Final Report for Capital Project 966 Cable Integration Studies

For: EirGrid PLC

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Client Reference: PSPF020
PSC Reference: JI7867-03-02
Revision: 2
Date: 12th March, 2020

Executive Summary

Capital project 966 relates to the introduction of increased transmission capacity between the Woodland and Dunstown substations in the east of Ireland. One component of this project is to investigate the technical issues associated with the integration of either 220 or 400 kV AC underground cable (UGC) along an assumed 60 km route. The UGC options studied in detail are the 220 kV, 400 kV (1 cable / phase) and the 400 kV (2 cable / phase). A UGC option with two 400 kV independent cable circuits was also considered but the analysis done for the 400 kV (2 cable / phase) already covers most of the technical aspects of this option. Thus, a short note on the requirements associated with the two 400 kV independent cable circuit solution is included in the conclusions.

The studies associated with cable integration cover:

1- Steady state load flow studies for the determination of reactive compensation

2- Frequency domain studies to establish harmonic voltage magnification and potential breaches and

3- Time domain studies to check possible temporary overvoltages (TOV) and zero-cross missing phenomenon during cable energisation.

The above studies were carried out based on model data provided by EirGrid and modified by PSC accordingly. The model data provided includes:

1. PSSE model for steady state studies that represents the planned network in 2030
2. DIgSILENT PowerFactory model for frequency domain studies
3. ATP-EMTP model for the time domain studies.

All models were reviewed and updated accordingly in order to cater for any missing or planned system developments and new customer connections.

The studies in this report were progressed in the following stages:

1- PSC carried out reactive compensation studies, harmonic analysis, TOV and ZMP analysis for the initially provided model data by EirGrid. This included detailed studies for the 220 kV and 400 kV (1 cable / phase) UGC options in all the study areas; whereas detailed reactive compensation studies were performed for the 400 kV (2 cable / phase) UGC option and sensitivity studies for TOV and ZMP analysis assuming the harmonic filtering solution from the 400 kV (1 cable / phase) UGC option

2- PSC carried out some additional studies that include revised reactive levels for all the different cable options considering a revised summer valley low wind 2030 study case and an alternative calculation methodology. The impact on the harmonic analysis and TOV studies were also investigated for the 220 kV and 400 kV (1 cable / phase) cable options. The additional studies also include detailed harmonic analysis and investigation on the harmonic mitigation solution as well as sensitivity checks for TOV and ZMP for the full length of UGC400 (2 cable / phase).

Reactive Compensation Requirements

Comprehensive load flow analysis taking into account all possible N-1 contingencies and under three different operating scenarios (summer valley low wind-SVLW, summer valley high wind-SVHW and winter peak high wind-WPHW) were carried out. Level of compensation required in order to maintain a post contingency voltage limit was established for three different UGC options: 220kV, 400kV with a single cable per phase and 400kV with two cables per phase (effectively doubling the power transfer capability). Sensitivity analysis was carried out checking the level of compensation by varying the cable lengths and replacing it with overhead line. Brief summary of the results is shown in the table below.

	220 kV	400 kV 1-cable/phase	400 kV 2-cables/phase
Cable Length (%)	Compensation (%)	Compensation (%)	Compensation (%)
100.0%	81.6% (198 Mvar)	88.4% (558 Mvar)	99.6% (1258 Mvar)
75.0%	72.5% (132 Mvar)	70.5% (349 Mvar)	83.0% (839 Mvar)
50.0%	50.3% (61 Mvar)	45.3% (162 Mvar)	71.6% (543 Mvar)
25.0%	0.0%	21.3% (47 Mvar)	38.8% (196 Mvar)

In most cases the compensation required is at both ends of the cable with specific details of the level given in the report.

Harmonic Analysis

The reactive compensation determined during the steady state load flow studies were implemented in the frequency domain model in order to analyse the impact of the new circuits on the harmonic distortions in the area. This was based on the calculation of harmonic voltage gain factors for a number of network contingencies and under the three operating scenarios (SVLW, SVHW and WPHW). For the determination of distortion levels, background harmonics calculated in a previous EirGrid project [6] were used. It should be noted that the overall results depend heavily on the level of the assumed background distortion and depending on how these compare with the actual levels, the perceived level of issues may be more or do not exist at all.

Levels of harmonic distortions exceeding the EirGrid planning levels were observed for different cable lengths (100 %, 50%, 25%, 12.5%) for the 220 kV and 400 kV (1cable/ph) UGC options. Although there is some improvement while the cable length decreases, there is no cable length option that results in no harmonic breach. Similar levels of exceedance were also observed for the full cable length (100 % - the most onerous length investigated) for the 400 kV (2cable/ph) UGC option. In general, there were harmonic breaches in multiple substations which are getting higher and more complex in the 400 kV UGC. Following an agreement with EirGrid, indicative harmonic mitigation solutions were investigated for the full length of 220 kV, 400 kV (1cable/ph) and 400 kV (2cable/ph) UGC options.

Mitigation solutions with five, seven and eight C-type filters were established for the 220 kV, 400 kV (1cable/ph) and 400 kV (2 cable/ph) options, respectively. A summary of these mitigation solutions along with the points they are connected is given in the next table.

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	220kV		400kV (1cable/phase)		400kV (2cable/phase)	
Node	Size (Mvar)	Tuning (Hz)	Size (Mvar)	Tuning (Hz)	Size (Mvar)	Tuning (Hz)
DSN2	32	420	20	550	20	550
CLN4	10	550	-	-	-	-
WOO4	-	-	50	200	-	-
OST4	-	-	40	300	50	300
MAY2B	30	525	30	530	37	530
MAY2A	15	550	15	550	20	550
MAY1	5	525	5	550	5	550
BEL2	-	-	30	500	30	500
BEL2	-	-	-	-	30	180
WOO2	-	-	-	-	40	315

Following the implementation of the mitigation solutions, there were still a few harmonic breaches that can be resolved with the filter fine tuning during the design stage once the final level of UGC option has been decided.

Temporary Overvoltages and Zero-cross Miss Phenomenon

The introduction of harmonic filters and underground cables into the network can introduce lower order harmonic resonances during particular contingencies that could result in TOV and risk damage to equipment. Since these studies are being carried out at a very early stage with indicative design data, a value of 1.6 p.u. was agreed with EirGrid as a screening value. This level normally is location and equipment dependant, but this agreed level is thought to give a good level of margin for safety. The analysis showed that there is a risk of TOV exceeding 1.6 p.u voltage level for a very short duration for Coolnabacky and Old Street 400 kV substations with the response of the system and the measured overvoltages to be very similar among the different UGC options. This may be within the capability of existing surge arresters on the EirGrid system and should be reviewed as part of the detailed design for the final CP966 UGC option. PSC believes that those overvoltages should not be a problem for the existing surge arresters due to the marginal exceedance and the very short duration but EirGrid are advised to confirm with their specific capability from the equipment technical specification.

The combination of long underground AC cables and shunt reactors can also lead to the zero-cross missing phenomenon (ZMP) during cable energisation with the potential of preventing the safe operation of the circuit breaker if a fault was to take place. Due to the high reactive compensation requirements of both 220 kV and 400 kV UGC options, the ZMP analysis indicated that there is a current DC offset during energisation and a mitigation solution such as a pre-insertion resistor or a delayed reactor switching should be considered in the future. The phenomenon is more pronounced in the 400 kV UGC option when compared to the 220 kV UGC option due to the higher reactive compensation (in %) requirement.

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Further Investigation and Sensitivity Checks

Reactive Compensation Requirements

Load flow analysis was carried out taking into account all possible N-1 contingencies for steady state conditions and the arrangement with the energisation of the cable from one end considering that it could accommodate a higher voltage during energisation. Revised reactive compensation levels were established for the three different UGC options and under three different operating scenarios (revised SV-LW, existing SV-HW and WP-HW). Sensitivity analysis was carried out checking the level of compensation by varying the cable lengths and replacing it with overhead line and the final revised reactive compensation is the worse from the two studies above and a brief summary of the results is shown in the table below.

	220 kV	400 kV 1-cable/phase	400 kV 2-cables/phase
Cable Length (%)	Compensation (%)	Compensation (%)	Compensation (%)
100.0%	45.3% (110 Mvar)	45.9% (290 Mvar)	68.9% (870 Mvar)
75.0%	34.1% (62 Mvar)	34.4% (170 Mvar)	57.4% (580 Mvar)
50.0%	8.2% (10 Mvar)	11.2% (40 Mvar)	39.6% (300 Mvar)
25.0%	0.0%	0.0%	4.0% (20 Mvar)

Harmonic Analysis

The revised reactive compensation was implemented in the frequency domain model in order to analyse the impact that the change in the reactive compensation has on the need for a harmonic filtering solution. The full cable length options of UGC220 and UGC400 (1 cable / phase) were assessed without any harmonic filters and the background harmonic amplification was reviewed for all the nodes of interest under the three operating scenarios (SVLW, SVHW and WPHW).

Similar levels of harmonic distortions exceeding the EirGrid planning levels were observed when comparing with the results for the initial reactive compensation requirements. For both options, the behaviour of the results was very similar with a few harmonic breaches observed only in the revised cases; whereas a few other harmonic breaches observed only in the revised case.

The sensitivity studies concluded that there is a slight impact on the harmonic analysis for the 220 kV and 400 kV (1 cable / phase) and the previously identified harmonic mitigation solutions can be used as the basis for designing the final solution at a later stage with the possibility of requiring some minor additional filtering solution. Those conclusions are expected to be also valid for the 400 kV (2 cable / phase) option.

Some qualitative analysis for a potential underground cable reinforcement with 2 independent cable circuits recommended by PSC was also performed and concluded that a possible harmonic mitigation solution for this cable reinforcement is expected to consist primarily from the solution of the 2 cable / phase option plus one more filter in the 400 kV Woodland substation similar to the one proposed for the 1 cable / phase option.

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Temporary Overvoltage and Zero-cross Miss Phenomenon

Further sensitivity studies were performed in order to check the impact of having no harmonic filters and of the revised reactive compensation on the TOV analysis through an investigation for the 400 kV (1 cable / phase) UGC option. The 400 kV (2 cable / phase) UGC option was also analysed considering the proposed harmonic mitigation solution and the revised reactive levels. The analysis indicated that in all the cases there is a very similar risk to the initial studies of TOV exceeding 1.6 p.u voltage level for a very short duration for Coolnabacky and Old Street 400 kV substations. This may be within the capability of the existing surge arresters on the EirGrid system and should be reviewed as part of the detailed design for the final CP966 UGC option. Those conclusions are expected to be also valid for the 220 kV UGC option.

A ZMP analysis was performed for the revised reactive compensation for the 400 kV (2 cable / phase) UGC option and indicated that there is a current DC offset during energisation that is very slightly lower than the one calculated in the initial studies. This conclusion is expected to be valid for the other cable configurations due to the reduction (in %) in the revised reactive compensation.

Conclusions

The reactive compensation studies performed for the three UGC options (220kV, 400kV with a single cable per phase and 400kV with two cables per phase) identified that there is a high compensation requirement (> 80%) in all options for full cable length. Those levels were reduced considerably (by at least 30%) during revised reactive compensation studies. The option with two cables per phase at 400 kV resulted to 1258 Mvar of reactive compensation for the initial studies which was high but reduced to 870 Mvar following the revised studies.

Harmonic analysis studies for the 220 kV, 400 kV (1 cable/ph) and 400 kV (2 cable/ph) identified that there are harmonic breaches in the full cable length which are generally getting higher and more complex in the 400 kV (2 cable/ph) option. Harmonic breaches are also identified in all the different cable lengths analysed for the 220 kV and 400 kV (1 cable/ph). Mitigation solutions with C-type filters were established for the full length of all the cable options which resolve most of the breaches and any remaining breaches can be resolved with the filter fine tuning during the design stage once the final level of UGC option has been decided. Sensitivity studies for the revised reactive compensation concluded that the mitigation solutions proposed are still applicable and there is possibility of requiring some minor additional filtering solution. The overall results depend heavily on the level of the assumed background distortion which is based on a previous EirGrid project [6] and depending on how these compare with the actual levels, the perceived level of issues may be more or do not exist at all.

TOV analysis for the full length of the 220 kV, 400 kV (1 cable/ph) and 400 kV (2 cable/ph) with the reactive compensation and harmonic filters identified that there is a small risk of TOV exceeding 1.6 p.u voltage level for a very short duration for Coolnabacky and Old Street 400 kV substations with the measured overvoltages being very similar among the different UGC options. Sensitivity studies for the revised reactive compensation and for cases with no harmonic filters indicated that the conclusions are very similar in terms of magnitude, duration and location for the TOV risk. The TOV risk may be within the capability of the existing surge arresters in the EirGrid system and should be reviewed as part of the detailed design.

ZMP analysis indicated that there is a current DC offset during the energisation of both cables due to the high reactive compensation requirements (in %) which is slightly improving for the revised reactive compensation requirements due to the reduction (in %) in the calculated reactive levels. However, there are different countermeasures available and a mitigation solution should be considered in the future. The phenomenon is more pronounced in the 400 kV UGC options when compared to the 220 kV UGC option due to the higher reactive compensation (in %) requirement.

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Appendices

1 Introduction

1.1 Who are EirGrid

EirGrid is a state-owned company, responsible for managing and operating Ireland's transmission grid. EirGrid is working to ensure a safe, secure and reliable supply of electricity to homes, businesses and industry across the island of Ireland. EirGrid develops the transmission grid to guarantee a secure supply of electricity now and for future generations, and to facilitate local, national and European policies.

1.2 What is Capital Project 966?

Capital Project 966 is a proposed network development that will help to transfer electricity to the east of the country and distribute it within the network in Meath, Kildare and Dublin.

The project will help meet the growing demand for electricity in the east. This growth is due to increased economic activity and the planned connection of new data centres in the region.

A significant number of Ireland's electricity generators are located in the South and South West. This is where many wind farms and some modern, conventional electricity generators are located. This power needs to be transported to where it is needed.

The power is mainly transported cross-country on the two existing 400 kV power lines from Moneypoint station in Clare to the Dunstown substation in Kildare and Woodland substation in Meath. Transporting large amounts of electricity on these 400 kV lines could cause problems that would affect the security of electricity supply throughout Ireland, particularly if one of the lines is lost unexpectedly.

To solve this emerging issue, there is a need to strengthen the electricity network between Dunstown and Woodland.

Capital Project 966 aims to strengthen the transmission network between Dunstown and Woodland substations. and suggests a number of technical solutions to do so.

1.3 Framework for Grid Development Explained

EirGrid follow a six-step approach when they develop and implement the best performing solution option to any identified transmission network problem. This six-step approach is described in the document 'Have Your Say' published on EirGrid's website [1]. The six steps are shown at a high level in Figure 1-1. Each step has a distinct purpose with defined deliverables and represents a lifecycle of a development from conception through to implementation and energisation.

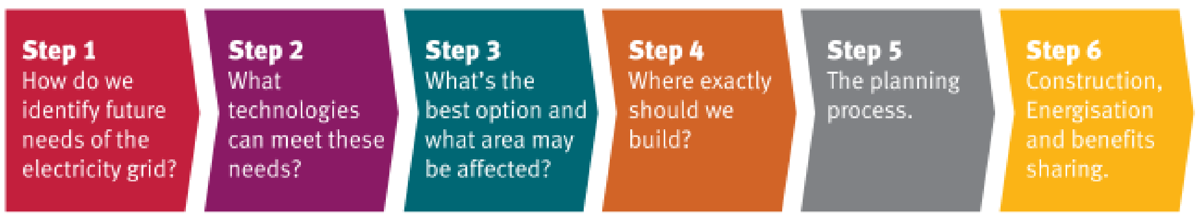

Figure 1-1: EirGrid's six step approach

[1] http://www.eirgridgroup.com/the-grid/have-your-say/

Capital Project 966 is in Step 3 of the above process. The aim of Step 3 is to identify a best performing solution option to the need identified. There are four remaining technical viable options to be investigated in Step 3. All options create a connection between Woodland and Dunstown substations and have common reinforcements associated in relation to voltage support devices and 110 kV uprates. The main four options are:

- Up-voltage existing 220 kV circuits to 400 kV to create new Dunstown – Woodland 400 kV overhead line (OHL);
- A new 400 kV overhead line;
- A new 220 kV underground cable,
- A new 400 kV underground cable.

Common reinforcements to all four options:

- Uprating of the Bracklone – Portlaoise 110 kV overhead line
- Dynamic reactive support device in greater Dublin area rated at approximately ±250 Mvar

These options will be evaluated against five criteria: technical, economic, environmental, deliverability and socio-economic and each criteria incorporates a number of sub-criteria. It shall be noted that the overall assessment is carried out by EirGrid, but certain aspects are investigated and assessed by various consultants and their assessment will feed into the overall assessment

1.4 Aim and Context of this Report

EirGrid (the Client) has engaged PSC to complete a technical investigation into system analysis of issues and impacts of the underground options being implemented into the transmission network. The tender reference is PSPF020. This report is aimed at presenting the findings of this investigation and the findings will feed into EirGrid's evaluation of the four remaining options.

Figure 1-2 shows the transmission network in greater Dublin area under investigation and the two substations Woodland and Dunstown, where the options will connect.

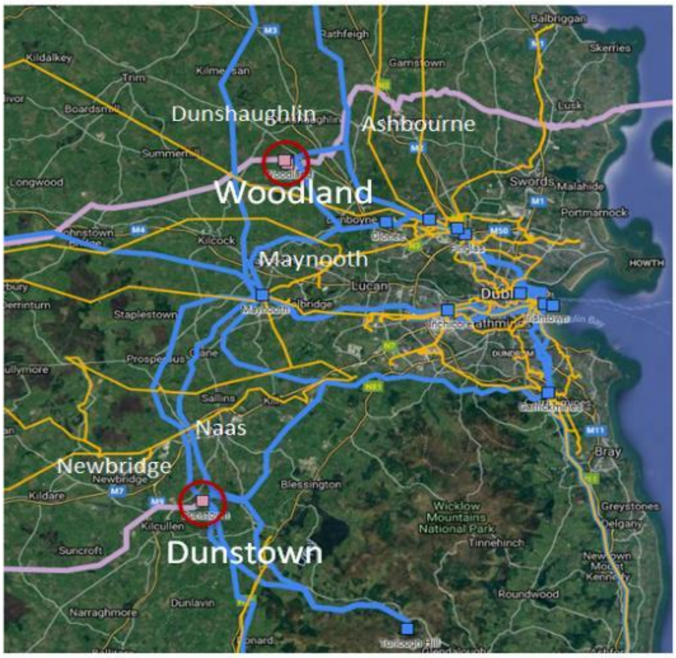

Figure 1-2: Area of development and connecting substations

EirGrid have identified the estimated route length of 60 km between the two substations to be considered for this study. This has been estimated by choosing a potential route via the existing road network between the two connection points and then adding some contingency.

This report relates to the technical evaluation of three UGC options and any mitigation options needed. If they cannot be accommodated in their entirety, then further investigation will be carried out to determine maximum lengths of UGC that can be accommodated.

This report is submitted as per the deliverable's requirements of the RFT [3] as follows:

Deliverable 3: Final Report (D3)

The final report will be provided to EirGrid in both Microsoft Word (*.doc) and Adobe Acrobat (*.pdf) format. The report will include the following:

- An executive summary indicating the issues and main findings of the investigation in a format agreed on with EirGrid;
- A detailed description of the scope of the investigation in terms of study assumptions, scenarios, and methodology;
- A detailed description of the modelling of key components in the data models used to conduct the studies;
- A description of the results obtained from each of the studies;
- A synopsis of the conclusions that can be drawn from the study results;
- Appendices detailing all data, inputs, assumptions, etc.

1.5 UGC Options Considered

The following three UGC options were considered:

- New Dunstown – Woodland 220 kV UGC;
- New Dunstown – Woodland 400 kV UGC (with 1 cable / phase);
- New Dunstown – Woodland 400 kV UGC (with 2 cables / phase).

These options were studied using the latest information available for standard cables used on the Irish transmission network. These parameters are listed in Appendix C.

The following reinforcements were also included for each of the three options:

a. Uprating of the Bracklone – Portlaoise 110 kV overhead line
b. Dynamic reactive support device in area of Inchicore station rated at approximately ±250 Mvar[2]

Sensitivity studies also included a North Dublin Corridor reinforcement consisting of:

- New 400 kV UGC from Woodland to Belcamp;
- New 400/220 kV transformer at Belcamp.

These reinforcements have been included in the system model as part of the review, updating and validation reported previously [1].

[2] EirGrid have also identified several additional locations where reactive support devices could be considered if system wide voltage issues are created as a result of the new cable reinforcement.

1.5.1 New Dunstown – Woodland 220 kV UGC

This option consists of a 2500 mm^2 Cu XPLE cable rated at 760 MVA. This option also requires the following reinforcements:

a. Uprating of the Cashla – Prospect 220 kV overhead line

b. Uprating of the Killonan – Shannonbridge 220 kV overhead line

c. Woodland 220 kV station would be required to be operated "split" in order to prevent thermal overloading of the new 220 kV cable for an unplanned loss of a circuit.

1.5.2 New Dunstown – Woodland 400 kV UGC (with 1 cable / phase)

This option consists of a 2500 mm^2 Cu XLPE cable rated at 1254 MVA. This is below the rating of an equivalent 400 kV overhead line but was selected as the maximum possible rating achievable for a cable buried in a typical trench or road arrangement.

1.5.3 New Dunstown – Woodland 400 kV UGC (with 2 cables / phase)

This option consists of two 2500 mm^2 Cu XLPE cables per phase rated at 2509 MVA. This exceeds the rating of an equivalent 400 kV overhead line but requires a larger strip of land or a second route. It also doubles the capacitance of the cable which increases reactive compensation and harmonic filter requirements and possibly increase the chances of encountering TOV issues during routine switching operations.

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2 Scope of Investigation

The following sections of this report set out at a high level the study assumptions, scenarios and methodology followed in carrying out these studies. Further details and justification behind these are detailed in the methodology report [2].

2.1 Study Assumptions

2.1.1 Planned Reinforcements

EirGrid already have several reinforcements planned for the transmission network, some of which are likely to have an impact on the cable integration studies which this report relates to. This section details the validation or updates of the data in the PSSE base models for the following reinforcements:

1. Uprating of Bracklone – Portaloise 110 kV OHL
2. Dynamic reactive support device at Inchicore 220 kV station
3. North Dublin corridor reinforcement
4. Series compensation on the existing 400 kV OHLs

There are several other reinforcements taking place in and around the Dublin network.

2.1.2 Capital Project 966 Reinforcements

Capital project 966 consists of two reinforcement options for the 60 km circuit between Dunstown and Woodland. The reinforcement options being studied in this project include the installation of a new 220 kV UGC (CP966_UGC220) along with several uprates to existing circuits or the installation of a new 400 kV UGC (CP966_UGC400).

CP966_UGC220: New Dunstown – Woodland 220 kV UGC and the following additional reinforcements:

a. Uprating of the Cashla – Prospect 220 kV overhead line

b. Uprating of the Killonan – Shannonbridge 220 kV overhead line

c. Woodland 220 kV station would be required to be operated "split" in order to prevent thermal overloading of the new 220 kV cable for an unplanned loss of a circuit.

CP966_UGC400: New Dunstown – Woodland 400 kV UGC

2.1.3 Generation and Load Dispatch

The generation and load dispatch for the three study cases (summer valley low wind-SVLW, summer valley high wind-SVHW and winter peak high wind-WPHW) were provided by EirGrid. The following table shows the generation and load for each of the operating scenarios and no change has been made to these dispatch arrangements.

Table 2-1: Generation and load dispatch for the operating scenarios under consideration

		SV LW	SV HW	WP HW
Load	MW	3506.0	3506.0	9023.8
Generation	MW	3540.2	3554.6	9614.3

The difference between the SV LW and SV HW dispatches is the change in proportion of wind generation in the dispatch mix. This results in an increase of approximately 450 MW of generation coming from wind located in the North and West of the EirGrid network and the associated reduction of traditional plant in the East and particularly around the Dublin region. In the WP HW case, the total system demand is increased to the forecast 2030 winter peak with a high level of wind generation.

2.1.4 Steady State Voltage Limits

Table 2-2 details the steady state voltage limits applicable to the EirGrid system. It should be noted that although the system nominal voltage is 400 kV it is operated at 380 kV and the per unit values detailed in this report are expressed against a 380 kV operational voltage.

Table 2-2: EirGrid Network Planning Voltage Limits [4]

Nominal Voltage (kV)	Base Case Limits (kV)	Post-Contingency Limits (kV)
400	370 – 410	360 – 410
220	210 – 240	200 – 240
275	260 - 300	250 - 303
110	105 - 120	99 - 120

2.2 Study Scenarios

2.2.1 PSSE Model

The PSSE model is considered the master model as it is the most up to date version of the network representing the planned network in 2030. This model is being updated by EirGrid regularly and it has been reviewed and used to develop the shortlisting of technology options under step 2 of the framework for grid development [5].

EirGrid has provided PSSE network models of the entire EirGrid 2030 network with three network dispatches:

1. Summer Valley Low Wind (SV LW)[3]
2. Summery Valley High Wind (SV HW)[4]
3. Winter Peak High Wind (WP HW)[5]

A review and update of this model has covered the following aspects and is detailed in [1]:

1. The project circuits and associated reinforcements are modelled correctly
2. The model is convergent for the base case plus identified contingencies
3. Voltages are within the planning limits for the base case scenarios
4. Line and cable parameters are sensible
5. Generation and the associated network are modelled in sufficient detail

[3] PSSE models “SNV2030Low_30snv_33_dc_Scenario 0_220kV UGC option.sav” and “SNV2030Low_30snv_33_dc_Scenario 0_400kV UGC option.sav”

[4] PSSE models “SNV2030HighW_30snv_33_dc_Scenario 0_220kV UGC option.sav” and “SNV2030HighW_30snv_33_dc_Scenario 0_400kV UGC option.sav”

[5] PSSE models “WP2030HW_30w_33_dc_Scenario 0_95%SW_220kV UGC option.sav” and “WP2030HW_30w_33_dc_Scenario 0_95%SW_400kV UGC option.sav”

6. Reactive compensation devices are modelled correctly

The resultant PSSE model is considered as the base model and the PowerFactory model was validated against it.

2.3 PowerFactory Model

EirGrid provided a PowerFactory network model[6] of the entire EirGrid network and covers the operating scenarios SV LW[7], SV HW[8] and WP HW[9]. A check has been conducted to confirm the model is suitable for carrying out frequency studies and that the topology represents that of the validated PSSE model.

2.3.1 Frequency Dependant Model

To ensure the PF model is suitable for harmonic analysis it needs to be a suitable frequency dependant model which required the following changes:

- Circuits are converted to all be modelled with distributed parameters
- Transformers all have a frequency dependant relationship for their resistance except generation step-up transformers.
- Synchronous machines all have a frequency dependant relationship for their stator resistance

2.3.2 Future Transmission System Reinforcements

A review of the PF model against PSSE showed that there were significant differences between the models. The PF model reflects the current system and some short-term changes whereas the PSSE model reflects a future 2030 system incorporating significant numbers of network reinforcements.

The methodology report details the specific changes to the PF model to represent the future system prior to the CP966 reinforcement. The following main network reinforcements were incorporated:

- EWIC Interconnector
- Belcamp Phase 2
- Kellystown 220 kV substation (Intel)
- North South Interconnector (Woodland – Turleenan 400 kV line)
- Laois Kilkenny Project including:
    - New 400/110 kV substation
    - Bracklone 110 kV substation
    - Lumcloon 110 kV substation
    - Ballyraget 110 kV substation

[6] PowerFactory model “AIM 2019-MODEL-RELEASE v1_1.pfd”

[7] Summer Val 2.5GW E500 M-200 W0.IntScenario

[8] Summer Val 2.5GW E500 M200 W2000.IntScenario

[9] Winter Peak 6.7GW E500 M200 W3750.IntScenario

2.3.3 Capital Project 966 Reinforcements

The CP966_UGC220 and CP966_UGC400 reinforcements were included in the PF model as appropriate including the associated reinforcements necessary to accommodate the 220 kV option. Further details regarding the specific technical data around these reinforcements are included in Appendix C.

2.4 ATP Model

The existing EirGrid ATP model has been developed for studies in and around the Dublin region for previous investigations into the impact of new 220 kV and 400 kV circuits in the region. This model will be developed further to carry out investigations into potential TOV or ZMP risks. Since these are dependent on specific network events or contingencies, they are developed specifically to capture those events incorporating any mitigation solutions identified for steady-state voltage rise (in PSS/E) or harmonic voltage distortion (in PowerFactory).

As detailed in Section 5, the nodes that there is a potential risk of TOV due to the CP966 UGC options have been identified to be around different locations of the 400 kV network. Thus, the existing base EirGrid ATP model was reviewed against the PowerFactory model and the model report [1] and updated accordingly. The updates include the following:

- The OHL lengths of:
    - Woodland – Turlenaan 400 kV
    - Moneypoint – Coolnabacky 400 kV
    - Coolnabacky – Dunstown 400 kV
    - Woodland – Clonee 220 kV
    - Maynooth – West Dublin (Castlebagot) 220 kV
    - West Dublin (Castlebagot) – Inchicore 220 kV
- The UGC lengths of:
    - Maynooth – West Dublin (Castlebagot) 220 kV
    - West Dublin (Castlebagot) – Inchicore 220 kV
- Removed the cable sections connecting Clonee 220 kV with Woodland 220 kV and Corduff 220 kV
- Updated the series compensation at Old Street 400 kV, Moneypoint 400 kV and Dunstown 400 kV
- Included the reactive compensation at Woodland 400 kV and Dunstown 400 kV
- Included a simplified model to represent the EWIC Interconnector that consists of an equivalent resistive loading and the harmonic filters

During the initial fault studies it was observed that there were some abnormal overvoltages due to the absence of protection devices across the series compensation of the existing 400 kV OHLs. Since this is an early stage evaluation, a simplified method of connecting a parallel resistor of 70 Ohms was used to maintain the overvoltages across the series capacitors within typical design limits. The impact of that resistor in the frequency response of the system is negligible so it is not affecting the TOV results.

The ATP model was updated accordingly to cover the nodes of interest detailed in Section 5 for the UGC 220 kV and UGC 400kV. These nodes were selected to include all the nodes identified from frequency scans and allowed the contingencies to be considered.

Table 2-3 presents all nodes that are electrically distant from the area of interest and have minimum impact on the frequency response of the system. They have been represented as an equivalent modelled as a voltage source (ACSOURCE) behind a Thevenin's impedance (LINESY_3) as shown in Figure 2-1 and is based on the PowerFactory model. An equivalent balanced load as shown in Figure 2-2 was also represented in the same nodes in ATP model. The data for those loads was based on the PowerFactory model and is given in Table 2-4.

Table 2-3: Boundary Electrically Distant Nodes for ATP Model

Key	Substation	Voltage (kV)
TLE2	Turleenan	275
LOU2	Louth	220
GOR2	Gorman	220
CDU1	Corduff	110
FIN2	Finglas	220
MAY1A	Maynooth	110
MAY1B	Maynooth	110
INC2	Inchicore	220
CKM2	Carrickmines	220
KLS2	Kellis	220
ATY1	Athy	110
BGT1	Ballyragget	110
PLS1	Portlaois	110
SH2	Shannonbridge	220
MP2	Moneypoint	220
TYN2	Tynagh	220

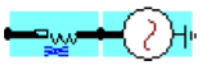

Figure 2-1: Boundary Node Equivalent Network ATPDraw Representation

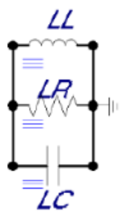

Figure 2-2: Equivalent Load representation in ATPDraw

Table 2-4: Load Data used in ATP Model

Key	Active Power (MW)	Reactive Power (Mvar)
TLE2	111.7	62.4
LOU2	99.9	32.4
GOR2	23.9	31.5
CDU1	88.8	64.8
FIN2	264.8	84.3
MAY1A	79	32.6
MAY1B	20.7	41.1
INC2	54.2	100.2
INC1	81.3	30.8
CKM2	175.8	28.5
KLS2	13.6	43.6
ATY1	6.6	1.3
BGT1	30.9	9.9
PLS1	59	16.5
SH2	-	16.4
MP2	-	20.9
TYN2	40.6	82.2
CTB1	22.5	5.2

In addition to the above updates, the ATP model was modified to include each of the UGC options with the relevant reactive compensation and harmonic filters as detailed in Section 3 and Section 4, respectively. The reactive compensation was modelled with shunt reactors at the UGC terminals; whereas the harmonic filters were modelled as C-type filters shown in Figure 2-3 using the appropriate resistor, inductor and capacitor and the technical data available in PowerFactory model.

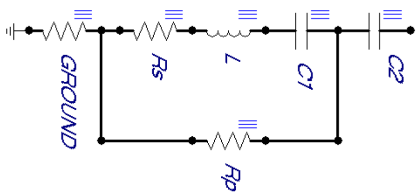

Figure 2-3: C-type Harmonic Filter ATPDraw Representation

The UGC 220 kV and UGC 400 kV have been modelled in 1.053 km sections (minor section) taking into consideration the cross-bonding of the cable sheaths and grounding every 3 sections (major section).

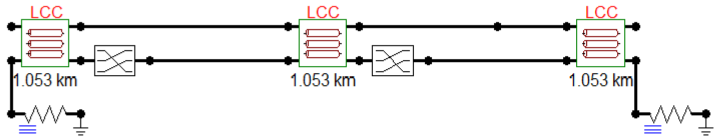

Figure 2-4: Underground Cable ATPDraw Representation

The final ATP model used for TOV and ZMP studies was validated in terms of comparison of the three-phase fault levels for the SVHW operating scenario and the frequency scans against those produced by PowerFactory. Table 2-5 presents the three-phase fault currents for the nodes of interest detailed in Section 5 and it shows that the results are of similar orders of magnitude which gives confidence that the model topology closely resemble each other. The frequency response of the system indicates that there is some discrepancy while the harmonic order is increasing. Since the impedance values for the frequency range of interest for TOV issues are relatively low, further investigation on the frequency response plots is not expected to have any noticeable impact on the TOV results.

Table 2-5: Three-phase fault currents

Key	UGC 220 kV		UGC 400 kV (1c/ph)	
	$I_{3ph\ fault}$ (kA) - PowerFactory	$I_{3ph\ fault}$ (kA) - ATP	$I_{3ph\ fault}$ (kA) - PowerFactory	$I_{3ph\ fault}$ (kA) - ATP
DSN4	7.79	8.58	11.78	12.28
CLN4	7.67	8.33	10.34	10.71
PRN4	11.77	10.59	13.55	13.25
OST4	9.54	9.10	9.91	9.83
WOO4	11.80	10.62	13.60	13.28

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3 Reactive Compensation Requirements

Underground cables have a greater capacitance per unit length than a standard overhead line installation. As a result, this additional capacitance can increase system voltages outside of acceptable limits and therefore need to be compensated for. This is achieved through the available reactive support on the system and where this is not sufficient, the introduction of shunt reactors. PSC has carried out reactive capability studies in PSSE in order to determine the reactive compensation in the form of shunt reactors required to accommodate each of the CP966 reinforcement options.

The PSSE models reviewed and updated as part of the model review were utilised for both the 220 kV and 400 kV UGC options [1].

3.1 Methodology

Contingency load flow studies have been conducted in order to determine the size and position of the reactors necessary to maintain the system voltages within the operational voltage limits detailed in Table 2-1 post-contingency and thermal loadings within circuit ratings. Voltages and power flows have been monitored at circuit terminal stations as well as at 25 %, 50 % and 75 % along the length of the circuit.

Reactive compensation requirements were determined for all of the contingencies detailed in Appendix A ensuring the voltage and thermal limits were maintained for the following operating scenarios:

- Summer Valley, Low Wind (SV-LW)
- Summer Valley, High Wind (SV-HW)
- Winter Peak, High Wind (WP-HW)

Prior to introducing either of the CP966 reinforcements studies were carried to confirm that the system remained within voltage and thermal limits in the base case. The results of these studies and modifications required to the PSSE model have been detailed in the model review report (JI7867-02) [1].

To establish the reactive compensation requirements necessary to maintain voltages within statutory limits the PSSE model had a generator modelled at either end of the UGC circuit (Dunstown and Woodland). This generator provided 0 MW of active power but was able to absorb reactive power sufficient to maintain the local busbar voltage within statutory limits whilst also ensuring thermal limits were not breached. These machines were initially set to very high target voltages and then through iterative studies the target voltages reduced until the system voltages remain within statutory limits. This approach ensures that reactive power absorption from other sources (existing generators, Inchicore STATCOM, etc.) is utilised first before additional reactive compensation is added.

For each operating scenario and contingency the level of reactive compensation required to maintain voltages within statutory limits was recorded. Once all the operating scenarios and contingencies had been tested, the maximum level of reactive compensation was recorded and applied to the model.

The final level of reactive compensation was then tested for each operating scenario and contingency to determine the pre- and post-contingency system voltages. The following sections detail the reactive compensation requirements for the 220 and 400 kV UGC options along with graphs of the system voltages.

3.2 Results

3.2.1 Steady State Voltage Limits

The following figures show the range of steady state voltages at each of the nodes for each operational scenario and contingency. The graphs present the range of voltages with whiskers showing the maximum and minimum values and boxes showing the applicable limits. All values are presented in per unit with limits based on the post-contingency limits shown in Table 2-2. It should be noted that although the system nominal voltage is 400 kV it is operated at 380 kV and the per unit values in the figures are expressed against a 380 kV operational voltage.

- Operational Scenario SV LW
- Operational Scenario SV HW
- Operational Scenario WP HW

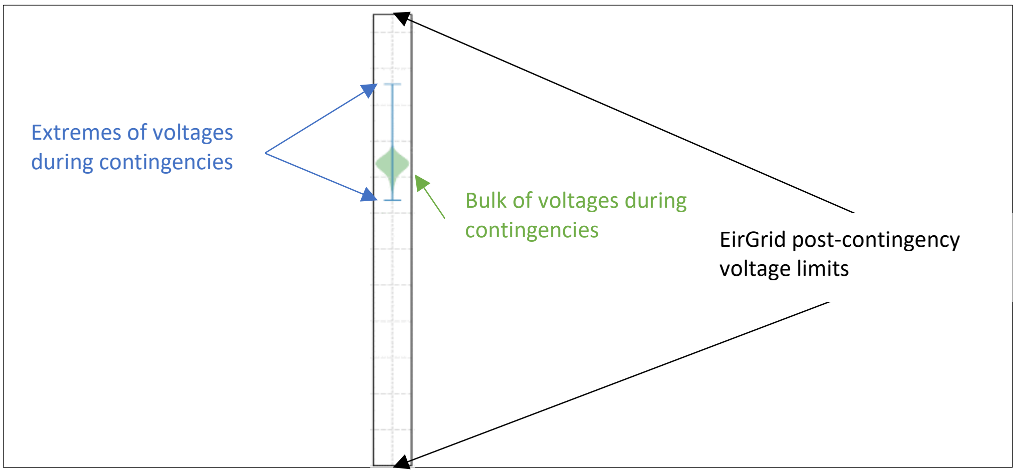

Figure 3-1: Explanation of voltage spread plots

3.2.2 Step Change Voltage Limits

The pre- and post- contingency voltage step change prior to any corrective action was within the following limits for all operating scenarios and contingencies:

- 3% voltage step during switching of reactive compensation
- 10% voltage step between pre- and post-contingency

3.3 Results for CP966_UGC220

The following shows the level and location of reactive compensation required for each cable length option for the 220 kV cable. The results in this table is based on the contingency (complete list in Appendix A) with the greatest reactive compensation requirement to maintain voltages within statutory limits. The reactive compensation requirement was driven by the steady state voltages during energisation of the circuit from one end and the requirement to maintain voltages within statutory limits. A further study detailed in section 6.1 compares the reactive compensation for this energisation arrangement against the reactive compensation for the remaining network contingencies.

As can be seen, for the 100 % cable option the cable requires just above 80 % reactive compensation (198 MVAR) but as the cable reduces the level of compensation also reduces. At greater than 50 % reactive compensation there is a significant risk of zero-miss phenomenon and this has been analysed further in section 5.2.

Table 3-1: Reactive compensation requirement for 220 kV UGC

Cable Length (%)	Cable Length (km)	Shunt Reactor (Mvar)			Compensation (%)
		Woodland 220kV (PSSE bus 546200)	Dunstown 220kV (PSSE bus 220200)	Total	
100.0%	60.0	99	99	198	81.6%
87.5%	52.5	63	109	172	81.0%
75.0%	45.0	40	92	132	72.5%
62.5%	37.5	17	76	93	61.3%
50.0%	30.0	0	61	61	50.3%
37.5%	22.5	0	34	34	37.4%
25.0%	15.0	0	0	0	0.0%
12.5%	7.5	0	0	0	0.0%

The following graphs (Figure 3-2 to Figure 3-4) show the range of system voltages pre- and post-contingency at the nodes of interest for full length 220 kV cable option with the appropriate compensation (as explained in Figure 3-1 above).

