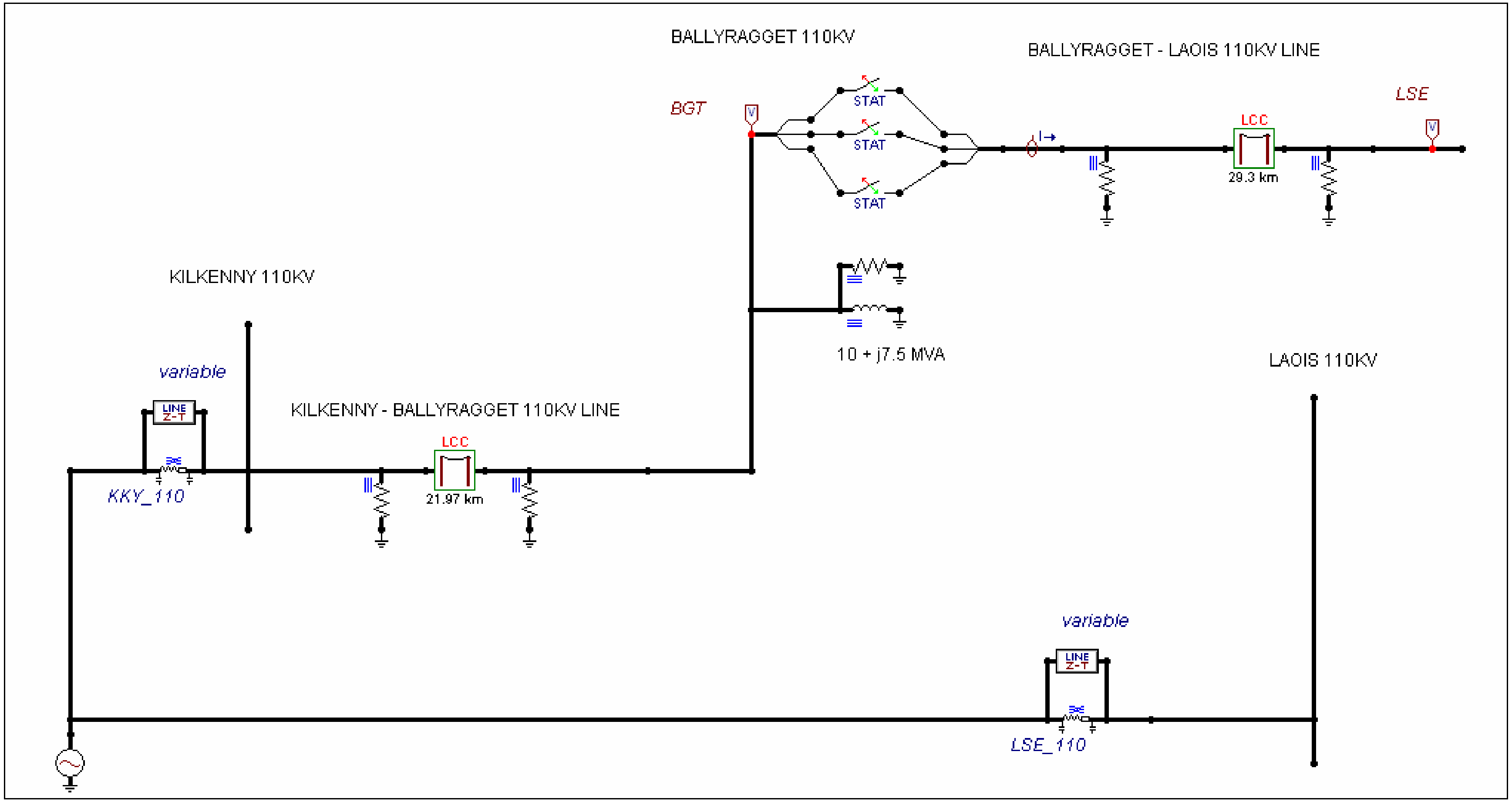


Figure C2 Energisation – Laois

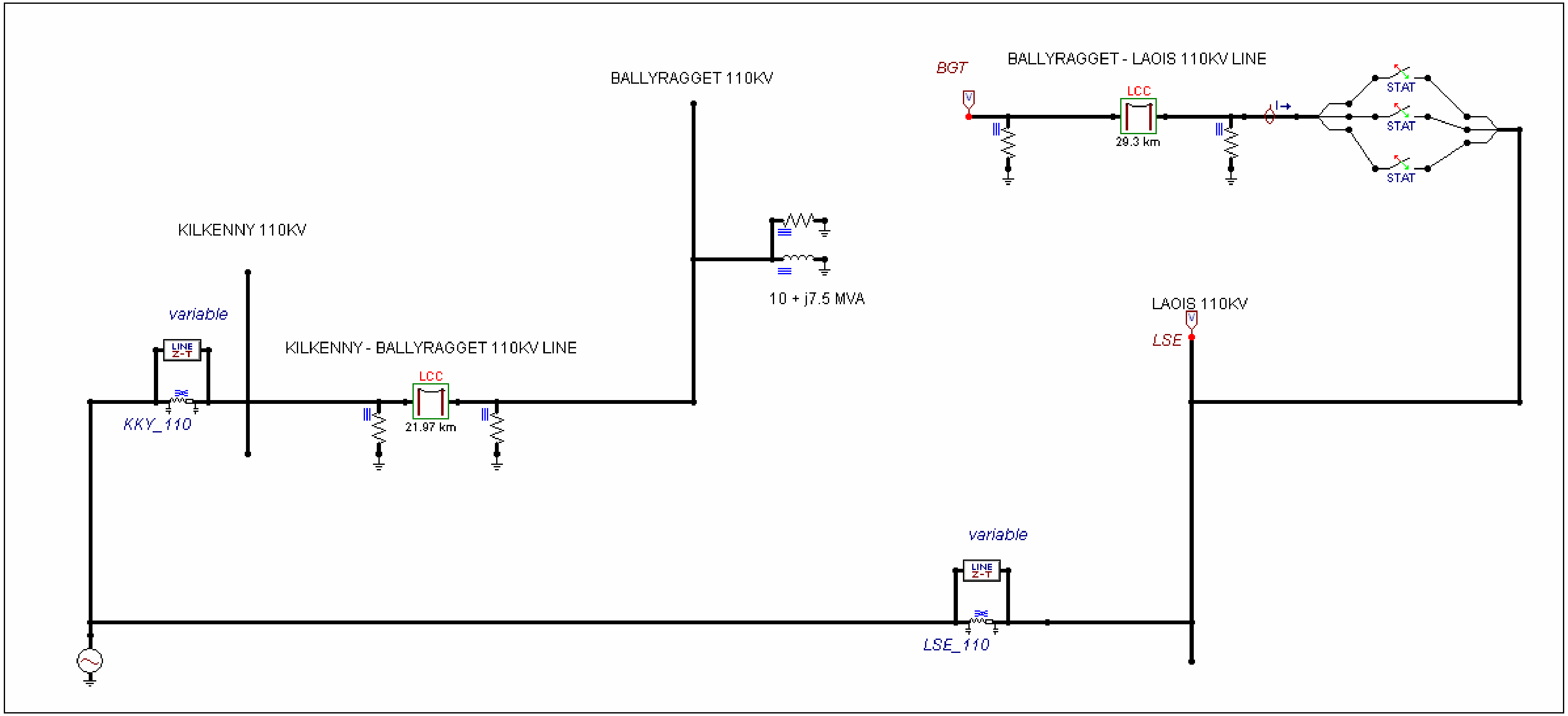


Figure C3 Single Line to Ground Fault – Ballyragget (No Restrike)

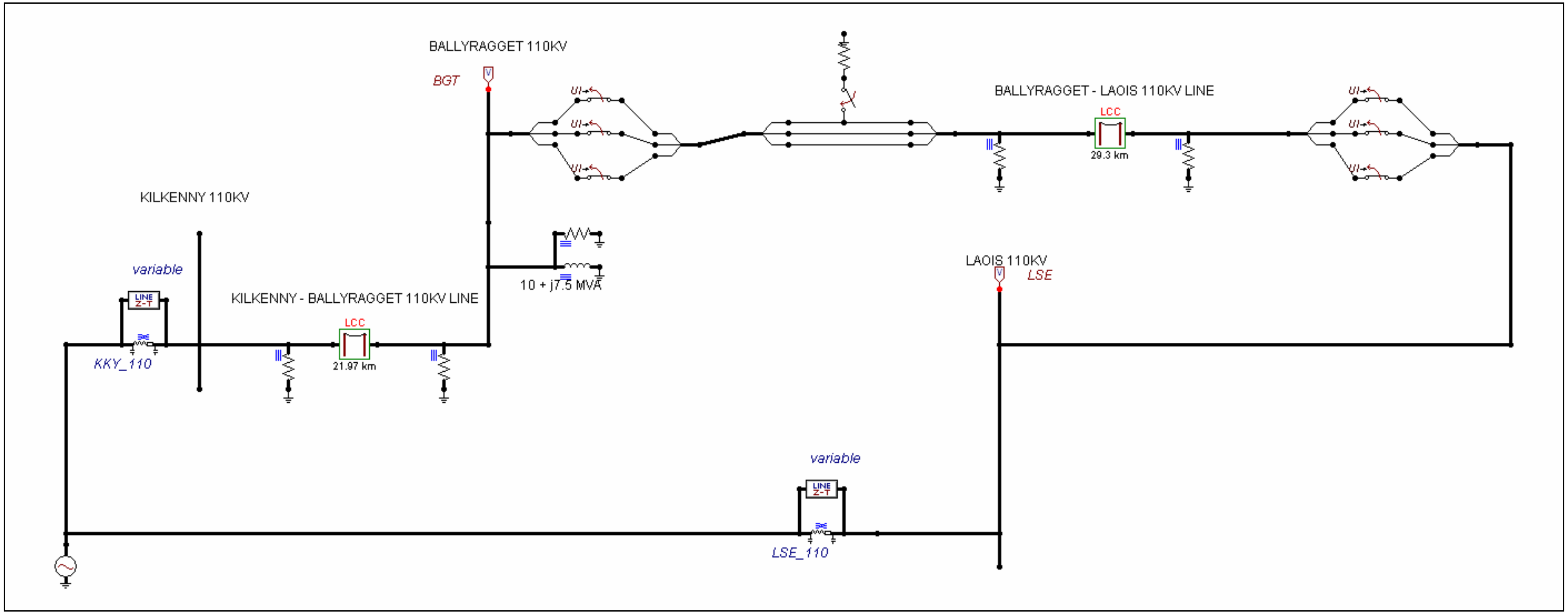


Figure C4 Single Line to Ground Fault – Laois (No –Restrike)