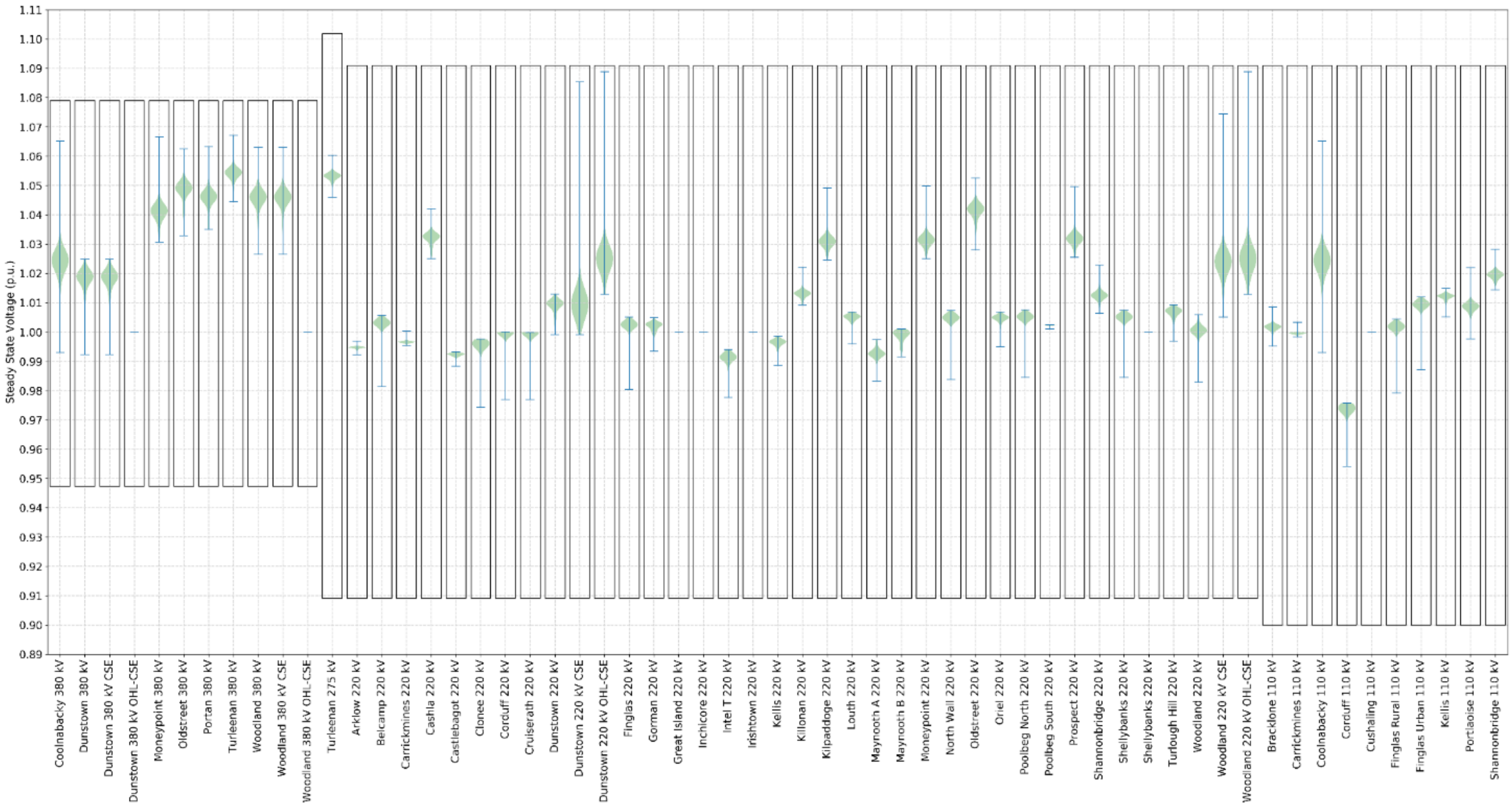

Figure 3-2: CP966_UGC220 post-contingency steady state voltages compared against EirGrid limits for operating scenario SV LW

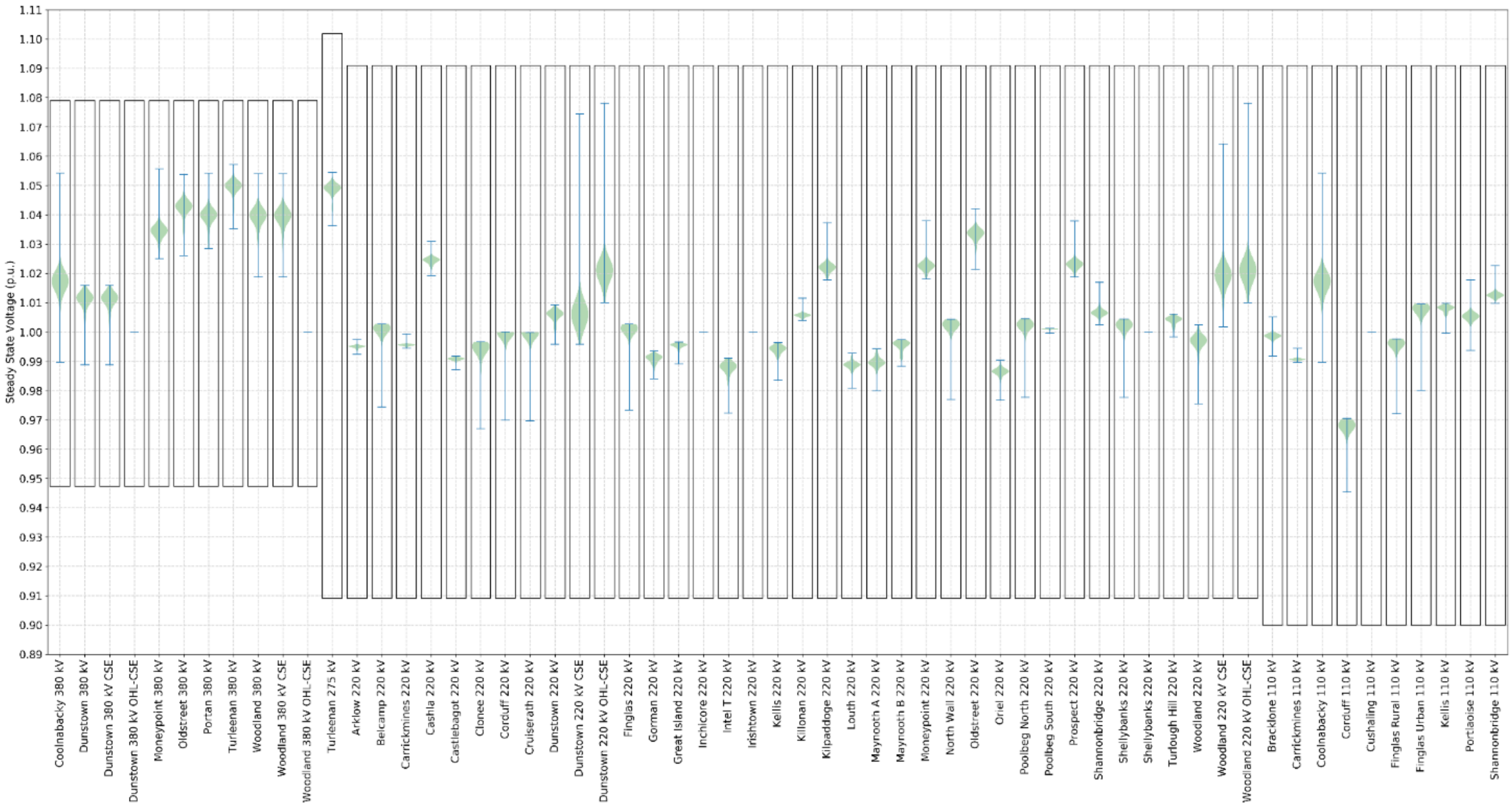

Figure 3-3: CP966_UGC220 post-contingency steady state voltages compared against EirGrid limits for operating scenario SV HW

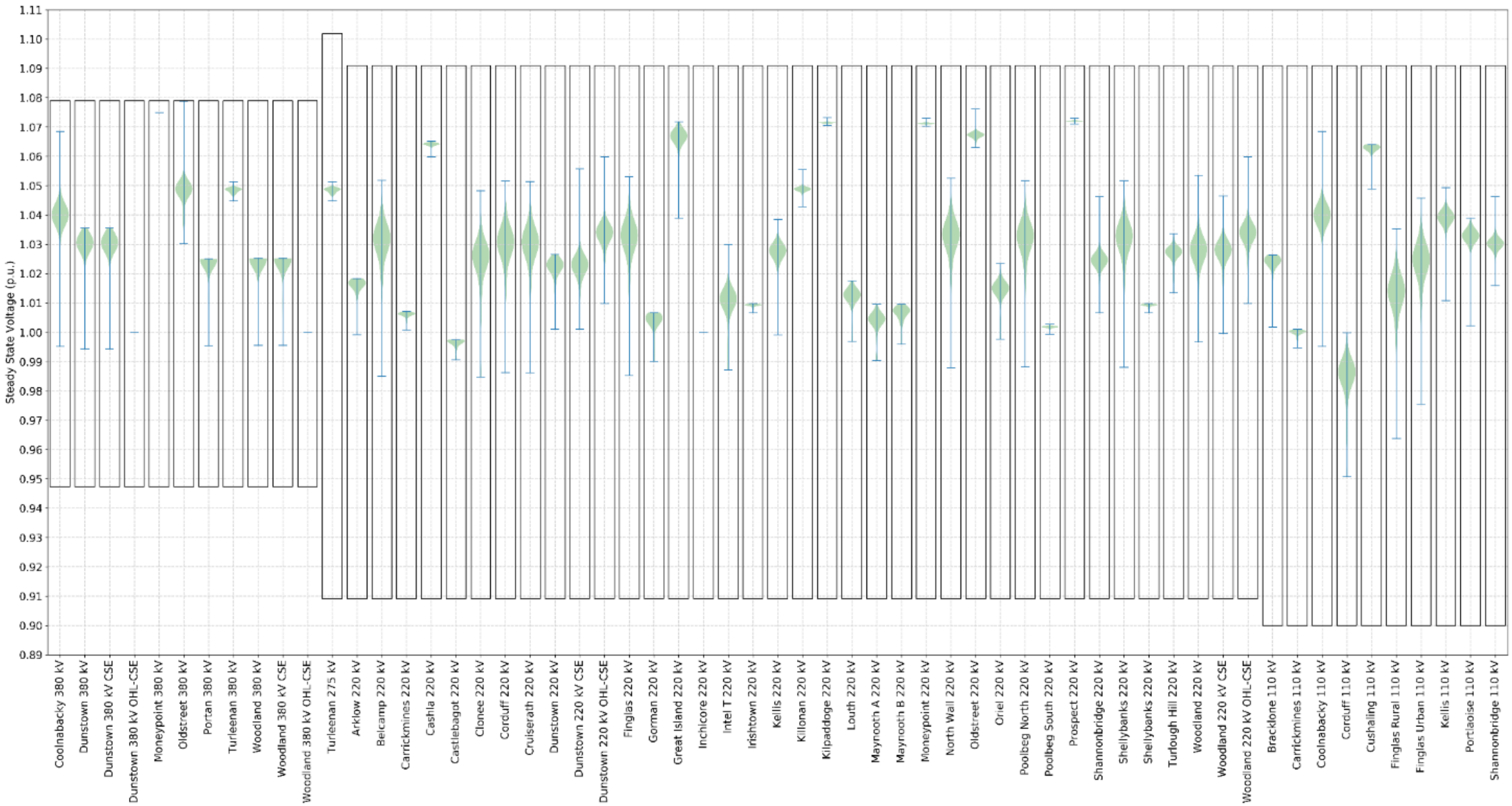

Figure 3-4: CP966_UGC220 post-contingency steady state voltages compared against EirGrid limits for operating scenario WP HW

3.4 Results for CP966_UGC400

The following shows the level and location of reactive compensation required for each cable length option for the 400 kV cable. Additionally, since the level of reactive compensation for the 400 kV, 2 cables per phase is very high, the reactive compensation requirements for 1 cable per phase were also calculated. The 1 cable per phase option will potentially result in restriction of the thermal loading when compared to the 2 cables per phase.

The results in these tables are based on the contingency (complete list in Appendix A) with the greatest reactive compensation requirement to maintain voltages within statutory limits. The reactive compensation requirement was driven by the steady state voltages during energisation of the circuit from one end and the requirement to maintain voltages within statutory limits. A further study detailed in section 6.1 compares the reactive compensation for this energisation arrangement against the reactive compensation for the remaining network contingencies.

As can be seen, for the 100 % cable option the cable requires nearly 100 % reactive compensation (1258 MVAR) for 2 cables per phase and nearly 90 % reactive compensation (558 MVAR) for 1 cable per phase but as the cable reduces the level of compensation also reduces. At greater than 50 % reactive compensation there is a significant risk of zero-miss phenomenon and this has been analysed further in section 5.2.

Table 3-2: Reactive compensation requirement for 400 kV UGC, 2 cables / phase

2 cables / phase		Shunt Reactor (Mvar)			
Cable Length (%)	Cable Length (km)	Woodland 400kV (PSSE bus 546400)	Dunstown 400kV (PSSE bus 220400)	Total	Compensation (%)
100.0%	60.0	629	629	1258	99.6%
87.5%	52.5	525	553	1078	94.8%
75.0%	45.0	365	474	839	83.0%
62.5%	37.5	326	395	721	81.5%
50.0%	30.0	227	316	543	71.6%
37.5%	22.5	132	237	369	58.4%
25.0%	15.0	38	158	196	38.8%
12.5%	7.5	0	64	64	16.9%

Table 3-3: Reactive compensation requirement for 400 kV UGC, 1 cable / phase

1 cable / phase		Shunt Reactor (Mvar)			
Cable Length (%)	Cable Length (km)	Woodland 400kV (PSSE bus 546400)	Dunstown 400kV (PSSE bus 220400)	Total	Compensation (%)
100.0%	60.0	279	279	558	88.4%
87.5%	52.5	169	277	446	79.2%
75.0%	45.0	112	237	349	70.5%
62.5%	37.5	59	198	257	60.3%
50.0%	30.0	4	158	162	45.3%
37.5%	22.5	0	109	109	37.6%
25.0%	15.0	0	47	47	21.3%
12.5%	7.5	0	0	0	0.0%

The following graphs (Figure 3-5 to Figure 3-10) show the range of system voltages pre- and -post contingency at the nodes of interest for full length 400 kV cable option with appropriate compensation (as explained in Figure 3-1 above).

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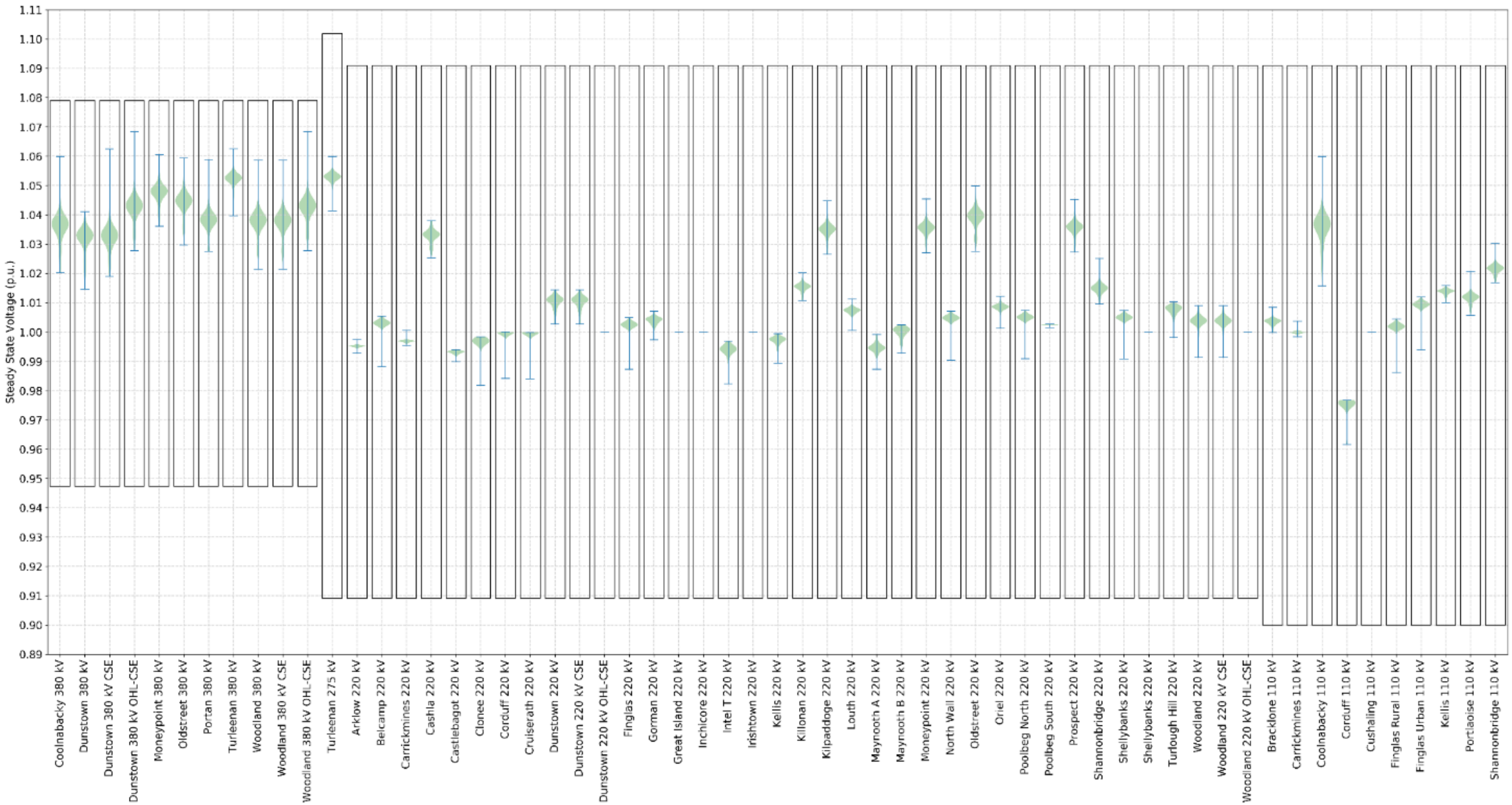

Figure 3-5: CP966_UGC400, 2 cables / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario SV LW

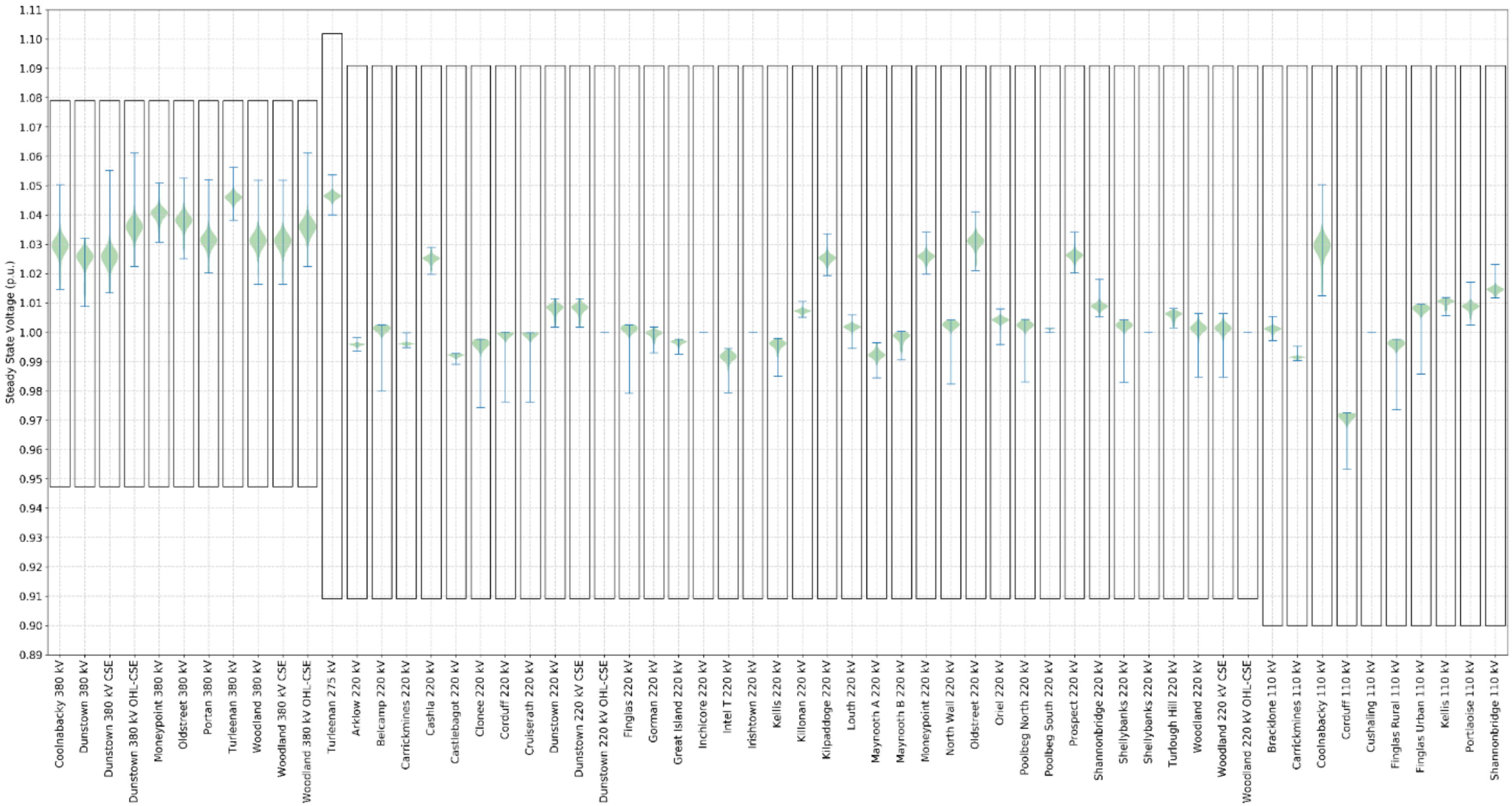

Figure 3-6: CP966_UGC400, 2 cables / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario SV HW

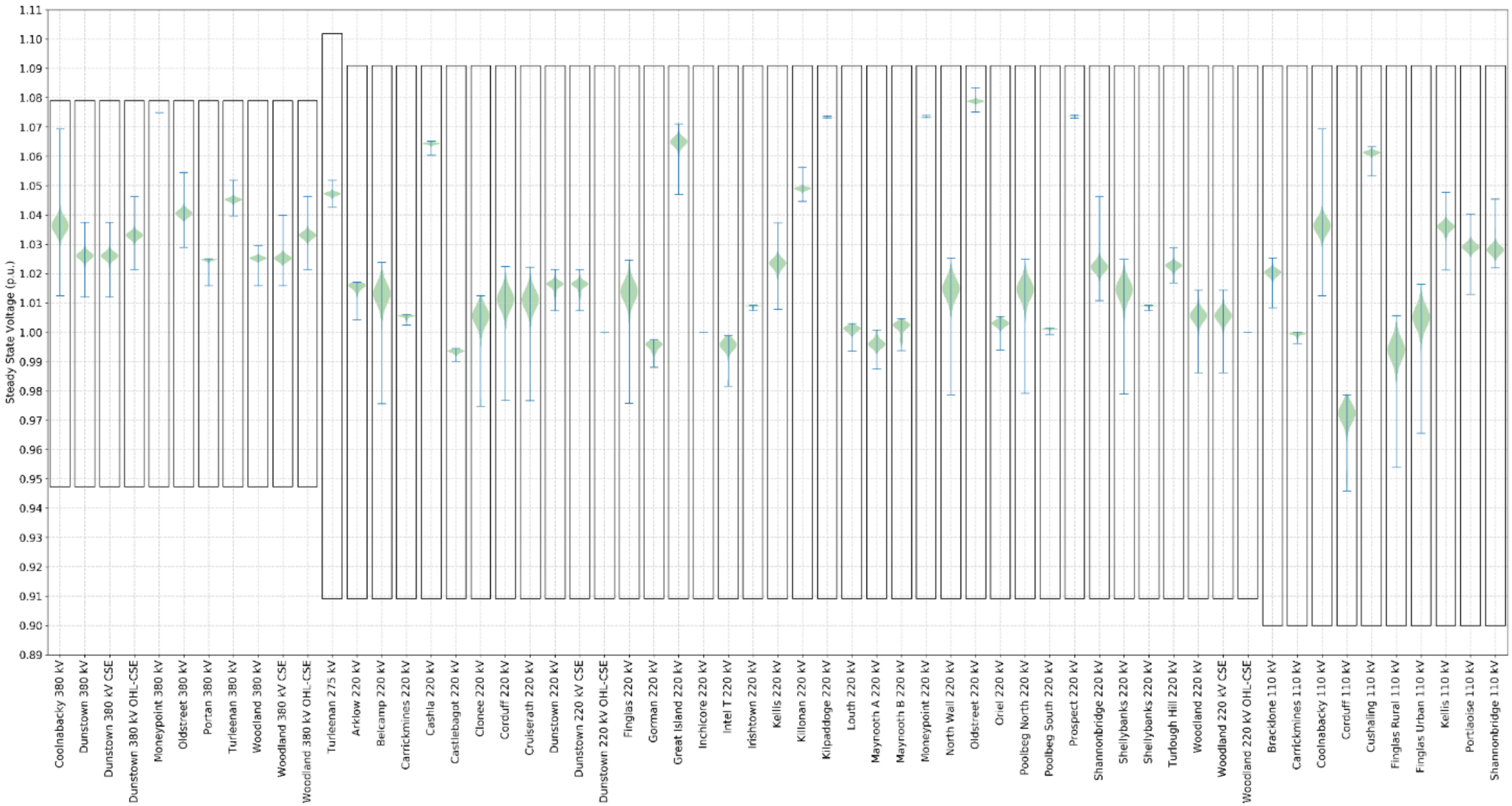

Figure 3-7: CP966_UGC400, 2 cables / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario WP HW

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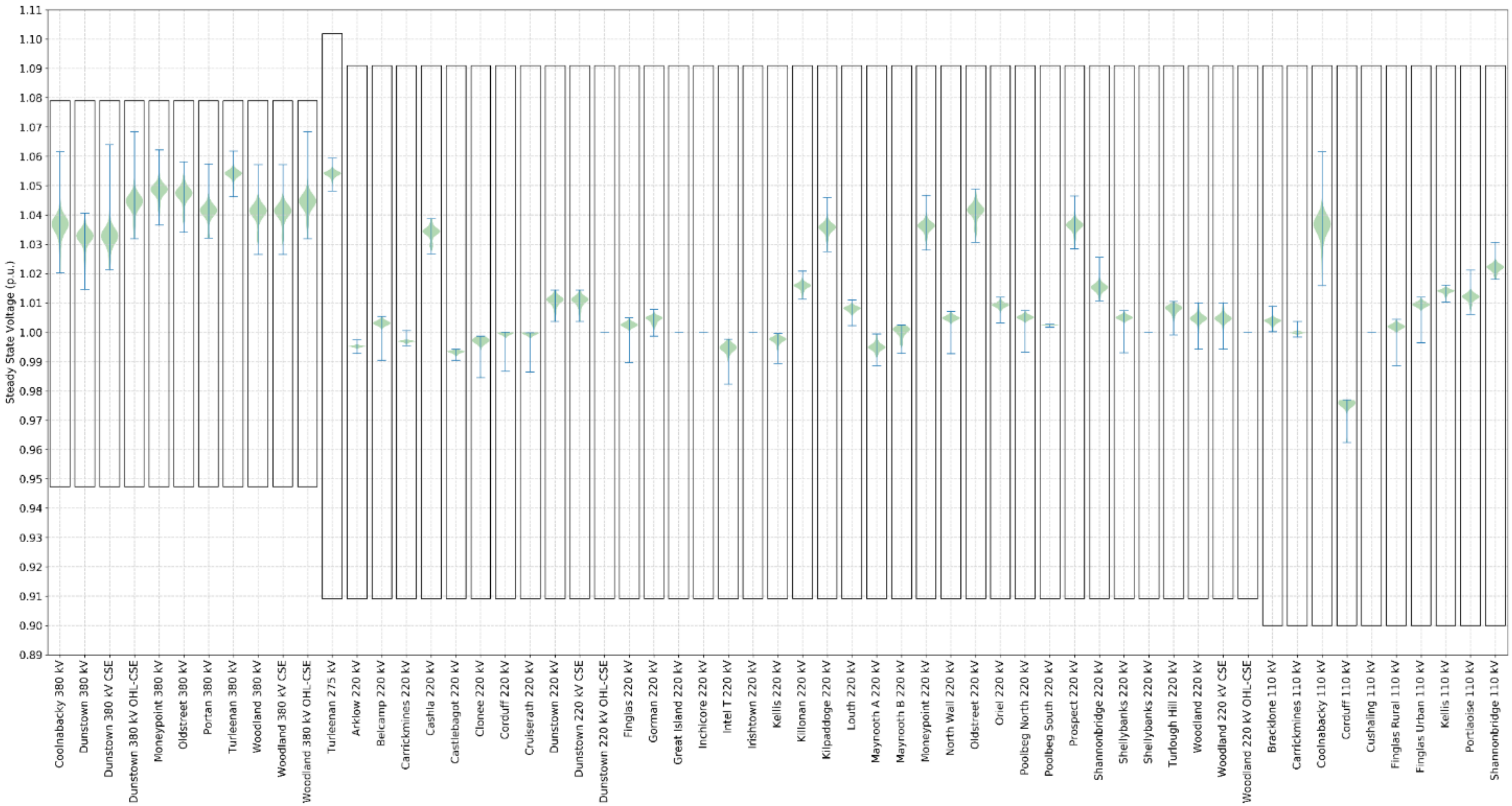

Figure 3-8: CP966_UGC400, 1 cable / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario SV LW

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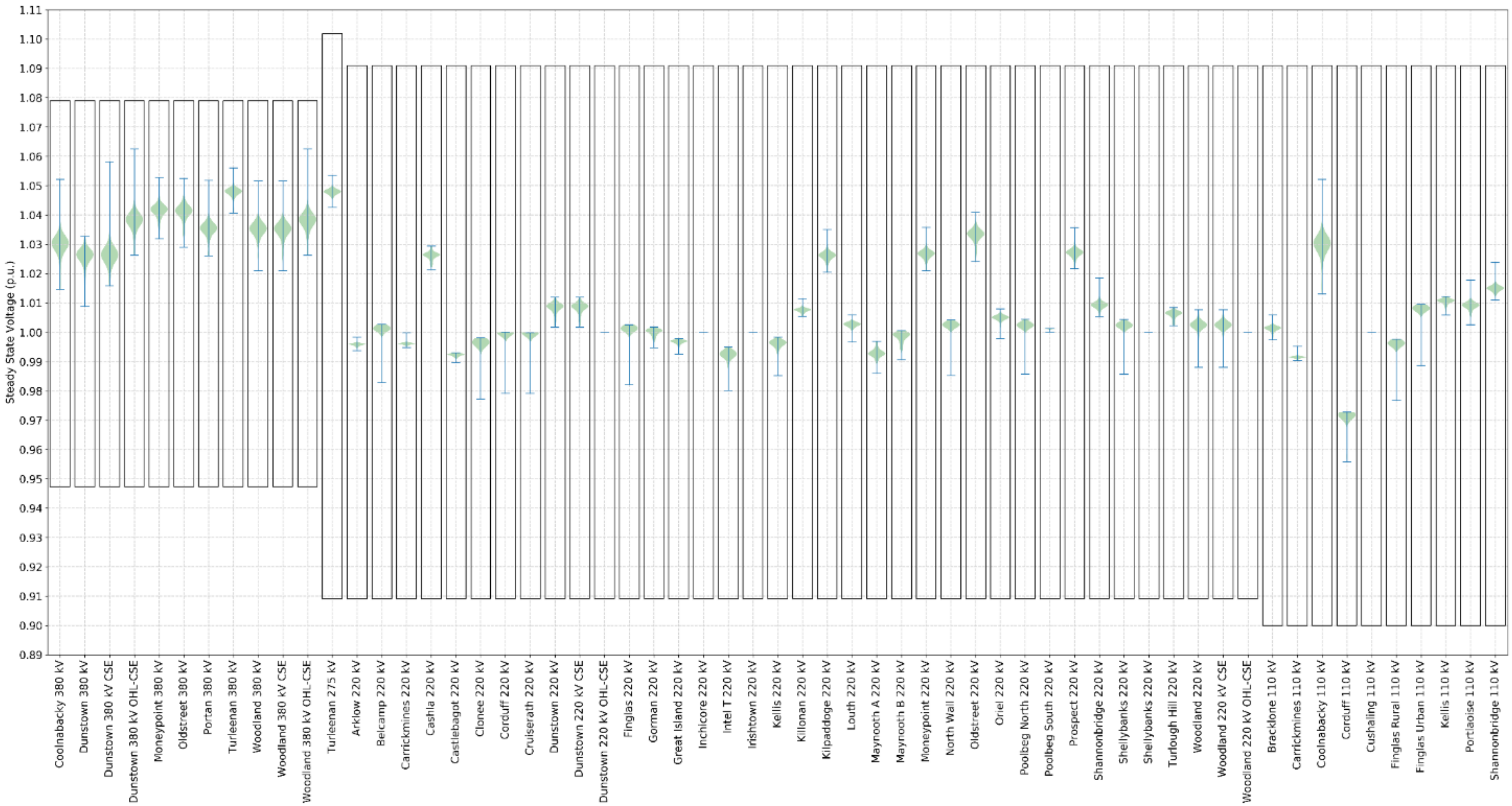

Figure 3-9: CP966_UGC400, 1 cable / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario SV HW

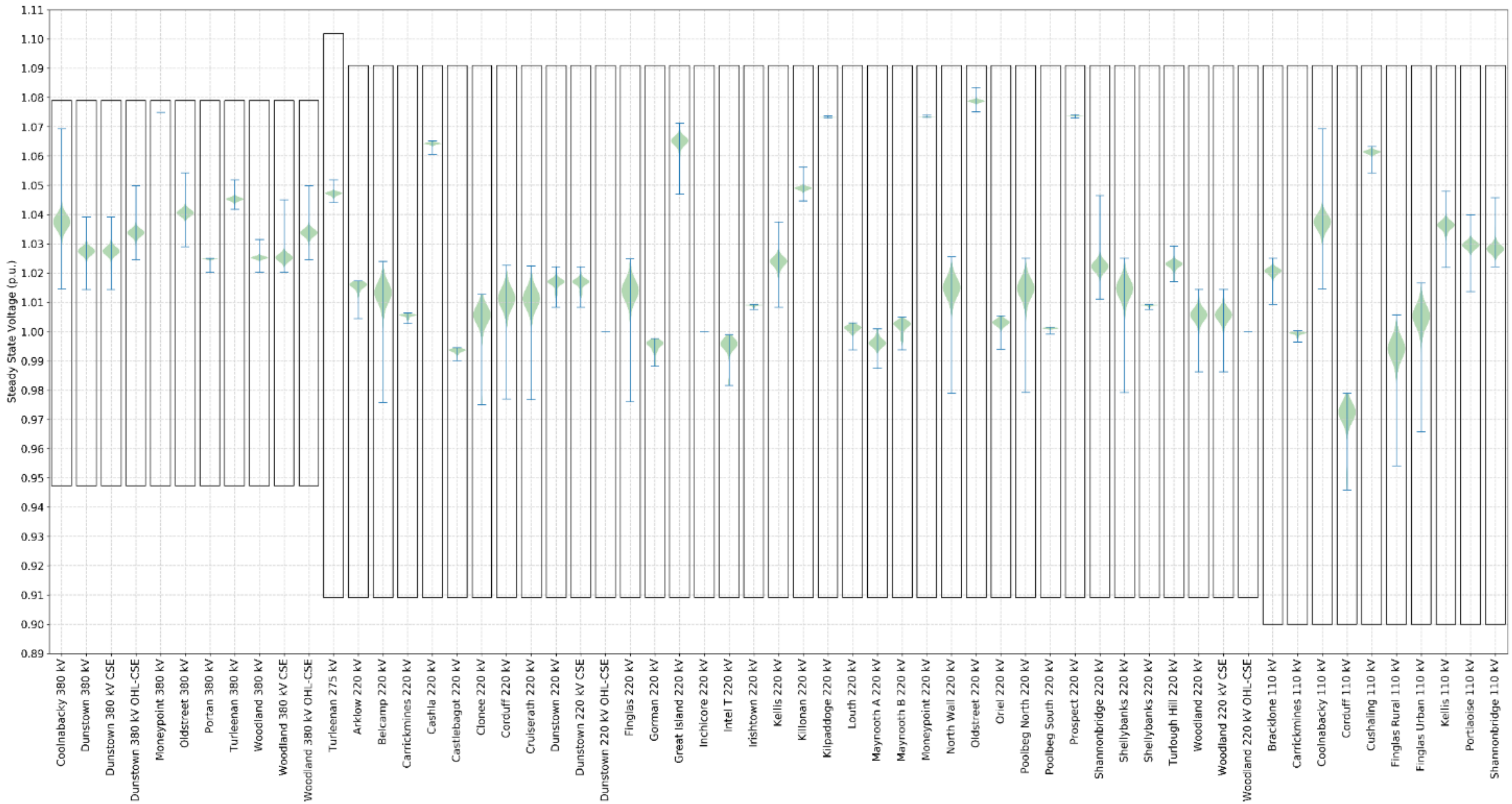

Figure 3-10: CP966_UGC400, 1 cable / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario WP HW

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4 Harmonic Analysis and Mitigation

PSC has carried out harmonic analysis studies in PowerFactory in order to calculate the future harmonic distortion and assess the compliance with the harmonic Planning Levels (PL) following the CP966 reinforcement options. Where harmonic breaches are observed, PSC has considered mitigation measures in the form of passive C-type harmonic filters.

The PowerFactory models reviewed and updated as part of the model review were utilised for both the 220 kV and 400 kV UGC options [1].

4.1 Methodology

Harmonic amplification studies were initially carried out as per the methodology document [2]. The background harmonic amplification was calculated for all the contingencies detailed in Appendix A and for the following operating scenarios:

- Summer Valley, Low Wind (SV-LW)
- Summer Valley, High Wind (SV-HW)
- Winter Peak, High Wind (WP-HW)

Frequency scans were performed for the nodes of interest presented in Table 4-1 using the EirGrid HAST tool in order to establish likely resonance points. Calculations were done for the base case prior to introducing any of the CP966 UGC options and for the 220 kV, 400 kV (1c/ph) and 400 kV (2c/ph) UGC options considering the reactive compensation calculated in Section 3. The tool was populated with the required contingencies and the frequency sweeps were carried out in the 50 Hz to 2000 Hz range with a 5 Hz fixed resolution to ensure that no narrow band resonances were missed. A series of non-convergent cases were identified during certain contingency scenarios caused by numerical instability (PowerFactory calculation issue). Those load flow convergent issues were primarily solved by changing the number of steps and applying a fixed relaxation factor in the Iteration Control tab of the Load Flow Calculation settings.

The background harmonic data for most of the nodes of interest were calculated in a previous EirGrid project [6] and they take into consideration the following assumptions:

- Existing background harmonic measurements on the system or assumed background where these are not available.
- The impact of reinforcements that are expected to be completed prior to the CP966 Project.
- The harmonic limits issued to any new customers not connected to the system yet.

For the nodes of interest where there were not any calculated future background harmonic data it was considered to be identical to electrically close stations as presented in Table 4-2.

It should be noted that EirGrid harmonic policy aims to keep harmonic distortions to within 75 % of the PL so that future connections and reinforcements can be accommodated. For the harmonics where the calculated future background data was higher due to the assumptions considered in the previous EirGrid project, the 75 % of the PL was considered as the level of existing background for the calculations.

Appendix D presents the future background harmonic distortion data considered in the harmonic analysis studies.

Table 4-1: Nodes of Interest

Key[10]	Substation	Voltage (kV)
CLE2	Clonee	220
CDU2	Corduff	220
CDU1	Corduff	110
DSN4	Dunstown	400
DSN2	Dunstown	220
FIN2	Finglas	220
GOR2	Gorman	220
KLS2	Kellis	220
LSE4 (CLN4)	Laois (Coolnabacky)	400
MAY2A	Maynooth	220
MAY2B	Maynooth	220
MAY1	Maynooth	110
OST4	Old Street	400
PRN4	Portan	400
WDU2 (CTB2)	West Dublin (Castlebagot)	220
WDU1 (CTB1)	West Dublin (Castlebagot)	110
WOO4	Woodland	400
WOO2	Woodland	220
BEL2	Belcamp	220
CKM2	Carrickmines	220
TH2	Turlough Hill	220

[10] The key is formed from the EirGrid 3 letter code followed by the voltage identifier (400 kV = 4, 220 kV = 2, 110 kV = 1). Where split busbars exist these will be appended with identifying letters (A, B, etc.) as appropriate.

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Table 4-2: Electrically equivalent nodes of interest

Key	Substation	Electrically equivalent - Key	Electrically equivalent - Substation
CDU1	Corduff	MUL1	Mullingar
DSN4	Dunstown	DSN2	Dunstown
FIN2	Finglas	CDU2	Corduff
MAY1	Maynooth	MAY2	Maynooth
OST4	Old Street	WOO4	Woodland
PRN4	Portan	WOO4	Woodland
WDU1 (CTB1)	West Dublin (Castlebagot)	WDU2 (CTB2)	West Dublin (Castlebagot)
W004	Woodland	WOO2	Woodland
TH2	Turlough Hill	DSN2	Dunstown
LSE4 (CLN4)	Laois (Coolnabacky)	DSN4	Dunstown

Harmonic amplification factors have been calculated as detailed in the methodology report [2] being effectively the ratio of self-impedance between the base case system and the system with each of the new cables in order to establish any breach due to the magnification of the future background distortion.

The voltage gain factor (γ) was calculated based on the change in self-impedance due to the new Dunstown-Woodland circuit for each N and N-1 condition (x) as:

$$\gamma_h(x) = \frac{Z_{h_{after\_reinforcement}}}{Z_{h_{before\_reinforcement}}}$$

where:

$Z_{h_{after\_reinforcement}}$: is the harmonic (h) self-impedance of the nodes after the Dunstown-Woodland circuit and uprates are modelled. This is calculated for every N and N-1 condition (x)

$Z_{h_{before\_reinforcement}}$: is the harmonic (h) self-impedance of the nodes before the new Dunstown-Woodland circuit and uprates are added. This is calculated for every N and N-1 condition (x)

This sequence was applied across the HAST tool results to determine voltage gain factors and the amplified harmonic background for each node under each contingency scenario considered.

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4.2 Results for CP966_UGC220

4.2.1 Harmonic Analysis

The full cable length solution was assessed and the background harmonic amplification was reviewed for all the nodes of interest under the three network operating scenarios and the contingencies considered as presented in Section 4.1. The full cable length study showed high harmonic amplification of the background harmonics resulting in breaching of harmonic limits in multiple substations. Further studies were performed for the reduced cable lengths of 50%, 25% and 12.5% considering an OHL section as explained in methodology report [2] in order to evaluate whether there is a maximum length of UGC that can be installed while avoiding system technical performance issues. The studies for all the cable length solutions showed that there is no such cable length that does not result in harmonic breaching without the inclusion of a harmonic mitigation solution.

Figure 4-1 to Figure 4-4 show an overview of the maximum harmonic distortions in the study area for the various UGC length options (100%, 50%, 25%, 12.5%) with the red bars showing the EirGrid adopted planning level for each harmonic. The results have been calculated for all the contingencies and network operating scenarios and for harmonics up to the 20th order. Higher order harmonic background data is thought to be less accurate due to the sensitivity of the EirGrid measurement equipment and so results are presented up to the 20th order.

Table 4-3 presents detailed results for each UGC cable length that give a side by side overview of the substations where the harmonic limits are exceeded along with the most onerous contingency, background harmonics and calculated amplified distortion. The results indicate that while the UGC cable length decreases, the number of the substations with harmonic breaching tends to decrease and the harmonic orders are becoming higher. Since every UGC option results in harmonic breaching a mitigation solution is required and it has been agreed with EirGrid to investigate a solution for the 100% cable length option. Details of the solution, assumptions and results are presented in the following Section 4.2.2. Frequency scans for different nodes are also presented in Section 4.2.2 for the base case prior to CP966 reinforcements and for the cases with and without the harmonic filtering following the CP966 reinforcements.

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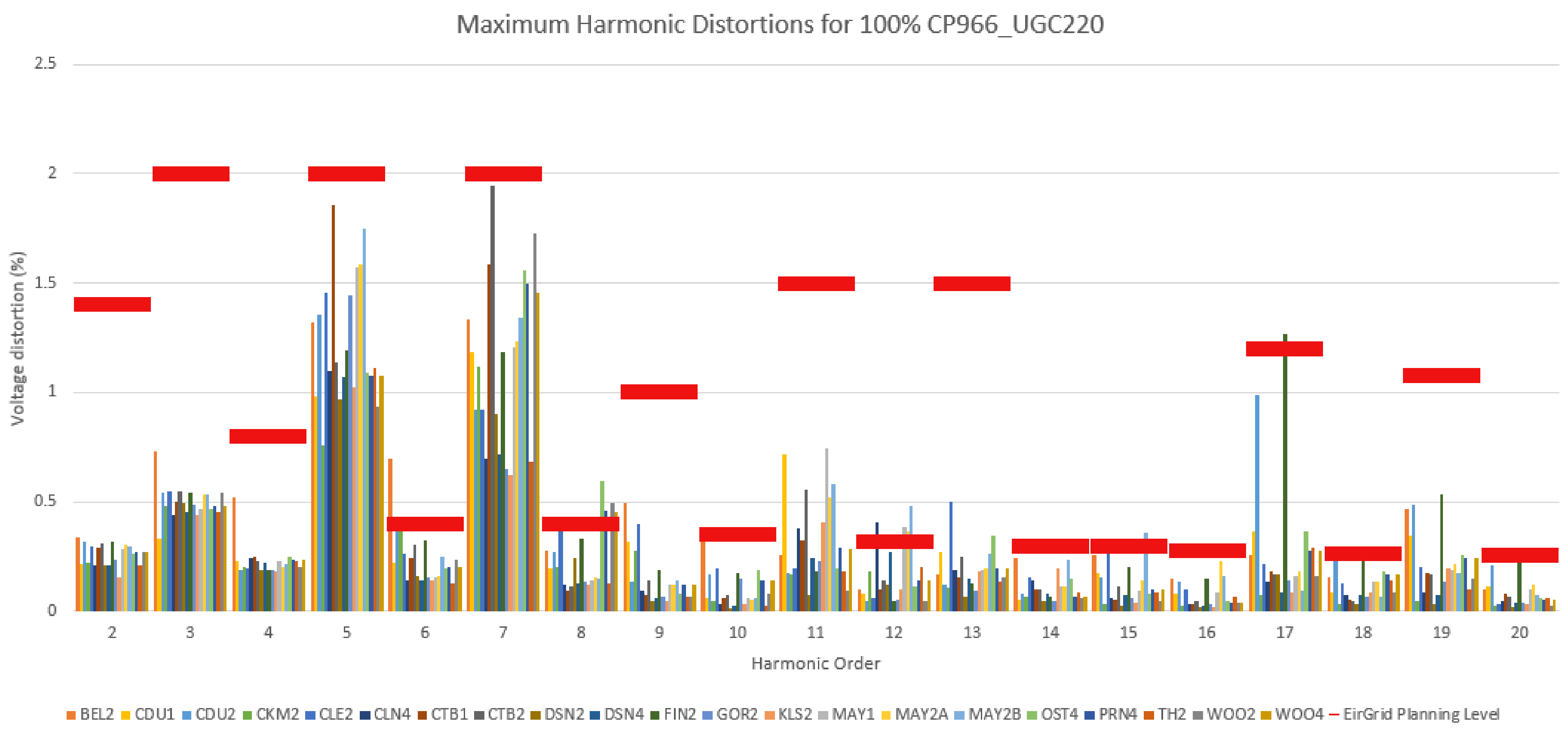