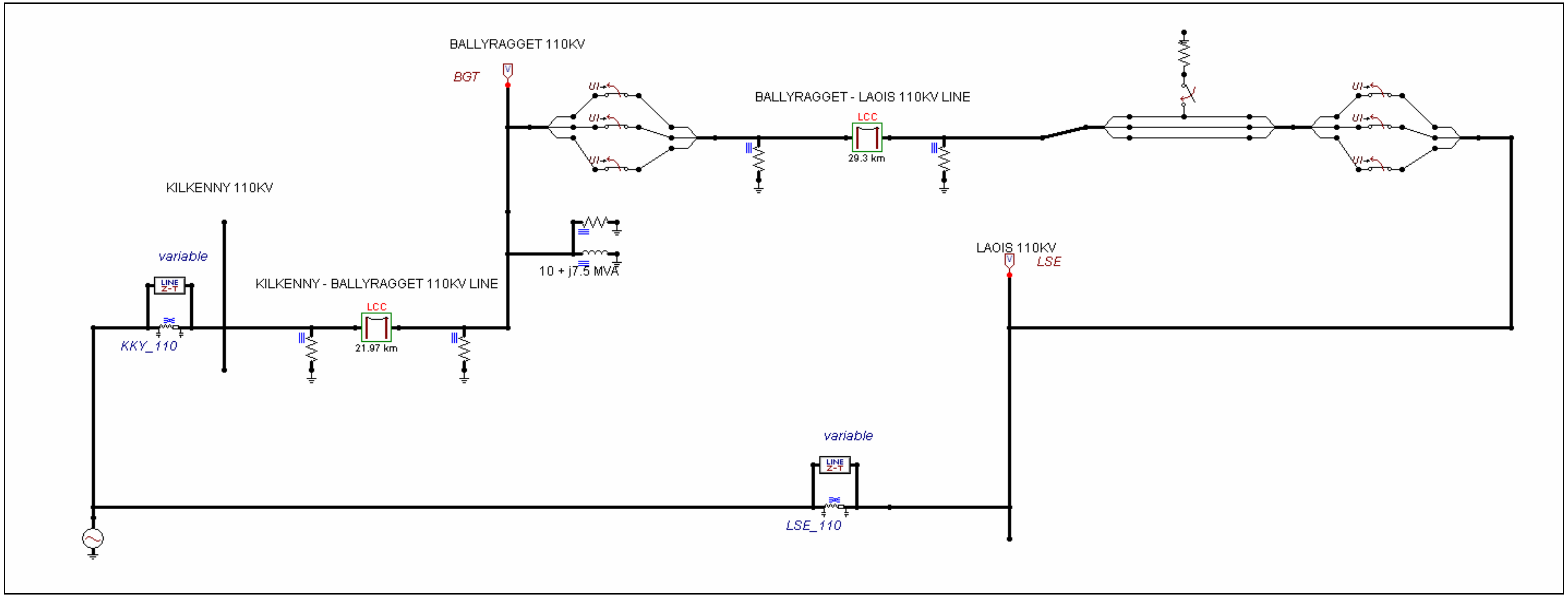


Figure C5 Three Phase Fault – Ballyragget

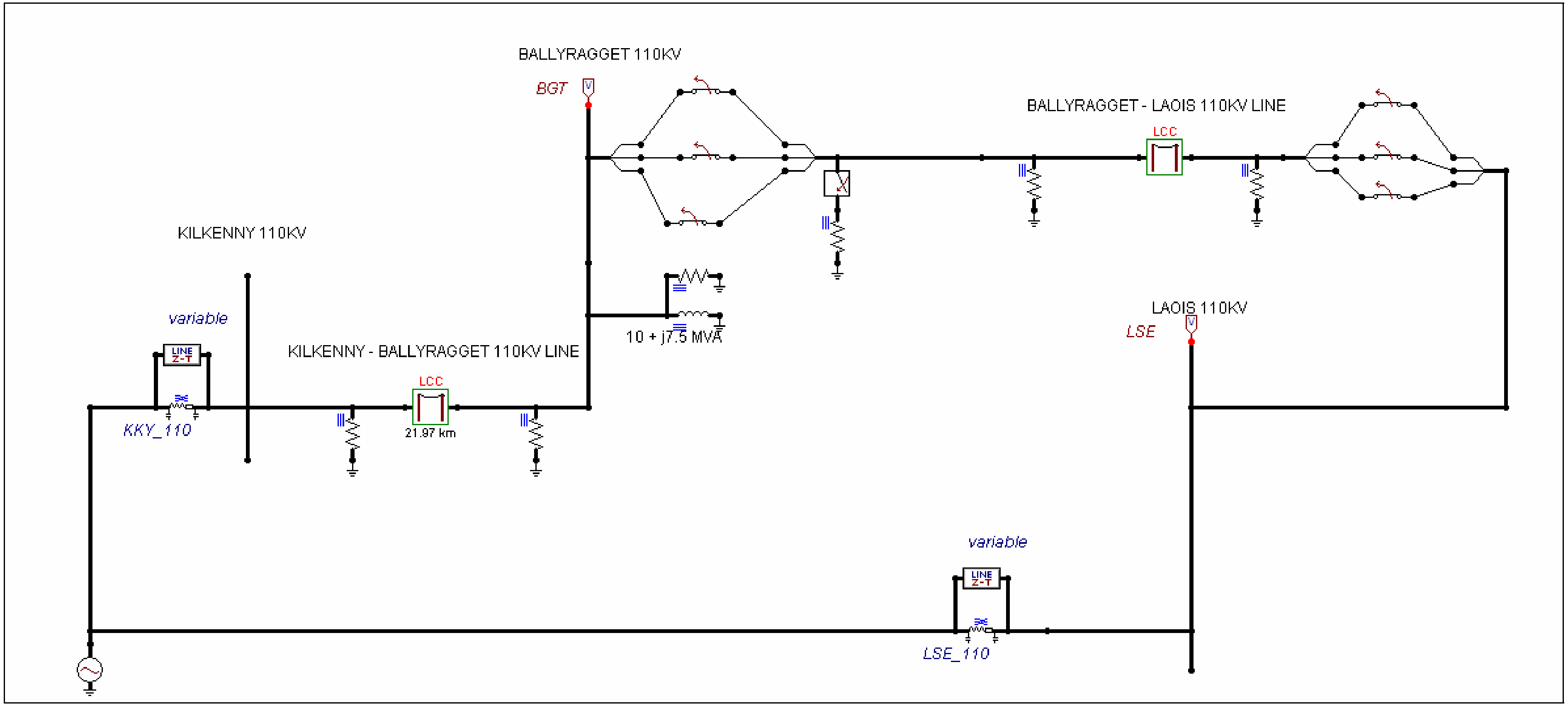
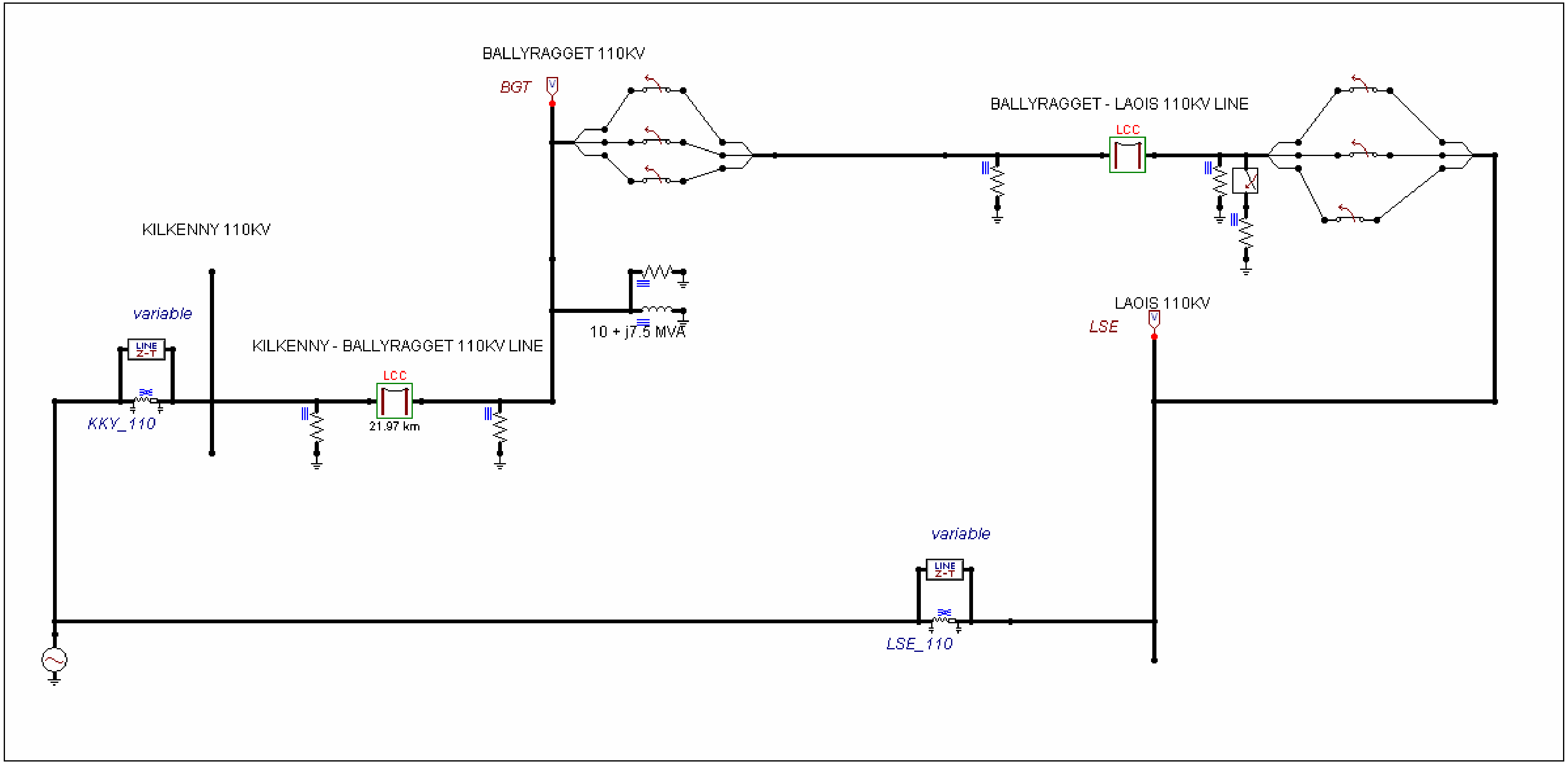
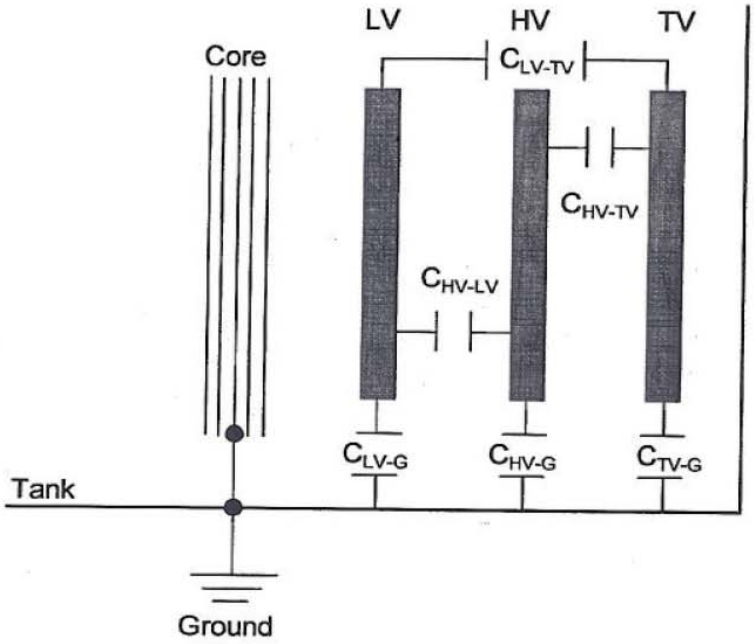