Figure 4-1: Maximum Harmonic Distortions for 100 % UGC220 cable length

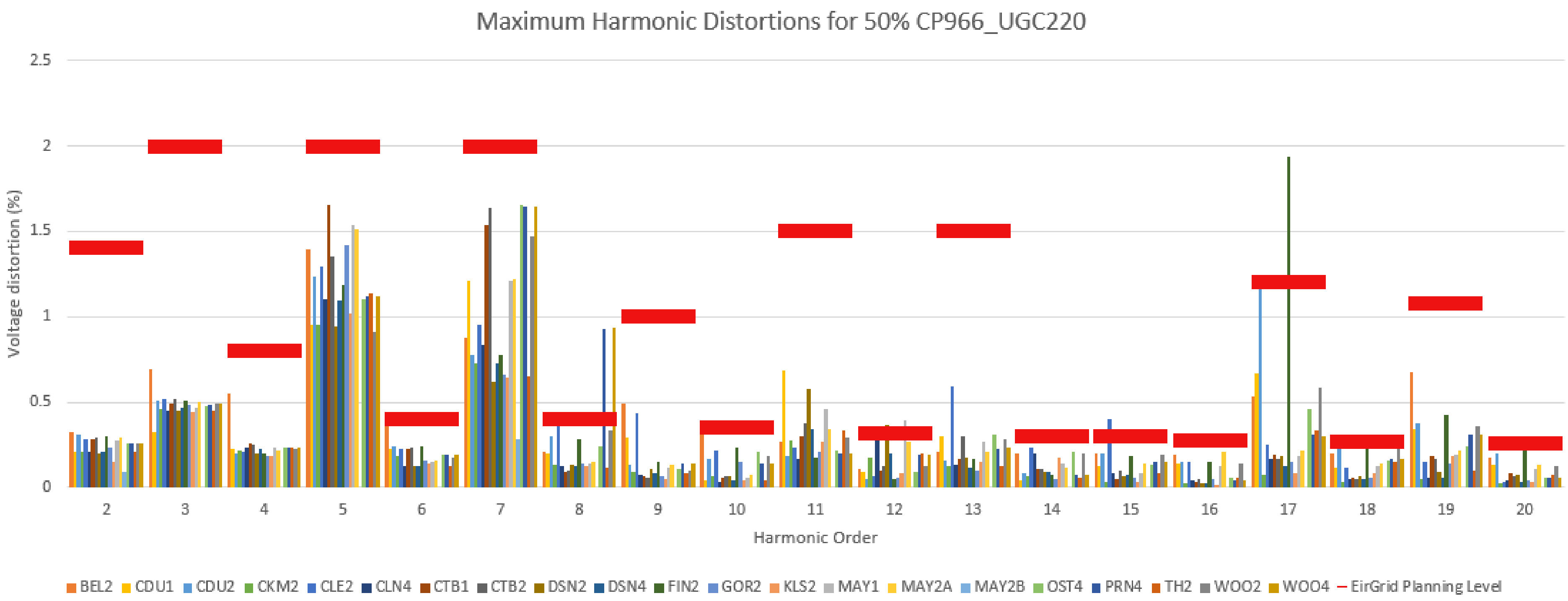

Figure 4-2: Maximum Harmonic Distortions for 50 % UGC220 cable length

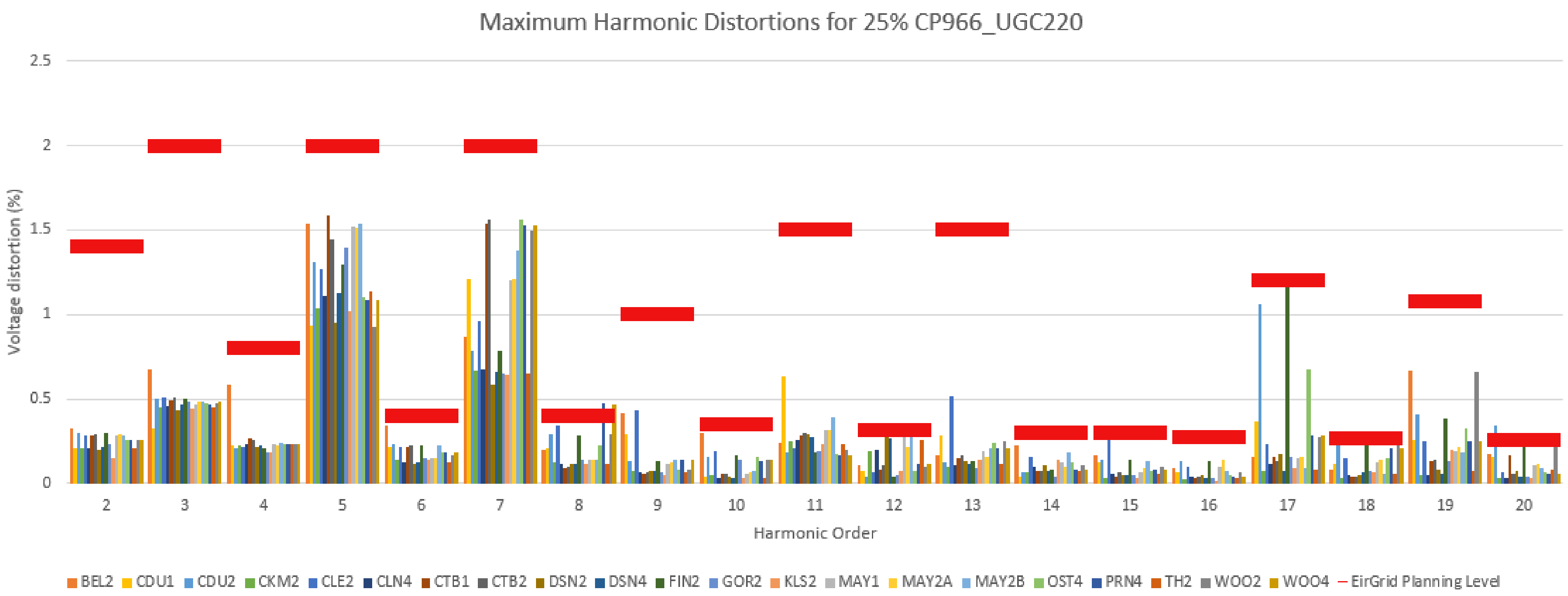

Figure 4-3: Maximum Harmonic Distortions for 25 % UGC220 cable length

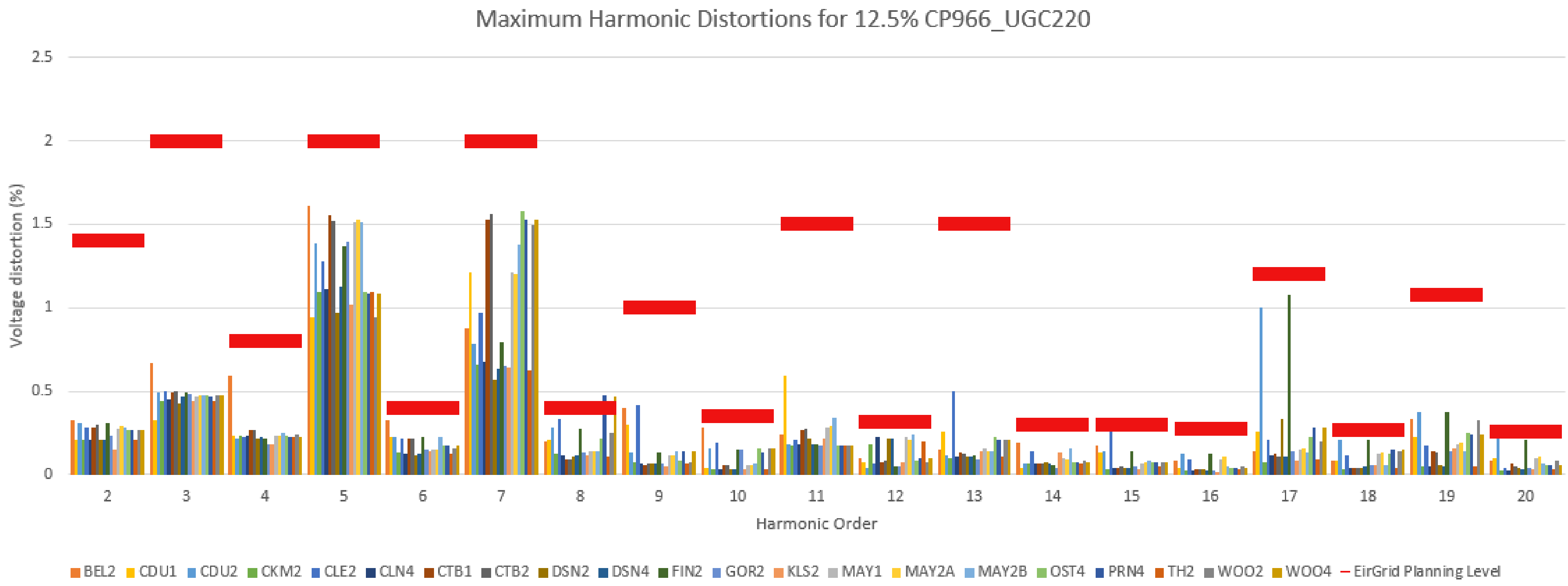

Figure 4-4: Maximum Harmonic Distortions for 12.5 % UGC220 cable length

Table 4-3: Harmonic Distortions Exceeding Planning Levels for Different UGC220 Lengths

Node	100 % UGC220				50 % UGC220				25 % UGC220				12.5 % UGC220			
	Harmonic order	Planning Level (%)	Contingency	Amplified Distortion (%)	Harmonic order	Planning Level (%)	Contingency	Amplified Distortion (%)	Harmonic order	Planning Level (%)	Contingency	Amplified Distortion (%)	Harmonic order	Planning Level (%)	Contingency	Amplified Distortion (%)
BEL2	6	0.4	CDU2B-WOO2A	0.695	10	0.35	DSN4-CLN4	0.362	-	-	-	-	-	-	-	-
CKM2	6	0.4	CKM2-DSN2	0.426	-	-	-	-	-	-	-	-	-	-	-	-
CLN4	12	0.318	CKM2-DSN2	0.403	-	-	-	-	-	-	-	-	-	-	-	-
FIN2	17	1.2	WOO4-TLE4	1.267	17	1.2	CDU2A-FIN2A	1.94	-	-	-	-	-	-	-	-
MAY1	12	0.318	CLN4-MP4	0.386	12	0.318	DSN4-CLN4	0.392	-	-	-	-	-	-	-	-
MAY2A	12	0.318	CLN4-MP4	0.367	-	-	-	-	-	-	-	-	-	-	-	-
MAY2B	12	0.318	CLN4-MP4	0.481	12	0.318	CLN4-MP4	0.434	-	-	-	-	-	-	-	-
MAY2B	15	0.3	DSN4-CLN4	0.354	15	0.3	DSN4-CLN4	0.300	-	-	-	-	-	-	-	-
OST4	8	0.4	CDU2B-WOO2A	0.594	-	-	-	-	-	-	-	-	-	-	-	-
PRN4	8	0.4	OST4-OST2	0.462	8	0.4	DSN2-TH2	0.928	8	0.4	CDU2B-WOO2A	0.474	8	0.4	WOO2-CLE2	0.473
WOO2	8	0.4	PRN4-Fshunt	0.493	-	-	-	-	-	-	-	-	-	-	-	-

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WOO 4	8	0.4	OST4-OST2	0.452	8	0.4	DSN2-TH2	0.938	8	0.4	CDU2B-WOO2A	0.464	8	0.4	WOO2-CLE2	0.464
CLE2	-	-	-	-	15	0.3	FIN2B-NW2	0.404	15	0.3	FIN2B-NW2	0.302	-	-	-	-
DSN2	-	-	-	-	12	0.318	OST4-MP4	0.369	12	0.318	DSN4-CLN4	0.353	-	-	-	-
FIN2	-	-	-	-	17	1.2	INT2-MAY2A	0.269	20	0.255	DSN2-TH2	0.265	-	-	-	-
CDU2	-	-	-	-	-	-	-	-	18	0.266	BEL2-FIN2A	0.266	-	-	-	-
CDU2	-	-	-	-	-	-	-	-	20	0.255	DSN2-TH2	0.340	-	-	-	-

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As explained, the calculation of the future background distortion is proportional to the amplification factor and to the background harmonics by 2030 prior to the CP966 reinforcements. Since the background harmonics have been calculated in a previous EirGrid project [6] based on various assumptions that might change in the future, the maximum permitted future background harmonics to avoid any performance issues have been calculated in Table 4-4 for the nodes with harmonic breaching and for the 100% cable length option. Those harmonics are for information only and indicate that if the future background data remain below them then the harmonic distortion will remain within the PL without the inclusion of a harmonic filtering.

Table 4-4: Maximum Permitted Future Background Harmonics (for EirGrid PL Compliance without Filters) for 100% UGC220

Node	100 % UGC220			
	Harmonic order	Planning Level (%)	Future Background Harmonics considered in this analysis (%)	Maximum Permitted Future Background Harmonics (%) (for PL Compliance without Filters)
BEL2	6	0.4	0.300	0.170
CKM2	6	0.4	0.121	0.112
CLN4	12	0.318	0.173	0.135
FIN2	17	1.2	0.900	0.843
MAY1	12	0.318	0.188	0.152
MAY2A	12	0.318	0.188	0.160
MAY2B	12	0.318	0.210	0.137
MAY2B	15	0.3	0.062	0.050
OST4	8	0.4	0.181	0.120
PRN4	8	0.4	0.181	0.154
WOO2	8	0.4	0.181	0.144
WOO4	8	0.4	0.181	0.157

4.2.2 Harmonic Mitigation Solution

The harmonic studies presented previously have identified that there are multiple nodes with harmonic breaching for the various UGC220 length options and it has been agreed with EirGrid to further investigate a mitigation solution for the 100% cable length. It is expected that if the final cable length option deviates significantly from the full length of 60 km then the filtering solution will need to be revisited in terms of size, tuning and location of the filters.

Due to the number of harmonic breaches and the complexity of the EirGrid network there was an attempt to avoid proposing filters in every single substation and perform sensitivity studies for finding solutions that could improve the harmonic performance of other nearby stations. This resulted in the five C-type filters presented in Table 4-5 where the filters in Maynooth substations are targeting more the local harmonic issues; whereas the remaining filters in Dunstown and Coolnabacky substations are targeting harmonic issues in local and nearby stations.

Table 4-5: Harmonic Mitigation Solution for 100% UGC220

Node	Size (Mvar)	Resonant Frequency (Hz)	Parallel Resistance (Rp)
DSN2	32	420	800
CLN4	10	550	1000
MAY2B	30	525	500
MAY2A	15	550	1000
MAY1	5	525	400

Figure 4-5 shows an overview of the maximum harmonic distortions in the study area for the 100% UGC220 and considering all the filters in service. The results have been calculated for all the contingencies and network operating scenarios and for harmonics up to the 20th order. During the detailed gain factor calculations and self-impedance analysis, there were some contingencies where the impedance values before and after were very low and therefore were excluded as spurious results.

The results show that most of the harmonic breaches of the EirGrid planning levels at any of the substations in the study area are being eliminated when the proposed C-type filters are in service with the only exception of the 12th harmonic in CLN4 and MAY2B that remain marginally above the limit. Since there are local filters proposed in those substations, their harmonic compliance will easily be resolved during the fine tuning of the mitigation solution in the next phase of the project.

Figure 4-6 to Figure 4-11 present the frequency scans for the nodes where the harmonic filters are being connected as well as for an additional node in order to present the impact that the filters have locally and in remote stations. Table 4-6 presents the list of the nodes along with the contingency for which the plots are being presented which normally represents the worst case in terms of harmonic breaching for that substation. Due to number and the complexity of the studies, it is not possible to present frequency scans for every single contingency and every node so some substations where high exceedances were observed are being presented.

For each node, frequency scans for the following cases are being presented:

- Base case prior to the CP966_UGC220 (in **Black**)
- Case following the CP966_UGC220 installation but without any mitigation solution (in **Green**)
- Case with the CP966_UGC220 installation and including the mitigation solution (in **Red**)

The results indicate that when comparing the cases prior and after the CP966_UGC220 there is a noticeable change in the complete frequency range in most of the nodes in terms of shifting resonant points, creating new resonances and changing the damping of the system. The impact of the cable installation is higher on stations that are electrically closer to the points of connection with the cable. The inclusion of the filters shows that there is a reasonable improvement in terms of decreasing the impedance values around the resonant frequency range of the filters and providing more damping in higher order harmonics.

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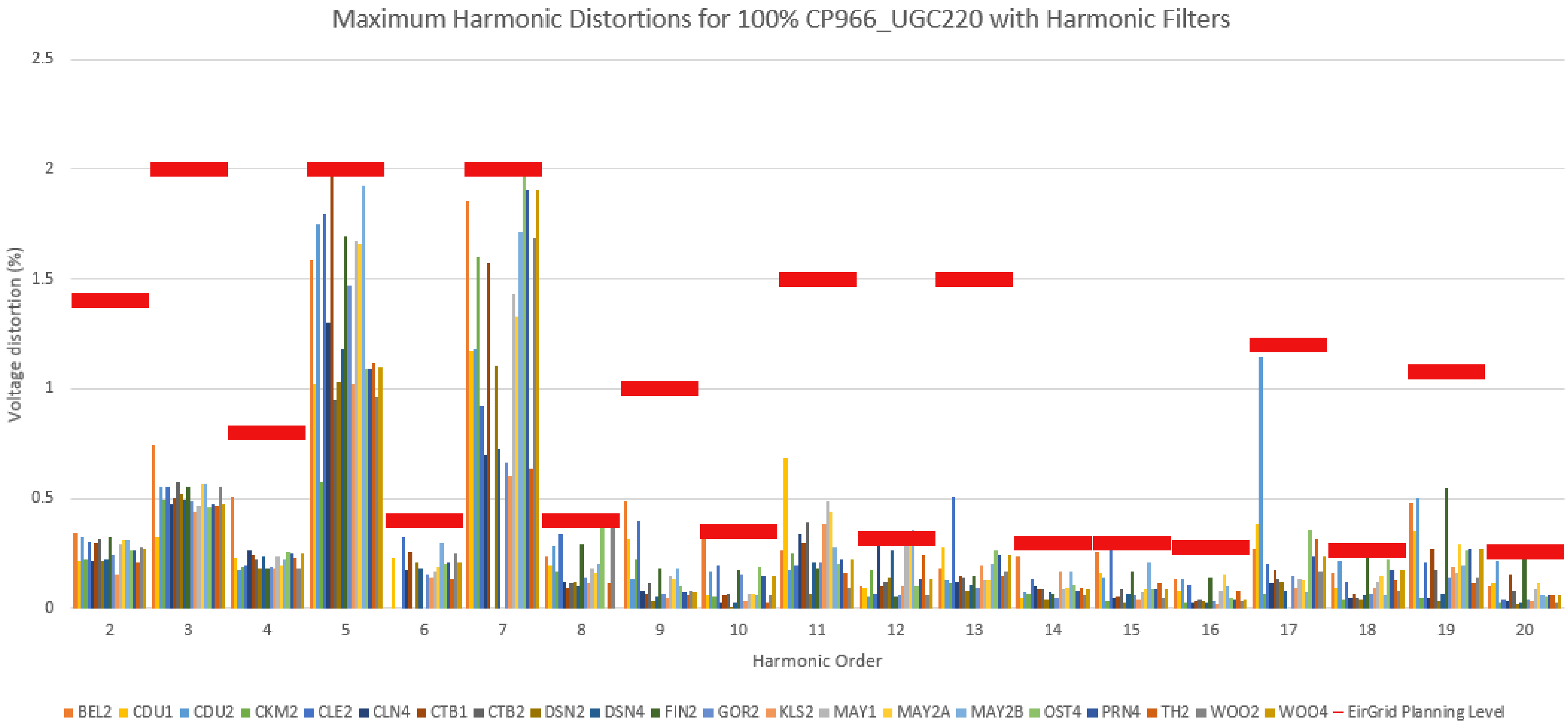

Figure 4-5: Maximum Harmonic Distortions for 100 % UGC220 cable length with harmonic filters

Table 4-6: Summary of Nodes for Frequency Response Plots

Node	Existence of local filter (Yes / No)	Contingency	Operating Scenario
DSN2	Yes	Intact System – Base	SVHW
CLN4	Yes	CKM2-DSN2	WPHW
MAY2B	Yes	CLN4-MP4	SVLW
MAY2A	Yes	CLN4-MP4	WPHW
MAY1	Yes	CLN4-MP4	WPHW
OST4	No	CDU2B-WOO2A	SVHW

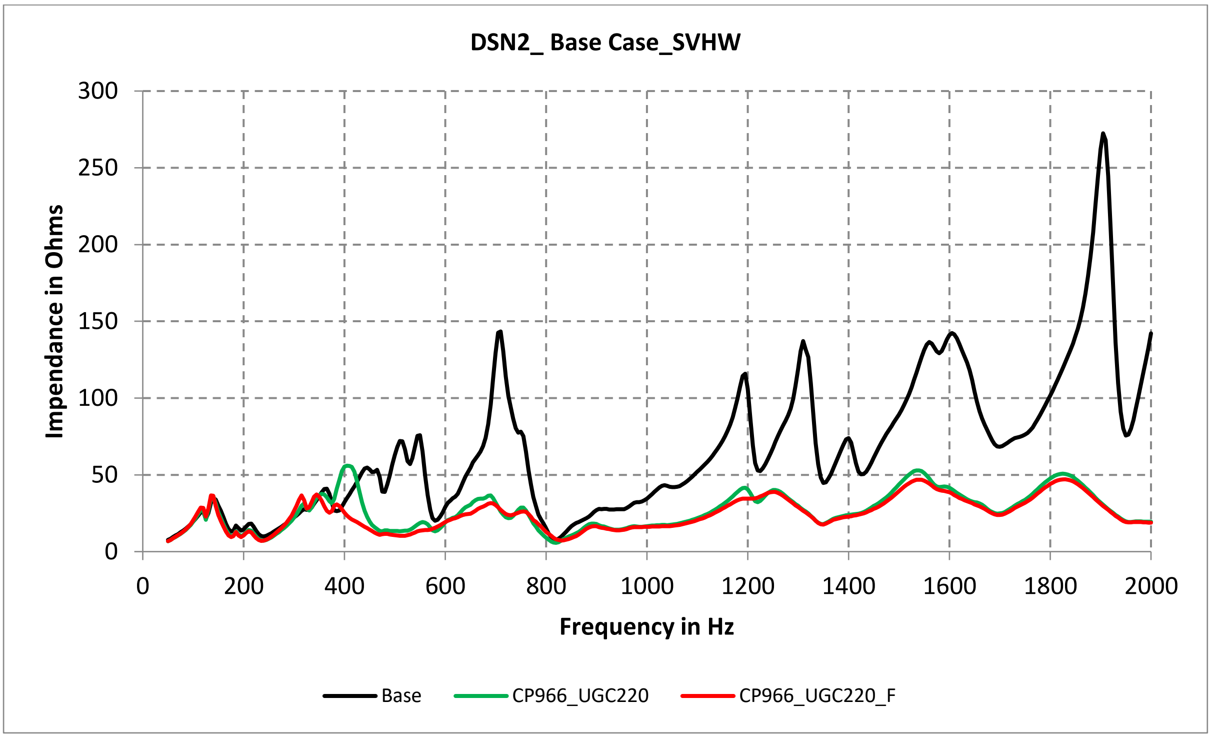

Figure 4-6: Self-impedance at Dunstown 220 kV substation at SVHW for the intact system

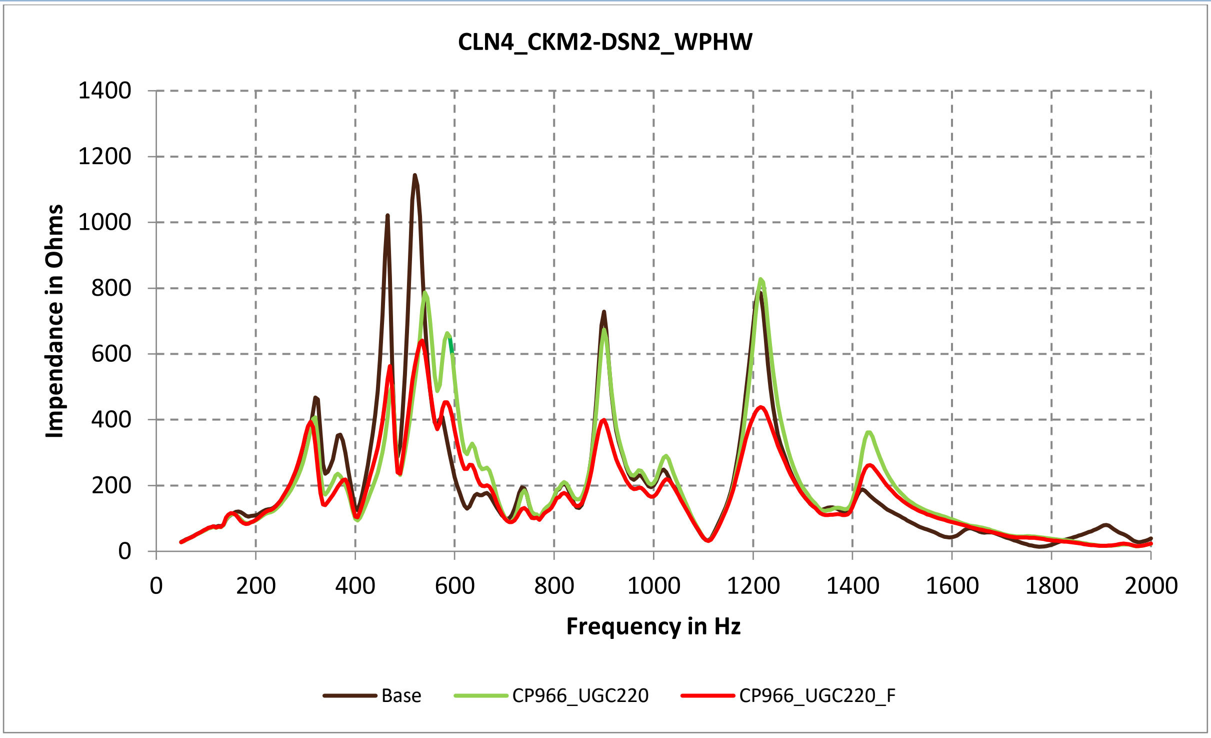

Figure 4-7: Self-impedance at Coolnabacky 400 kV substation at WPHW during CKM2-DSN2 contingency

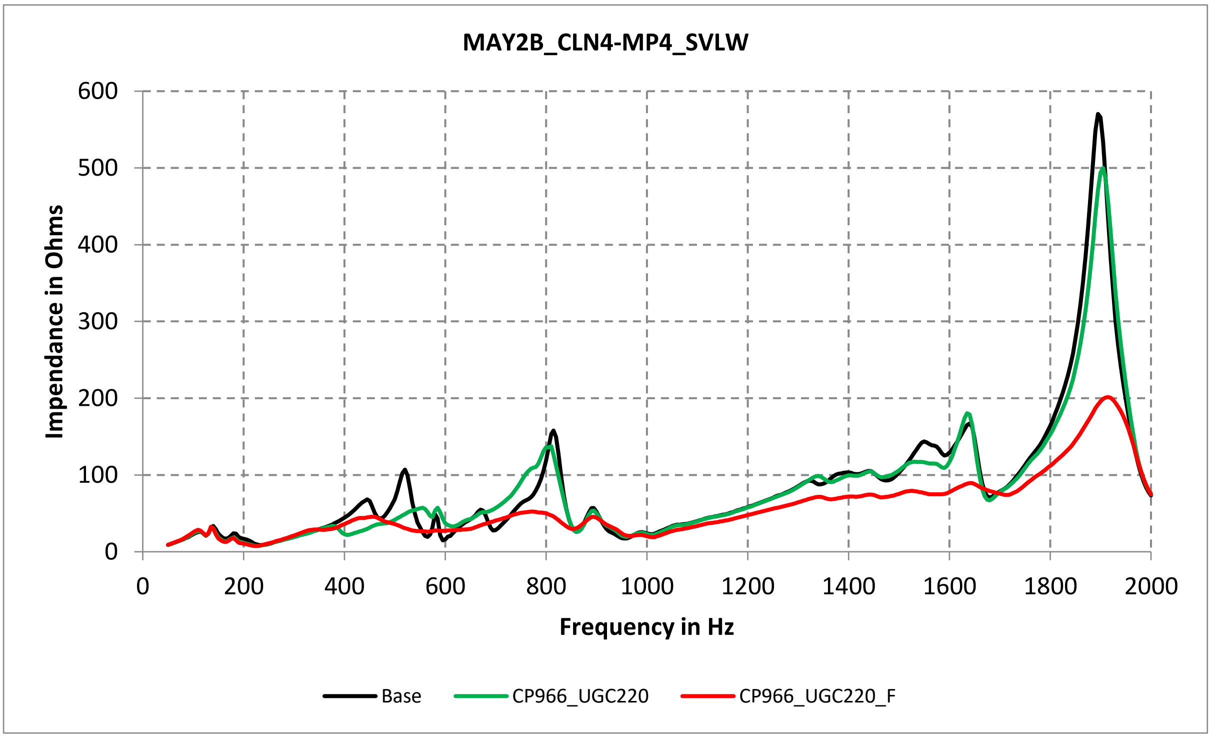

Figure 4-8: Self-impedance at MaynoothB 220 kV substation at SVLW during CLN4-MP4 contingency

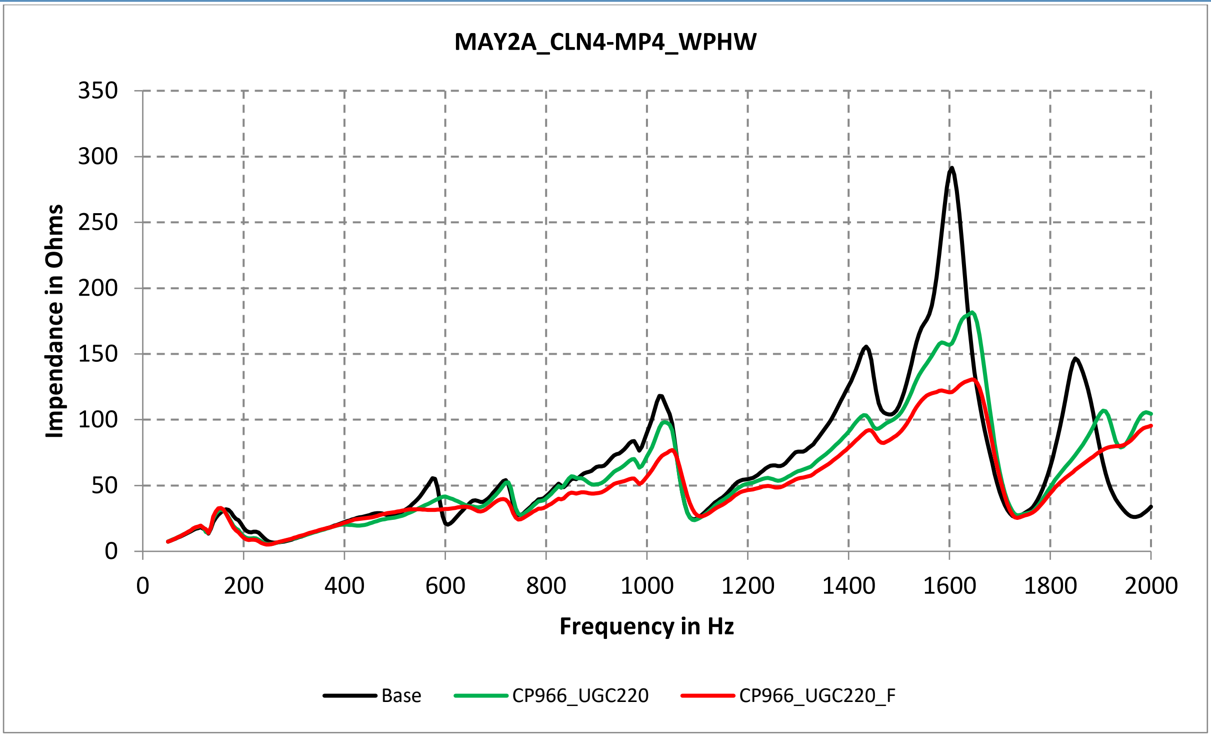

Figure 4-9: Self-impedance at MaynoothA 220 kV substation at WPHW during CLN4-MP4 contingency

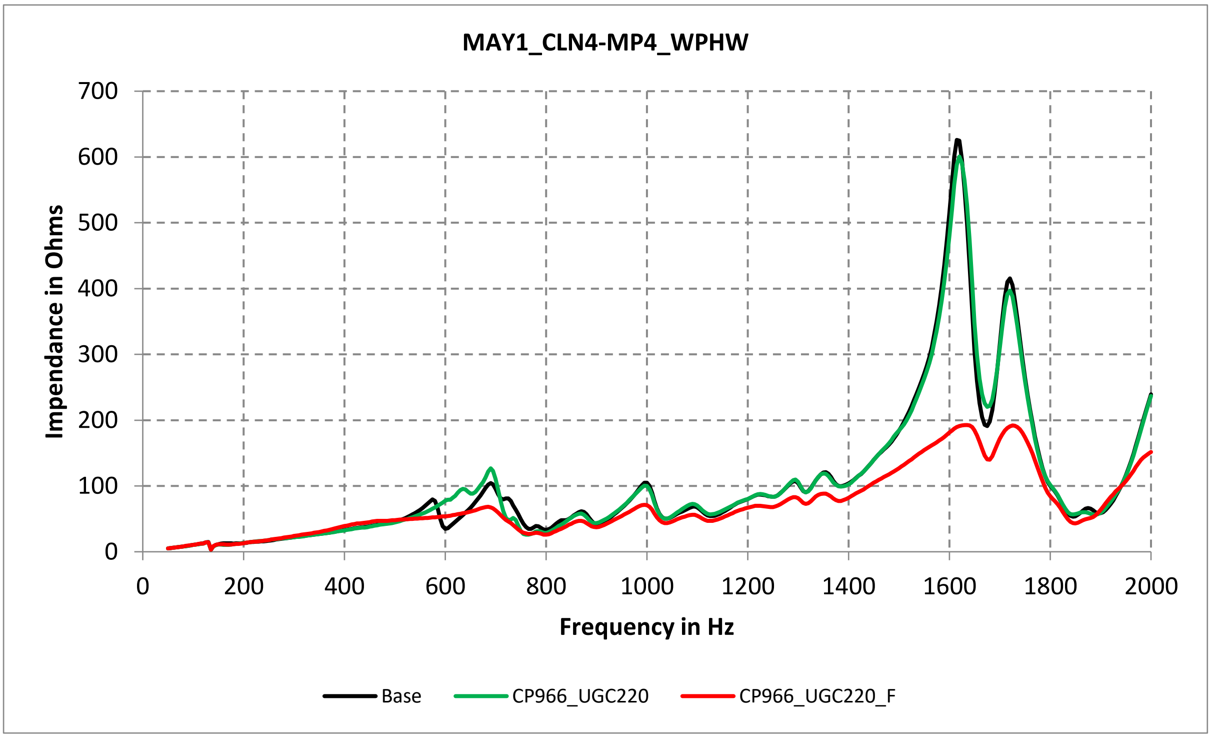

Figure 4-10: Self-impedance at Maynooth 110 kV substation at WPHW during CLN4-MP4 contingency

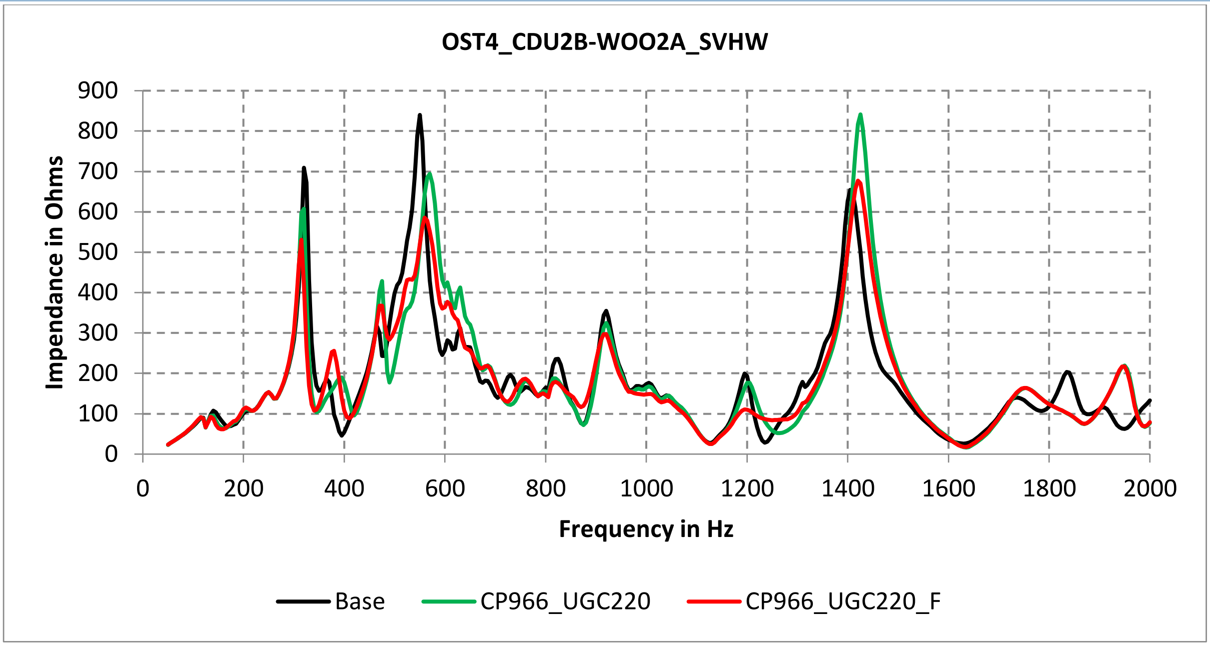

Figure 4-11: Self-impedance at Old Street 400 kV substation at SVHW during CDU2B-WOO2A contingency

4.3 Results for CP966_UGC400 (1c/ph)

4.3.1 Harmonic Analysis

The 100% cable solution was assessed and the background harmonic amplification was reviewed for all the nodes of interest under the three network operating scenarios and the contingencies considered as presented in Section 4.1. The full cable length study showed high harmonic amplification of the background harmonics resulting in breaching of harmonic limits in multiple substations. Further studies were performed for the reduced cable lengths of 50%, 25% and 12.5% considering an OHL section as explained in methodology report [2] in order to evaluate whether there is a maximum length of UGC that can be installed while avoiding system technical performance issues. The studies for all the cable length solutions showed that there is no such cable length that does not result in harmonic breaching without the inclusion of a harmonic mitigation solution.

Figure 4-12 to Figure 4-15 show an overview of the maximum harmonic distortions in the study area for the various UGC length options (100%, 50%, 25%, 12.5%) with the red bars showing the EirGrid Planning Levels for each harmonic. The results have been calculated for all the contingencies and network operating scenarios and for harmonics up to the 20th order. Higher order harmonic background data is thought to be less accurate due to the sensitivity of the EirGrid measurement equipment and so results are presented up to the 20th order.

Table 4-7 presents detailed results for each UGC cable length that give a side by side overview of the substations where the harmonic limits are exceeded along with the most onerous contingency, background harmonics and calculated amplified distortion. The results indicate that while the UGC cable length decreases, the number of the substations with harmonic breaching tends to decrease and the harmonic orders are becoming higher. Since every UGC option results in harmonic breaching a mitigation solution is required and it has been agreed with EirGrid to estimate the size of a possible solution for the 100% cable length option. In case the UGC400 option is selected for the next phase of the project, further investigation will be necessary to fully achieve harmonic compliance that will be based on the existing solution. Details of the solution, assumptions and results are presented in the following Section 4.3.2. Frequency scans for different nodes are also presented in Section 4.3.2 for the base case prior to CP966 reinforcements and for the cases with and without the harmonic filtering following the CP966 reinforcements.

Comparing the results of the UGC400 with the UGC220, it is observed that there is a higher number of harmonics breaching the planning levels for all the different UGC400 lengths resulting in a more complex mitigation solution with more and bigger harmonic filters. Additionally, the harmonic orders at which the breaching is observed are generally lower in the UGC400 option which might result in more expensive harmonic filters and in higher possibility of having TOV issues.

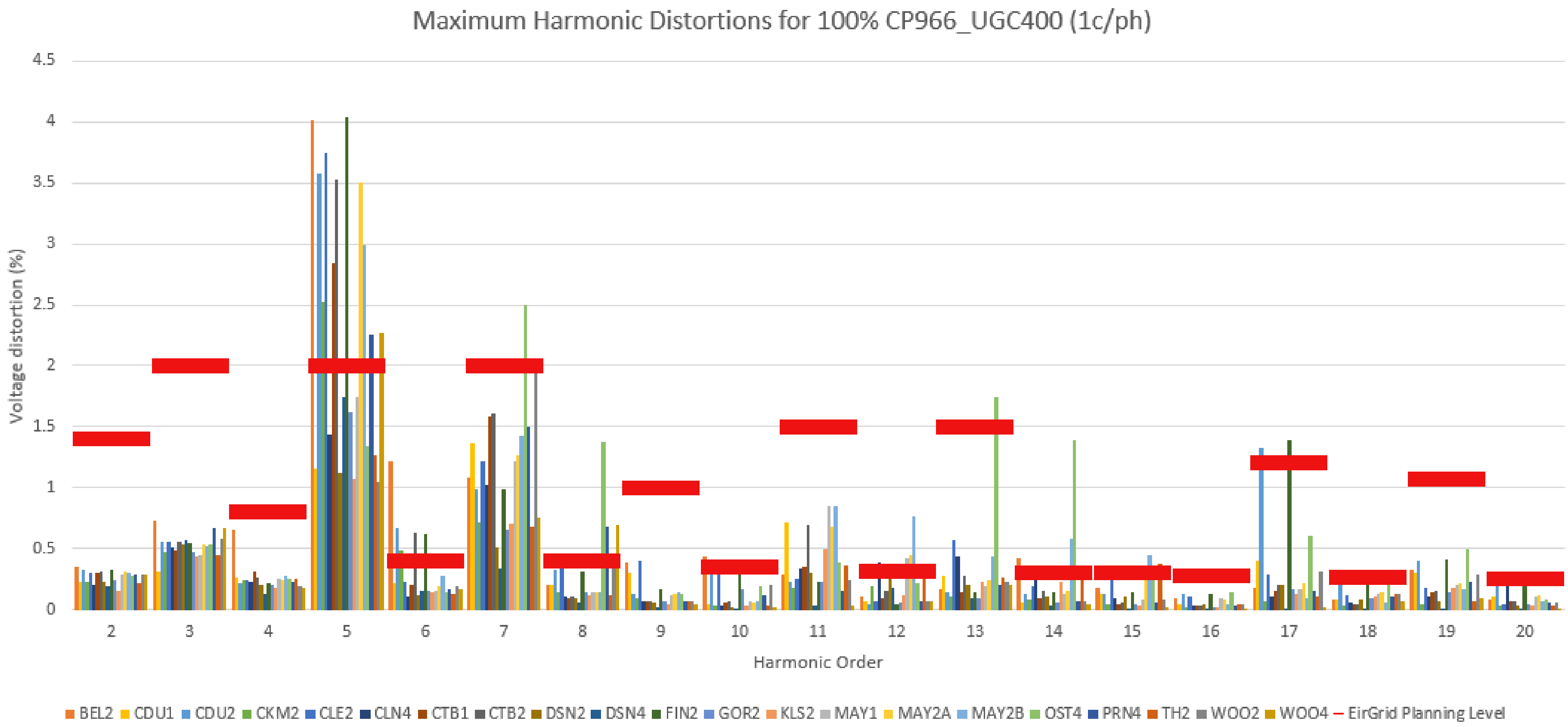

Figure 4-12: Maximum Harmonic Distortions for 100 % UGC400 cable length

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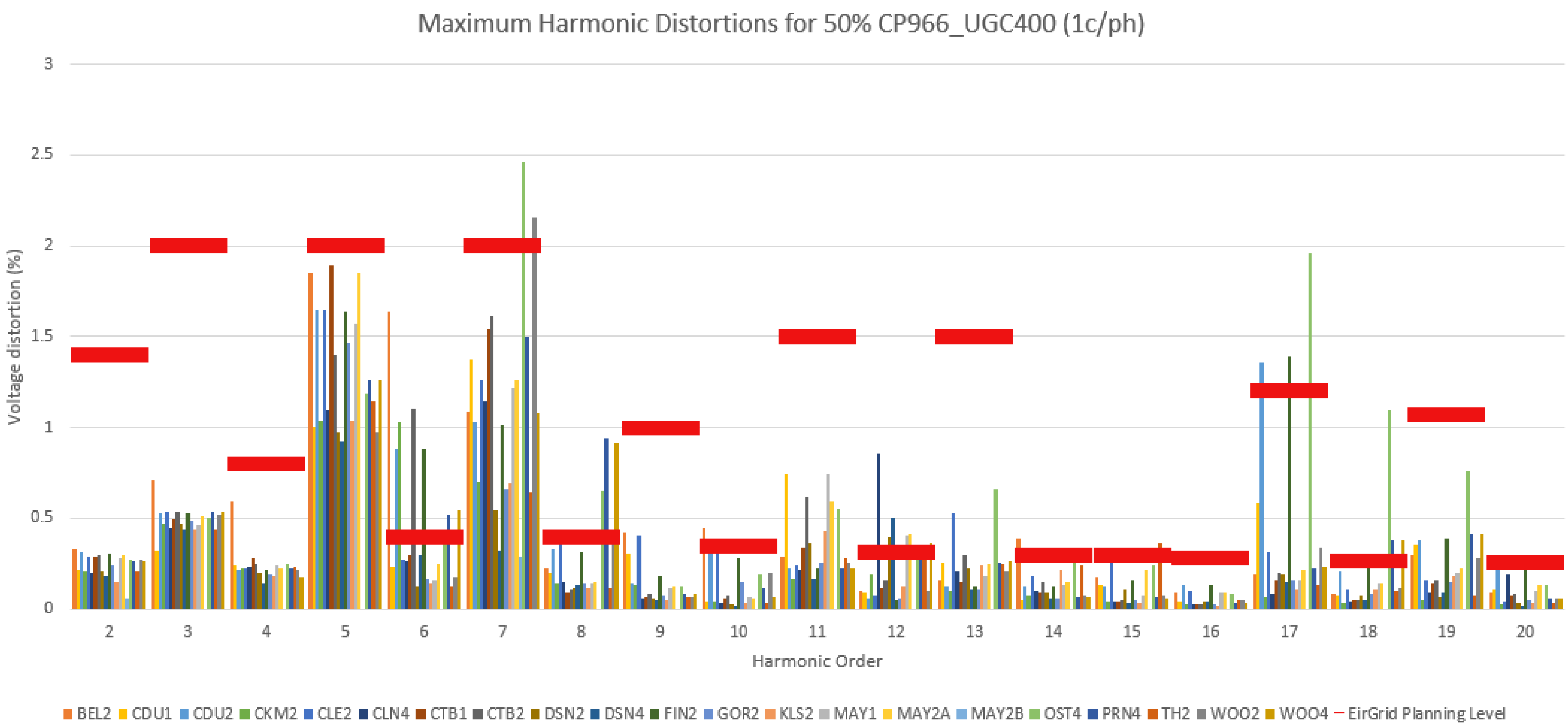

Figure 4-13: Maximum Harmonic Distortions for 50 % UGC400 cable length

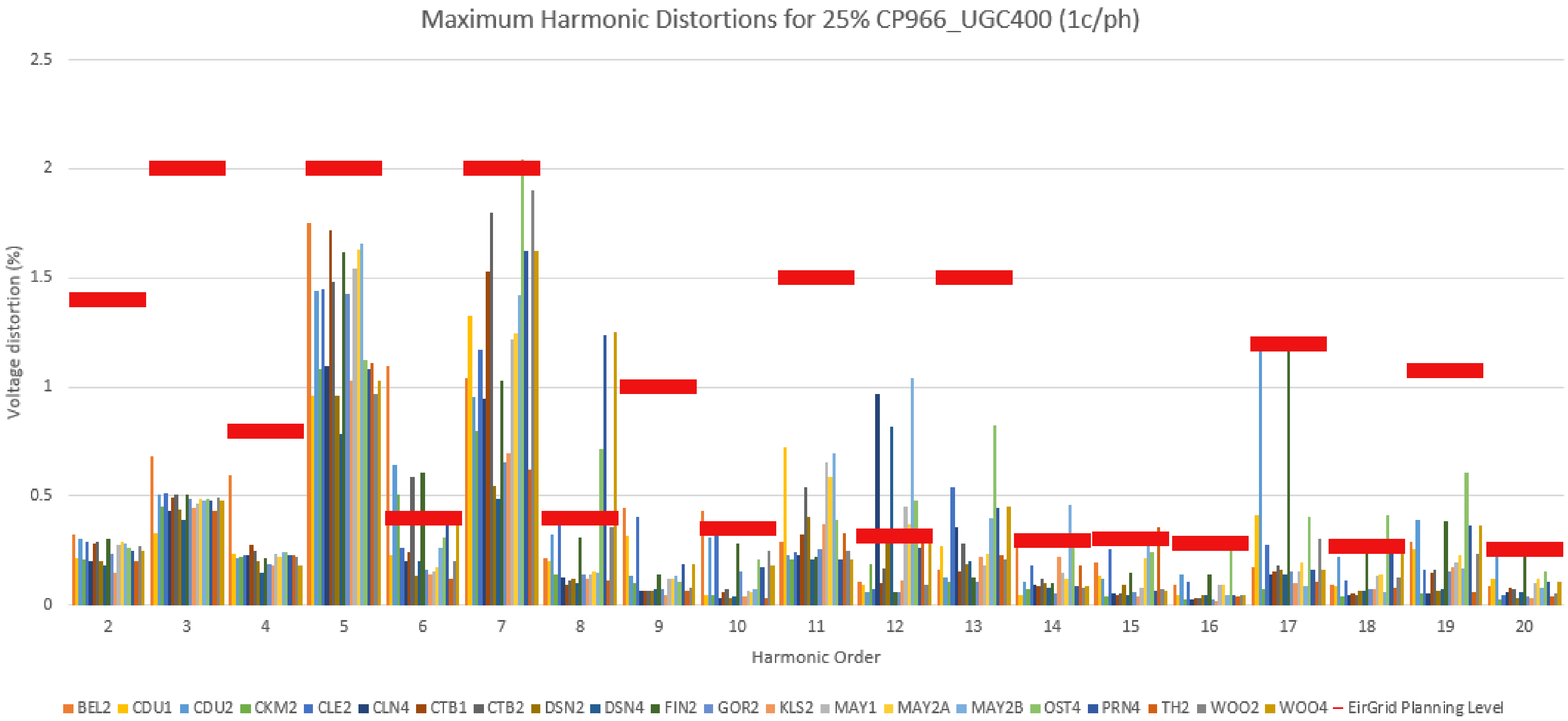

Figure 4-14: Maximum Harmonic Distortions for 25 % UGC400 cable length

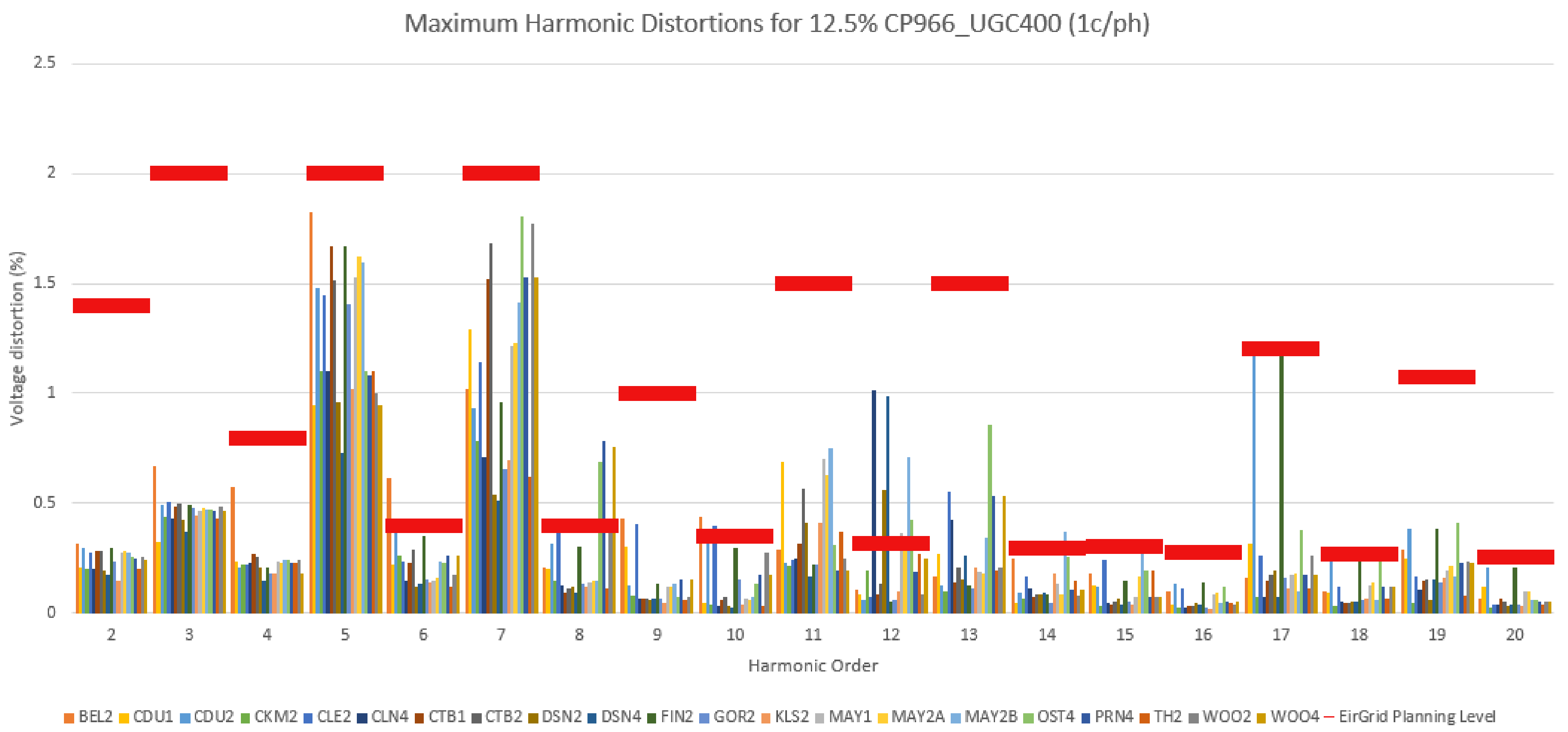

Figure 4-15: Maximum Harmonic Distortions for 12.5 % UGC400 cable length

Table 4-7: Harmonic Distortions Exceeding Planning Levels for Different UGC400 (1c/ph) Lengths

Node	100 % UGC400 (1c/ph)				50 % UGC400 (1c/ph)				25 % UGC400 (1c/ph)				12.5 % UGC400 (1c/ph)			
	Harmonic order	Planning Level (%)	Contingency	Amplified Distortion (%)	Harmonic order	Planning Level (%)	Contingency	Amplified Distortion (%)	Harmonic order	Planning Level (%)	Contingency	Amplified Distortion (%)	Harmonic order	Planning Level (%)	Contingency	Amplified Distortion (%)
BEL2	5	2	WOO4-TLE4	4.012	6	0.4	WOO2-LOU2	1.641	6	0.4	WOO4-TLE4	1.095	6	0.4	WOO4-TLE4	0.617
BEL2	6	0.4	CLN4-MP4	1.212	10	0.35	WOO4-PRN4	0.447	10	0.35	WOO4-PRN4	0.428	10	0.35	WOO4-PRN4	0.439
BEL2	10	0.35	WOO4-PRN4	0.440	14	0.296	CLN4-MP4	0.384	14	0.296	CLN4-MP4	0.314	-	-	-	-
BEL2	14	0.296	CLN4-MP4	0.420	-	-	-	-	-	-	-	-	-	-	-	-
CDU2	5	2	WOO4-TLE4	3.577	6	0.4	MAY2A-SH2	0.882	6	0.4	WOO4-TLE4	0.640	-	-	-	-
CDU2	6	0.4	CLN4-MP4	0.666	17	1.2	WOO2-INT2	1.358	17	1.2	CLN4-MP4	1.211	-	-	-	-
CDU2	17	1.2	WOO2-INT2	1.330	20	0.255	DSN2-TH2	0.270	20		DSN2-TH2	0.255	-	-	-	-
CKM2	5	2	WOO4-TLE4	2.529	6	0.4	WOO2-LOU2	1.029	6	0.4	WOO4-TLE4	0.504	-	-	-	-
CKM2	6	0.4	WOO4-WOO2A	0.487	-	-	-	-	-	-	-	-	-	-	-	-
CLE2	5	2	WOO4-TLE4	3.746	10	0.35	WOO4-PRN4	0.356	10	0.35	WOO4-PRN4	0.368	10	0.35	WOO4-PRN4	0.396
CLE2	10	0.35	WOO4-PRN4	0.367	-	-	-	-	-	-	-	-	-	-	-	-

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CLN4	12	0.318	WOO4-PRN4	0.391	12	0.318	WOO4-PRN4	0.858	12	0.318	WOO4-PRN4	0.969	12	0.318	WOO4-PRN4	1.011
CLN4	14	0.296	PRN4-Fshunt	0.344	-	-	-	-	-	-	-	-	-	-	-	-
CTB1	5	2	NW2-PB2B	2.839	-	-	-	-	-	-	-	-	-	-	-	-
CTB2	5	2	WOO4-TLE4	3.527	6	0.4	INT2-MAY2A	1.103	6	0.4	OST4-OST2	0.584	-	-	-	-
CTB2	6	0.4	WOO4-PRN4	0.628	-	-	-	-	-	-	-	-	-	-	-	-
DSN2	12	0.318	CKM2-DSN2	0.341	12	0.318	OST4-WOO4	0.394	-	-	-	-	12	0.318	DSN2-MAY2B	0.561
FIN2	5	2	WOO4-TLE4	4.036	6	0.4	WOO4-TLE4	0.884	6	0.4	WOO4-TLE4	0.606	-	-	-	-
FIN2	6	0.4	BEL2-SHL2	0.624	17	1.2	WOO2-INT2	1.394	17	1.2	WOO2-INT2	1.233	-	-	-	-
FIN2	17	1.2	WOO2-INT2	1.384	20	0.255	DSN2-TH2	0.282	20	0.255	DSN2-TH2	0.263	-	-	-	-
FIN2	20	0.255	DSN2-TH2	0.256	-	-	-	-	-	-	-	-	-	-	-	-
MAY1	12	0.318	CLN4-MP4	0.421	12	0.318	CLN4-MP4	0.406	12	0.318	CLN4-MP4	0.448	12	0.318	CLN4-MP4	0.365
MAY2A	5	2	WOO4-TLE4	3.505	12	0.318	CLN4-MP4	0.414	12	0.318	CLN4-MP4	0.371	12	0.318	CLN4-MP4	0.326
MAY2A	12	0.318	CLN4-MP4	0.447	-	-	-	-	-	-	-	-	-	-	-	-
MAY2B	5	2	WOO4-TLE4	2.991	12	0.318	CLN4-MP4	1.044	12	0.318	CLN4-MP4	1.041	12	0.318	CLN4-MP4	0.710
MAY2B	12	0.318	CLN4-MP4	0.770	14	0.296	CLN4-MP4	0.541	14	0.296	CLN4-MP4	0.459	14	0.296	CLN4-MP4	0.371

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MAY2 B	14	0.296	CLN4-MP4	0.582	15	0.3	DSN4-CLN4	0.422	-	-	-	-	-	-	-	-
MAY2 B	15	0.3	DSN4-CLN4	0.452	-	-	-	-	-	-	-	-	-	-	-	-
OST4	7	2	WOO4-TLE4	2.497	7	2	OST4-WOO4	2.461	7	2	OST4-WOO4	2.044	8	0.4	PRN4-Fshunt	0.690
OST4	8	0.4	WOO4-PRN4	1.373	8	0.4	PRN4-Fshunt	0.655	8	0.4	PRN4-Fshunt	0.718	12	0.318	WOO4-PRN4	0.425
OST4	13	1.5	WOO4-PRN4	1.741	14	0.296	OST4-MP4	0.339	12	0.318	WOO4-PRN4	0.477	-	-	-	-
OST4	14	0.296	PRN4-Fshunt	1.386	17	1.2	DSN2-TH2	1.960	14	0.296	WOO4-PRN4	0.312	-	-	-	-
OST4	15	0.3	OST4-MP4	0.355	18	0.266	WOO4-TLE4	1.093	18	0.266	OST4-WOO4	0.413	-	-	-	-
PRN4	5	2	DSN4-DSN2	2.261	6	0.4	PRN4-Fshunt	0.521	8	0.4	DSN2-TH2	1.237	8	0.4	WOO2-CLE2	0.782
PRN4	8	0.4	DSN2-TH2	0.686	8	0.4	WOO2-CLE2	0.939	18	0.266	OST4-OST2	0.267	-	-	-	-
TH2	15	0.3	CLN4-MP4	0.370	12	0.318	CLN4-MP4	0.347	12	0.318	CLN4-MP4	0.325	-	-	-	-
WOO 2	7	2	BEL2-SHL2	2.010	7	2	BEL2-SHL2	2.158	-	-	-	-	8	0.4	PRN4-Fshunt	0.423
WOO 4	5	2	DSN4-DSN2	2.265	6	0.4	WOO4-PRN4	0.542	8	0.4	DSN2-TH2	1.245	8	0.4	WOO2-CLE2	0.759
WOO 4	8	0.4	DSN2-TH2	0.698	8	0.4	WOO2-CLE2	0.917	-	-	-	-	-	-	-	-
DSN4	-	-	-	-	12	0.318	WOO4-PRN4	0.504	12	0.318	WOO4-PRN4	0.817	12	0.318	OST4-OST2	0.983
PRN4	-	-	-	-	12	0.318	PRN4-Fshunt	0.358	-	-	-	-	-	-	-	-

PRN4	-	-	-	-	18	0.266	WOO4-TLE4	0.376	-	-	-	-	-	-	-	-
TH2	-	-	-	-	15	0.3	CLN4-MP4	0.361	15	0.3	CLN4-MP4	0.358	-	-	-	-
WOO 4	-	-	-	-	12	0.318	PRN4-Fshunt	0.359	-	-	-	-	-	-	-	-
WOO 4	-	-	-	-	18	0.266	W004-TLE4	0.377	-	-	-	-	-	-	-	-

Similar to the UGC220 option, the calculation of the future background distortion is proportional to the amplification factor and to the background harmonics by 2030 prior to the CP966 reinforcements. Since the background harmonics have been calculated in a previous EirGrid project [6] based on various assumptions that might change in the future, the maximum permitted future background harmonics to avoid any performance issues have been calculated in Table 4-8 for the nodes with harmonic breaching and for the 100% cable length option. Those harmonics are for information only and indicate that if the future background data remain below them then the harmonic distortion will remain within the PL without the inclusion of a harmonic filtering.

Table 4-8: Maximum Permitted Future Background Harmonics (for EirGrid PL Compliance without Filters) for 100% UGC400 (1c/ph)

100 % UGC400 (1c/ph)				
Node	Harmonic order	Planning Level (%)	Future Background Harmonics Considered in this analysis (%)	Maximum Permitted Future Background Harmonics (%) (for PL Compliance without Filters)
BEL2	5	2	1.500	0.740
BEL2	6	0.4	0.300	0.097
BEL2	10	0.35	0.263	0.206
BEL2	14	0.296	0.166	0.115
CDU2	5	2	1.309	0.724
CDU2	6	0.4	0.231	0.137
CDU2	17	1.2	0.900	0.803
CKM2	5	2	1.095	0.856
CKM2	6	0.4	0.121	0.098
CLE2	5	2	1.288	0.680
CLE2	10	0.35	0.167	0.158
CLN4	12	0.318	0.173	0.139
CLN4	14	0.296	0.060	0.051
CTB1	5	2	1.500	1.045
CTB2	5	2	1.500	0.841
CTB2	6	0.4	0.210	0.132
DSN2	12	0.318	0.173	0.159
FIN2	5	2	1.309	0.642
FIN2	6	0.4	0.231	0.146
FIN2	17	1.2	0.900	0.772
FIN2	20	0.255	0.191	0.188
MAY1	12	0.318	0.188	0.140
MAY2A	5	2	1.500	0.847
MAY2A	12	0.318	0.188	0.132
MAY2B	5	2	1.500	0.993

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MAY2B	12	0.318	0.210	0.085
MAY2B	14	0.296	0.119	0.059
MAY2B	15	0.3	0.061	0.040
OST4	7	2	1.500	1.189
OST4	8	0.4	0.181	0.052
OST4	13	1.5	0.193	0.164
OST4	14	0.296	0.067	0.014
OST4	15	0.3	0.063	0.052
PRN4	5	2	1.079	0.944
PRN4	8	0.4	0.181	0.104
TH2	15	0.3	0.032	0.025
WOO2	7	2	1.500	1.480
WOO4	5	2	1.079	0.942
WOO4	8	0.4	0.181	0.102

4.3.2 Harmonic Mitigation Solution

The harmonic studies presented previously have identified that there are multiple nodes with harmonic breaching for the various UGC400 (1c/ph) length options and it has been agreed with EirGrid to estimate the size of a possible solution for the 100% cable length option. In case the UGC400 (1c/ph) option is selected for the next phase of the project, further investigation will be necessary to fully achieve harmonic compliance that will be based on the existing solution. It is expected that if the final cable length option deviates significantly from the full length of 60 km then the filtering solution will need to be revisited in terms of size, tuning and location of the filters.

Due to the number of harmonic breaches and the complexity of the EirGrid network there was an attempt to avoid proposing filters in every single substation and perform sensitivity studies for finding solutions that could improve the harmonic performance of other nearby stations. This resulted in the seven C-type filters presented in Table 4-9 where the filters in Maynooth and Belcamp substations are targeting more the local harmonic issues; whereas the remaining filters in Dunstown, Woodland and Old Street substations are targeting harmonic issues in local and nearby stations.

Table 4-9: Harmonic Mitigation Solution for 100% UGC400 (1c/ph)

Node	Size (Mvar)	Resonant Frequency (Hz)	Parallel Resistance (Rp)
DSN2	20	550	650
WOO4	50	200	1000
OST4	40	300	1100
MAY2B	30	530	500
MAY2A	15	550	1000
MAY1	5	550	500
BEL2	30	500	750

Figure 4-16 shows an overview of the maximum harmonic distortions in the study area for the 100% UGC400 and considering all the filters in service. The results have been calculated for all the contingencies and network operating scenarios and for harmonics up to the 20th order. During the detailed gain factor calculations and self-impedance analysis, there were some contingencies where the impedance values before and after were very low and therefore were excluded as spurious results.

The results show that most of the harmonic breaches of the EirGrid planning levels at any of the substations in the study area are being eliminated when the proposed C-type filters are in service with the exception of the 8th harmonic in OST4, PRN4 and WOO4 that remains above the limit. Since there are local filters proposed in OST4, WOO4 and PRN4 is electrically close to WOO4, their harmonic compliance will be resolved during the fine tuning of the mitigation solution in the next phase of the project. The 20th harmonic at FIN2 remains also just above the limit which is expected to improve by optimising the damping of the proposed filters which will have some impact on higher order harmonics.

Figure 4-17 to Figure 4-24 present the frequency scans for the nodes where the harmonic filters are being connected as well as for an additional node in order to present the impact that the filters have locally and in remote stations. Table 4-10 presents the list of the nodes along with the contingency for which the plots are being presented which normally represents the worst case in terms of harmonic breaching for that substation. Due to number and the complexity of the studies, it is not possible to present frequency scans for every single contingency and every node so some substations where high exceedances were observed are being presented.

For each node, frequency scans for the following cases are being presented:

- Base case prior to the CP966_UGC400 (1c/ph) (in **Black**)
- Case following the CP966_UGC400 (1c/ph) installation but without any mitigation solution (in **Green**)
- Case with the CP966_UGC400 (1c/ph) installation and including the mitigation solution (in **Red**)

The results indicate that when comparing the cases prior and after the CP966_UGC400 there is a noticeable change in the complete frequency range in most of the nodes in terms of shifting resonant points, creating new resonances and changing the damping of the system. The impact of the cable installation is higher on stations that are electrically closer to the points of connection with the cable. The inclusion of the filters shows that there is a reasonable improvement in terms of decreasing the impedance values around the resonant frequency range of the filters and providing more damping in higher order harmonics.

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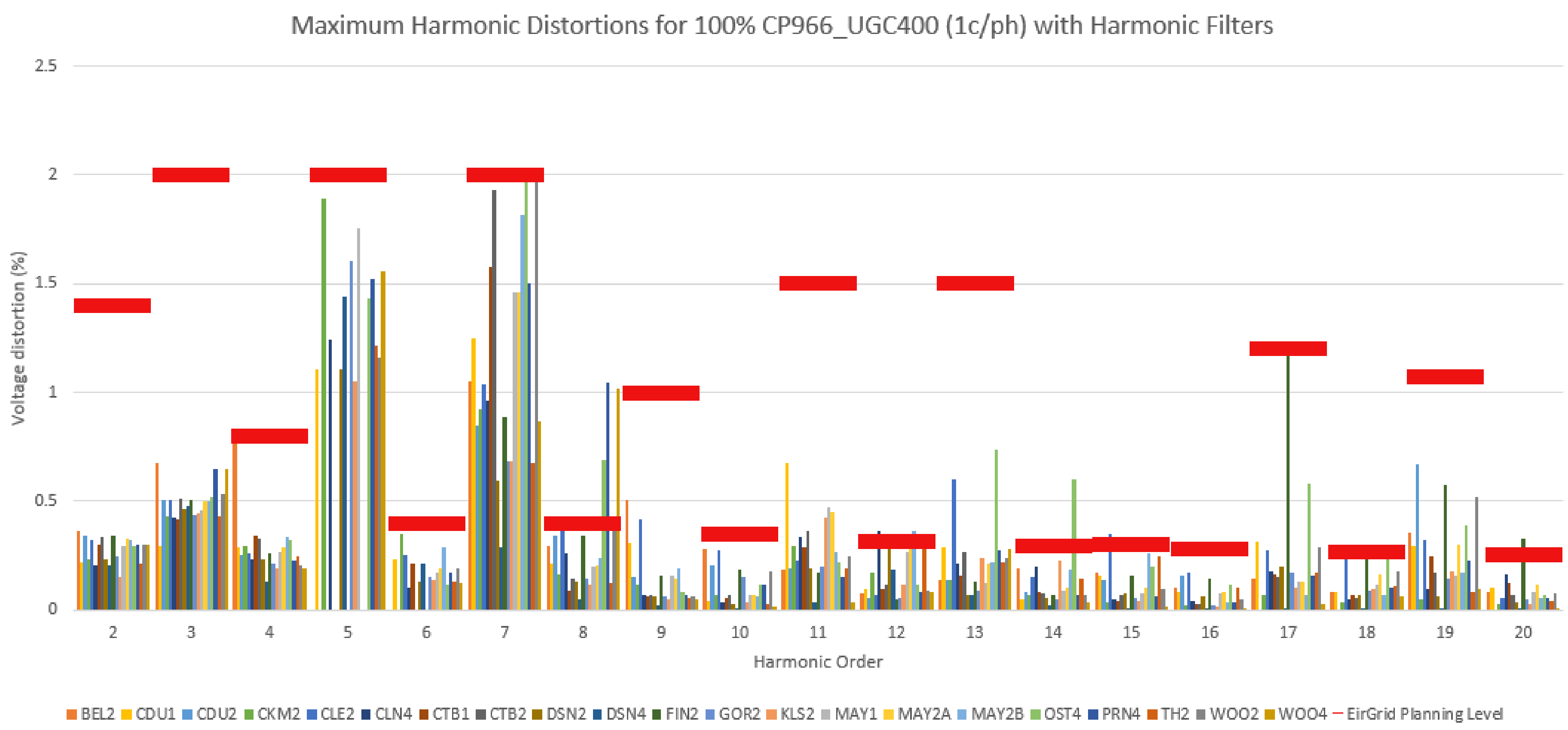

Figure 4-16: Maximum Harmonic Distortions for 100 % UGC400 cable length with harmonic filters

Table 4-10: Summary of Nodes for Frequency Response Plots

Node	Existence of local filter (Yes / No)	Contingency	Operating Scenario
DSN2	Yes	CKM2-DSN2	WPHW
WOO4	Yes	DSN4-DSN2	SVLW
OST4	Yes	WOO4-PRN4	SVHW
MAY2B	Yes	CLN4-MP4	SVLW
MAY2A	Yes	CLN4-MP4	WPHW
MAY1	Yes	CLN4-MP4	WPHW
BEL2	Yes	CLN4-MP4	SVLW
FIN2	No	WOO2-INT2	SVHW

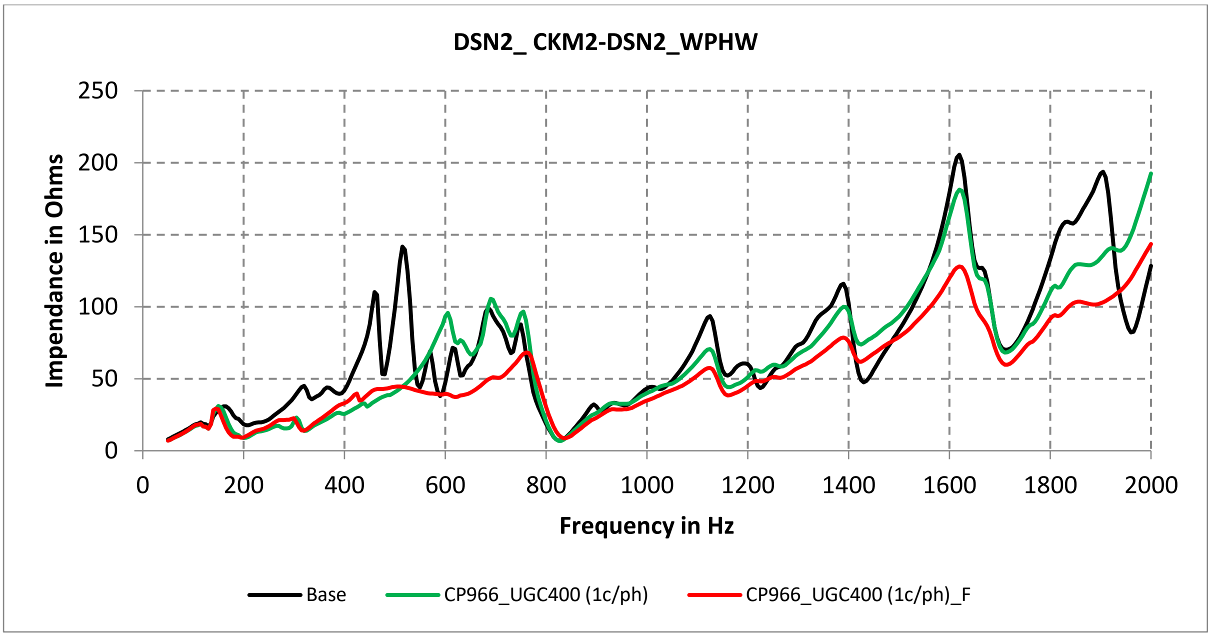

Figure 4-17: Self-impedance at Dunstown 220 kV substation at WPHW during CKM2-DSN2 contingency

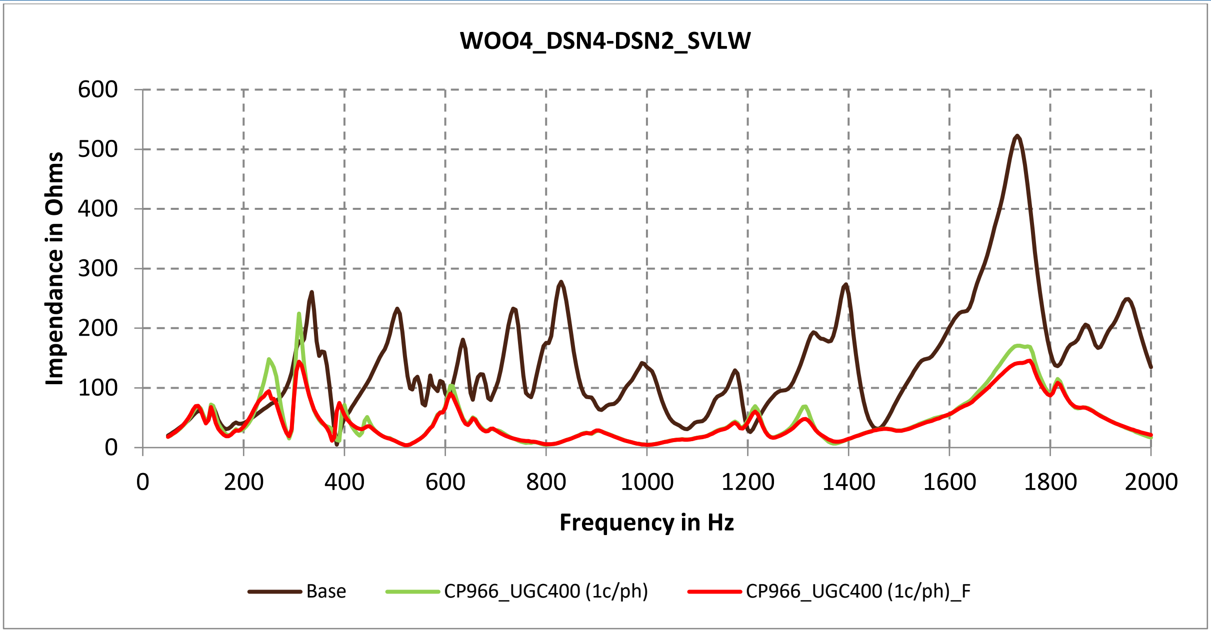

Figure 4-18: Self-impedance at Woodland 400 kV substation at SVLW during DSN4-DSN2 contingency

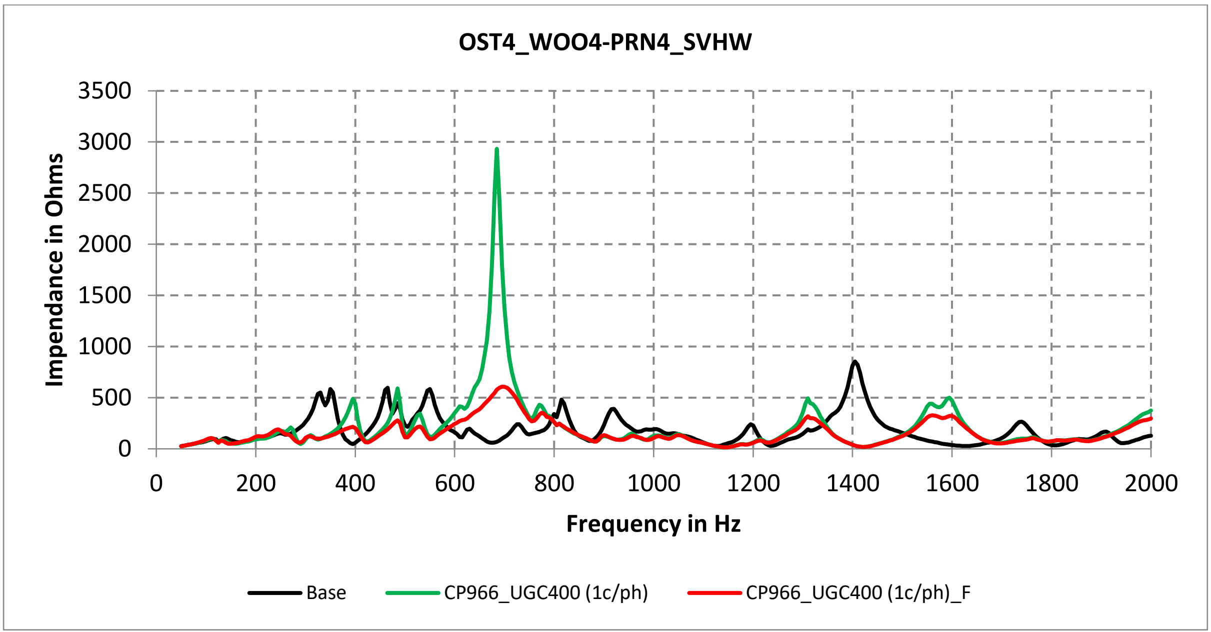

Figure 4-19: Self-impedance at Old Street 400 kV substation at SVHW during WOO4-PRN4 contingency

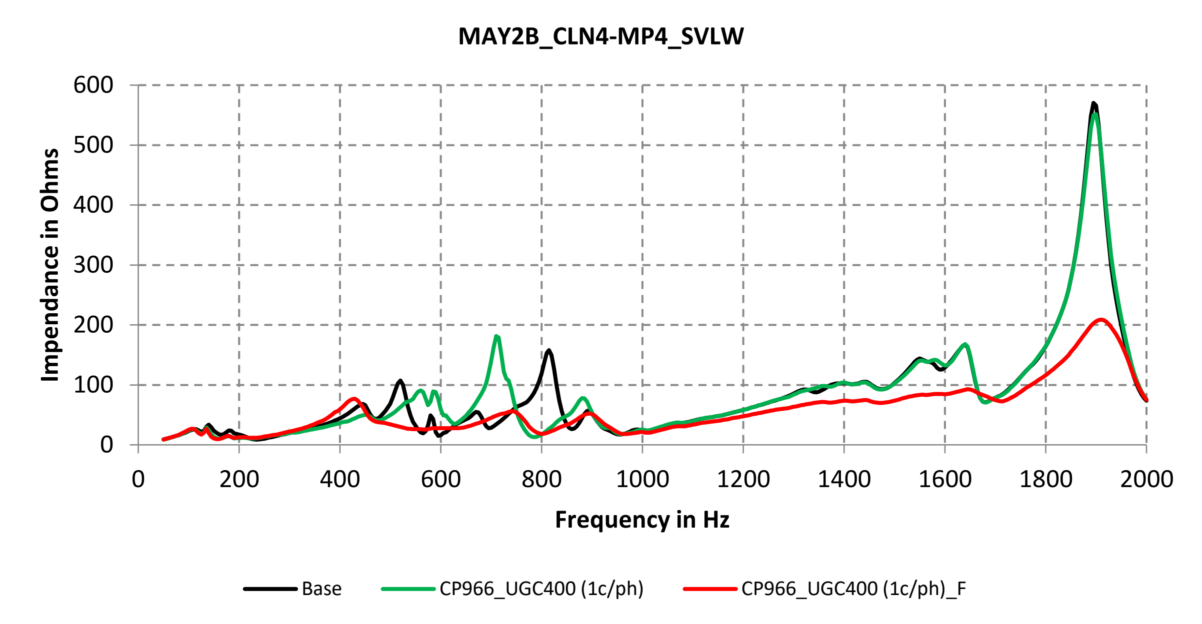

Figure 4-20: Self-impedance at MaynoothB 220 kV substation at SVLW during CLN4-MP4 contingency

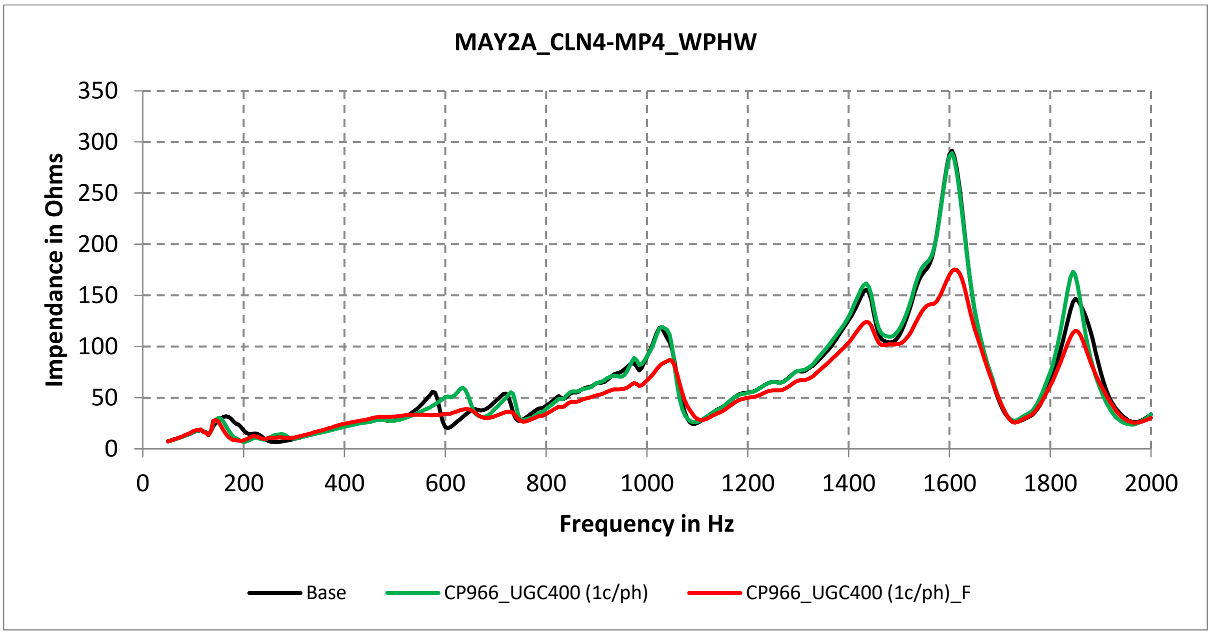

Figure 4-21: Self-impedance at MaynoothA 220 kV substation at WPHW during CLN4-MP4 contingency

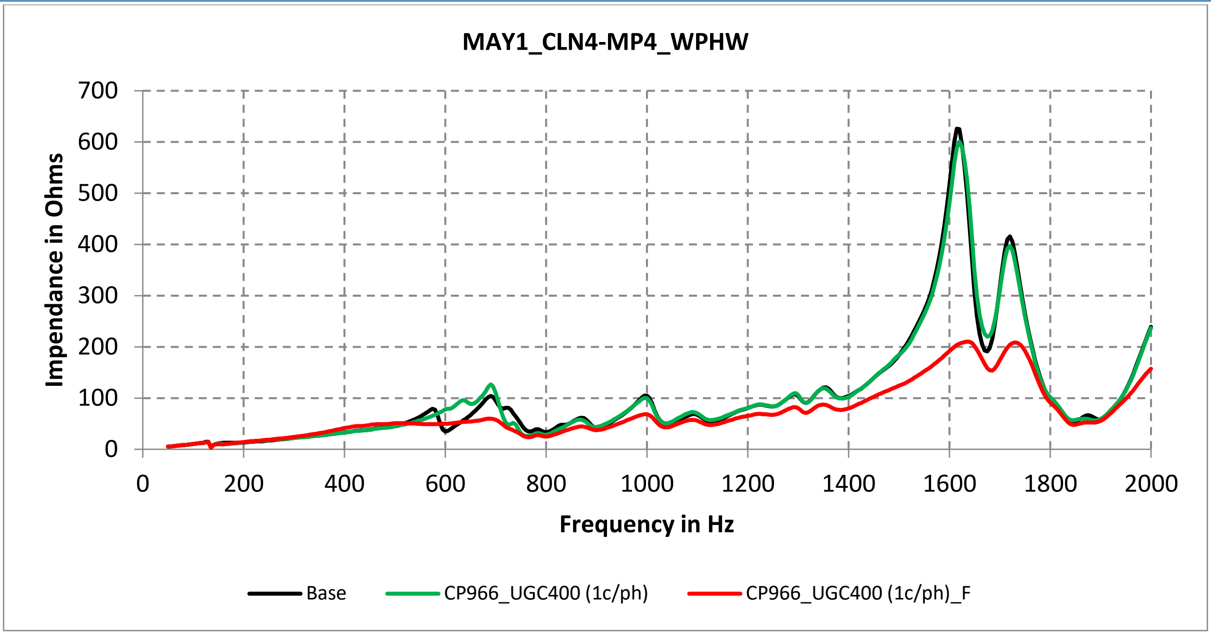

Figure 4-22: Self-impedance at Maynooth 110 kV substation at WPHW during CLN4-MP4 contingency

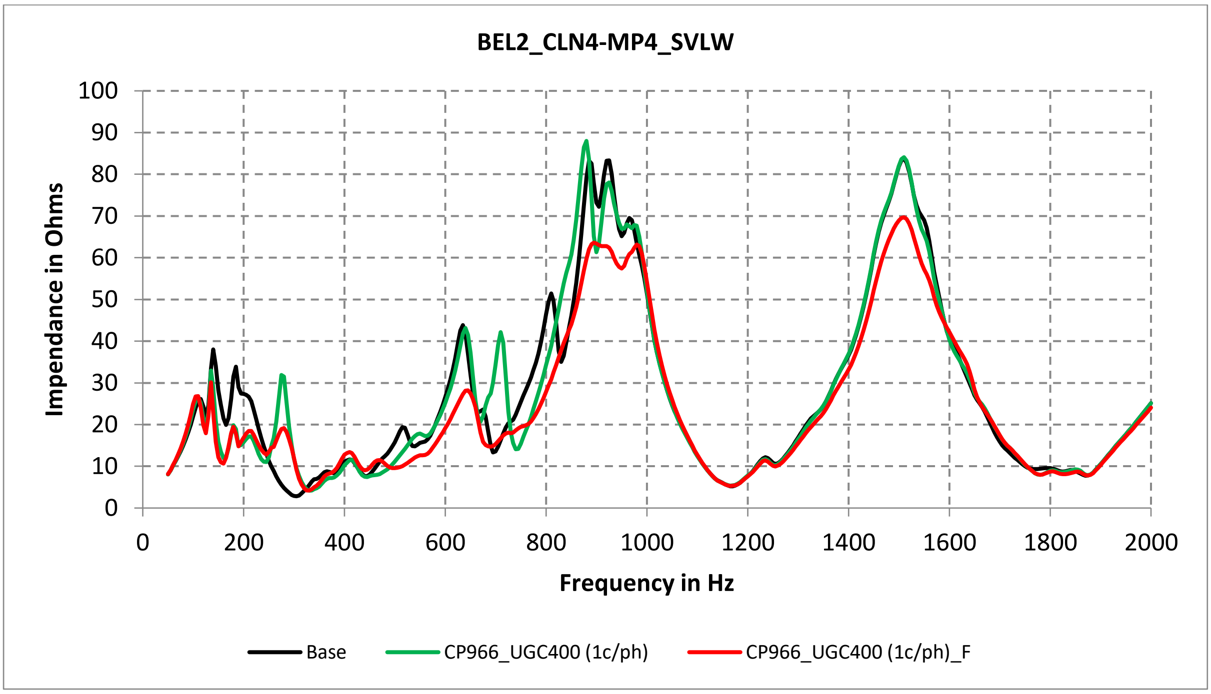

Figure 4-23: Self-impedance at Belcamp 220 kV substation at SVLW during CLN4-MP4 contingency

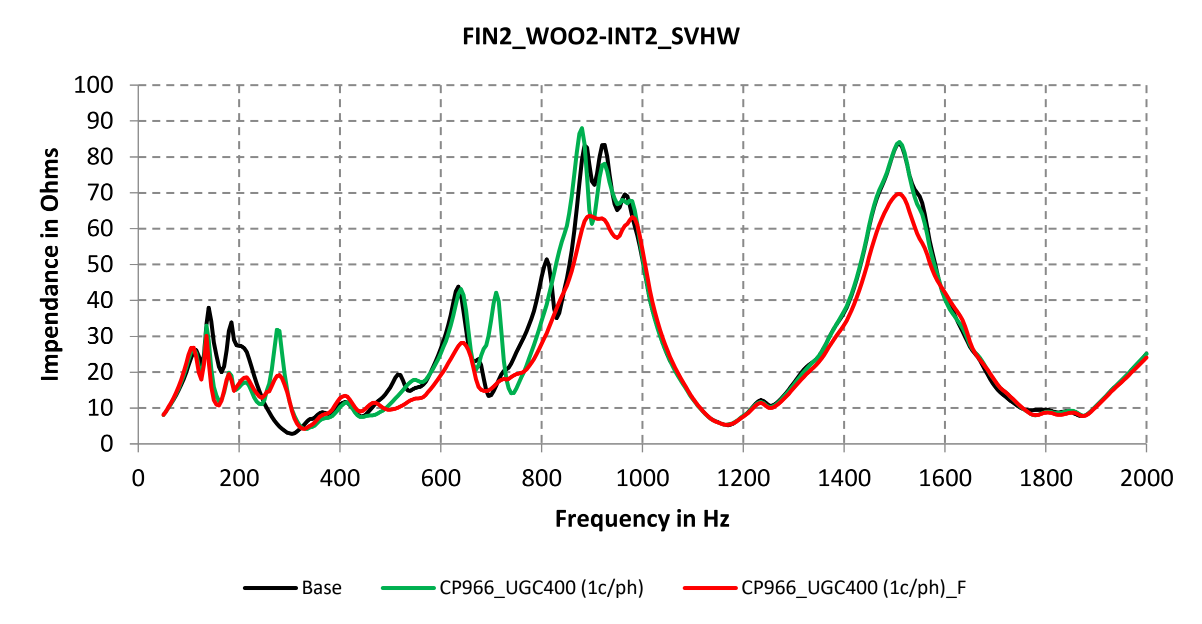

Figure 4-24: Self-impedance at Finglas 220 kV substation at SVHW during WOO2-INT2 contingency

4.4 Results for CP966_UGC400 (2c/ph)

4.4.1 Harmonic Analysis

The 100% cable solution was assessed and the background harmonic amplification was reviewed for all the nodes of interest under the three network operating scenarios and the contingencies considered as presented in Section 4.1. The full cable length study showed high harmonic amplification of the background harmonics resulting in breaching of harmonic planning levels in multiple substations. Following agreement with EirGrid, no further studies were performed for the reduced cable lengths on the basis that the full cable length option results is the most onerous harmonic breaching condition as observed from the analysis of the 220 kV and 400 kV (1c/ph) UGC options.

Figure 4-25 shows an overview of the maximum harmonic distortions in the study area for the full UGC length option with the red bars showing the EirGrid Planning Levels for each harmonic. The results have been calculated for all the contingencies and network operating scenarios and for harmonics up to the 20th order. Higher order harmonic background data is thought to be less accurate due to the sensitivity of the EirGrid measurement equipment and so results are presented up to the 20th order.

Table 4-11 presents detailed results for the full cable length option that give a side by side overview of the substations where the harmonic limits are exceeded along with the most onerous contingency, background harmonics and calculated amplified distortion. Since the results indicate that there is harmonic breaching in a number of substations, a mitigation solution is required and it will be estimated for the full cable length. In case the UGC400 (2c/ph) option is selected for the next phase of the project, further investigation will be necessary to fully achieve harmonic compliance that will be based on the existing solution. Details of the solution, assumptions and results are presented in the following Section 4.4.2. Frequency scans for different nodes are also presented in Section 4.4.2 for the base case prior to CP966 reinforcements and for the cases with and without the harmonic filtering following the CP966 reinforcements.

Comparing the results of the UGC400 (2c/ph) with that of the UGC400 (1c/ph), it is observed that there is a slightly higher number of harmonic orders breaching the planning levels for the full cable length option resulting in a more complex mitigation solution with more and bigger harmonic filters. Additionally, the harmonic orders at which the breaching is observed are generally lower in the UGC400 (2c/ph) option which might result in more expensive harmonic filters and in higher possibility of having TOV issues.