Figure C6 Three Phase Fault – Laois



Appendix D Transformer Energisation Data

Figure D1 Winding Capacitances and Dissipation Factors



Connection of Tettex	to test object	Test Mode	meas. Capacitance	C_x / nF	Dissipation factor corrected to 20°C tanδ / %
High volt.	HV				
Input A	LV	UST A	C_{HV-LV}	9.132	0.15
Input B	TV	UST B	C_{HV-TV}	20.14	0.17
HV-ground	Tank	GSTg A+B	C_{HV-G}	5.483	0.22
High volt.	LV				
Input A	HV				
Input B	TV	UST B	C_{LV-TV}	0.06327	0.31
HV-ground	Tank	GSTg A+B	C_{LV-G}	13.98	0.20
High volt.	TV				
Input A	HV				
Input B	LV				
HV-ground	Tank	GSTg A+B	C_{TV-G}	3.747	0.18

Table D1 Excitation Losses, Excitation Losses and Short Circuit Losses [5]

Voltage rating $V_{high}/V_{low}/V_{tertiary}$:		400/132/18 kV
Winding connection:		Yyn0d11
Power rating:		250 MVA (75 MVA tertiary)
Excitation losses:		140 kW
Excitation current:		0.2 %
Short circuit losses:	High to Low:	710 kW
	High to Tertiary:	188 kW
	Low to Tertiary:	159 kW

Graph D1 Saturation Curve – Graphical Representation [5]