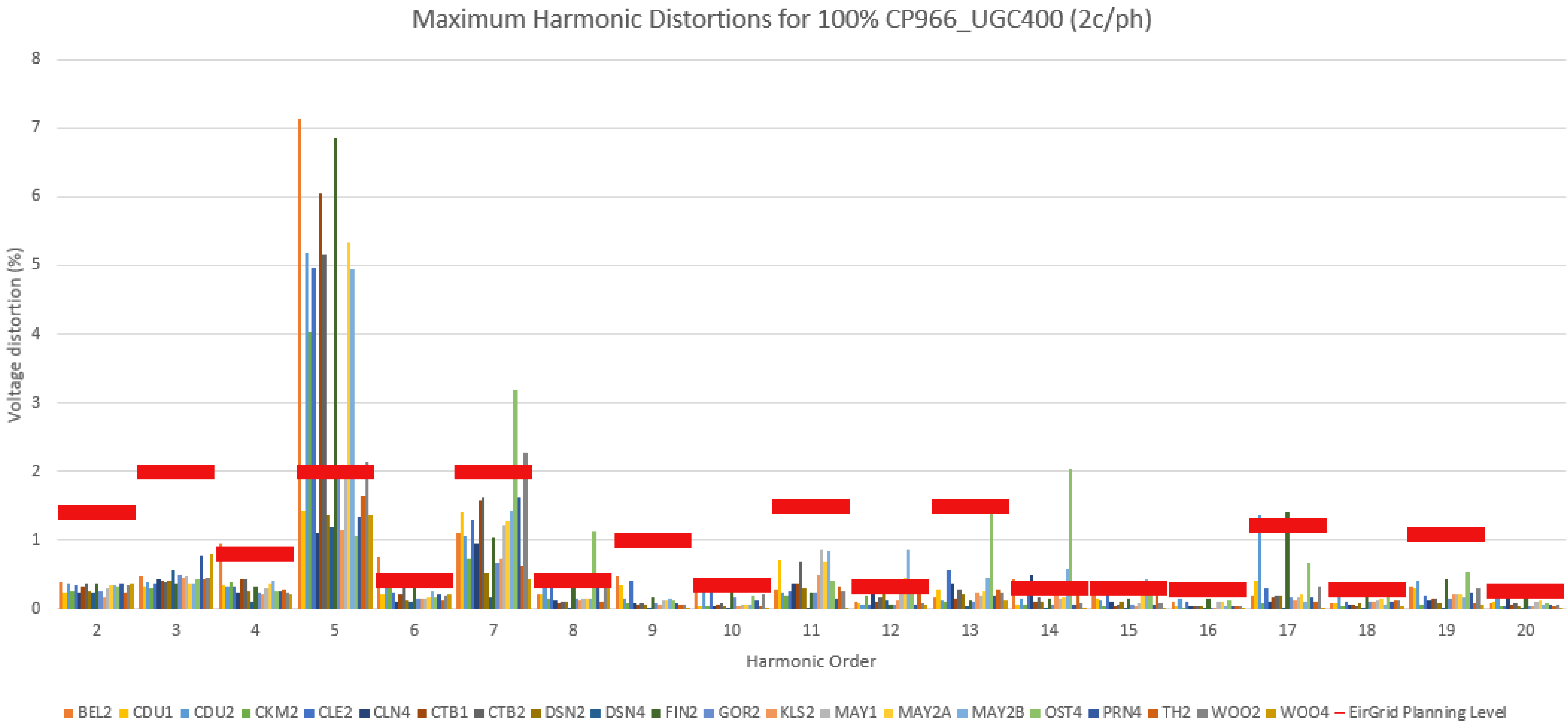

Figure 4-25: Maximum Harmonic Distortions for 100% UGC400 (2c/ph) cable length

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Table 4-11: Harmonic Distortions Exceeding Planning Levels for Full UGC400 (2c/ph) Length

Node	100 % UGC400 (2c/ph)			
	Harmonic order	Planning Level (%)	Contingency	Amplified Distortion (%)
BEL2	4	0.8	BEL2-FIN2A	0.944
BEL2	5	2	CLN4-MP4	7.133
BEL2	6	0.4	CLN4-MP4	0.754
BEL2	10	0.35	WOO4-PRN4	0.441
BEL2	14	0.296	CLN4-MP4	0.433
CDU2	5	2	CLN4-MP4	5.189
CDU2	6	0.4	CLN4-MP4	0.468
CDU2	17	1.2	WOO2-INT2	1.356
CKM2	5	2	WOO4-PRN4	4.031
CLE2	5	2	WOO4-WOO2A	4.959
CLE2	10	0.35	WOO4-PRN4	0.368
CLN4	12	0.318	WOO4-PRN4	0.368
CLN4	14	0.296	PRN4-Fshunt	0.484
CTB1	5	2	NW2-PB2B	6.047
CTB2	5	2	WOO4-WOO2A	5.157
CTB2	6	0.4	WOO4-PRN4	0.505
DSN2	12	0.318	OST4-WOO4	0.344
FIN2	5	2	CLN4-MP4	6.846
FIN2	6	0.4	WOO4-TLE4	0.515
FIN2	17	1.2	WOO2-INT2	1.410
FIN2	20	0.255	DSN2-TH2	0.256
MAY1	12	0.318	CLN4-MP4	0.420
MAY2A	5	2	WOO4-PRN4	5.331
MAY2A	12	0.318	CLN4-MP4	0.443
MAY2B	5	2	NW2-PB2B	4.955
MAY2B	12	0.318	CLN4-MP4	0.866
MAY2B	14	0.296	CLN4-MP4	0.574
MAY2B	15	0.3	DSN4-CLN4	0.430
OST4	7	2	OST4-OST2	3.192
OST4	8	0.4	DSN2-TH2	1.122
OST4	13	1.5	WOO4-PRN4	1.576
OST4	14	0.296	PRN4-Fshunt	2.029
OST4	15	0.3	OST4-MP4	0.310
PRN4	8	0.4	OST4-OST2	0.518

TH2	15	0.3	CLN4-MP4	0.358
WOO2	5	2	NW2-PB2B	2.144
WOO2	7	2	BEL2-SHL2	2.272
WOO2	8	0.4	PRN4-Fshunt	0.407
WOO4	8	0.4	OST4-OST2	0.506

4.4.2 Harmonic Mitigation Solution

The harmonic studies presented previously have identified that there are multiple nodes with harmonic breaching for the 100% UGC400 (2c/ph) length option and it has been agreed with EirGrid to estimate the size of a possible solution. In case the UGC400 (2c/ph) option is selected for the next phase of the project, further investigation will be necessary to fully achieve harmonic compliance that will be based on the existing solution. It is expected that if the final cable length option deviates significantly from the full length of 60 km then the filtering solution will need to be revisited in terms of size, tuning and location of the filters.

Due to the number of harmonic breaches and the complexity of the EirGrid network there was an attempt to avoid proposing filters in every single substation and perform sensitivity studies for finding solutions that could improve the harmonic performance of other nearby stations. This resulted in the eight C-type filters presented in Table 4-12 where the filters in Maynooth and Belcamp substations are targeting more the local harmonic issues; whereas the remaining filters in Dunstown, Woodland and Old Street substations are targeting harmonic issues in local and nearby stations.

Table 4-12: Harmonic Mitigation Solution for 100% UGC400 (2c/ph)

Node	Size (Mvar)	Resonant Frequency (Hz)	Parallel Resistance (Rp)
DSN2	20	550	650
WOO2	40	315	800
OST4	50	300	750
MAY2B	37	530	500
MAY2A	20	550	750
MAY1	5	550	500
BEL2	30	500	750
BEL2	30	180	900

Figure 4-26 shows an overview of the maximum harmonic distortions in the study area for the 100% UGC400 (2c/ph) and considering all the filters in service. The results have been calculated for all the contingencies and network operating scenarios and for harmonics up to the 20th order. During the detailed gain factor calculations and self-impedance analysis, there were some contingencies where the impedance values before and after were very low and therefore were excluded as spurious results.

The results show that most of the harmonic breaches of the EirGrid planning levels at any of the substations in the study area are being eliminated when the proposed C-type filters are in service with the exception of the 4th harmonic in BEL2 and a few higher order harmonics (7th and above) in OST4, CLN4, FIN2 and CLE2 that remain above the limit. Since there are either local filters proposed in those

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stations or they are electrically close to nearby stations with filters, their harmonic compliance will be resolved during the fine tuning and optimisation of the damping of the mitigation solution in the next phase of the project.

Figure 4-27 to Figure 4-34 present the frequency scans for the nodes where the harmonic filters are being connected as well as for an additional node in order to present the impact that the filters have locally and in remote stations. Table 4-13 presents the list of the nodes along with the contingency for which the plots are being presented which normally represents the worst case in terms of harmonic breaching for that substation. Due to number and the complexity of the studies, it is not possible to present frequency scans for every single contingency and every node so some substations where high exceedances were observed are being presented.

For each node, frequency scans for the following cases are being presented:

- Base case prior to the CP966_UGC400 (2c/ph) (in **Black**)
- Case following the CP966_UGC400 (2c/ph) installation but without any mitigation solution (in **Green**)
- Case with the CP966_UGC400 (2c/ph) installation and including the mitigation solution (in **Red**)

The results indicate that when comparing the cases prior and after the CP966_UGC400 (2c/ph) there is a noticeable change in the complete frequency range in most of the nodes in terms of shifting resonant points, creating new resonances and changing the damping of the system. The impact of the cable installation is higher on stations that are electrically closer to the points of connection with the cable. The inclusion of the filters shows that there is a reasonable improvement in terms of decreasing the impedance values around the resonant frequency range of the filters and providing more damping in higher order harmonics.

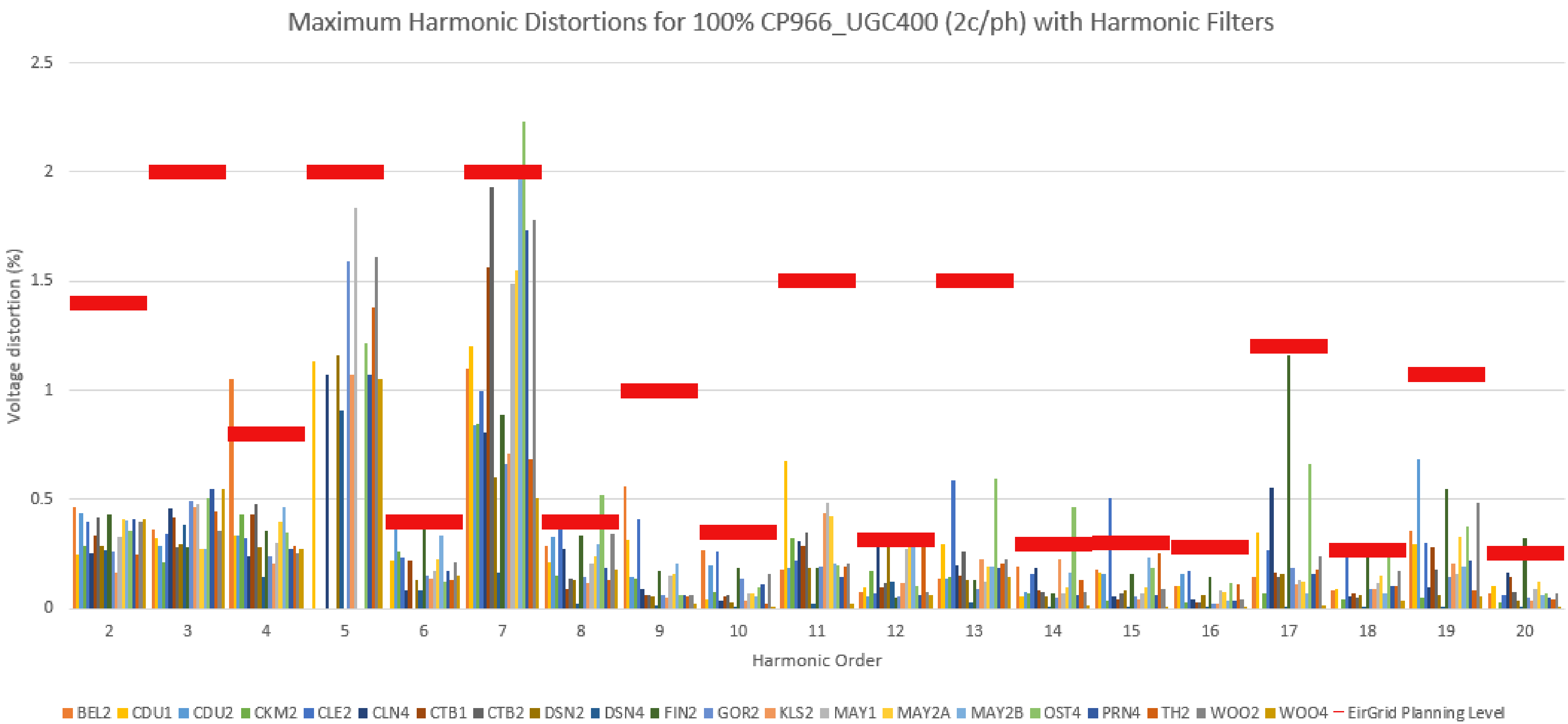

Figure 4-26: Maximum harmonic distortions for 100% CP966_UGC400 (2c/ph) cable length with harmonic filters

Table 4-13: Summary of Nodes for Frequency Response Plots

Node	Existence of local filter (Yes / No)	Contingency	Operating Scenario
DSN2	Yes	OST4-WOO4	SVHW
WOO2	Yes	BEL2-SHL2	SVHW
OST4	Yes	OST4-OST2	SVLW
MAY2B	Yes	CLN4-MP4	SVLW
MAY2A	Yes	CLN4-MP4	WPHW
MAY1	Yes	CLN4-MP4	WPHW
BEL2	Yes	CLN4-MP4	SVLW
FIN2	No	WOO2-INT2	SVLW

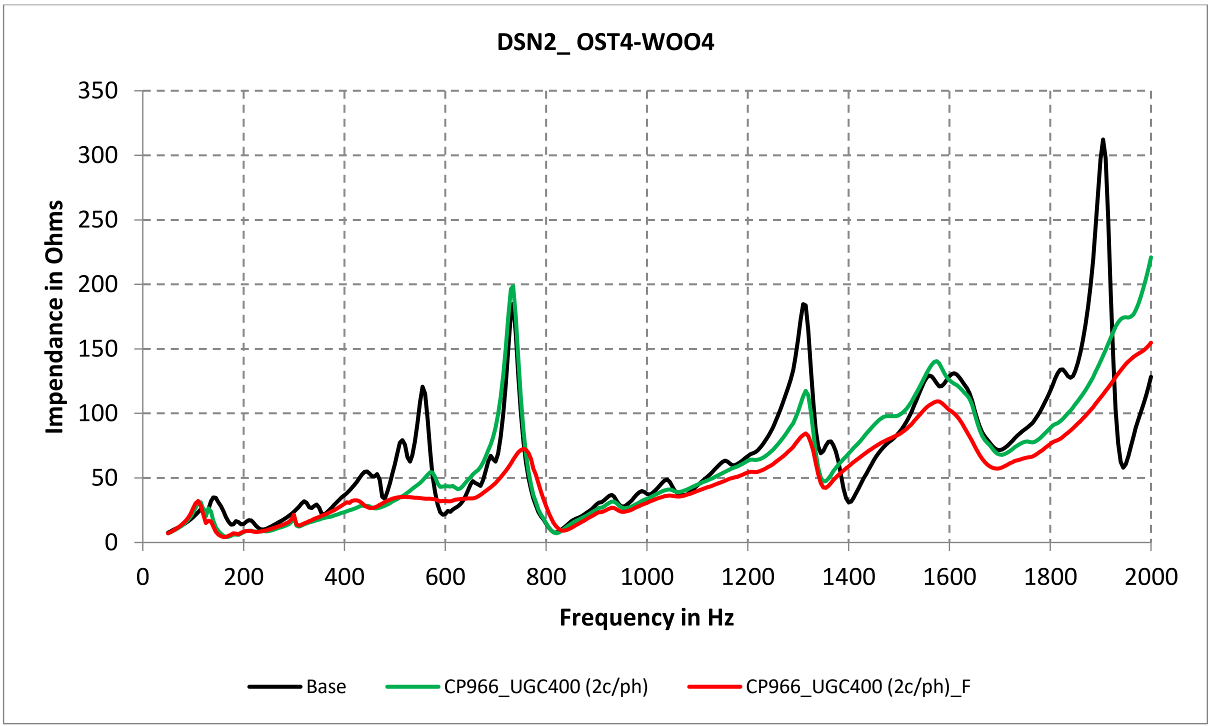

Figure 4-27: Self-impedance at Dunstown 220 kV substation at SVHW during OST4-WOO4 contingency

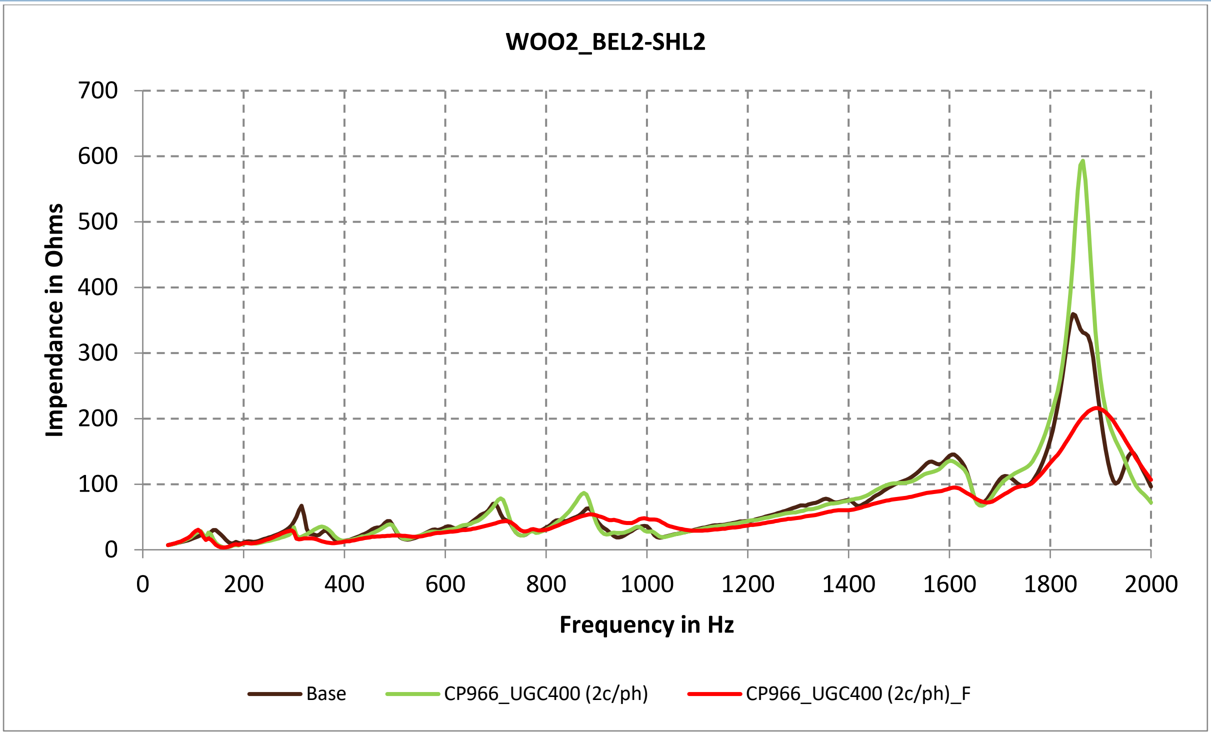

Figure 4-28: Self-impedance at Woodland 220 kV substation at SVHW during BEL2-SHL2 contingency

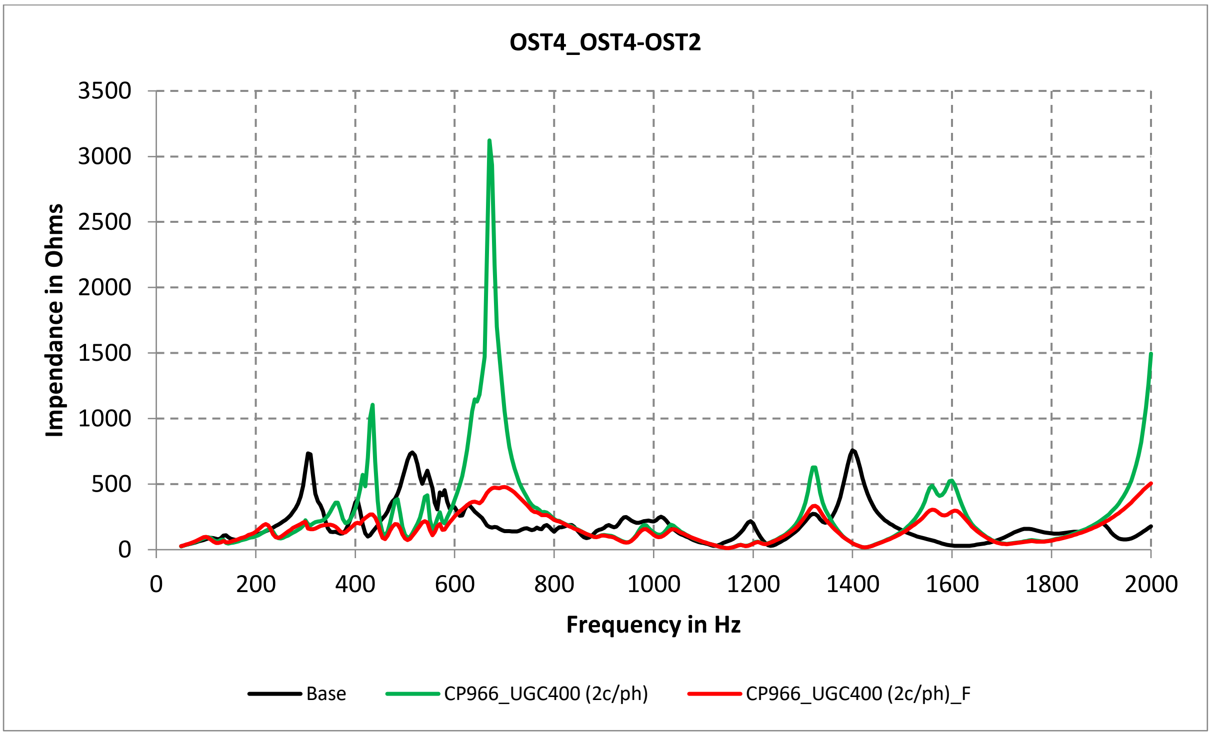

Figure 4-29: Self-impedance at Old Street 400 kV substation at SVLW during OST4-OST2 contingency

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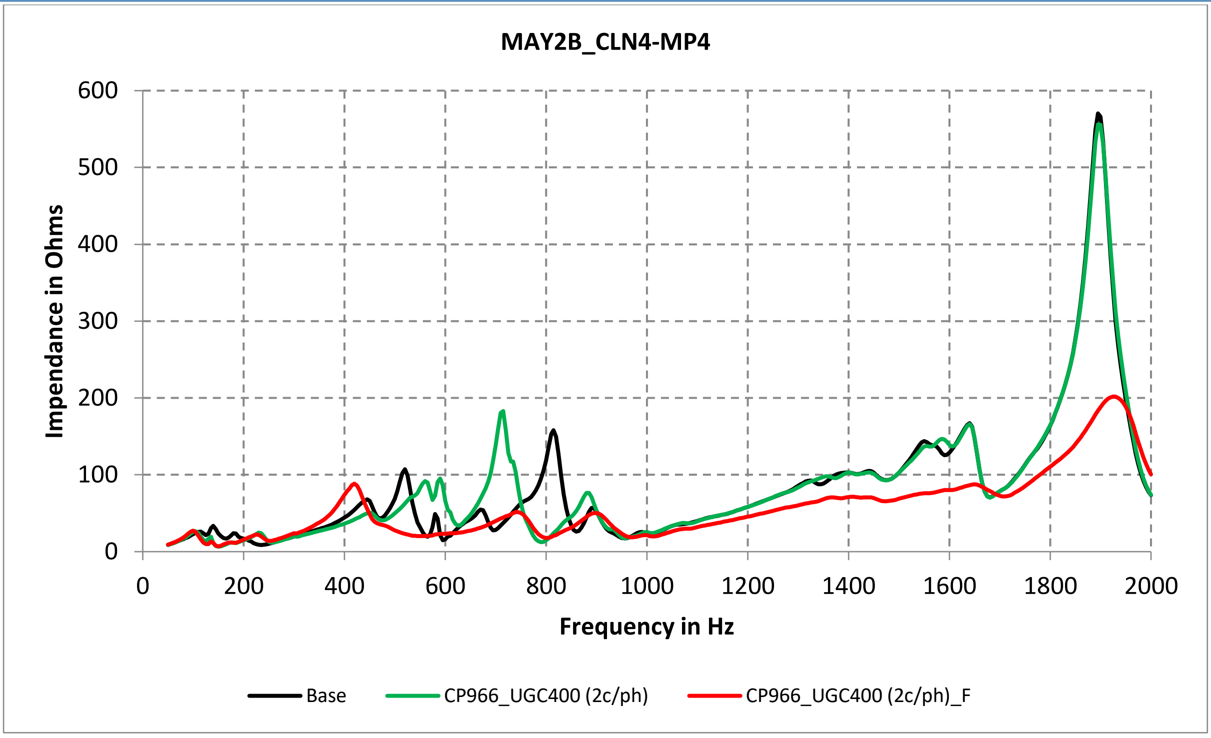

Figure 4-30: Self-impedance at MaynoothB 220 kV substation at SVLW during CLN4-MP4 contingency

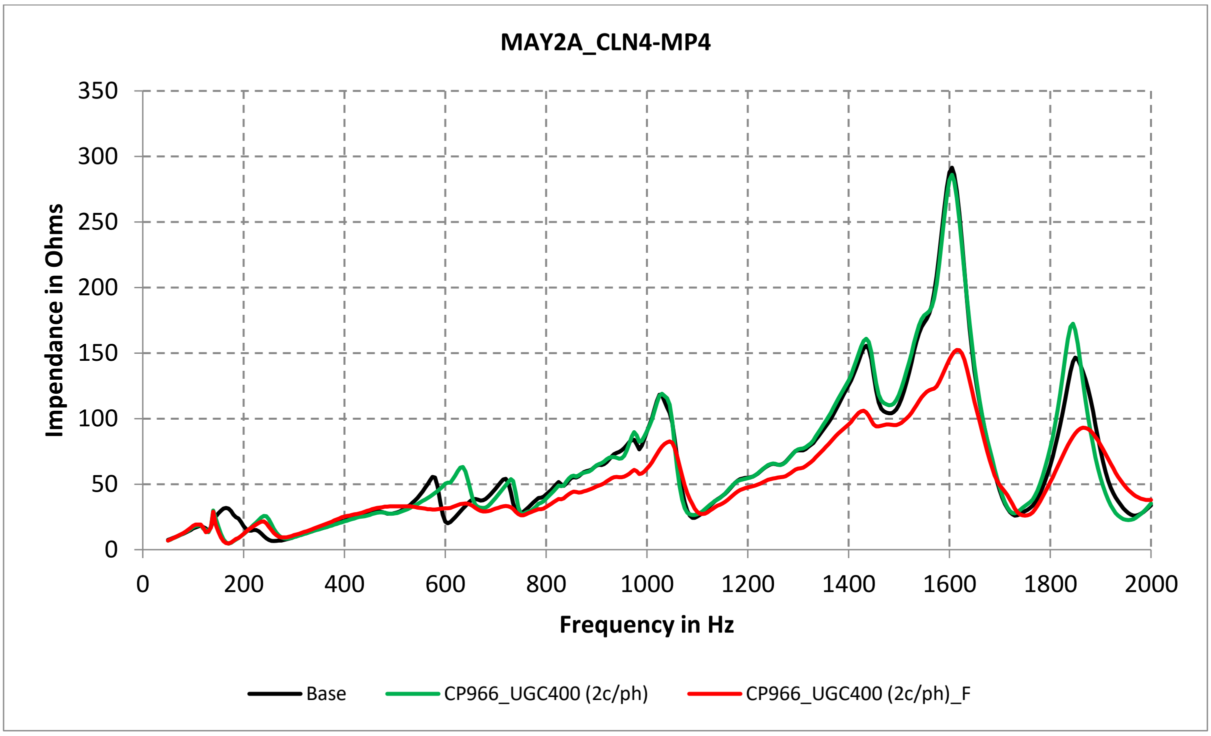

Figure 4-31: Self-impedance at MaynoothA 220 kV substation at WPHW during CLN4-MP4 contingency

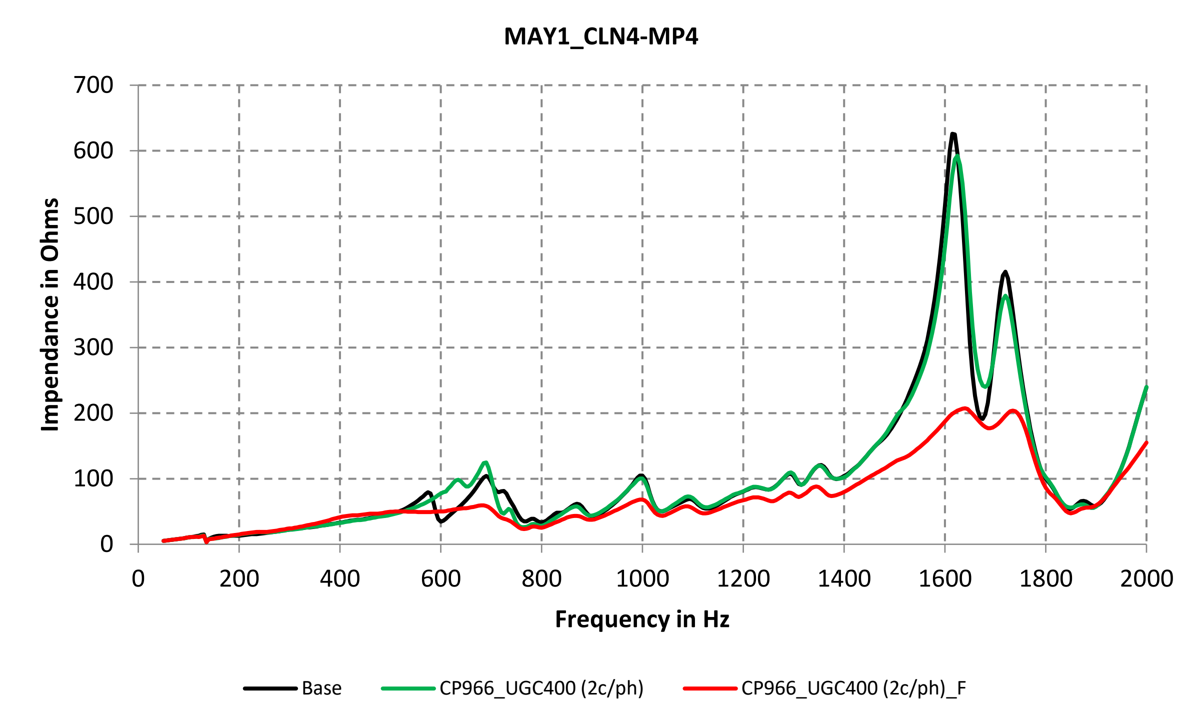

Figure 4-32: Self-impedance at Maynooth 110 kV substation at WPHW during CLN4-MP4 contingency

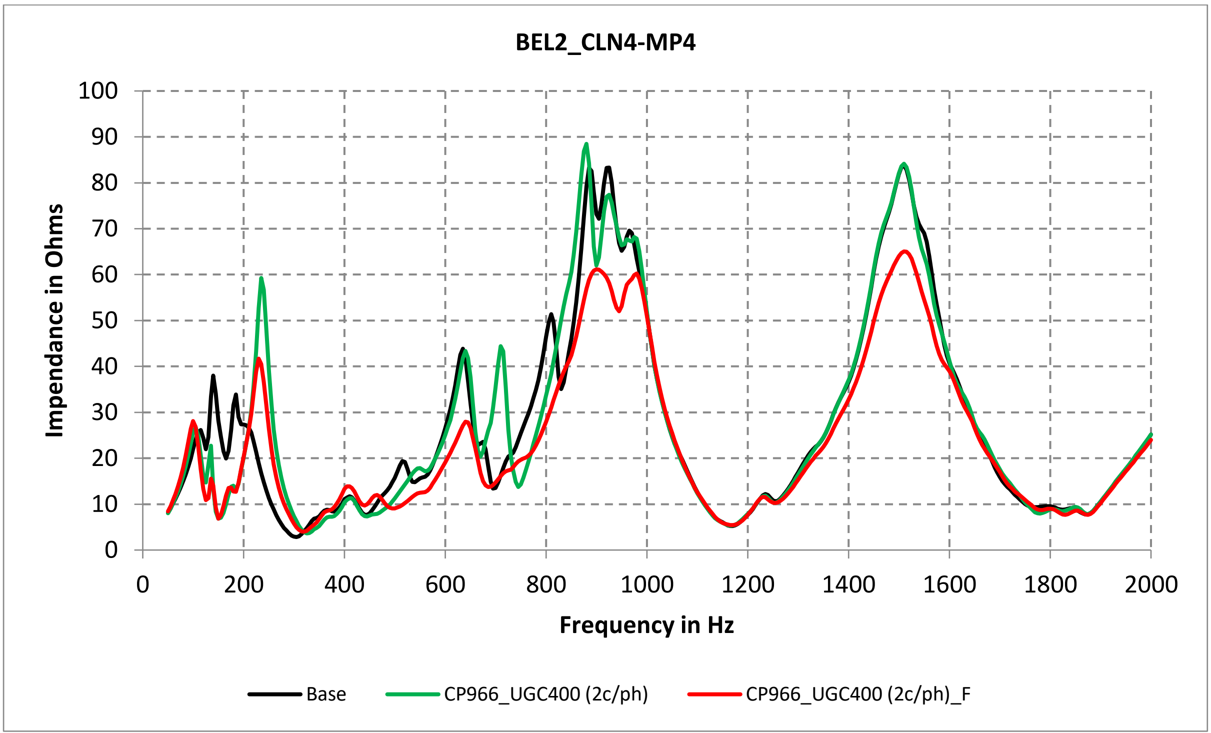

Figure 4-33: Self-impedance at Belcamp 220 kV substation at SVLW during CLN4-MP4 contingency

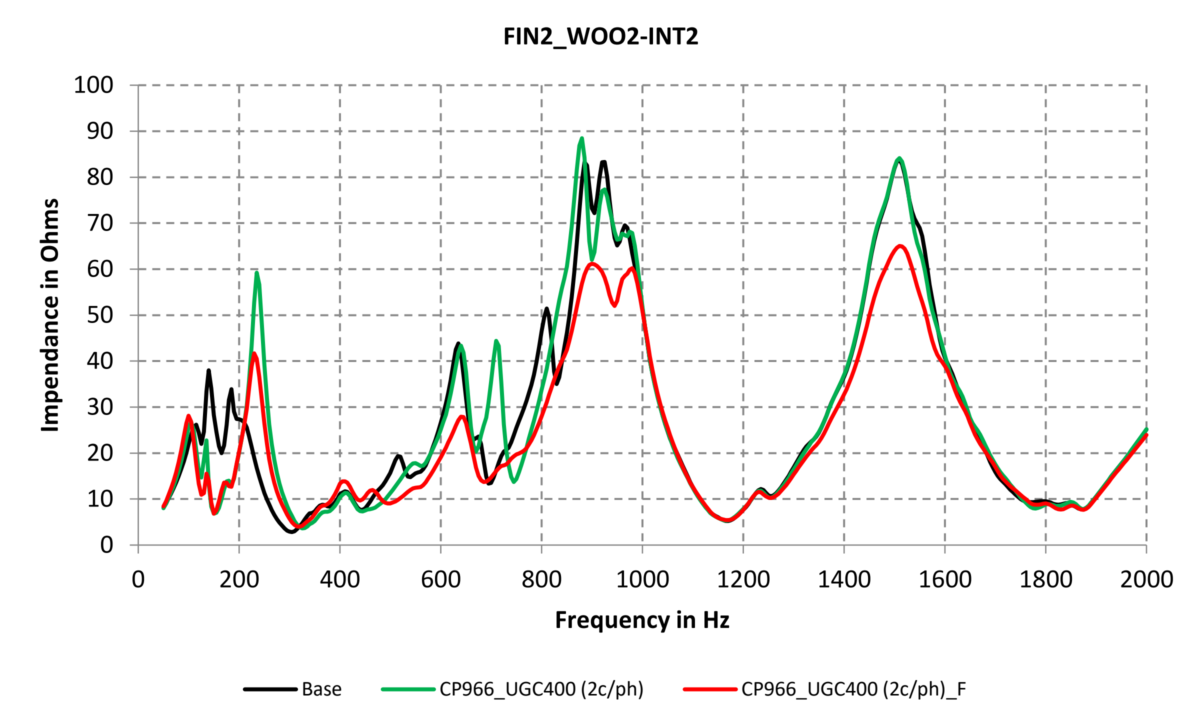

Figure 4-34: Self-impedance at Finglas 220 kV substation at SVLW during WOO2-INT2 contingency

4.5 Assumptions for Low Impedance Results

During the detailed gain factor calculations and self-impedance analysis, there were some contingencies where the self-impedance values before and after the introduction of new circuits were very low and as a result the calculated gain factor is high resulting in breach of PL levels. On the basis that the resulting impedance values were relatively low, the calculated gain factors were deemed to be impractical and, therefore were excluded as spurious results.

This phenomenon is more visible in the UGC400 (2c/ph) option where the effective higher capacitance of the cable has an impact on the frequency response of the system around the 5th harmonic resulting in slight changes in the parallel and series resonant points. Since the magnitude of the impedance around those harmonics is very low, a minor change will result in high calculated gain factors and hence harmonic breaches. These are not expected to be real and thus were excluded as spurious results.

Two examples related to the issue are presented. The first case in Figure 4-35 presents a contingency for BEL2 substation following the introduction of the UGC400 (2c/ph) where the marginal change in the 6th harmonic impedance results in high gain factor due to the extremely low impedance values.

The second case in Figure 4-36 presents a contingency for CKM2 substation following the introduction of the UGC400 (2c/ph) where the slight shift of the parallel resonance around 5th harmonic results in high gain factor due to the low impedance values. It is important to note that, if such cases are considered as valid, then it is possible to be resolved with a local harmonic filter tuned at the specific harmonic. To illustrate this, the solution for the specific case is shown on the same plot with the red line where an indicative C-Type filter (25 Mvar, 250 Hz) was used.

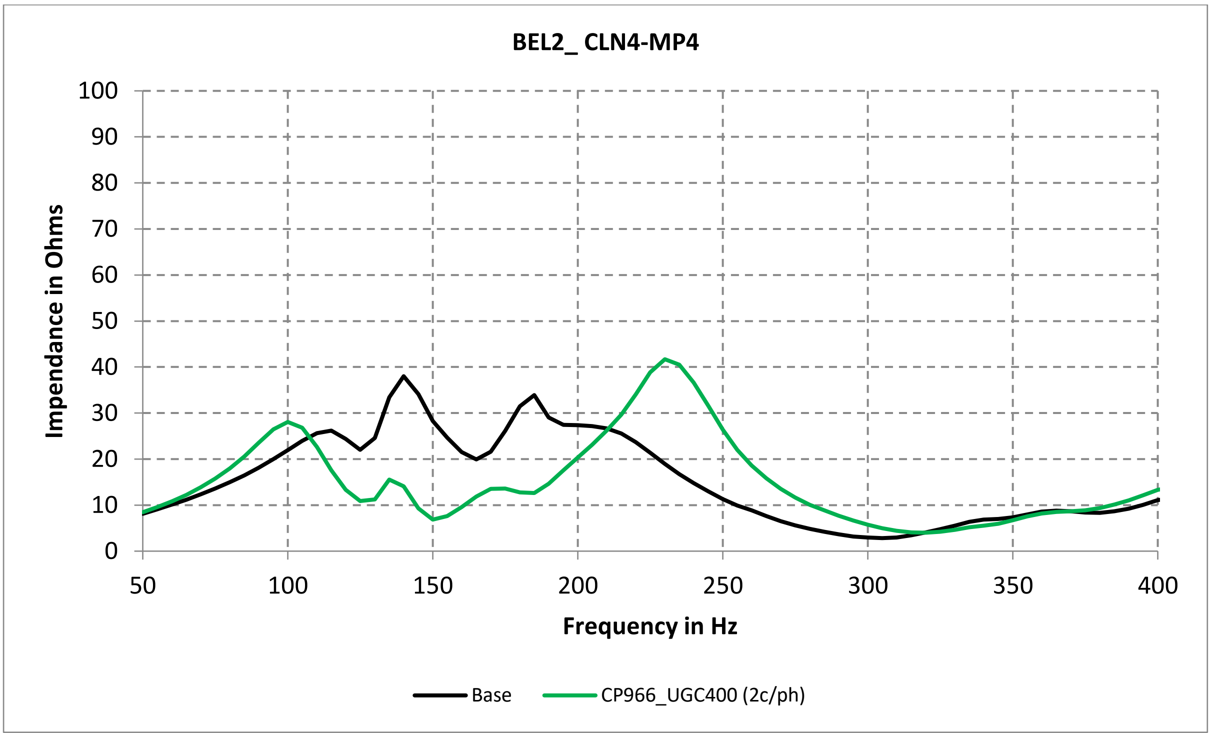

Figure 4-35: Self-impedance results at Belcamp 220 kV substation (spurious result at 300 Hz)

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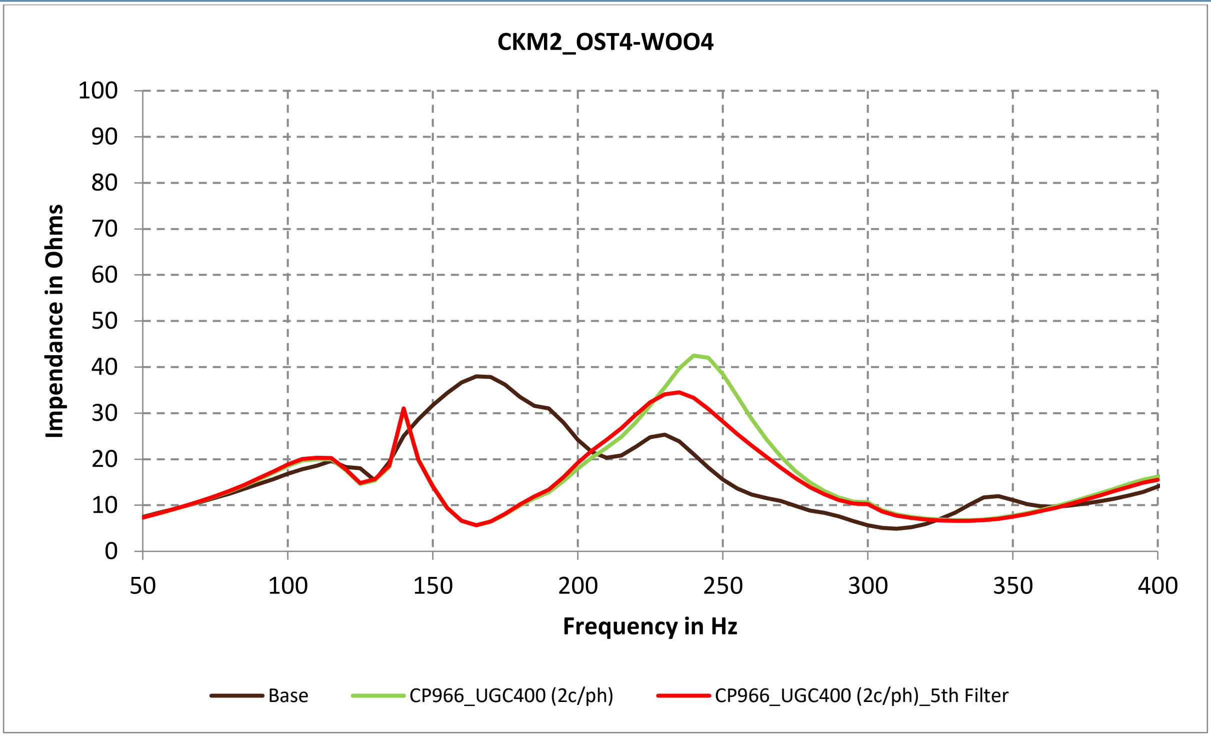

Figure 4-36: Self-impedance results at Carrickmines 220 kV substation with and without a filter (spurious result at 250 Hz)

4.6 Comparison of CP966 UGC Options

Table 4-14 presents a comparison of the proposed harmonic filters for the 100 % cable length of the 220 kV, 400 kV (1c/ph) and 400 kV (2c/ph) UGC options.

Table 4-14: Comparison of the Mitigation Solutions for the CP966 UGC Options

	220kV		400kV (1cable/phase)		400kV (2cables/phase)	
Node	Size (Mvar)	Tuning (Hz)	Size (Mvar)	Tuning (Hz)	Size (Mvar)	Tuning (Hz)
DSN2	32	420	20	550	20	550
CLN4	10	550	-	-	-	-
WOO4	-	-	50	200	-	-
OST4	-	-	40	300	50	300
MAY2B	30	525	30	530	37	530
MAY2A	15	550	15	550	20	550
MAY1	5	525	5	550	5	550
BEL2	-	-	30	500	30	500
BEL2	-	-	-	-	30	180
WOO2	-	-	-	-	40	315

The complete harmonic analysis for the UGC 220 kV indicates that there is some harmonic breaching due to the cable installation. This cable option is feasible from harmonic point of view and might not need all the harmonic filters proposed. In case that some of the breaches are identified as very crucial for the network operation then the proposed harmonic filters can be utilised.

The complete harmonic analysis for both UGC 400 kV options indicates that there is a more pronounced harmonic breaching at lower order harmonics due to the cable installation that is becoming worse for the 2 cable/phase option when compared to the 1 cable/phase. This option is also feasible from harmonic point of view but there is higher likelihood that the harmonic filters will be required to mitigate the lower order resonances.

The above conclusions are based on a certain set of future background harmonics calculated in a previous EirGrid project [6]. There is a possibility that those harmonics might change in the future which might either result in higher or lower background harmonics. In such case, the studies will need to be revisited prior to any final harmonic filter design.

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5 Temporary Overvoltage and Zero-Miss Phenomenon Analysis

PSC has carried out temporary overvoltage (TOV) and zero miss phenomenon (ZMP) analysis by performing time domain studies in EMTP-ATP software. The TOV analysis identified whether there are any sustained overvoltages that could be a risk for the equipment; whereas the ZMP analysis focused on the impact that the proposed reactive shunt compensation has on the circuit breaker operation during the cable energisation.

Studies have been performed in more detail for the full length of the 220 kV and 400 kV (1c/ph) UGC options. A quick evaluation was performed for the 400 kV (2c/ph) UGC option in order to estimate the impact of the additional core per phase.

5.1 Temporary Overvoltage Study

TOVs occur when a resonance is excited due to a network event and is poorly damped resulting in sustained overvoltages. These sustained overvoltages may lead to equipment damage. The specific frequency of any network resonance depends on the parameters of the network elements modelled and it is therefore important to investigate the potential for TOV under different system conditions and equipment parameters.

The transmission network around the connection nodes of the proposed Dunstown-Woodland UGC options is strongly connected to the rest of the system and therefore any overvoltages are likely to be strongly damped. However, the introduction of the new UGC cable options introduces new resonances or shifts the existing ones. As a result, there is an interest as part of this project to investigate the risk of TOV after the installation of the new UGC options and associated harmonic filters detailed in Section 4.

5.1.1 Region of Interest

The overall region of interest for these TOV studies is the 400 and 220 kV network around the UGC connection nodes of Woodland and Dunstown. To carry out the TOV studies a reduced model suitable for the transient time domain studies was prepared based on the latest ATP model provided by EirGrid. The extent of this model was dependent on the specific contingencies and network elements that need to be studied and these were identified from the frequency scans carried out during the harmonic analysis studies in PowerFactory.