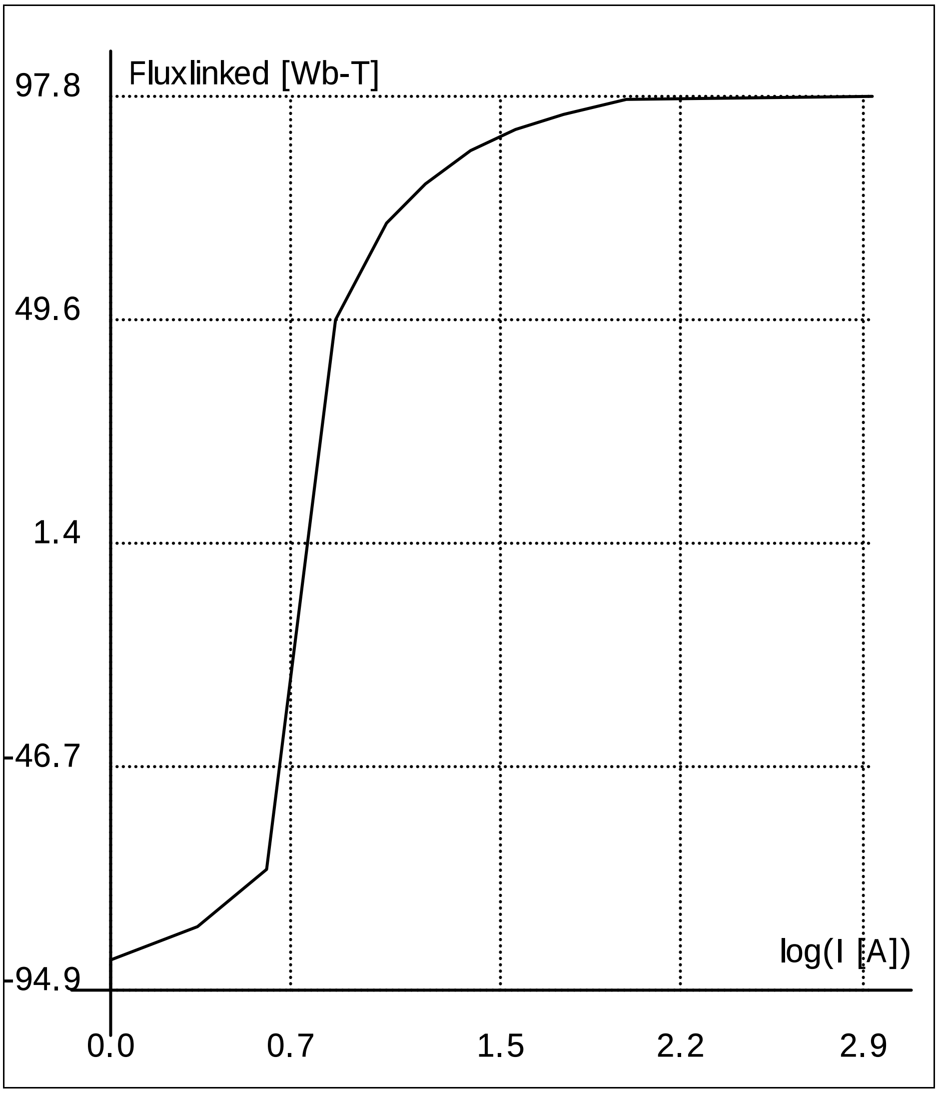
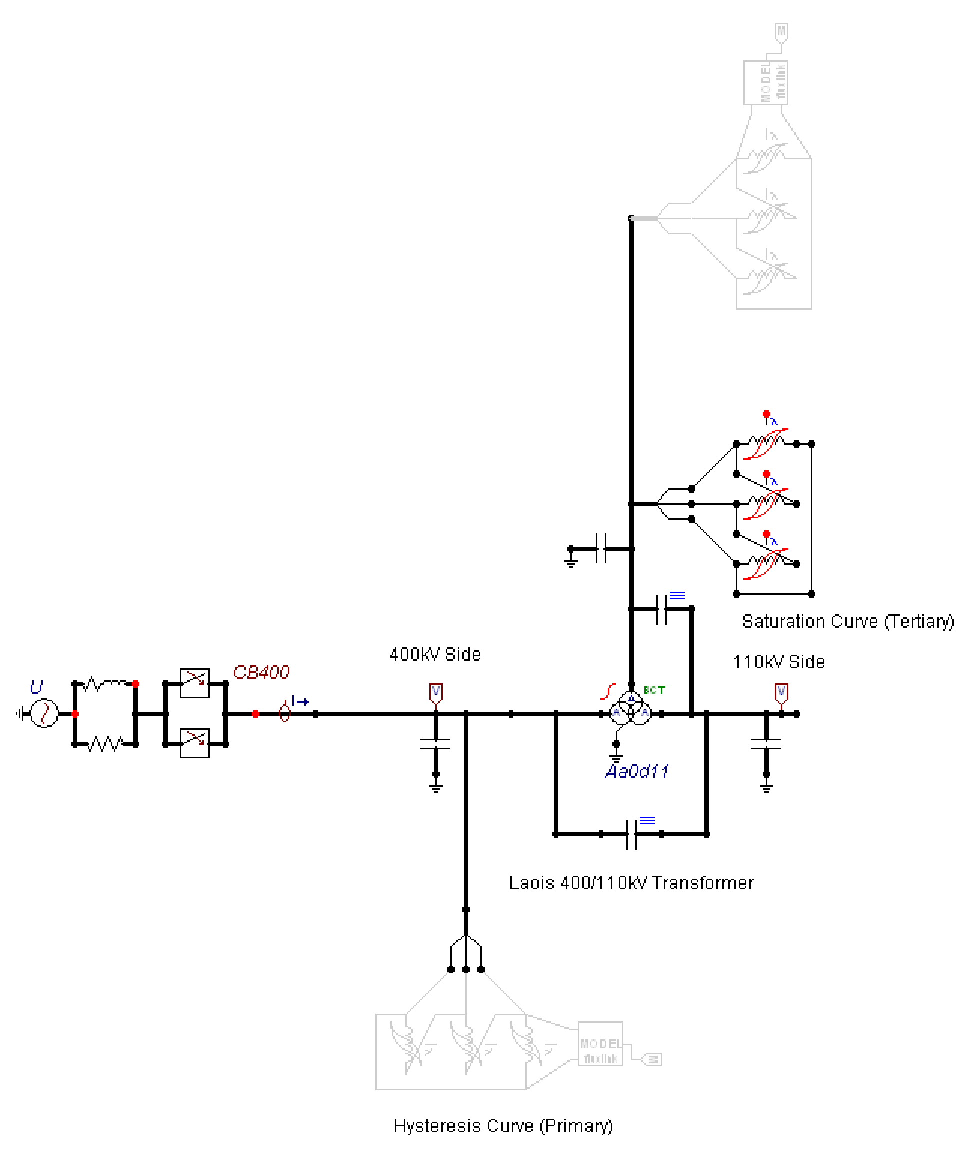


Table D2 Saturation Curve [5]

I[A]	FluxLinked [Wb-T]
-36.83	-94.91
-24.55	-94.34
-11.05	-92.34
-4.91	-90.34
-1.84	-88.62
0.61	-85.19
2.15	-81.19
3.56	-74.33
4.30	-62.89
4.91	-45.74
6.14	30.59
6.75	42.31
8.59	57.18
11.05	68.61
13.38	74.33
17.49	80.05
23.94	85.19
32.84	89.20
42.96	92.05
61.38	94.91
98.20	97.20
875.03	97.77

Figure D2 Simplified ATP Model



Appendix E Overhead Line and Cable Overvoltages

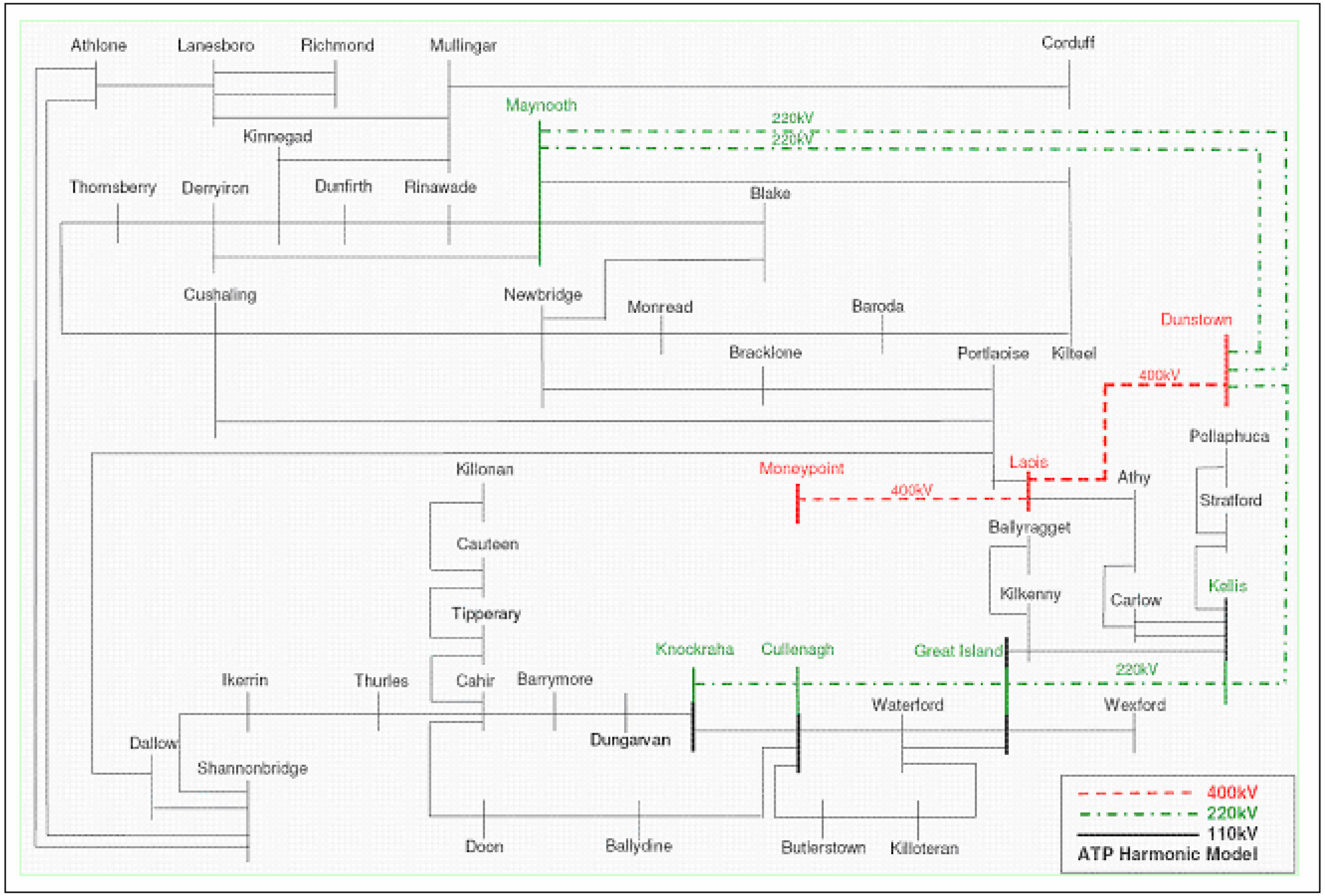
Cable								
	Laois Bus Voltage		**Ballyragget Bus Voltage**		**Laois End Voltage**		**Ballyragget End Voltage**	
	L-L	**L-G**	**L-L**	**L-G**	**L-L**	**L-G**	**L-L**	**L-G**
Charged Switching Ballyragget (Max)			350kV	259kV	372kV	270kV		
Charged Switching Ballyragget (Mean))				153kV		154kV		
Charged Switching Laois (Max)	337kV	224kV					488kV	343kV
Charged Switching Laois (Mean)		142kV						193kV
Energisation Ballyragget (Max)			270kV	173kV	300kV	184kV		
Energisation Ballyragget (Mean)				123kV		125kV		
Energisation Laois (Max)	215kV	153kV					328kV	211kV
Energisation Laois (Mean)		120kV						150kV
De-Energisation Ballyragget			154kV	93kV	191kV	98kV		
De-Energisation Laois	155kV	90kV					184kV	94kV
Single Line to Ground Fault Ballyragget	280kV	200kV	167kV	118kV				
Single Line to Ground Fault Laois	215kV	150kV	193kV	125kV				
Three Phase Fault Ballyragget	316kV	205kV	166kV	150kV				
Three Phase Fault Laois	250kV	162kV	182kV	137kV				
De-Energisation Ballyragget (restrike)			400kV	233kV	435kV	254kV		
De-Energisation Laois (restrike)	324kV	208kV					440kV	315kV
Single Line to Ground Fault Ballyragget (restrike)	300kV	202kV	167kV	118kV				
Single Line to Ground Fault Laois (restrike)	217kV	154kV	310kV	260kV				

Table E1 Results of Studies with Cable

	Overhead Line							
	Laois Bus Voltage		**Ballyragget Bus Voltage**		**Laois End Voltage**		**Ballyragget End Voltage**	
	L-L	**L-G**	**L-L**	**L-G**	**L-L**	**L-G**	**L-L**	**L-G**
Charged Switching Ballyragget (Max)			252kV	160kV	310kV	264kV		
Charged Switching Ballyragget (Mean))				120kV		170kV		
Charged Switching Laois (Max)	277kV	171kV					463kV	320kV
Charged Switching Laois (Mean)		117kV						202kV
Energisation Ballyragget (Max)			187kV	130kV	239kV	161kV		
Energisation Ballyragget (Mean)				105kV		126kV		
Energisation Laois (Max)	185kV	116kV					313kV	214kV
Energisation Laois (Mean)		107kV						152kV
De-Energisation Ballyragget			154kV	93kV	191kV	98kV		
De-Energisation Laois	155kV	90kV					184kV	94kV
Single Line to Ground Fault Ballyragget	198kV	126kV	205kV	138kV				
Single Line to Ground Fault Laois	285kV	194kV	190kV	120kV				
Three Phase Fault Ballyragget	235kV	141kV	165kV	151kV				
Three Phase Fault Laois	264kV	181kV	155kV	117kV				
De-Energisation Ballyragget (restrike)			238kV	181kV	329kV	246kV		
De-Energisation Laois (restrike)	277kV	149kV					445kV	289kV
Single Line to Ground Fault Ballyragget (restrike)	274kV	157kV	205kV	138kV				
Single Line to Ground Fault Laois (restrike)	285kV	194kV	256kV	165kV				

Table E2 Results of Studies with Overhead Line

Appendix F SIMPLIFIED ATP HARMONIC MODEL SLD



Please Note that the diagram above is a simplified representation of the harmonic model created in ATP. Transformers, Loads, Reactive Compensation etc. were modelled as part of the harmonic study but are not included in the above diagram

Appendix G

SIMPLIFIED TRANSIENT ATP MODEL VS DETAILED MODEL

The purpose of this appendix is to show the difference in maximum overvoltages experienced for a simplified ATP transient model and a detailed ATP transient model.

Two models were setup in ATP. The first model shown in Figure G1 is a simplified ATP model of the Thurles – Ikerrin – Shannonbridge 110kV network. The second model shown in Figure G2 is also a representation of the Thurles – Ikerrin – Shannonbridge 110kV network. However, in the case of second model (Figure G2), the local system MVA loading, the capacitor bank at Thurles, generation (Lisheen) and the two 110kV lines heading to Cahir and Lisheen are also modelled. At t=0ms it is assumed that the breakers on the following outlets are open:

- Shannonbridge 110kV Substation – Ikerrin/Thurles 110kV Outlet
- Ikerrin 110kV Substation – Thurles/Shannonbridge 110kV Outlet
- Thurles 110kV Substation – Ikerrin/Shannonbridge 110kV Outlet

At t=10ms, the breaker on the Ikerrin/Shannonbridge 110kV outlet at Thurles closes. Figures C3 and C4 show the voltage on the A phase at the Shannonbridge End of the Thurles – Ikerrin – Shannonbridge 110kV line. In the case of the simplified switching model, the worse case overvoltage is 175.75kV. However, in the case of the slightly more detailed model, the maximum overvoltage is 182.6kV. This represents a difference of approximately 3.89% between the simplified model and the model which contained more of the local system. The main conclusion is that while the ATP model containing the more detail yielded the higher overvoltages, the difference between the maximum overvoltages experienced in both models was approximately 3-4%. Therefore the results in the simplified ATP model are valid.