5.1.2 Acceptance Criteria

TOVs relate to sustained overvoltages which are weakly dampened and can last at a given location for a relatively long duration. Establishing acceptable limits for TOVs is site specific and depends on the specific equipment installed at a location. At this stage of a study a general limit is required and therefore has been assumed to be restricted by the presence of Metal-Oxide Varistor (MOV) based surge arresters. MOV surge arresters can conduct a small amount of current to keep the voltage at their terminals below acceptable limits. However, a surge arrested is limited in the amount of energy it can dissipate before it becomes unstable.

The TOV limit for a surge arrester is dependant on the magnitude and duration of any overvoltage, taking into consideration the energy dissipation as a result of previous overvoltage events [7]. For short durations (<1 second) a typical limit for TOVs is between 1.5 p.u and 1.8 p.u [8,9] This range is dependent on the surge arrester selected and the equipment they are designed to protect. TOV limits

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for other equipment such as transformers are typically 1.7 to 1.8 p.u. for short durations (<1 second) [7,10].

Since these studies are being carried out at an early stage with indicative design data, a value of 1.6 p.u. has been agreed with EirGrid as a screening value. Any TOV exceeding 1.6 p.u. will be identified for further consideration in the next stage of any system design.

5.1.3 Area of Interest – ATP Model

To determine the extent of the model that needed to be developed for transient time domain studies, the frequency scans previously produced in PowerFactory were analysed. Contingencies which showed the following characteristics were considered for TOV studies:

- Parallel resonance between 100 and 500 Hz (2nd to 10th harmonic)
- Impedance > 150 Ohms

These parameters were used as an initial screening to shortlist the contingencies shown in Table 5-1 and Table 5-2 for the UGC 220 kV and UGC 400 kV, respectively. These resulted in the self-impedance at one of the network nodes demonstrating the above characteristics.

Table 5-1: Contingencies Considered for TOV Analysis for UGC 220 kV

ATP Key	Outage
INTACT	
DSLS40	Dunstown 400 kV – Coolnabacky 400 kV circuit
WOOS40	Woodland 400 kV – Old Street 400 kV circuit
OSMP40	Old Street 400 kV – Moneypoint 400 kV circuit
WOPR40	Woodland 400 kV – Portan 400 kV circuit

Table 5-2: Contingencies Considered for TOV Analysis for UGC 400 kV

ATP Key	Outage
INTACT	
DSLS40	Dunstown 400 kV – Coolnabacky 400 kV circuit
WOOS40	Woodland 400 kV – Old Street 400 kV circuit
OSMP40	Old Street 400 kV – Moneypoint 400 kV circuit
WOPR40	Woodland 400 kV – Portan 400 kV circuit
WOTL40	Woodland 400 kV – Turleenan 400 kV circuit

The existing EirGrid ATP model was updated accordingly as detailed in Section 2.4 in order to cover these contingencies and the nodes shown in Table 5-3 which are the same for UGC 220 kV and UGC 400 kV. The selection includes all the nodes identified from the frequency scans and allowed the above contingencies to be considered. At the edges of the ATP network model (Table 2-3), the rest of the system was represented as an equivalent modelled as a voltage source behind an impedance as detailed in Section 2.4.

Table 5-3: Monitored Nodes for ATP Model

ATP Key	Substation	Voltage
DSN4	Dunstown	400 kV
CLN4	Coolnabacky	400 kV
PRN4	Portan	400 kV
OST4	Old Street	400 kV
WOO4	Woodland	400 kV

5.1.4 Time Domain Studies

This section presents results from time domain studies to investigate the extent of overvoltages that may exist after the proposed CP966 system reinforcements. Studies were carried out to represent a delayed auto-reclose (DAR) event for a fault at the nodes which showed resonances at frequencies of concern during the contingencies listed in Table 5-1 and Table 5-2.

The DAR event is modelled as a fault on a circuit close to a substation followed by a circuit breaker open and re-close event. This combination of events results in the substation voltage collapsing to zero followed by the re-energisation of the local transformers. For all the fault studies, the following timings were considered:

- Time domain simulation for 0 to 2 seconds with simulation time steps of 1µs
- Fault impedance of 0.1 Ohms was assumed
- 0.02 s – fault applied
- 0.14 s – circuit breakers open to isolate fault (120 ms after fault applied)
- 0.64 s – circuit breaker closes back onto the fault
- 0.69 s – circuit breaker re-opens since fault is still in place

Table 5-4 presents the faults considered for TOV analysis for the UGC 220 kV and UGC 400 kV. For the UGC 220 kV, those faults were considered for all the outage contingencies mentioned in Table 5-1. For the UGC 400 kV, it was agreed with EirGrid to only simulate the worst-case contingencies for each substation and fault condition. Those worst-case contingencies were identified from the frequency response analysis from PowerFactory.

Table 5-4: Faults Considered for TOV Analysis

Fault	Fault Description
DSN4F_3ph	Dunstown 400 kV 3-phase fault
DSN4F_1ph	Dunstown 400 kV 1-phase fault
DSN2F_3ph	Dunstown 220 kV 3-phase fault
DSN2F_1ph	Dunstown 220 kV 1-phase fault
CLN4F_3ph	Coolnabacky 400 kV 3-phase fault
CLN4F_1ph	Coolnabacky 400 kV 1-phase fault

PRN4F_3ph	Portan 400 kV 3-phase fault
PRN4F_1ph	Portan 400 kV 1-phase fault
OST4F_3ph	Old Street 400 kV 3-phase fault
OST4F_1ph	Old Street 400 kV 1-phase fault
WOO4F_3ph	Woodland 400 kV 3-phase fault
WOO4F_1ph	Woodland 400 kV 1-phase fault
WOO2F_3ph	Woodland 220 kV 3-phase fault
WOO2F_1ph	Woodland 220 kV 1-phase fault

The following sub-sections present the TOV results, the frequency response and details of the outage and fault combination producing the worst overvoltages for the following UGC options. The TOV results for each of these options are shown in kV and for the duration from 0 to 2 seconds as well as in detail for the time around the worst fault clearing event.

- CP966_UGC220
- CP966_UGC400 (1c/ph)
- CP966_UGC400 (2c/ph)

The results show that after the introduction of any of the above CP966 UGC options and including the required harmonic filters, there is a risk of TOV exceeding 1.6[11] p.u for a short duration of few milliseconds for Coolnabacky and Old Street 400 kV substations. The response of the system and the observed overvoltages are very similar among the different UGC options. This is primarily happening because following the installation of the UGC options the magnitude of the impedance remains relatively low in the frequency range of interest for TOV analysis.

Although the overvoltage slightly exceeds the EirGrid limit of 1.6 p.u for few milliseconds, it may be within the capability of existing surge arresters [7,10]. PSC believes that those overvoltages should not be a problem for the existing surge arresters due to the marginal exceedance and the very short duration but EirGrid are advised to confirm with their specific capability from the equipment technical specification.

Once the specific circuit route is identified, changes in the existing system and specific cable lengths could alter the system impedance and associated resonance conditions which in turn may alter the overvoltage magnitude and duration. Therefore, once further details of the route with specific cable lengths and associated harmonic filters are available for TOV studies should be reviewed and surge arresters specified as appropriate.

[11] Equivalent to 496.4 kV phase to ground peak value at 380 kV system.

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Results for CP966_UGC220

- *400 kV Coolnabacky Substation*

Figure 5-1 and Figure 5-2 present the worst case TOV results for the 400 kV Coolnabacky substation for a **3-phase fault during an outage of Dunstown 400 kV – Coolnabacky 400 kV circuit**; whereas Figure 5-3 presents the frequency response of the substation for the same contingency.

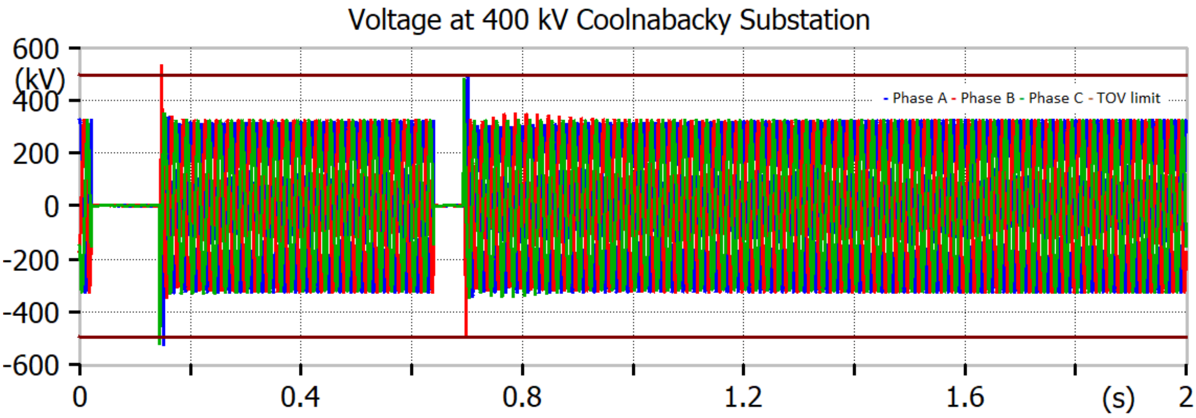

Figure 5-1: Voltage at 400 kV Coolnabacky Substation

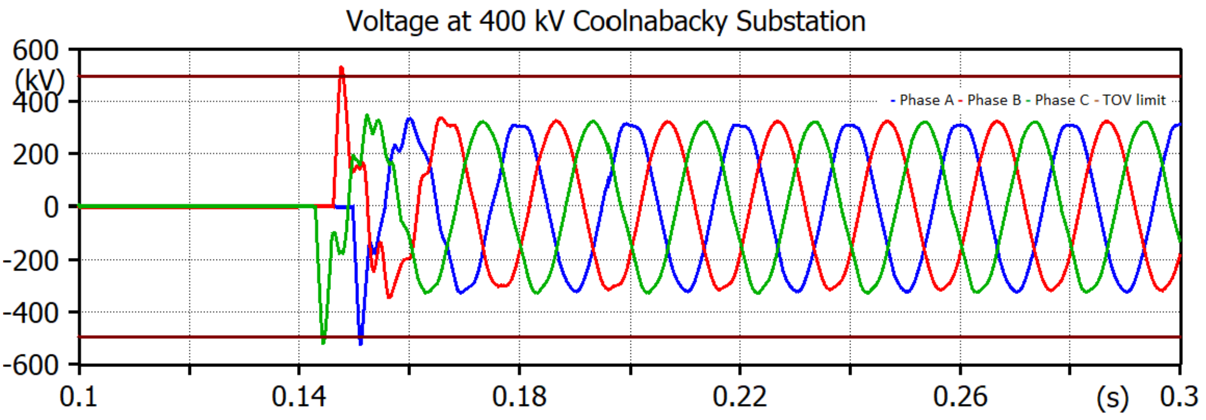

Figure 5-2: Voltage at 400 kV Coolnabacky Substation – Worst Fault Clearing Event

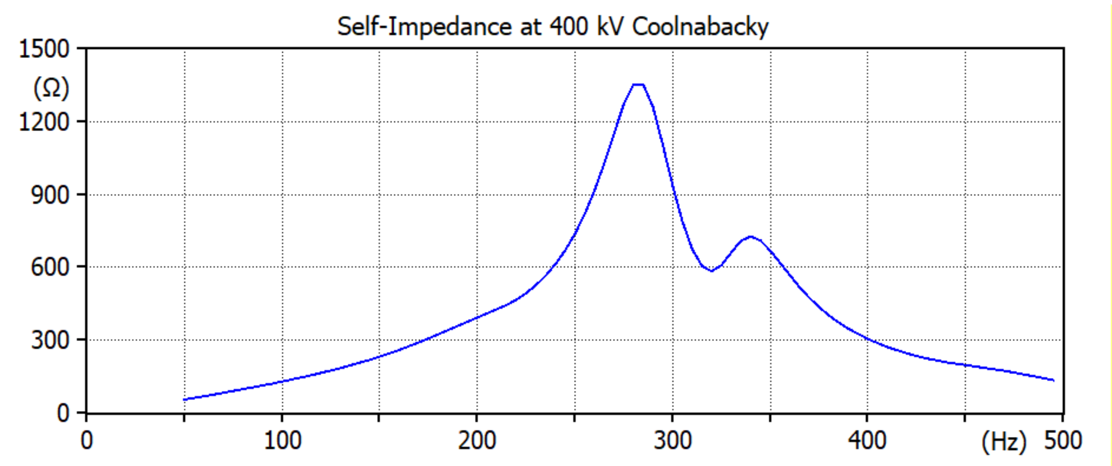

Figure 5-3: Self-Impedance at 400 kV Coolnabacky

- *400 kV Dunstown Substation*

Figure 5-4 and Figure 5-5 present the worst case TOV results for the 400 kV Dunstown substation for a **3-phase fault during an outage of Old Street 400 kV – Moneypoint 400 kV circuit**; whereas Figure 5-6 presents the frequency response of the substation for the same contingency.

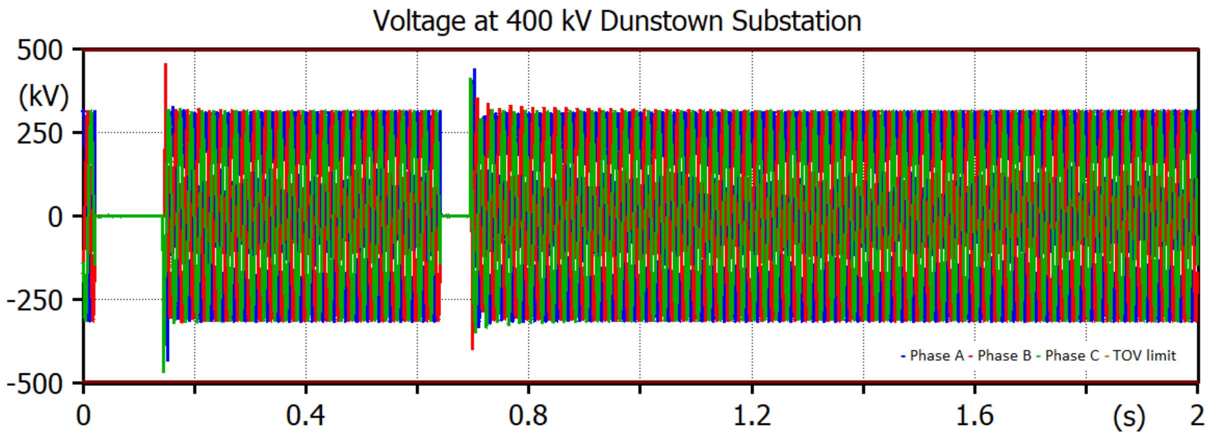

Figure 5-4: Voltage at 400 kV Dunstown Substation

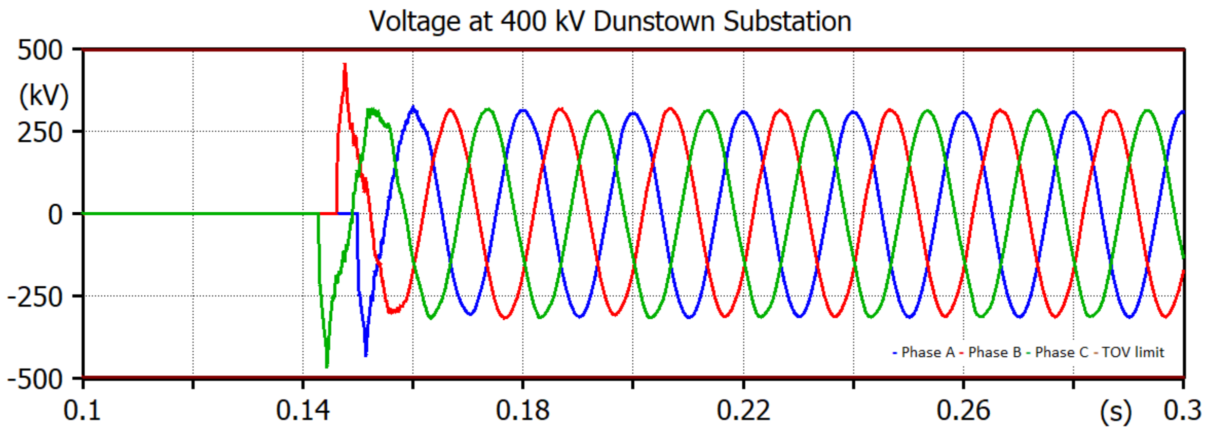

Figure 5-5: Voltage at 400 kV Dunstown Substation – Worst Fault Clearing Event

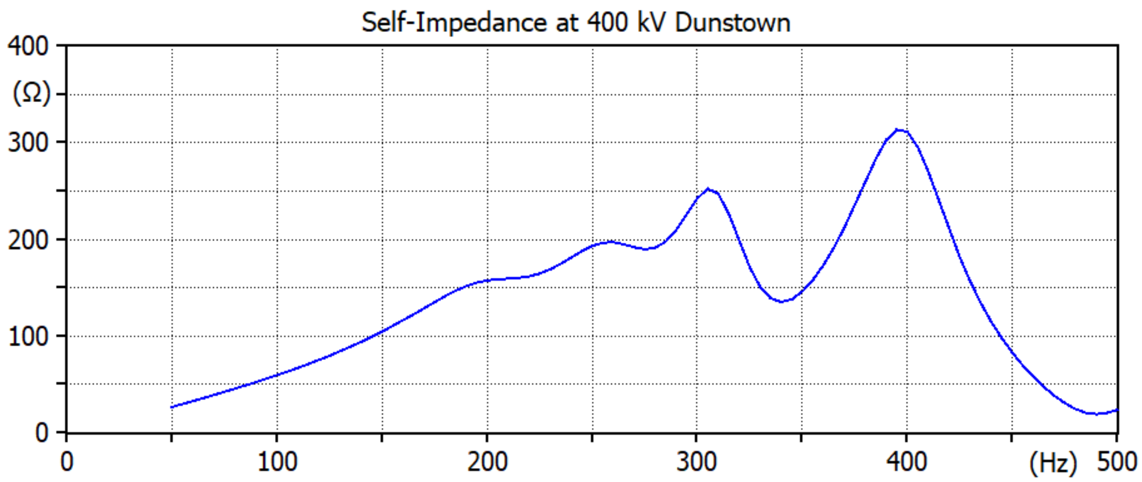

Figure 5-6: Self-Impedance at 400 kV Dunstown

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- *400 kV Old Street Substation*

Figure 5-7 and Figure 5-8 present the worst case TOV results for the 400 kV Old Street substation for a **3-phase fault during an outage of Old Street 400 kV – Moneypoint 400 kV circuit**; whereas Figure 5-9 presents the frequency response of the substation for the same contingency.

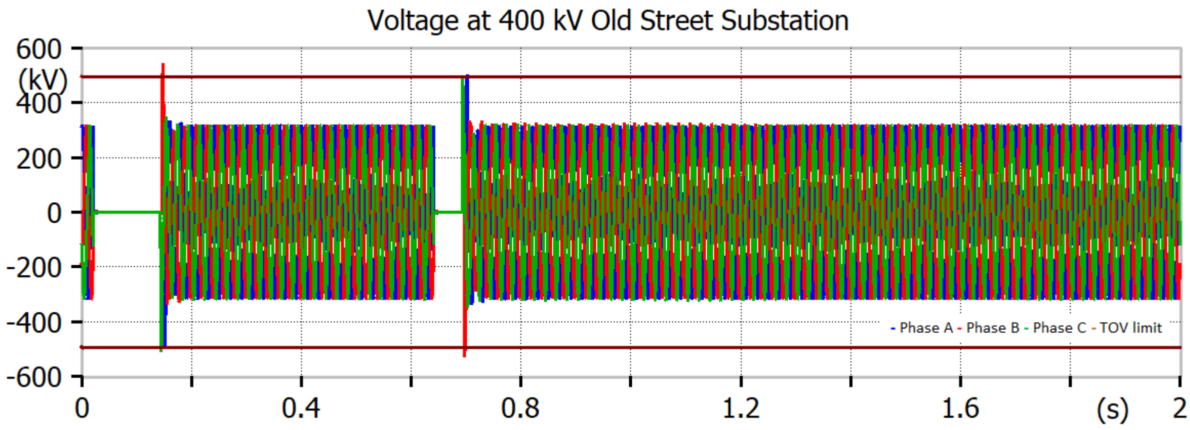

Figure 5-7: Voltage at 400 kV Old Street Substation

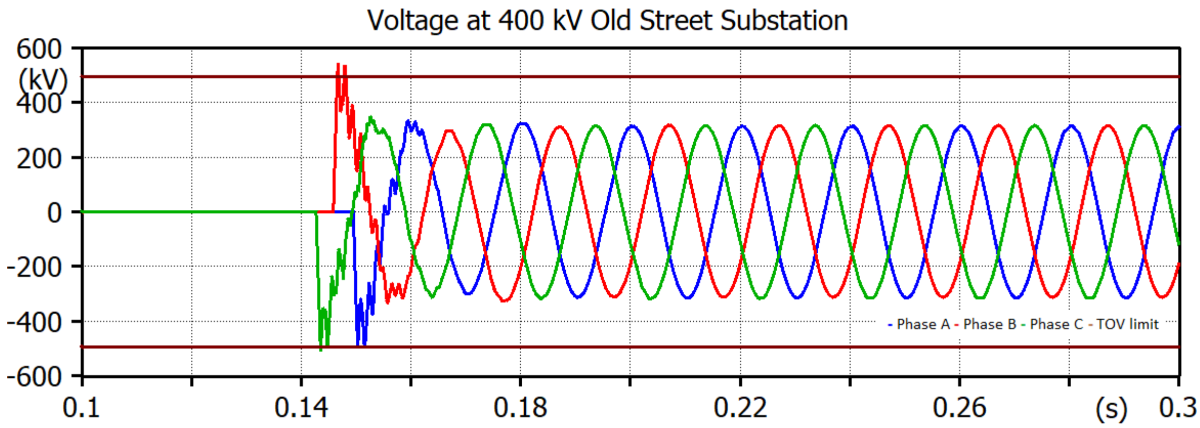

Figure 5-8: Voltage at 400 kV Old Street Substation – Worst Fault Clearing Event

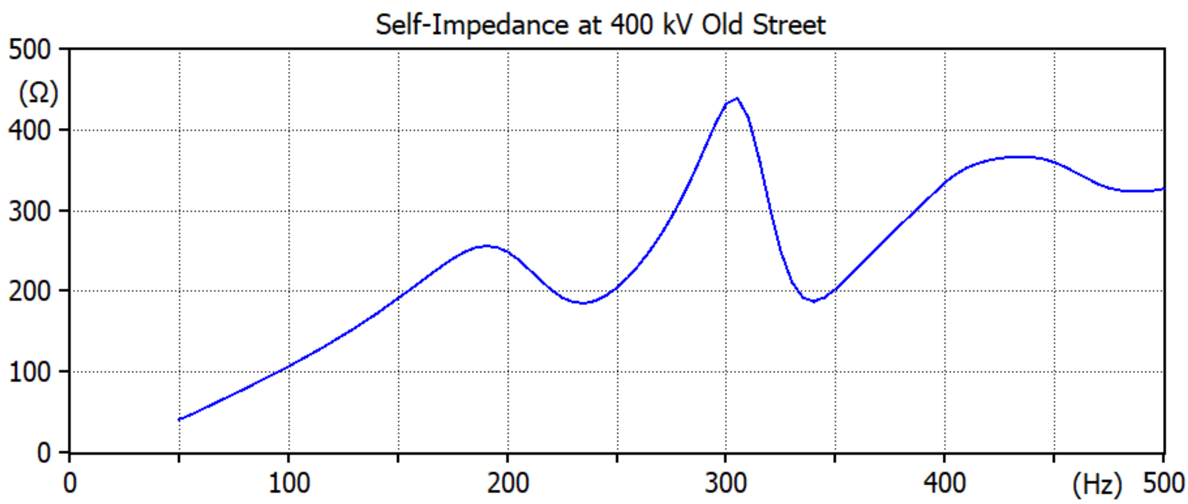

Figure 5-9: Self-Impedance at 400 kV Old Street

- *400 kV Portan Substation*

Figure 5-10 and Figure 5-11 present the worst case TOV results for the 400 kV Portan substation for a **3-phase fault during an outage of Dunstown 400 kV – Coolnabacky 400 kV circuit**; whereas Figure 5-12 presents the frequency response of the substation for the same contingency.

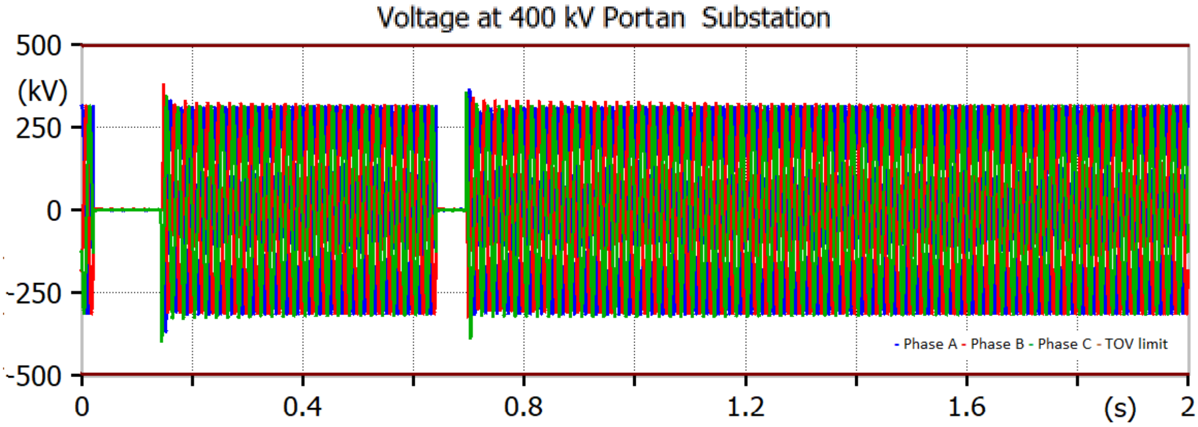

Figure 5-10: Voltage at 400 kV Portan Substation

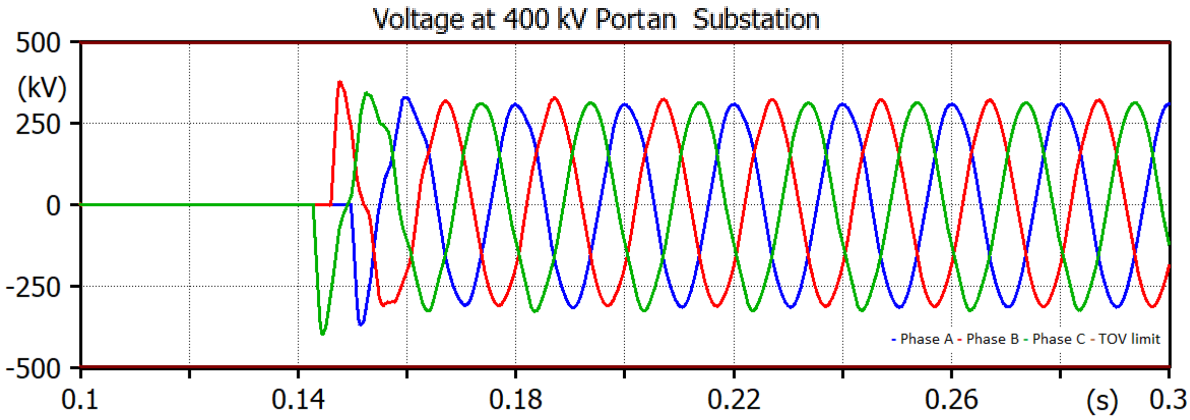

Figure 5-11: Voltage at 400 kV Portan Substation – Worst Fault Clearing Event

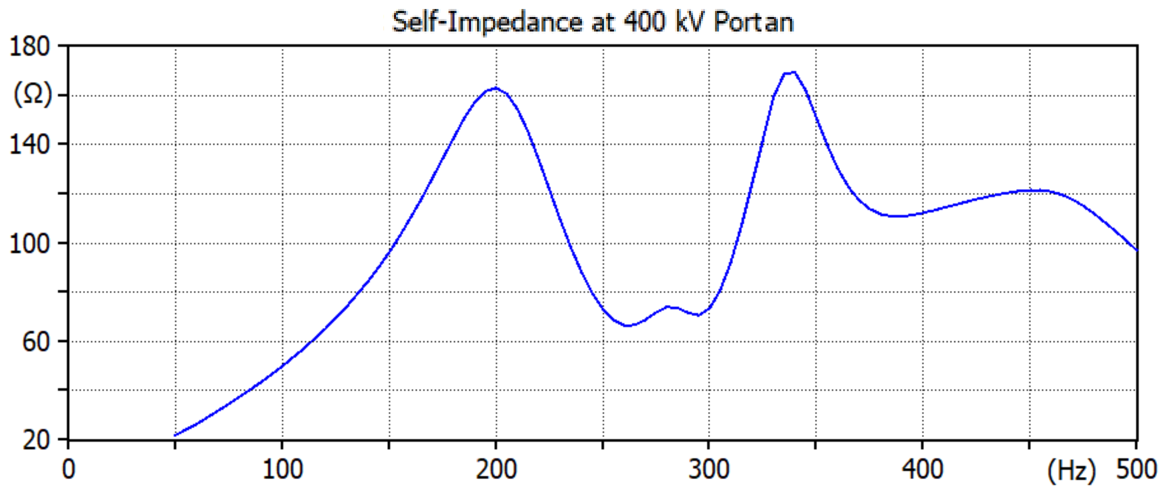

Figure 5-12: Self-Impedance at 400 kV Portan

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- *400 kV Woodland Substation*

Figure 5-13 and Figure 5-14 present the worst case TOV results for the 400 kV Woodland substation for a **3-phase fault during an outage of Woodland 400 kV – Portan 400 kV circuit**; whereas Figure 5-15 presents the frequency response of the substation for the same contingency.

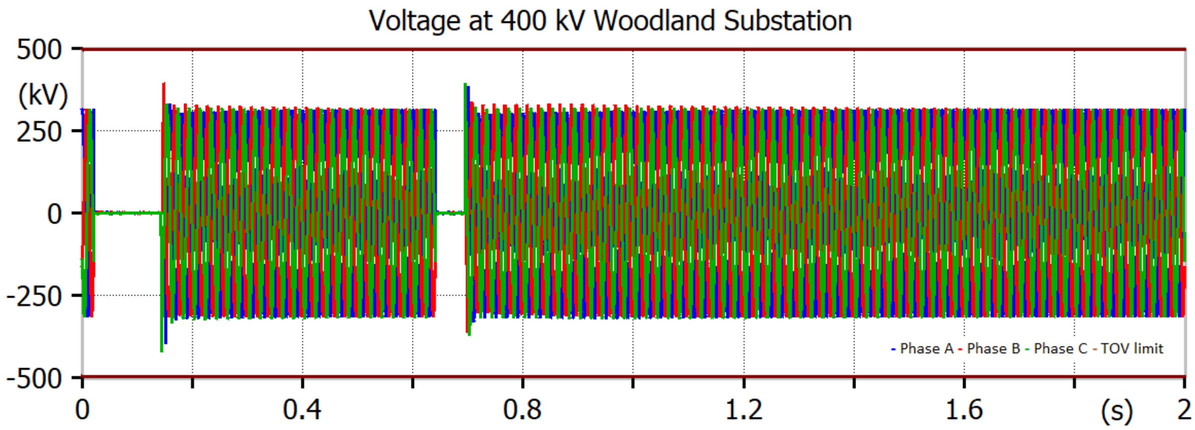

Figure 5-13: Voltage at 400 kV Woodland Substation

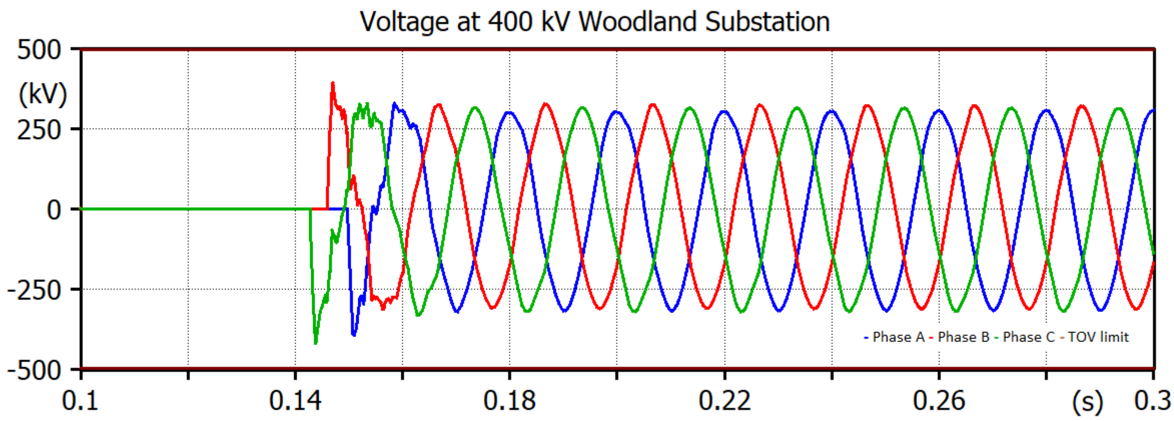

Figure 5-14: Voltage at 400 kV Woodland Substation – Worst Fault Clearing Event

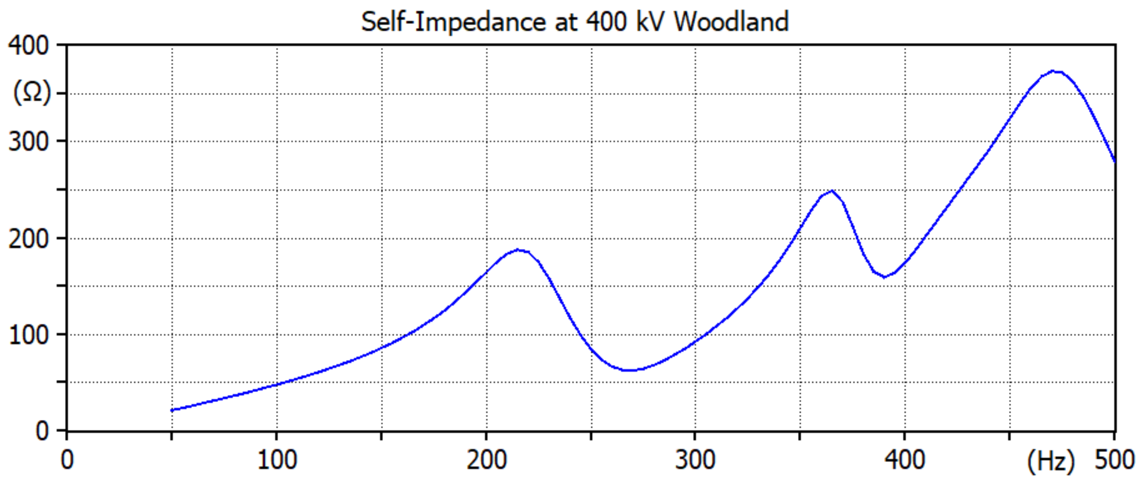

Figure 5-15: Self-Impedance at 400 kV Woodland

Results for CP966_UGC400 (1c/ph)

- *400 kV Coolnabacky Substation*

Figure 5-16 and Figure 5-17 present the worst case TOV results for the 400 kV Coolnabacky substation for a **3-phase fault during an outage of Dunstown 400 kV – Coolnabacky 400 kV circuit**; whereas Figure 5-18 presents the frequency response of the substation for the same contingency.

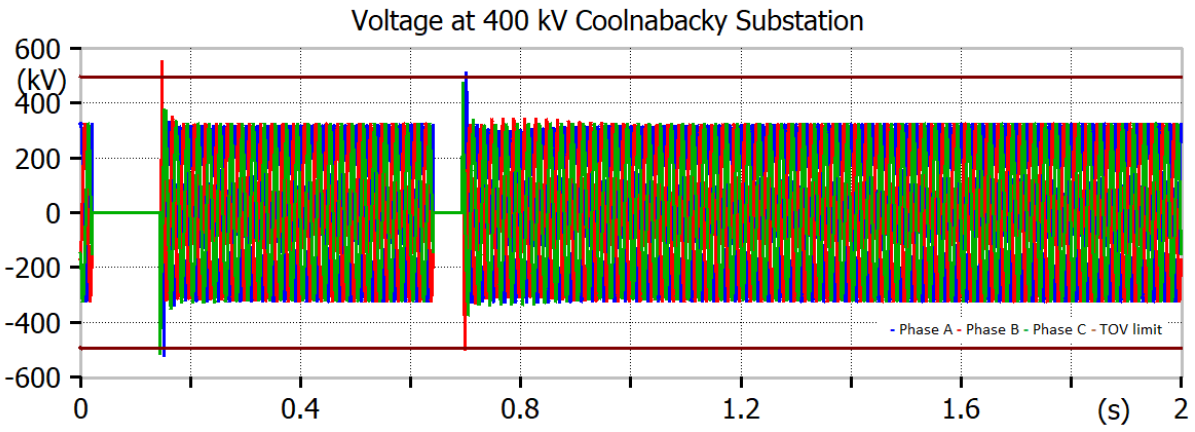

Figure 5-16: Voltage at 400 kV Coolnabacky Substation

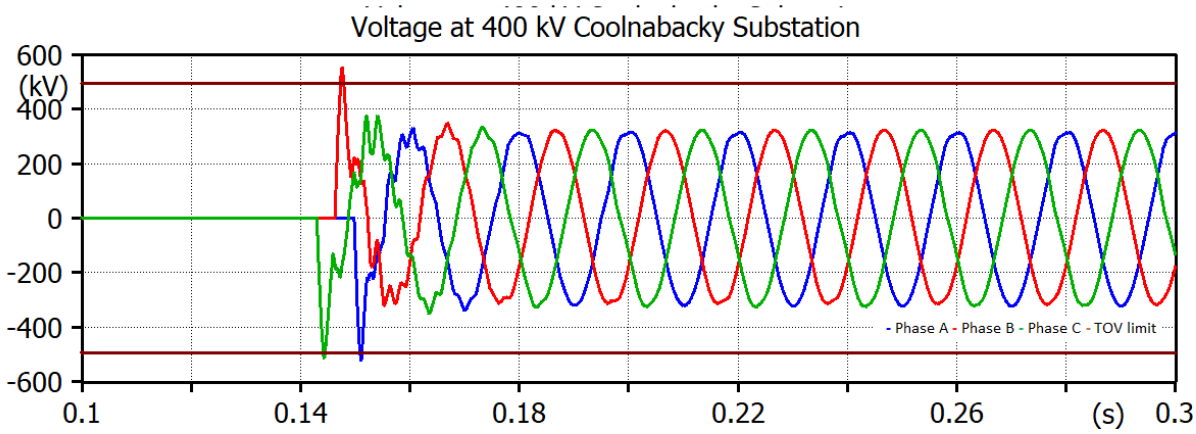

Figure 5-17: Voltage at 400 kV Coolnabacky Substation – Worst Fault Clearing Event

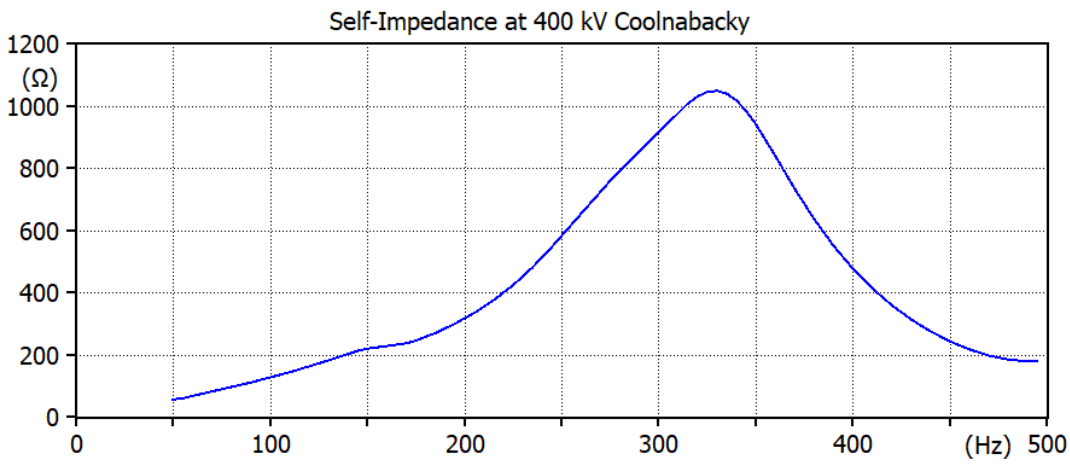

Figure 5-18: Self-Impedance at 400 kV Coolnabacky

- *400 kV Dunstown Substation*

Figure 5-19 and Figure 5-20 present the worst case TOV results for the 400 kV Dunstown substation for a **3-phase fault during an outage of Dunstown 400 kV – Coolnabacky 400 kV circuit**; whereas Figure 5-21 presents the frequency response of the substation for the same contingency.

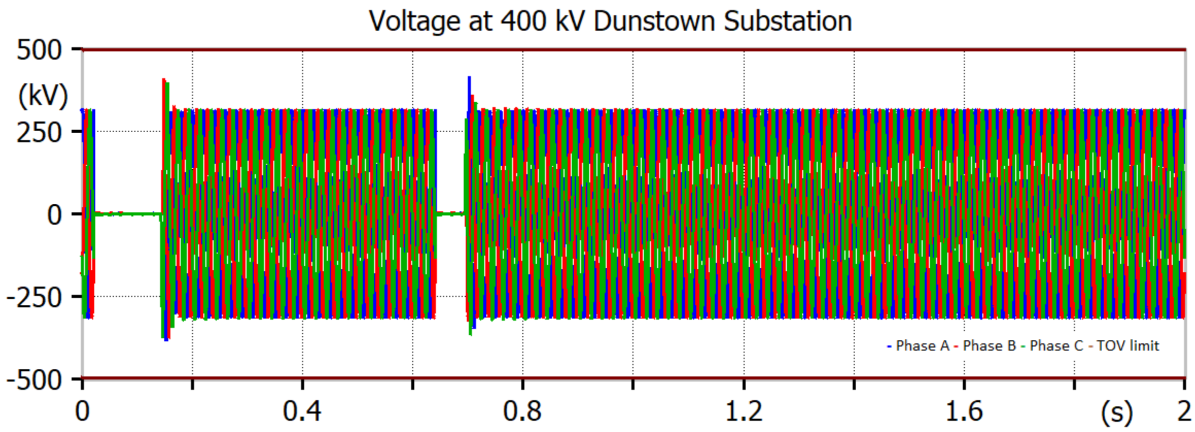

Figure 5-19: Voltage at 400 kV Dunstown Substation

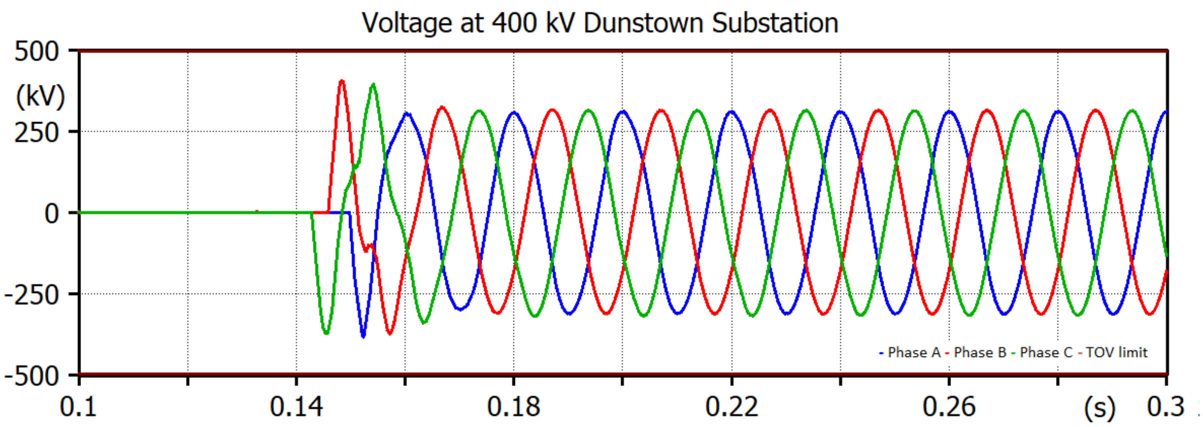

Figure 5-20: Voltage at 400 kV Dunstown Substation – Worst Fault Clearing Event

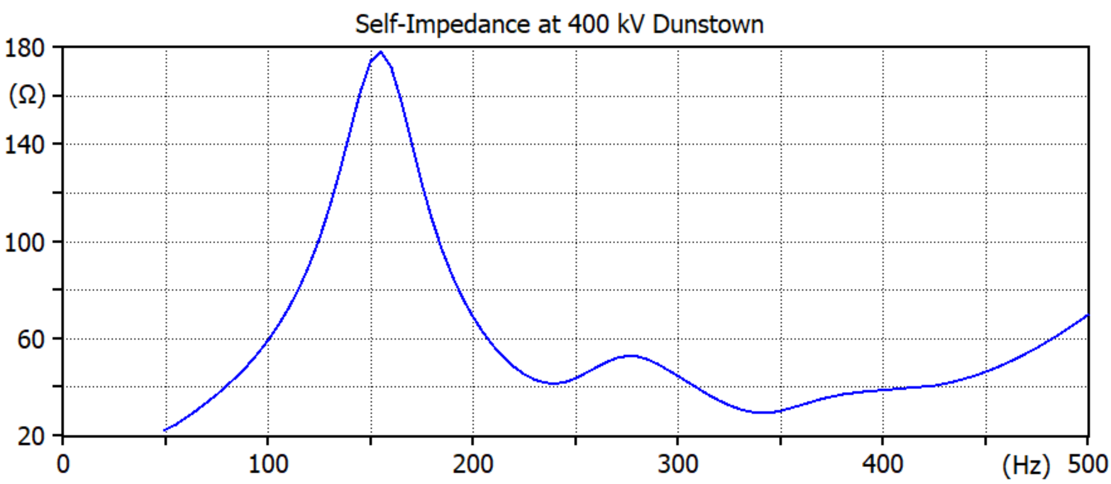

Figure 5-21: Self-Impedance at 400 kV Dunstown

- *400 kV Old Street Substation*

Figure 5-22 and Figure 5-23 present the worst case TOV results for the 400 kV Old Street substation for a **3-phase fault during an outage of Old Street 400 kV – Moneypoint 400 kV circuit**; whereas Figure 5-24 presents the frequency response of the substation for the same contingency.