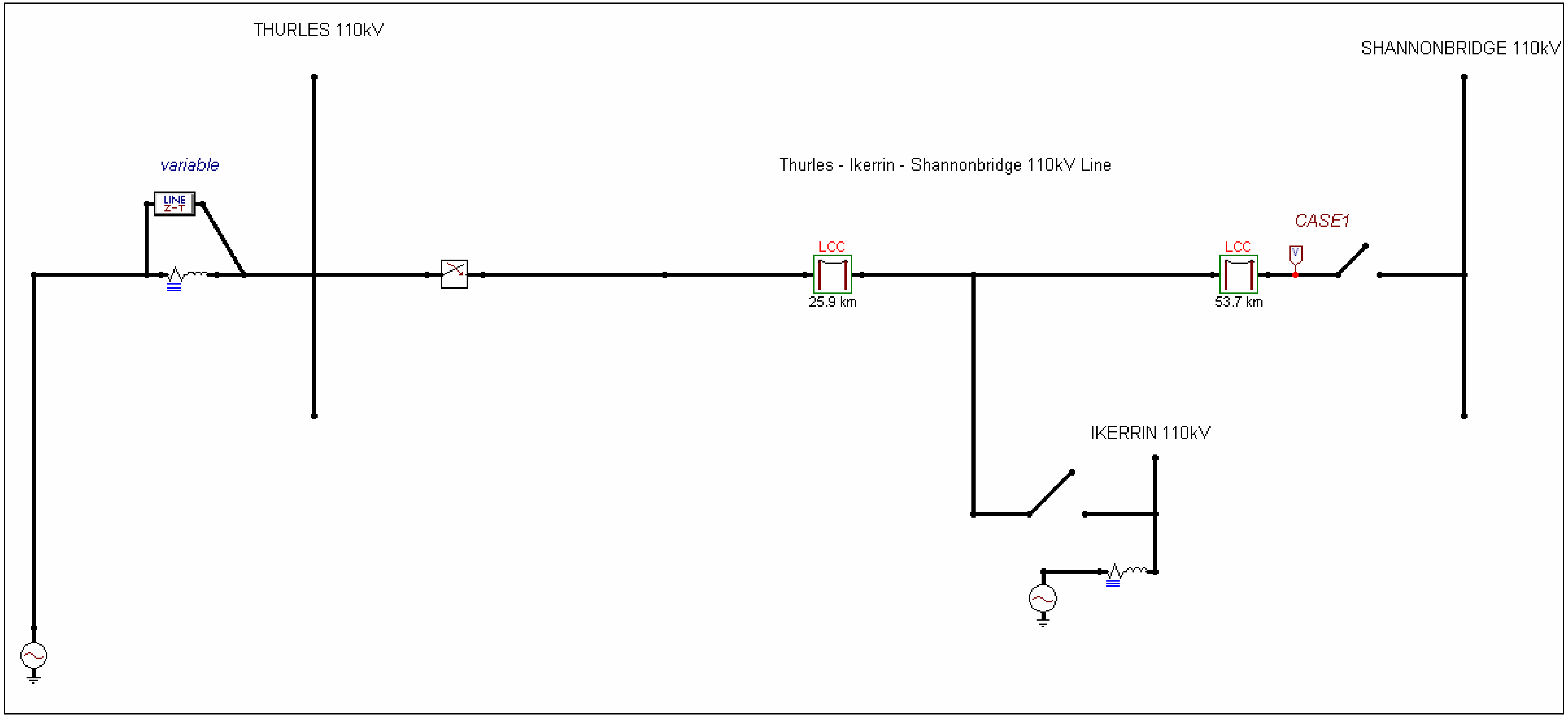


Figure G1: Simplified ATP Model

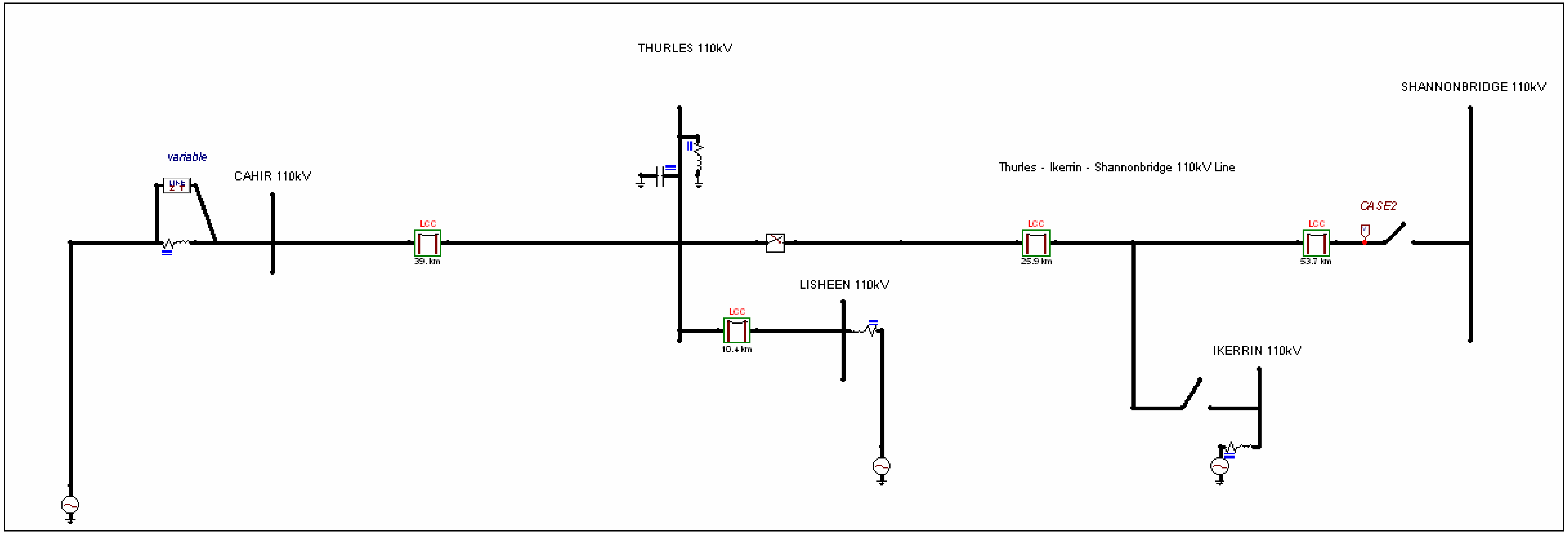


Figure G2: ATP Model Containing More Detail

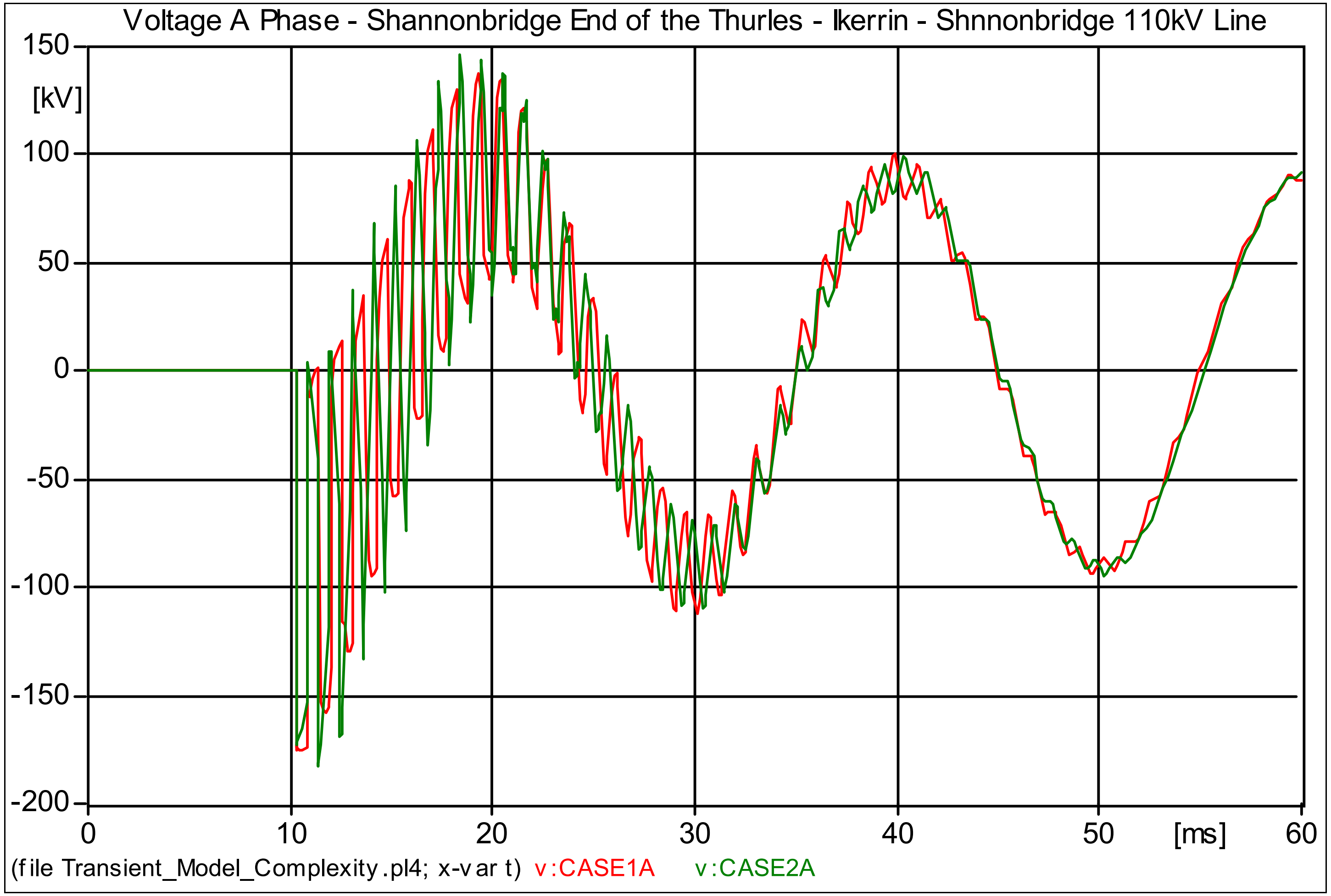