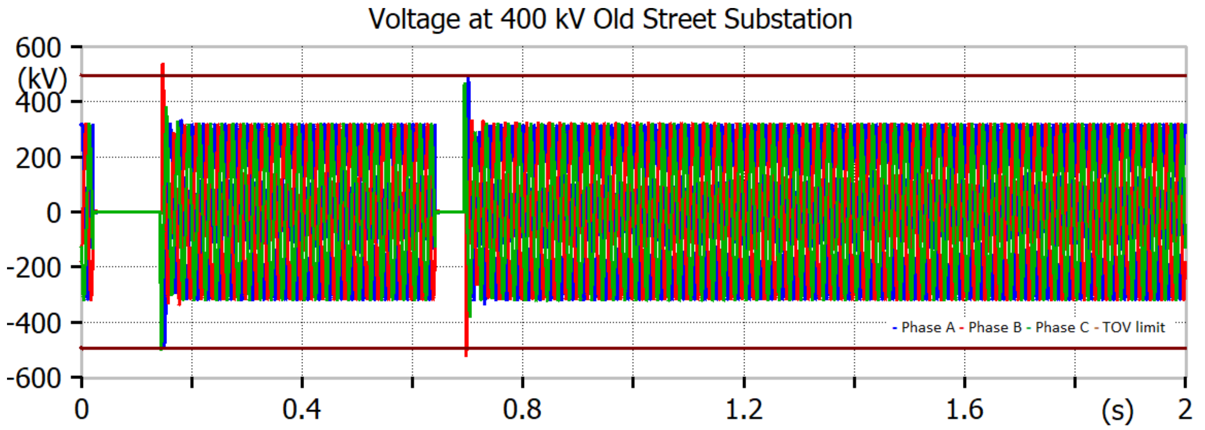

Figure 5-22: Voltage at 400 kV Old Street Substation

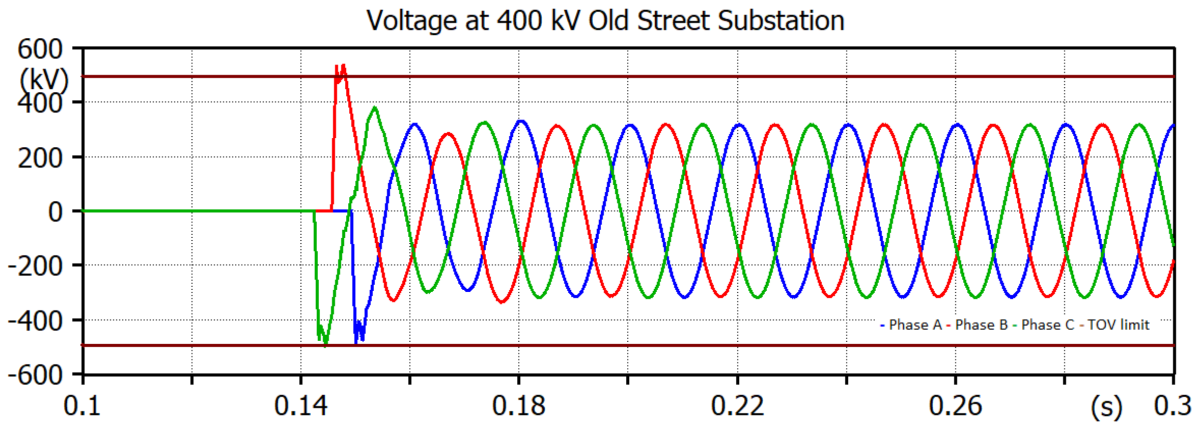

Figure 5-23: Voltage at 400 kV Old Street Substation – Worst Fault Clearing Event

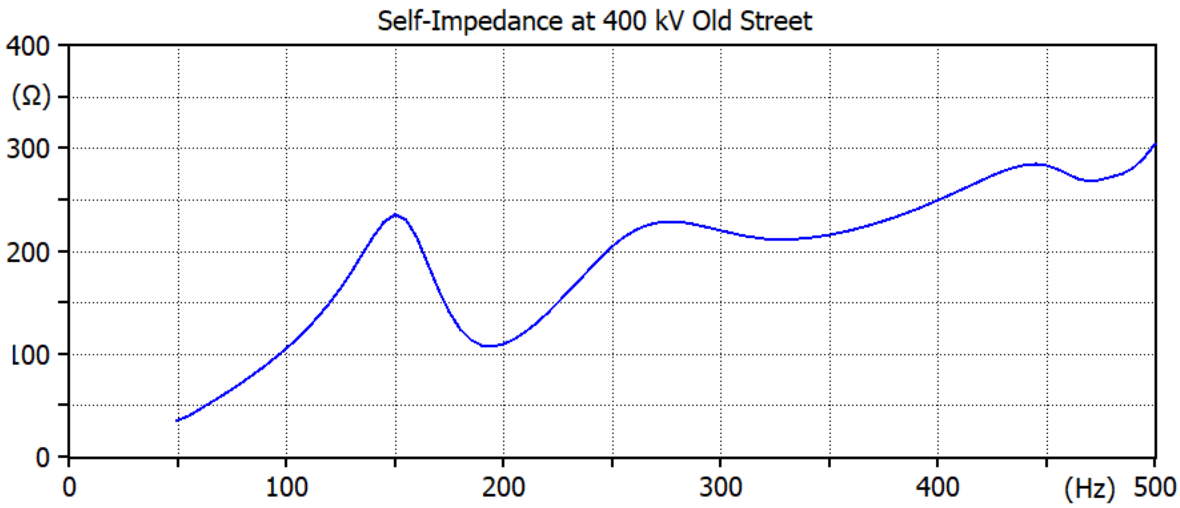

Figure 5-24: Self-Impedance at 400 kV Old Street

- *400 kV Portan Substation*

Figure 5-25 and Figure 5-26 present the worst case TOV results for the 400 kV Portan substation for a **3-phase fault during an outage of Old Street 400 kV – Woodland 400 kV circuit**; whereas Figure 5-27 presents the frequency response of the substation for the same contingency.

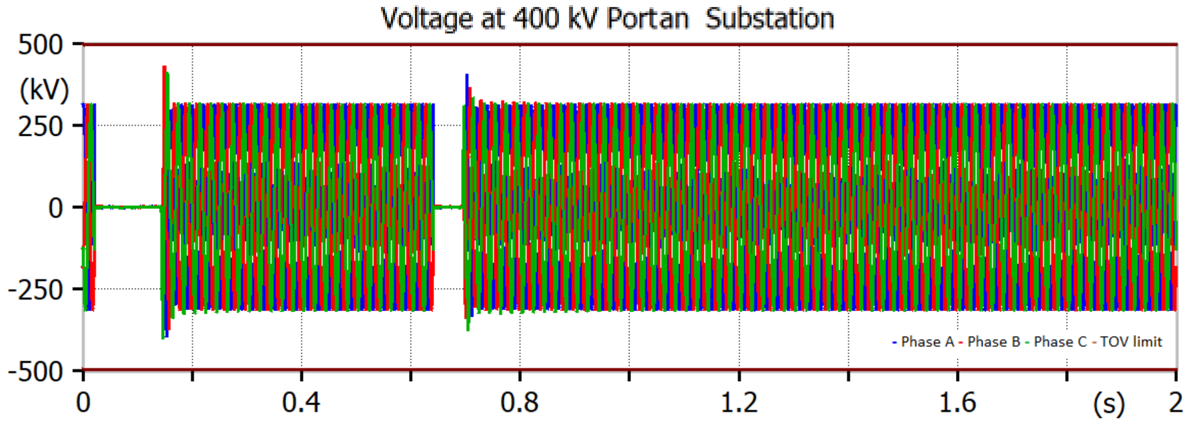

Figure 5-25: Voltage at 400 kV Portan Substation

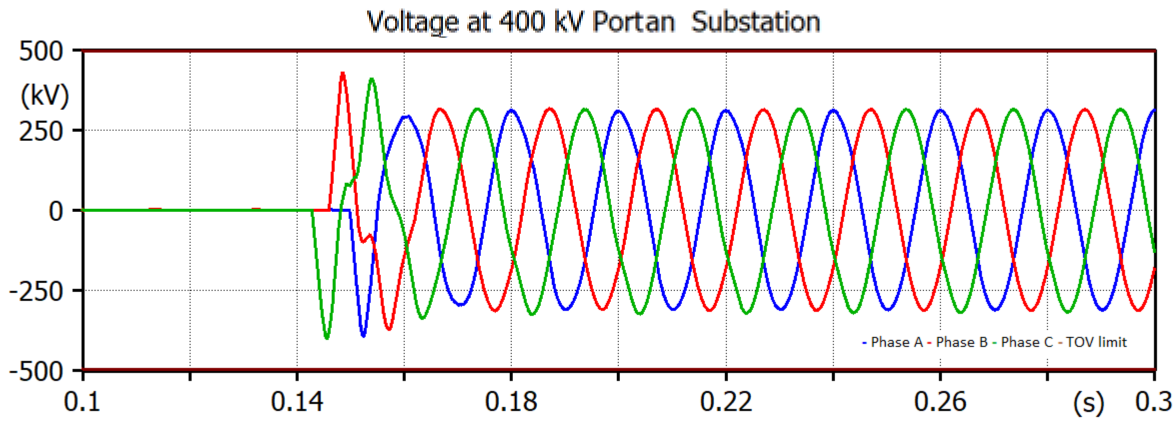

Figure 5-26: Voltage at 400 kV Portan Substation – Worst Fault Clearing Event

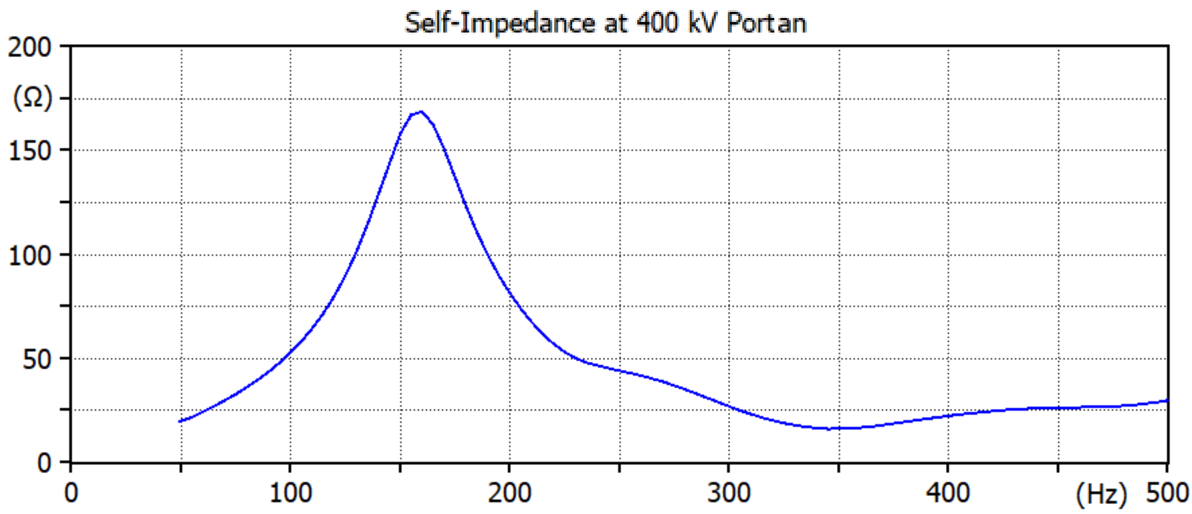

Figure 5-27: Self-Impedance at 400 kV Portan

- *400 kV Woodland Substation*

Figure 5-28 and Figure 5-29 present the worst case TOV results for the 400 kV Woodland substation for a **3-phase fault during an outage of Woodland 400 kV – Turleenan 400 kV circuit**; whereas Figure 5-30 presents the frequency response of the substation for the same contingency.

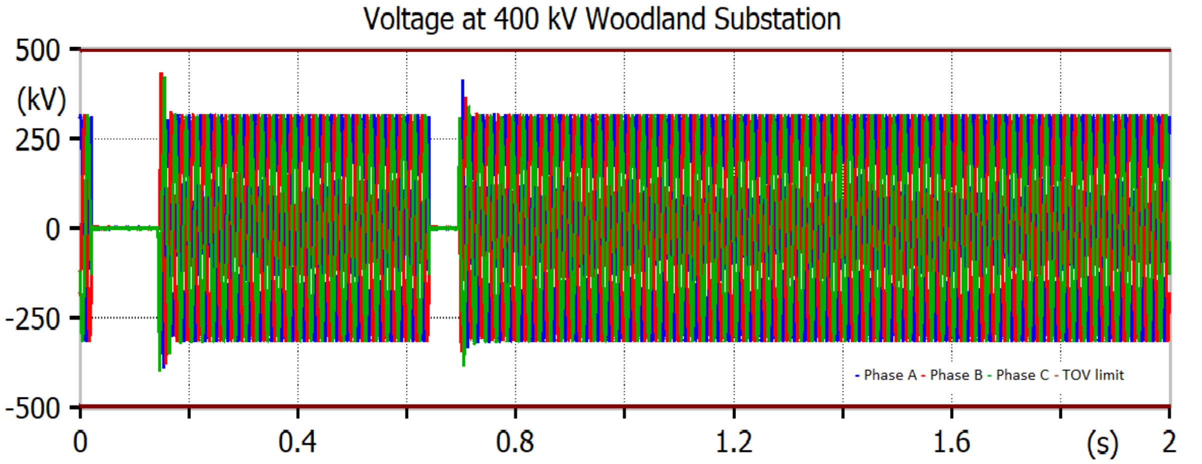

Figure 5-28: Voltage at 400 kV Woodland Substation

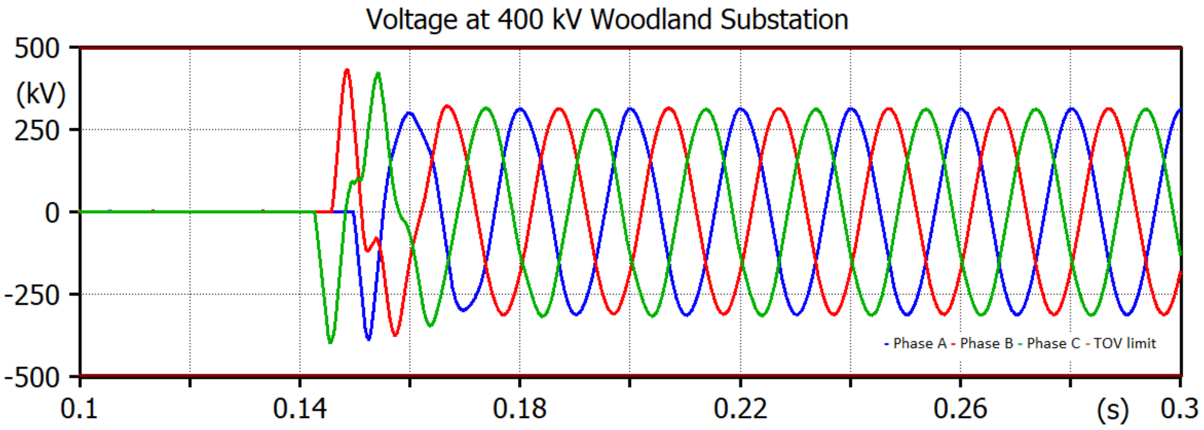

Figure 5-29: Voltage at 400 kV Woodland Substation – Worst Fault Clearing Event

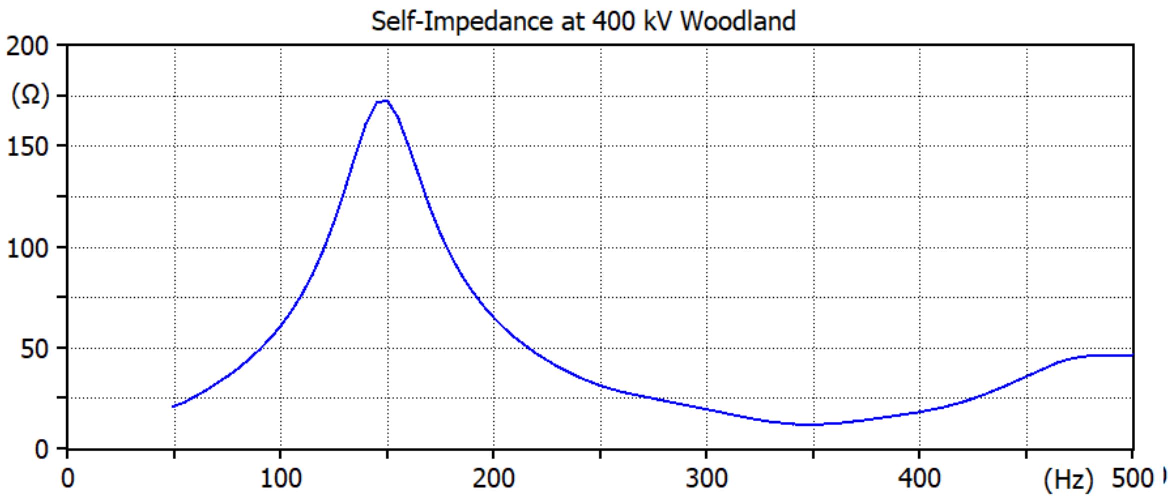

Figure 5-30: Self-Impedance at 400 kV Woodland

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Results for CP966_UGC400 (2c/ph)

It should be noted that since it was agreed with EirGrid to not perform detailed harmonic analysis and mitigation solution studies for this cable configuration, those results are based on the mitigation solution from the UGC 400 kV (1c/ph) and should be used for information only.

- *400 kV Coolnabacky Substation*

Figure 5-31 and Figure 5-32 present the worst case TOV results for the 400 kV Coolnabacky substation for a **3-phase fault during an outage of Dunstown 400 kV – Coolnabacky 400 kV circuit**; whereas Figure 5-33 presents the frequency response of the substation for the same contingency.

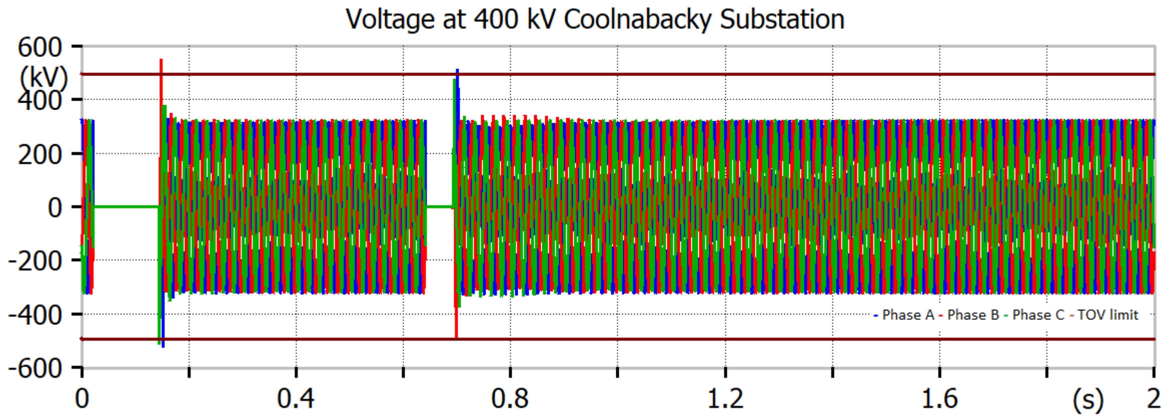

Figure 5-31: Voltage at 400 kV Coolnabacky Substation

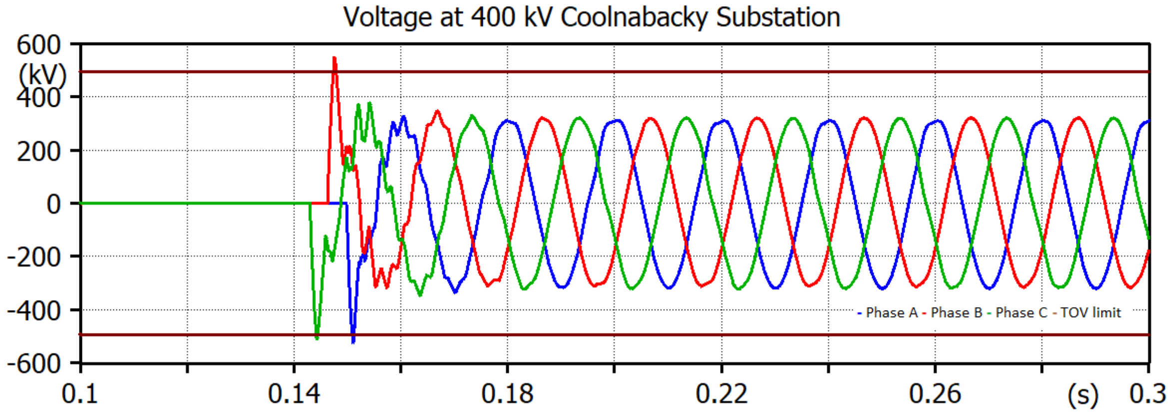

Figure 5-32: Voltage at 400 kV Coolnabacky Substation – Worst Fault Clearing Event

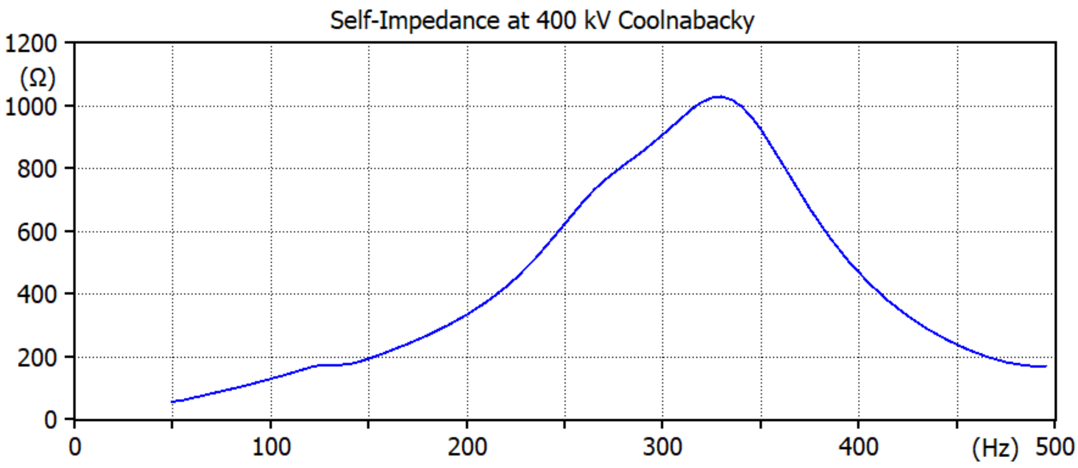

Figure 5-33: Self-Impedance at 400 kV Coolnabacky

- *400 kV Dunstown Substation*

Figure 5-34 and Figure 5-35 present the worst case TOV results for the 400 kV Dunstown substation for a **3-phase fault during an outage of Dunstown 400 kV – Coolnabacky 400 kV circuit**; whereas Figure 5-36 presents the frequency response of the substation for the same contingency.

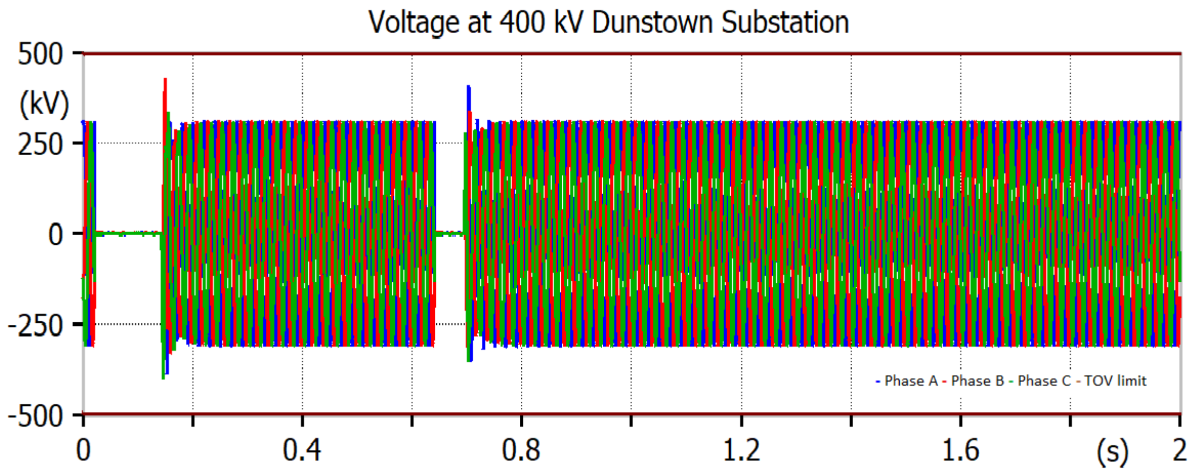

Figure 5-34: Voltage at 400 kV Dunstown Substation

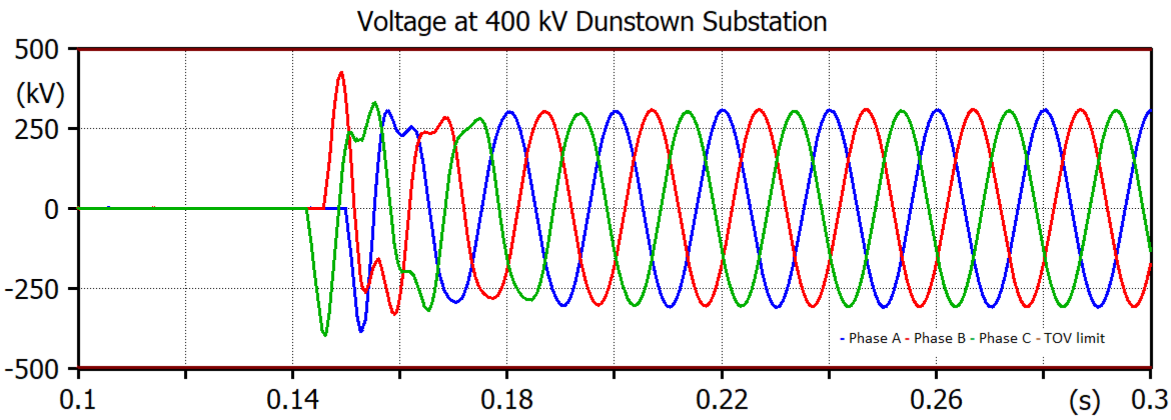

Figure 5-35: Voltage at 400 kV Dunstown Substation – Worst Fault Clearing Event

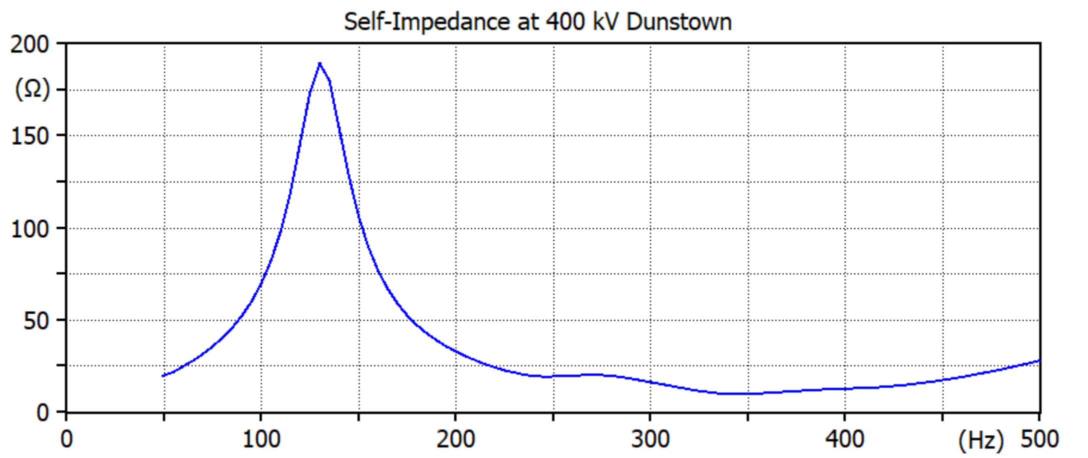

Figure 5-36: Self-Impedance at 400 kV Dunstown

- *400 kV Old Street Substation*

Figure 5-37 and Figure 5-38 present the worst case TOV results for the 400 kV Old Street substation for a **3-phase fault during an outage of Old Street 400 kV – Moneypoint 400 kV circuit**; whereas Figure 5-39 presents the frequency response of the substation for the same contingency.

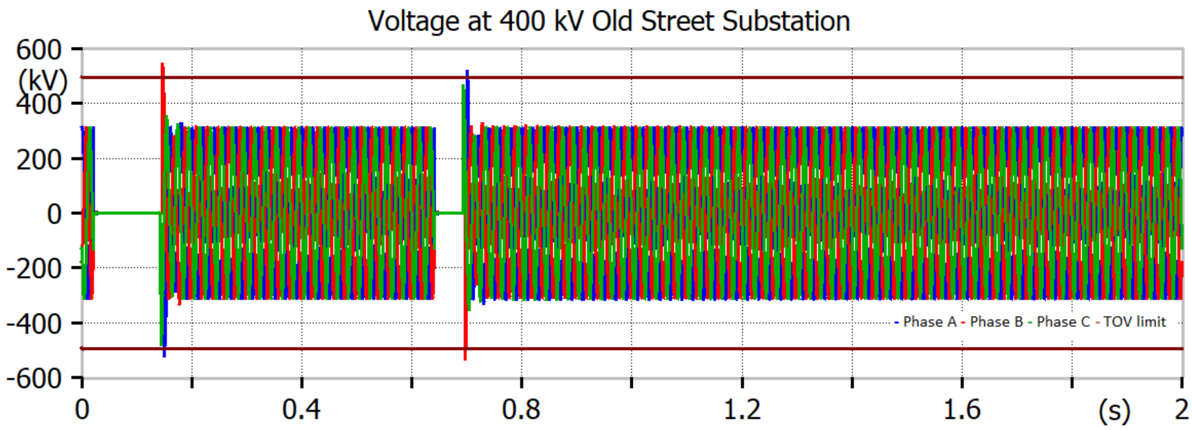

Figure 5-37: Voltage at 400 kV Old Street Substation

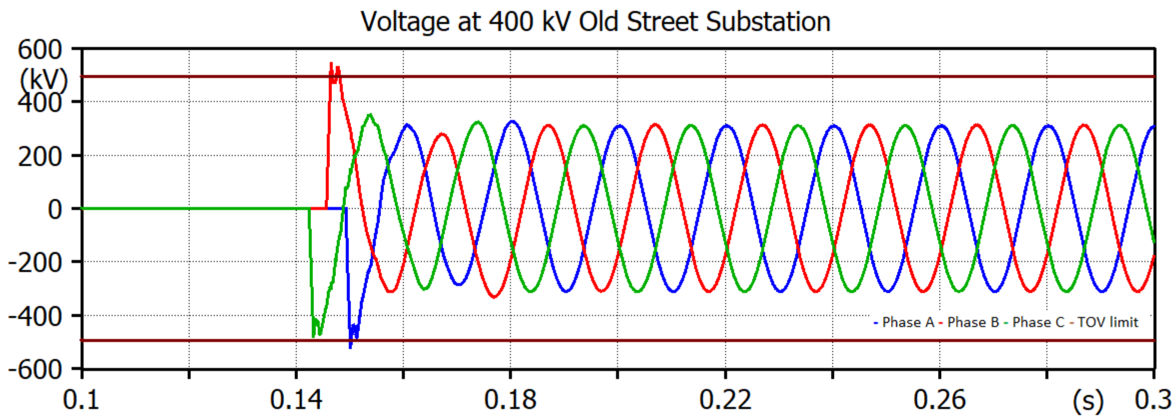

Figure 5-38: Voltage at 400 kV Old Street Substation – Worst Fault Clearing Event

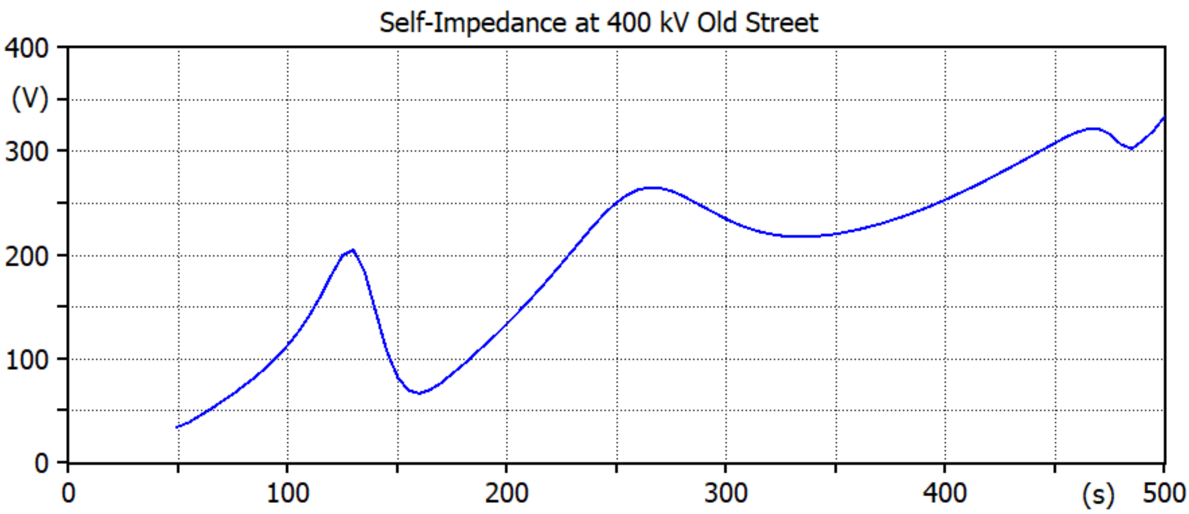

Figure 5-39: Self-Impedance at 400 kV Old Street

- *400 kV Portan Substation*

Figure 5-40 and Figure 5-41 present the worst case TOV results for the 400 kV Portan substation for a **3-phase fault during an outage of Old Street 400 kV – Woodland 400 kV circuit**; whereas Figure 5-42 presents the frequency response of the substation for the same contingency.

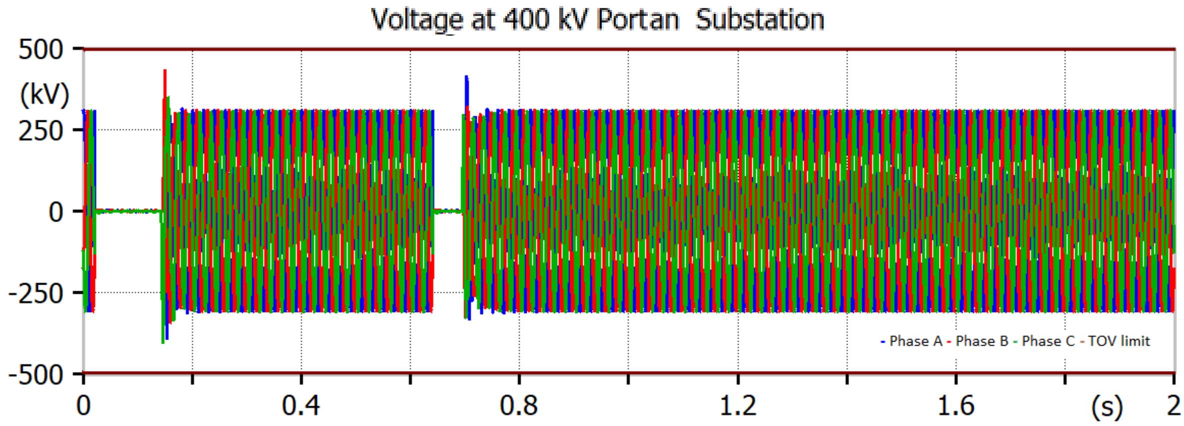

Figure 5-40: Voltage at 400 kV Portan Substation

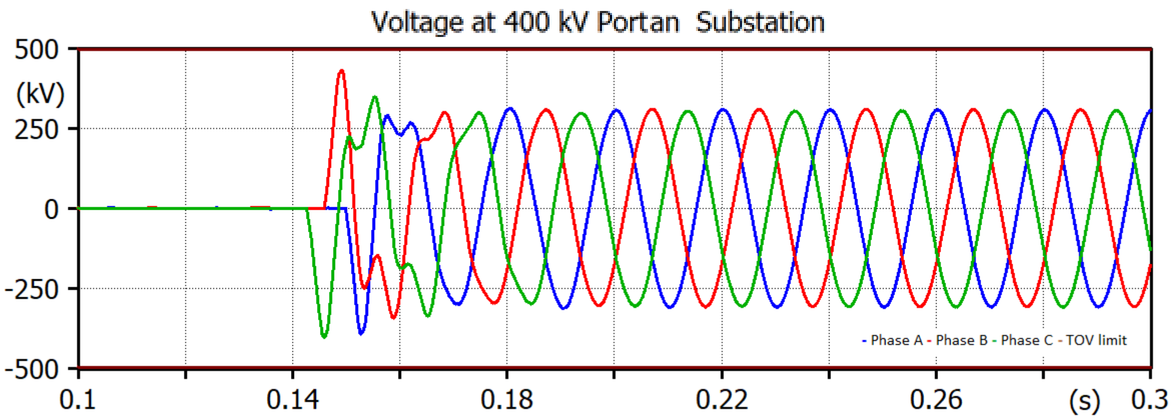

Figure 5-41: Voltage at 400 kV Portan Substation – Worst Fault Clearing Event

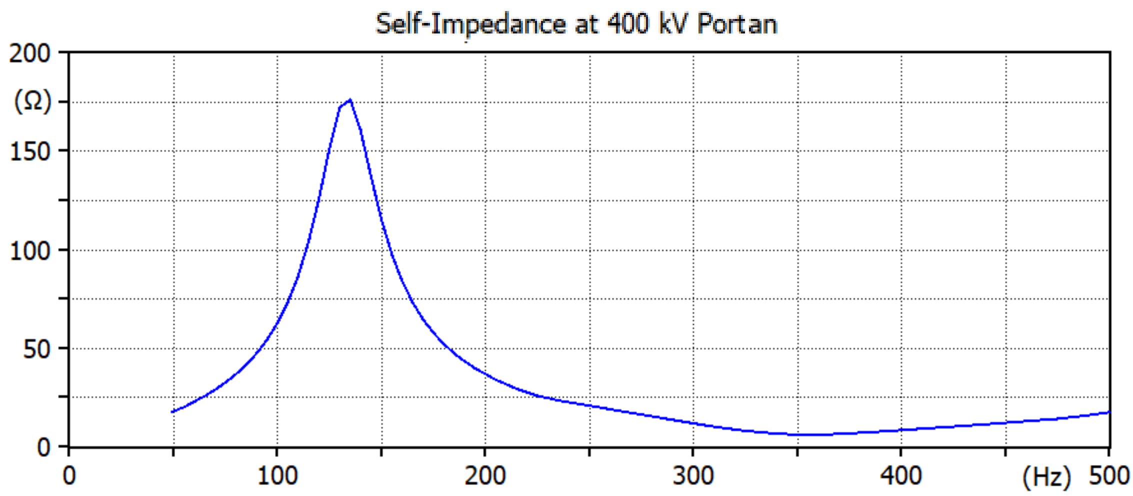

Figure 5-42: Self-Impedance at 400 kV Portan

- *400 kV Woodland Substation*

Figure 5-43 and Figure 5-44 present the worst case TOV results for the 400 kV Woodland substation for a **3-phase fault during an outage of Woodland 400 kV – Turleenan 400 kV circuit**; whereas Figure 5-45 presents the frequency response of the substation for the same contingency.

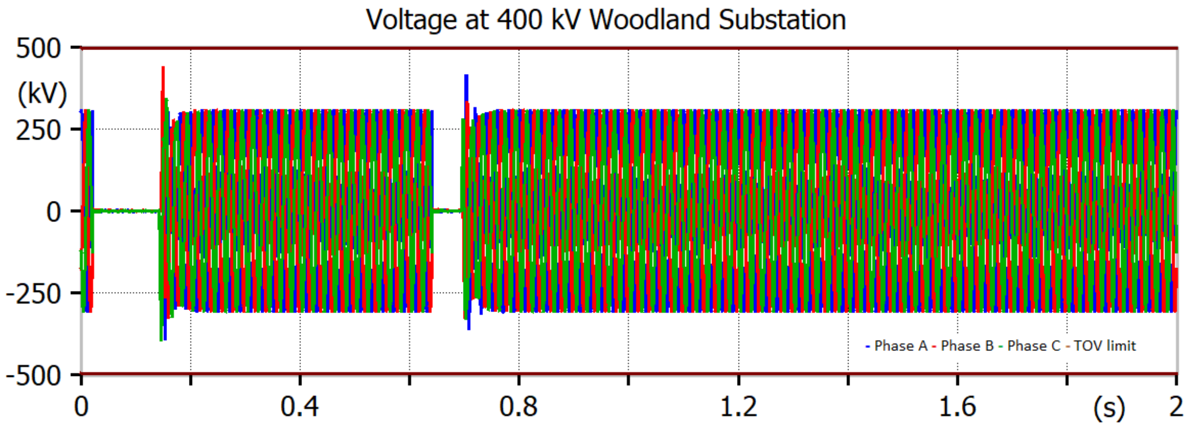

Figure 5-43: Voltage at 400 kV Woodland Substation

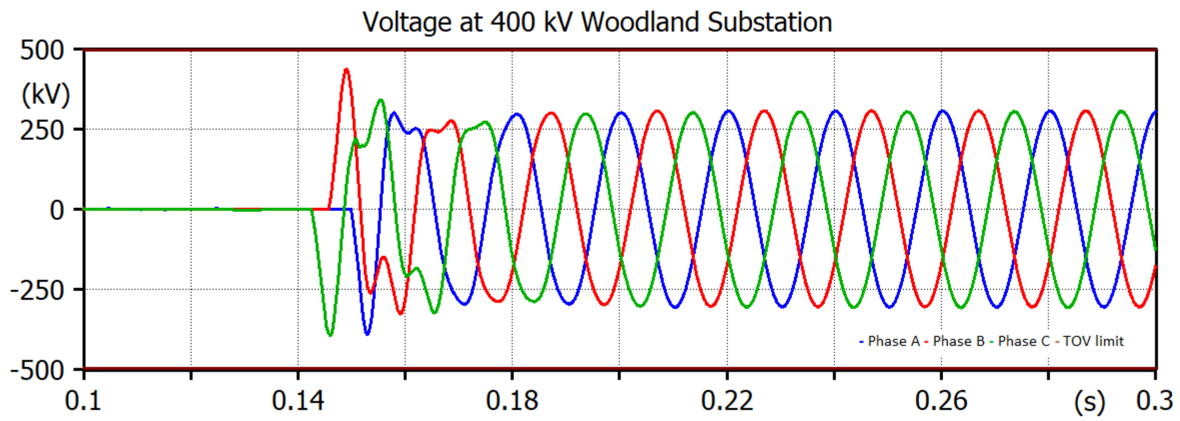

Figure 5-44: Voltage at 400 kV Woodland Substation – Worst Fault Clearing Event

Figure 5-45: Self-Impedance at 400 kV Woodland

5.2 Zero-Miss Phenomenon Analysis

Often the introduction of long underground AC cables necessitates the installation of shunt reactors to control the overvoltages during switching and the capacitive current. The simultaneous energisation of the cable and the shunt reactor can result in the zero-miss phenomenon (ZMP). This means that the charging current in the circuit breaker has a DC offset and it does not cross zero for several cycles preventing the safe operation of the circuit breaker if a fault was to take place. As a result, the system is vulnerable and unprotected against faults if these studies are not carried out to understand the risk and identify countermeasures [11,12].

During the harmonic and TOV studies the analysis focused on the full length UGC options which are highly compensated (>50%) as detailed in Section 3. In particular, the compensation of the 220 kV UGC is around 80%; whereas the compensation of the 400 kV (1c/ph) and 400 kV (2c/ph) is around 90% and 100% respectively. For ZMP studies, the full cable length options will result in the most onerous DC offset because of the highest amount (in %) of reactive compensation compared to the shorter cable lengths.

Time domain studies were performed in EMTP-ATP by energizing the underground cables from one end while the other was maintained open and the current was recorded. The results were very similar during the energisation from either end of the cable so only the results from one station are being presented. The current DC offset is dependent on the time that the circuit breaker closure is happening with the most onerous case being when the breaker closes during a zero crossing of the voltage. Studies have been performed for the following cases:

- Energisation during zero crossing of the voltage of phase A (scenario 1)
- Energisation during zero crossing of the voltage of phase B (scenario 2)
- Energisation during zero crossing of the voltage of phase C (scenario 3)
- Energisation during peak of voltage of phase A (scenario 4)

It is observed that the DC offset is very similar for a breaker closure event during a zero crossing of phase A, B or C so the results only for phase A are being presented. Results for an energisation during peak of voltage of phase A are also presented.

The energisation is set to happen at 0.095sec for scenario 1 and at 0.12sec for scenario 4. The time domain simulation lasts for 1.3 seconds.

The results presented in the following sections indicate that in all the different UGC options there is a zero-miss phenomenon when energising the proposed cables and, dependant on the time the energisation occurs, it takes at least 1 second for the current to cross zero. The higher the reactive compensation (in %) of the cable, the higher the DC current offset and the overvoltage observed. Since the 400 kV UGCs require higher reactive compensation (in %) than the 200 kV UGC, the resulting current DC-offset is higher.

The existence of ZMP does not impact the normal operation of the system and can only be an issue in cases where the UGC is being energised and there is a permanent fault in the cable so it needs to be disconnected to isolate the fault. Since it is a well-known phenomenon, there are available countermeasures [11,12] such as a pre-insertion resistor or a delayed reactor switching that could be used to mitigate the problem. A detailed design will be performed during the next stage of the project for the final cable selected and the solution and approach to be implemented will be agreed with EirGrid.

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5.2.1 Results for CP966_UGC220

Figure 5-46 and Figure 5-47 present the current waveforms at Dunstown 220 kV for energisation of the UGC 220 kV during zero crossing of voltage of phase A and during peak of voltage of phase A, respectively.