Figure G3: Voltage A Phase for Case A (Simplified) and Case B (More Detail)

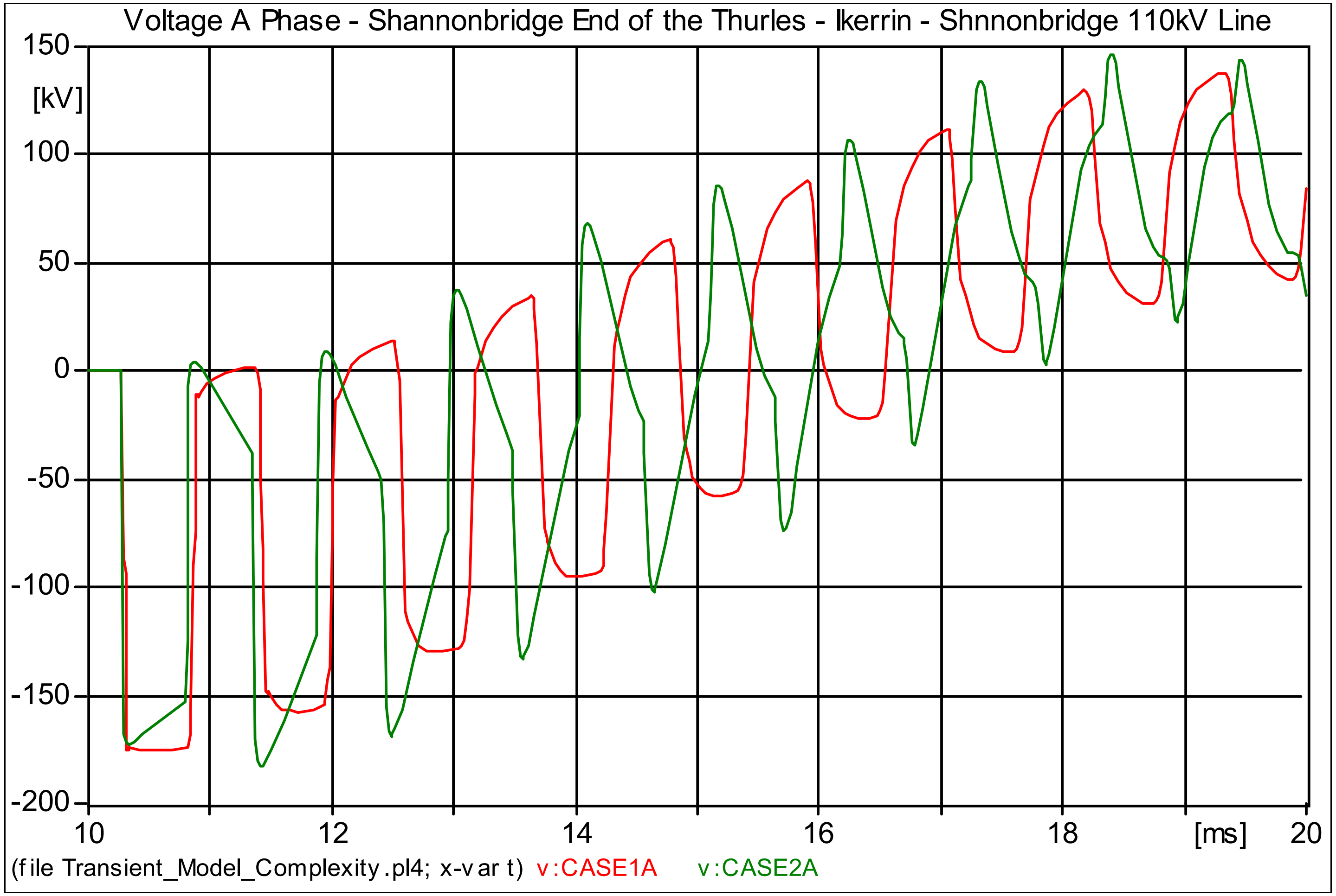


Figure G4: Voltage A Phase for Case A and Case B