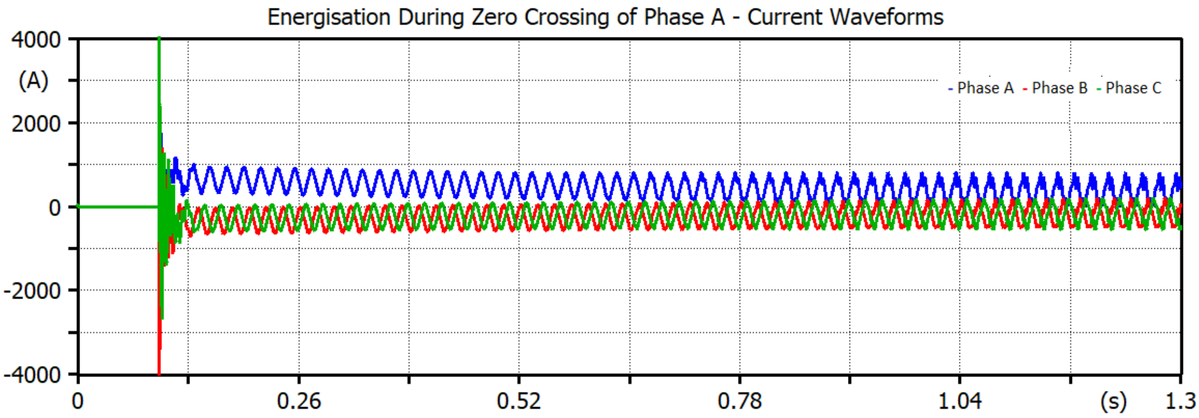

Figure 5-46: Current at Dunstown 220 kV for energisation during zero crossing of voltage of phase A

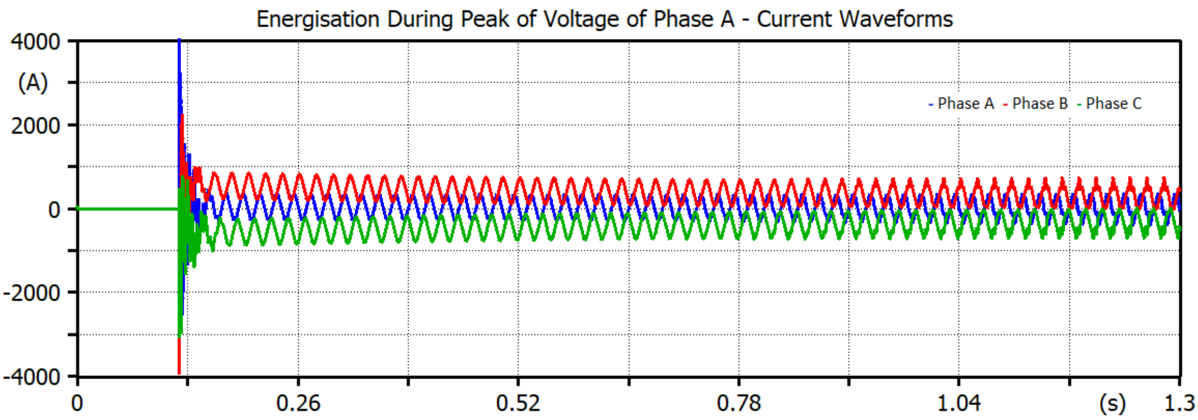

Figure 5-47: Current at Dunstown 220 kV for energisation during peak of voltage of phase A

5.2.2 Results for CP966_UGC400 (1c/ph)

Figure 5-48 and Figure 5-49 present the current waveforms at Dunstown 400 kV for energisation of the UGC 400 kV (1c/ph) during zero crossing of voltage of phase A and during peak of voltage of phase A, respectively.

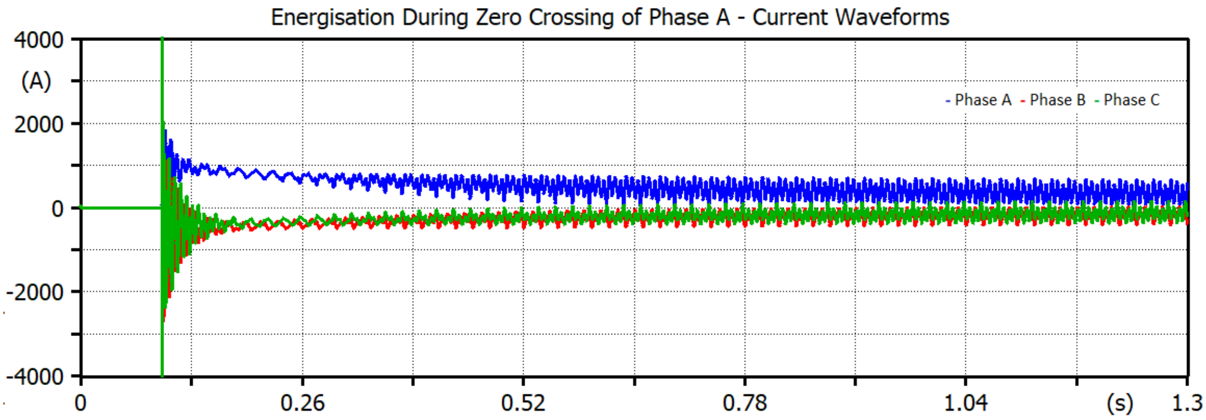

Figure 5-48: Current at Dunstown 400 kV for energisation during zero crossing of voltage of phase A

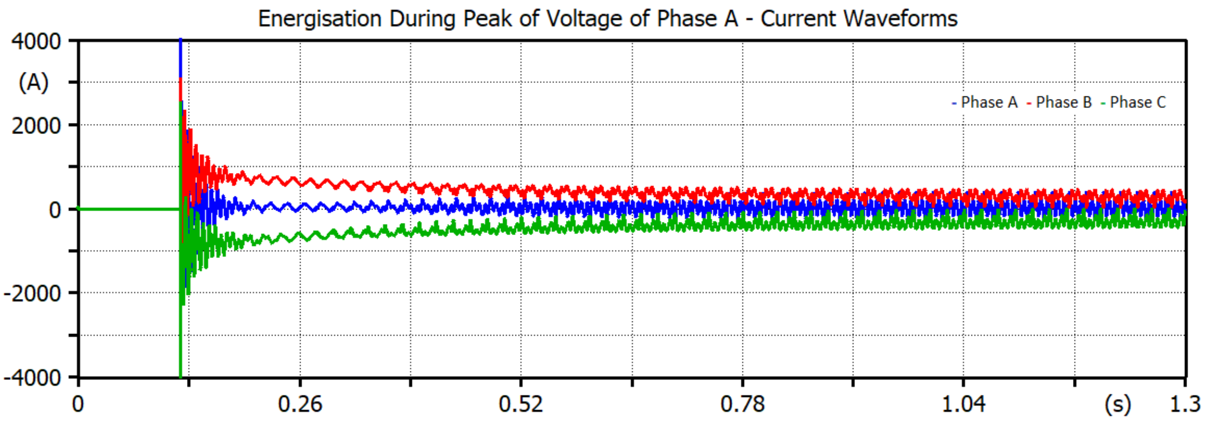

Figure 5-49: Current at Dunstown 400 kV for energisation during peak of voltage of phase A

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5.2.3 Results for CP966_UGC400 (2c/ph)

Figure 5-50 presents the current waveform at Dunstown 400 kV for energisation of the UGC 400 kV (2c/ph) during zero crossing of voltage of phase A.

It should be noted that since it was agreed with EirGrid to not perform detailed harmonic analysis and mitigation solution studies for this cable configuration, those results are based on the mitigation solution from the UGC 400 kV (1c/ph) and should be used for information only. However, a more detailed filtering solution is not expected to impact the ZMP results significantly.

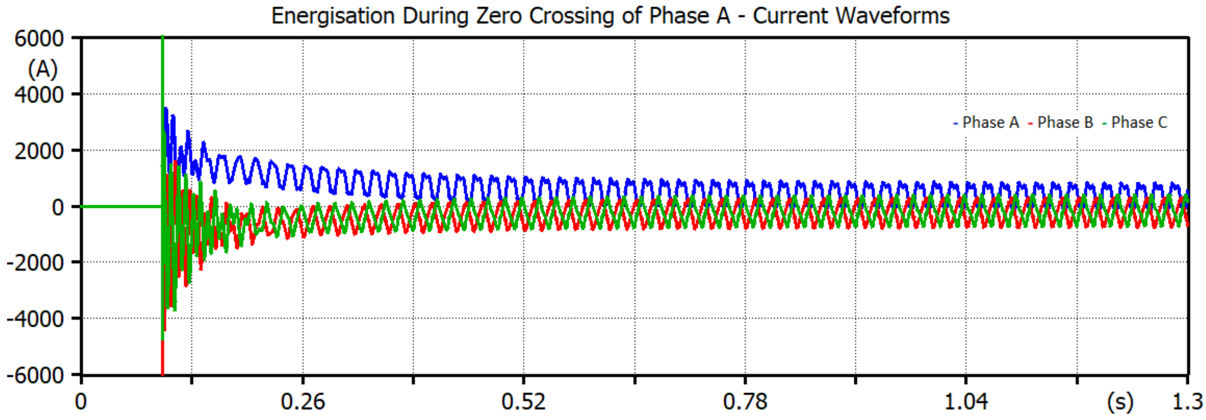

Figure 5-50: Current at Dunstown 400 kV for energisation during zero crossing of voltage of phase A

6 Further Investigation and Sensitivity Studies

Following the initial review of this report and after discussions with EirGrid it has been identified that it is important to further investigate some of the 2 cable per phase options and perform some additional studies and sensitivity checks.

Those include revised reactive compensation and its impact on the harmonic analysis and TOV studies that are detailed in the following subsections for the 220 kV and 400 kV (1 cable / phase) cable options. They also include detailed harmonic studies and investigation on the harmonic mitigation solution for the full length of UGC400 (2c/ph) option which is detailed in Section 4.4 for the initially identified reactive compensation requirements as well as TOV and ZMP analysis that is detailed in the following subsections.

Another potential option for this cable reinforcement recommended by PSC is the installation of 2 independent cable circuits (as opposed to 1 circuit with 2 cables / phase) which in general has the same network configuration and contingencies as the 2 cables / phase. During this case, one of the differences identified is an additional contingency during a loss of 1 circuit which may have an impact on the harmonic solution when compared to the 2 cables / phase option. A sensitivity study analysing the suitability of the 2 cables / phase harmonic mitigation solution during this contingency is detailed in Section 6.2.2.

6.1 Reactive Compensation Requirements

The initial reactive capability studies were carried out for a set of contingencies that included various N-1 circuit outages as well as the energisation of the new cable circuit from one end. The latter is the most restrictive arrangement resulting in the need for very high levels of reactive compensation.

This arrangement (i.e. the energisation of the cable from one end) is not considered as a credible contingency for steady state conditions and in practice the cable could accommodate a higher voltage during energisation (420 kV instead of 410 kV). Revised reactive compensation levels were worked out using this higher level limits. Additionally, revised reactive levels for steady state conditions considering a revised summer valley low wind 2030 study case (SV-LW) which incorporates the reactive power exchange of the EWIC Interconnector were calculated.

6.1.1 Without Reactive Compensation

The following tables set out the resulting overvoltage and worst case N-1 contingency (Table 6-1) and energisation direction (Table 6-2) for each of the underground cable reinforcement options with 100% cable length. Appendix D includes figures showing the range of system voltages that can be expected covering all the N-1 contingencies with 100% underground cable when there is no reactive compensation considered.

Table 6-1: Maximum steady state voltage during contingencies (N-1) without reactive compensation

Reinforcement	Cables /Phase	Cable Length	Contingency	Operating Scenario	Max Voltage		Node
					(p.u.)	(kV)	
UGC220	1	100%	WOO4-WOO2C-1	SV-LW	1.040	228.7	Woodland 220 kV
UGC400	1	100%	WOO4-WOO2C-1	SV-LW	1.026	410.2	Woodland 400 kV
UGC400	2	100%	DSN4-DSN2	SV-LW	1.101	440.3	Dunstown 400 kV

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Table 6-2: Maximum steady state voltage during energisation without reactive compensation

Reinforcement	Cables /Phase	Cable Length	Energisation Direction	Operating Scenario	Max Voltage (p.u.)	Max Voltage (kV)	Node
UGC220	1	100%	DSN4-WOO4-1B	SV-LW	1.156	254.4	Woodland 220 kV
UGC400	1	100%	DSN4-WOO4-1B	SV-LW	1.082	432.6	Woodland 400 kV
UGC400	2	100%	DSN4-WOO4-1B	SV-LW	1.210	484.0	Dunstown 400 kV

6.1.2 Revised Reactive Compensation Requirements

To establish the revised reactive compensation requirements an additional methodology to the one presented in Section 3.1 has been considered. Shunt reactive compensation was modelled at each end of the new circuit at either 220 kV or 400 kV as appropriate. The size of the reactive compensation was then increased in 10 Mvar steps (5 Mvar at each end) until voltages remain within limits for all contingencies during all operating scenarios.

Table 6-3 and Table 6-4 show the level and location of the revised reactive compensation required for each cable length option for the 220 kV cable during cable energisation and steady state conditions, respectively. Table 6-5 and Table 6-6 show the same for the 400 kV cable with 2 cables / phase; whereas Table 6-7 and Table 6-8 show the results for the 400 kV cable with 1 cable / phase. Appendix D includes figures showing the range of system voltages that can be expected covering all the N-1 contingencies with 100% underground cable with the revised reactive compensation levels.

Comparing with the reactive requirements in Section 3, the revised levels have been decreased by at least 30% for the full cable length option with the percentual compensation being reduced while the cable length reduces. The total reduction is expected to have a positive impact on the zero-miss phenomenon by reducing the DC offset during the circuit breaker closure.

It should be noted that the sensitivities studies for TOV and harmonic analysis consider the worst revised reactive compensation of the two studies above and some analysis is carried out for the minimum reactive levels for the harmonic analysis in Section 6.2.

Table 6-3: Reactive compensation requirement during cable energisation for 220 kV UGC

Cable Length (%)	Cable Length (km)	Shunt Reactor (Mvar) - Energisation			
		Woodland 220kV (PSSE bus 546200)	Dunstown 220kV (PSSE bus 220200)	Total	Compensation (%)
100.0%	60.0	55	55	110	45.3%
87.5%	52.5	45	45	90	42.4%
75.0%	45.0	31	31	62	34.1%
62.5%	37.5	20	20	40	26.4%
50.0%	30.0	5	5	10	8.2%
37.5%	22.5	0	0	0	0.0%
25.0%	15.0	0	0	0	0.0%
12.5%	7.5	0	0	0	0.0%

Table 6-4: Reactive compensation requirements for steady state conditions for 220 kV UGC

Cable Length (%)	Cable Length (km)	Shunt Reactor (Mvar) – N-1 outage			
		Woodland 220kV (PSSE bus 546200)	Dunstown 220kV (PSSE bus 220200)	Total	Compensation (%)
100.0%	60.0	0	0	0	0.0%
87.5%	52.5	0	0	0	0.0%
75.0%	45.0	0	0	0	0.0%
62.5%	37.5	0	0	0	0.0%
50.0%	30.0	0	0	0	0.0%
37.5%	22.5	0	0	0	0.0%
25.0%	15.0	0	0	0	0.0%
12.5%	7.5	0	0	0	0.0%

Table 6-5: Reactive compensation requirement during cable energisation for 400 kV UGC, 2 cables / phase

2 cable / phase		Shunt Reactor (Mvar) – Energisation			
Cable Length (%)	Cable Length (km)	Woodland 400kV (PSSE bus 546400)	Dunstown 400kV (PSSE bus 220400)	Total	Compensation (%)
100.0%	60.0	435	435	870	68.9%
87.5%	52.5	365	365	730	64.2%
75.0%	45.0	290	290	580	57.4%
62.5%	37.5	220	220	440	49.8%
50.0%	30.0	150	150	300	39.6%
37.5%	22.5	80	80	160	25.3%
25.0%	15.0	10	10	20	4.0%
12.5%	7.5	0	0	0	0.0%

Table 6-6: Reactive compensation requirement for steady state conditions for 400 kV UGC, 2 cables / phase

2 cable / phase		Shunt Reactor (Mvar) – N-1 outage			
Cable Length (%)	Cable Length (km)	Woodland 400kV (PSSE bus 546400)	Dunstown 400kV (PSSE bus 220400)	Total	Compensation (%)
100.0%	60.0	325	325	650	51.5%
87.5%	52.5	255	255	510	44.9%
75.0%	45.0	180	180	360	35.6%
62.5%	37.5	105	105	210	23.7%
50.0%	30.0	31	31	62	8.2%
37.5%	22.5	5	5	10	1.6%
25.0%	15.0	0	0	0	0.0%
12.5%	7.5	0	0	0	0.0%

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Table 6-7: Reactive compensation requirement during cable energisation for 400 kV UGC, 1 cables / phase

1 cables / phase		Shunt Reactor (Mvar) – Energisation			
Cable Length (%)	Cable Length (km)	Woodland 400kV (PSSE bus 546400)	Dunstown 400kV (PSSE bus 220400)	Total	Compensation (%)
100.0%	60.0	145	145	290	45.9%
87.5%	52.5	115	115	230	40.8%
75.0%	45.0	85	85	170	34.4%
62.5%	37.5	55	55	110	25.8%
50.0%	30.0	20	20	40	11.2%
37.5%	22.5	0	0	0	0.0%
25.0%	15.0	0	0	0	0.0%
12.5%	7.5	0	0	0	0.0%

Table 6-8: Reactive compensation requirement for steady state conditions for 400 kV UGC, 1 cables / phase

1 cables / phase		Shunt Reactor (Mvar) – N-1 outage			
Cable Length (%)	Cable Length (km)	Woodland 400kV (PSSE bus 546400)	Dunstown 400kV (PSSE bus 220400)	Total	Compensation (%)
100.0%	60.0	10	10	20	3.2%
87.5%	52.5	5	5	10	1.8%
75.0%	45.0	0	0	0	0.0%
62.5%	37.5	0	0	0	0.0%
50.0%	30.0	0	0	0	0.0%
37.5%	22.5	0	0	0	0.0%
25.0%	15.0	0	0	0	0.0%
12.5%	7.5	0	0	0	0.0%

6.2 Harmonic Analysis

6.2.1 Sensitivity Studies

PSC has carried out sensitivity studies for the 220 kV and 400 kV (1 cable / phase) for the worst revised reactive compensation levels presented in Section 6.1 in order to analyse the impact that the change in the reactive compensation has on the need for a harmonic filter solution.

The full cable length options without any harmonic filters were assessed and the background harmonic amplification was reviewed for all the nodes of interest under the three network operating scenarios and the contingencies considered as presented in Section 4.1.

Table 6-9 presents detailed results for the UGC220 option for the initial and revised reactive compensation that gives a side by side overview of the substations where the harmonic limits are exceeded along with the background harmonics and calculated amplified distortion. The results show that the substations, the harmonic orders and the magnitude of the harmonic breaches are relatively similar. There are a few harmonics where a marginal harmonic breach is observed only in the revised case; whereas a few other harmonics where the breach is observed only in the initial case. Additionally, there are only two substations where a considerable increase in two harmonics is observed. Therefore, if the case with the revised reactive compensation is considered for further analysis in the future, the harmonic mitigation solution detailed in Section 4.2.2 is still valid and will form the basis of the final solution with the possibility of requiring some minor additional filtering solution.

Table 6-10 presents detailed results for the UGC400 (1c/ph) option for the initial and revised reactive compensation that gives a side by side overview of the substations where the harmonic limits are exceeded along with the background harmonics and calculated amplified distortion. The behaviour of the results is very similar to the UGC220 option showing that the substations, the harmonic orders and the magnitude of the harmonic breaches are relatively similar. There is one harmonic where a marginal harmonic breach is observed only in the revised case; whereas a few other harmonics where the breach is observed only in the initial case. Additionally, there are only a few substations where a considerable change is observed. Therefore, if the case with the revised reactive compensation is considered for further analysis in the future, the harmonic mitigation solution detailed in Section 4.3.2 is still valid and will form the basis of the final solution with the possibility of requiring some minor additional filtering solution.

The analysis of the results for the revised reactive compensation for the 220 kV and 400 kV (1 cable / phase) options concludes that for both cases there is a slight impact on the harmonic analysis and the previously identified harmonic mitigation solutions and, in general, they can be used as the basis for designing the final solution at a later stage. Although sensitivity studies have not been performed for the 400 kV (2 cable / phase), it is expected that the revised reactive compensation requirements will have a moderate impact on the harmonic analysis and the previously identified solution can be used as a basis for finalising the studies at a later stage.

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Table 6-9: Harmonic distortions exceeding planning levels for full UGC220 length with different reactive requirements

Node	100 % UGC220			
	Harmonic order	Planning Level (%)	Amplified Distortion (%) – Initial Reactive Requirements	Amplified Distortion (%) – Revised Reactive Requirements
BEL2	6	0.4	0.695	0.700
CKM2	6	0.4	0.426	0.467
CLN4	12	0.318	0.403	0.442
FIN2	17	1.2	1.267	1.280
MAY1	12	0.318	0.386	0.381
MAY2A	12	0.318	0.367	0.361
MAY2B	12	0.318	0.481	0.446
MAY2B	15	0.3	0.354	0.354
OST4	8	0.4	0.594	0.602
PRN4	8	0.4	0.462	-
WOO2	8	0.4	0.493	0.632
WOO4	8	0.4	0.452	-
CDU2	6	0.4	-	0.404
CLE2	8	0.4	-	0.420
DSN4	12	0.318	-	0.327

Table 6-10: Harmonic distortions exceeding planning levels for full UGC400 (1c/ph) length with different reactive requirements

Node	100 % UGC400 (1c / ph)			
	Harmonic Order	Planning Level (%)	Amplified Distortion (%) – Initial Reactive Requirements	Amplified Distortion (%) – Revised Reactive Requirements
BEL2	5	2	4.012	4.089
BEL2	6	0.4	1.212	1.202
BEL2	10	0.35	0.440	0.463
BEL2	14	0.296	0.420	0.450
CDU2	5	2	3.577	3.586
CDU2	6	0.4	0.666	0.669
CDU2	17	1.2	1.330	1.345
CKM2	5	2	2.529	2.598
CKM2	6	0.4	0.487	0.470
CLE2	5	2	3.746	3.952
CLE2	10	0.35	0.367	0.381
CLN4	12	0.318	0.391	0.396
CLN4	14	0.296	0.344	0.363
CTB1	5	2	2.839	2.914
CTB2	5	2	3.527	3.769
CTB2	6	0.4	0.628	0.652
DSN2	12	0.318	0.341	0.331
FIN2	5	2	4.036	4.064
FIN2	6	0.4	0.624	0.624
FIN2	17	1.2	1.384	1.405

Node	100 % UGC400 (1c / ph)			
	Harmonic Order	Planning Level (%)	Amplified Distortion (%) – Initial Reactive Requirements	Amplified Distortion (%) – Revised Reactive Requirements
FIN2	20	0.255	0.256	-
MAY1	12	0.318	0.421	0.418
MAY2A	5	2	3.505	3.483
MAY2A	12	0.318	0.447	0.442
MAY2B	5	2	2.991	2.945
MAY2B	12	0.318	0.770	0.644
MAY2B	14	0.296	0.582	0.627
MAY2B	15	0.3	0.452	0.424
OST4	7	2	2.497	2.665
OST4	8	0.4	1.373	1.311
OST4	13	1.5	1.741	1.750
OST4	14	0.296	1.386	1.405
OST4	15	0.3	0.355	0.343
PRN4	5	2	2.261	2.205
PRN4	8	0.4	0.686	-
TH2	15	0.3	0.370	0.357
WOO2	7	2	2.010	2.034
WOO4	5	2	2.265	2.209
WOO4	8	0.4	0.698	-
WOO2	8	0.4	-	0.408

Figure 6-1 to Figure 6-4 present the frequency scans for Dunstown and Woodland for the intact system without the harmonic filters with the sole purpose of visualising the impact of the revised reactive requirements. In the plots, the red line presents the additional results for the minimum possible reactive requirements (cases without considering the energisation of the cables from one end) defined in Section 6.1. These indicate that the general conclusions derived from the harmonic analysis in this section are most likely to be still valid. In case those reactive levels are considered in the future, the harmonic analysis and the harmonic mitigation solution will need to be revisited to confirm compliance.

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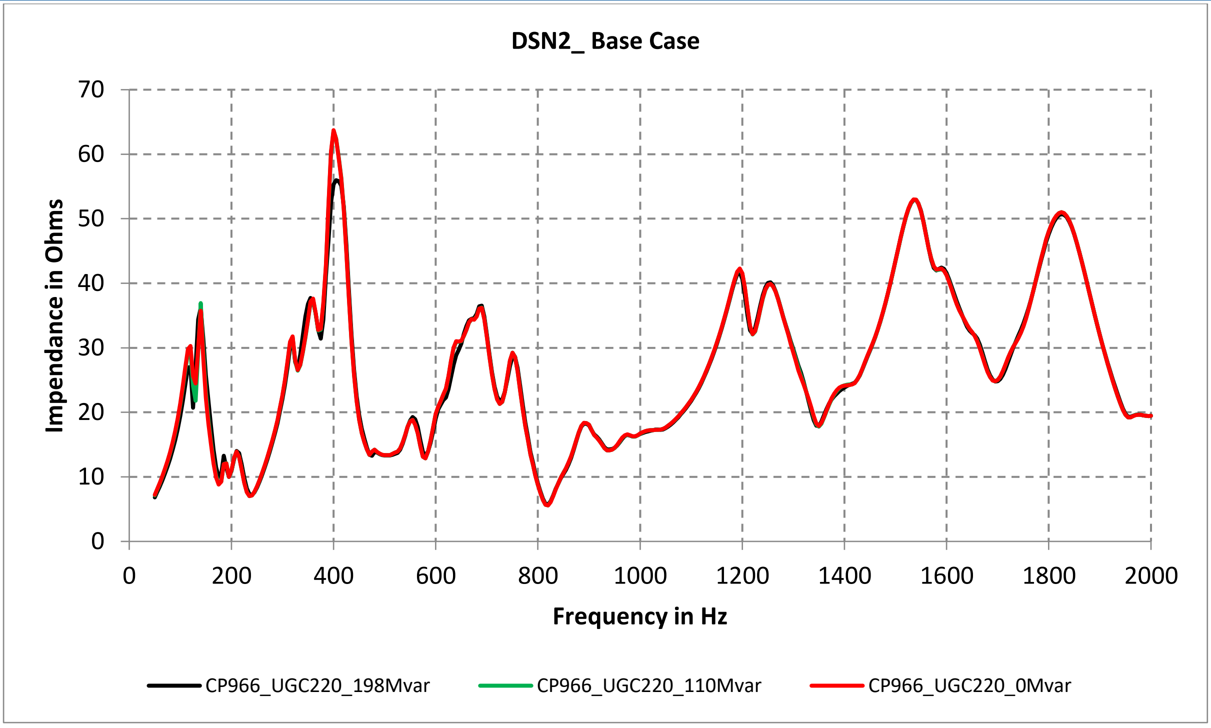

Figure 6-1: Self-impedance at Dunstown 220 kV substation for the intact system for different reactive compensation

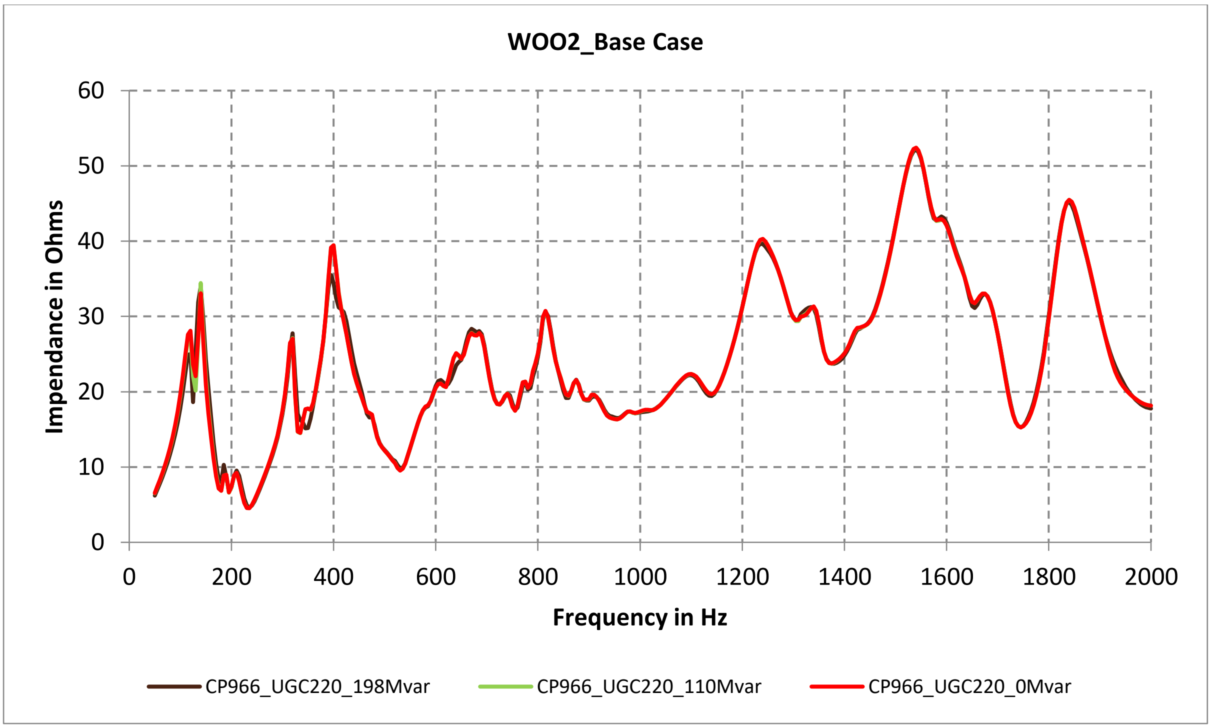

Figure 6-2: Self-impedance at Woodland 220 kV substation for the intact system for different reactive compensation

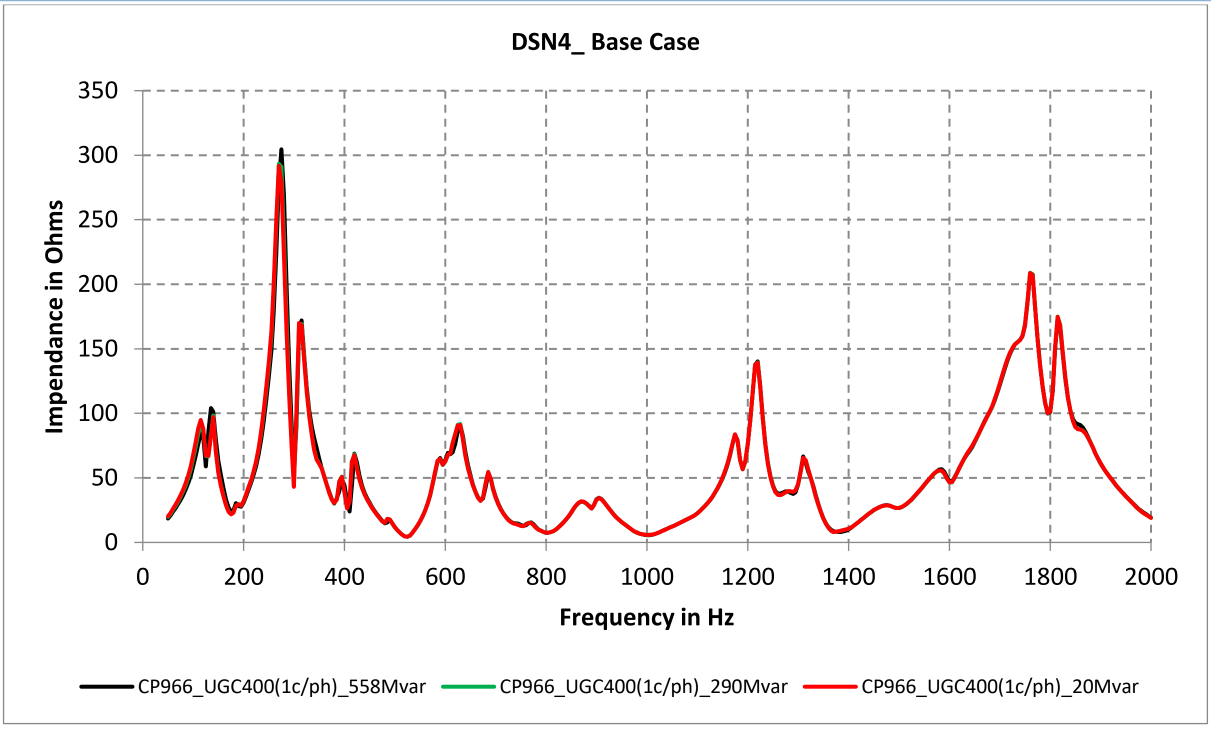

Figure 6-3: Self-impedance at Dunstown 400 kV substation for the intact system for different reactive compensation

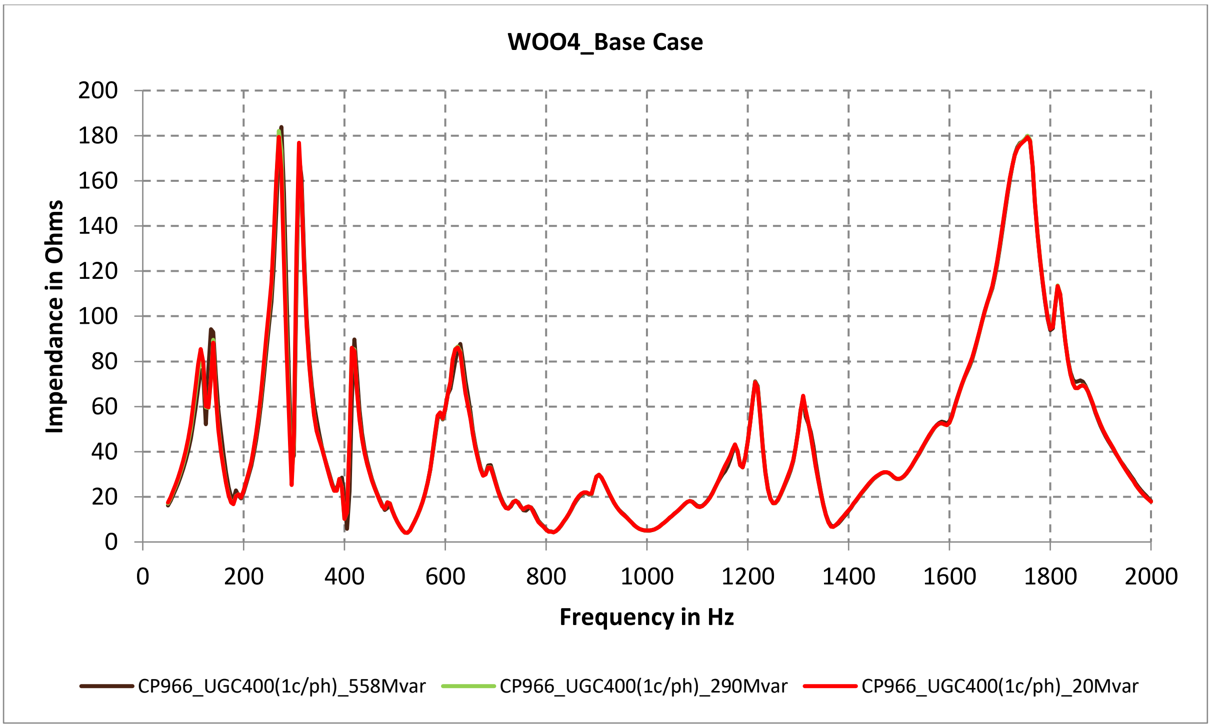

Figure 6-4: Self-impedance at Woodland 400 kV substation for the intact system for different reactive compensation

6.2.2 Analysis for Cable Reinforcement with 2 Independent Cable Circuits

An underground cable reinforcement with two independent cable circuits was recommended and discussed with EirGrid on the basis that it offers improved availability in terms of maintaining 50% of the total cable circuit capacity for a loss of one cable due to a fault or maintenance but has higher initial cost to complete.

This option has in general the same network configuration and contingencies as the 2 cables / phase with the exemption of a contingency during the loss of 1 circuit which effectively becomes similar to the 1 cable / phase option.

The previous harmonic analysis presented in Section 4.3 and Section 4.4 indicates that the locations and the range of the harmonics where harmonic breaches are observed are relatively similar and hence the harmonic filtering solutions have plenty of similarities in both options. Some main differences identified are that the 2 cable / phase option results in shifting the harmonic breaches at lower order harmonics and has new harmonic breaches in the 220 kV Woodland substation; whereas the 1 cable / phase option has more harmonic breaches in the 400 kV Woodland substation.

In summary it is expected that a potential harmonic mitigation solution for this cable reinforcement will consist primarily from the solution presented in Section 4.4 for the 2 cable / phase plus one more filter in the 400 kV Woodland substation similar to the one proposed in Section 4.3 for the 1 cable per phase option taking also into account the assumptions presented in Section 4.5. It should be noted that this is a qualitative analysis and detailed studies will be required in case this cable option moves forward in order to analyse whether any more resonances are excited due to the combination of the harmonic filters.

6.3 Temporary Overvoltage and Zero-Miss Phenomenon Analysis

Further sensitivity studies are performed in order to check the impact of having no harmonic filters and of the revised reactive compensation on the TOV analysis. The impact of the harmonic mitigation solution proposed in Section 4.4 and the revised reactive compensation for the 400 kV (2 cable / phase) option is also analysed for TOV and ZMP.

6.3.1 Temporary Overvoltage Study

The following sensitivity studies were performed and the results are presented in the following sub-sections for the same outage and fault combination as detailed in Section 5.1. The TOV results for each of these studies are shown in kV and for the duration from 0 to 2 seconds as well as in detail for the time around the worst fault clearing event.

- CP966_UGC400 (1c/ph) with no harmonic filters and the initially identified reactive compensation
- CP966_UGC400 (1c/ph) with all the harmonic filters and the revised reactive compensation
- CP966_UGC400 (2c/ph) with all the harmonic filters detailed in Section 4.4.2 and the revised reactive compensation

Comparing the results for the UGC 400 (1c/ph) option with the ones calculated in Section 5.1.4 it is observed that:

- When no harmonic filters are considered, there is a risk of TOV exceeding 1.6 p.u for a short duration of few milliseconds for Coolnabacky and Old Street 400 kV substations which are the same substations as in the initial studies. However, the results are slightly worse in terms of magnitude and duration in Old Street substation and if the operation without harmonic filters is considered as a valid option, the existing surge arresters on the EirGrid system should be reviewed as part of the detailed design.
- When the revised reactive compensation is considered, the results are almost identical to the ones previously calculated meaning that the conclusions are very similar and there is the same risk of TOV exceeding 1.6 p.u for a short duration of few milliseconds for Coolnabacky and Old Street 400 kV substations. This conclusion is also justifiable by the harmonic analysis studies which indicate that the impact of the reduced reactive compensation on the frequency response of the system is very small.

Comparing the results for the UGC 400 (2c/ph) option with the ones calculated in Section 5.1.4 it is observed that they are almost identical and the conclusions are very similar. There is the same risk of TOV exceeding 1.6 p.u for a short duration of few milliseconds for Coolnabacky and Old Street 400 kV substations. This conclusion is justifiable by the expected small impact that the revised reactive compensation has on the frequency response as presented in Section 6.2 as well as by the similarity that the proposed harmonic mitigation solution has with the one of the 400 kV (1 cable / phase) option.

Although sensitivity studies have not been performed for the UGC220 option, it is expected that the conclusions when no harmonic filters or the revised reactive compensation are considered, will be very similar to the ones in Section 5.1.4.

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Results for CP966_UGC400 (1c/ph) – no harmonic filters and initially identified reactive compensation

- *400 kV Coolnabacky Substation*

Figure 6-5 and Figure 6-6 present the worst case TOV results for the 400 kV Coolnabacky substation for a **3-phase fault during an outage of Dunstown 400 kV – Coolnabacky 400 kV circuit**.

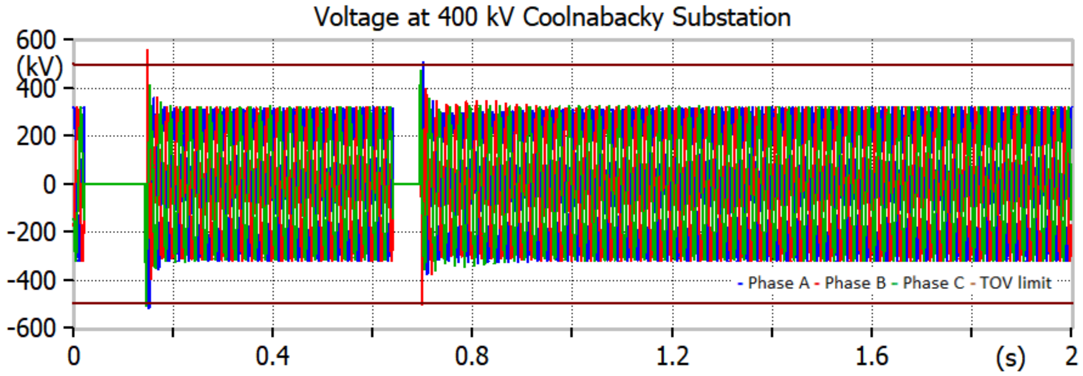

Figure 6-5: Voltage at 400 kV Coolnabacky Substation

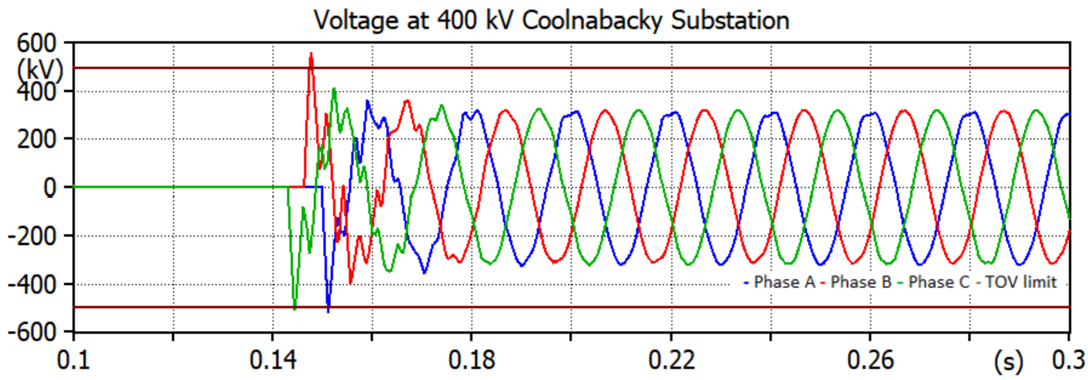

Figure 6-6: Voltage at 400 kV Coolnabacky Substation – Worst Fault Clearing Event

- *400 kV Dunstown Substation*

Figure 6-7 and Figure 6-8 Figure 5-19present the worst case TOV results for the 400 kV Dunstown substation for **a 3-phase fault during an outage of Dunstown 400 kV – Coolnabacky 400 kV circuit**.

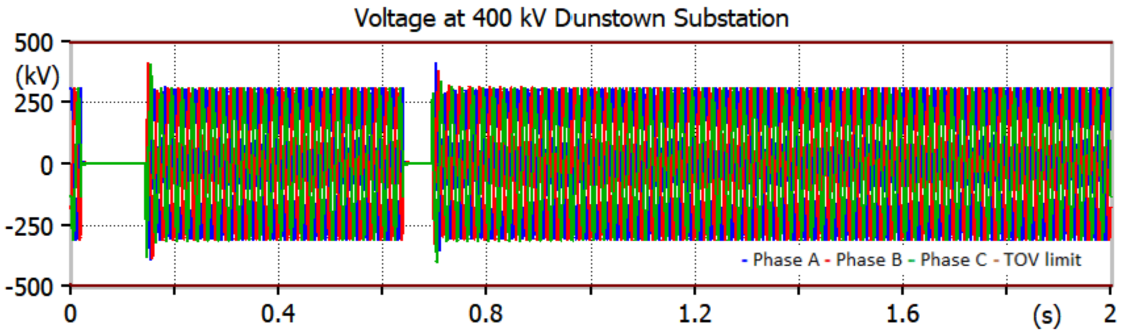

Figure 6-7: Voltage at 400 kV Dunstown Substation

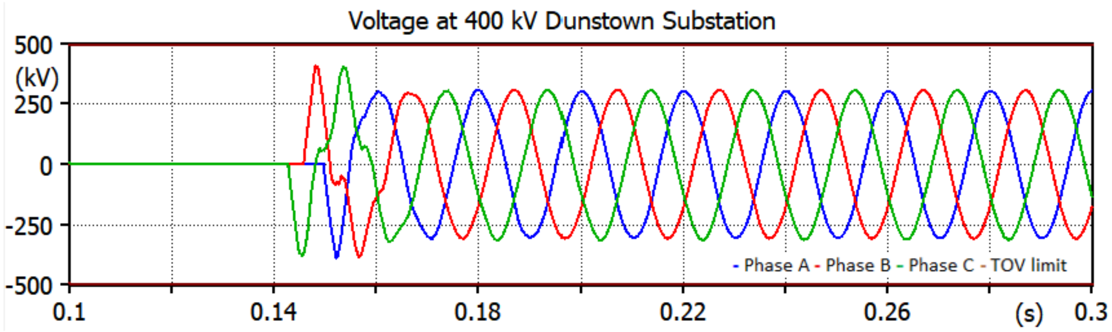

Figure 6-8: Voltage at 400 kV Dunstown Substation – Worst Fault Clearing Event

- *400 kV Old Street Substation*

Figure 6-9 and Figure 6-10 present the worst case TOV results for the 400 kV Old Street substation for a **3-phase fault during an outage of Old Street 400 kV – Moneypoint 400 kV circuit**.

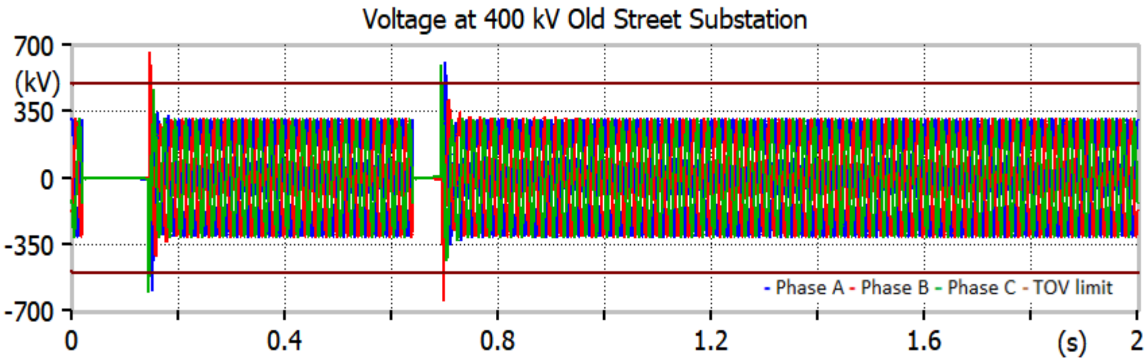

Figure 6-9: Voltage at 400 kV Old Street Substation

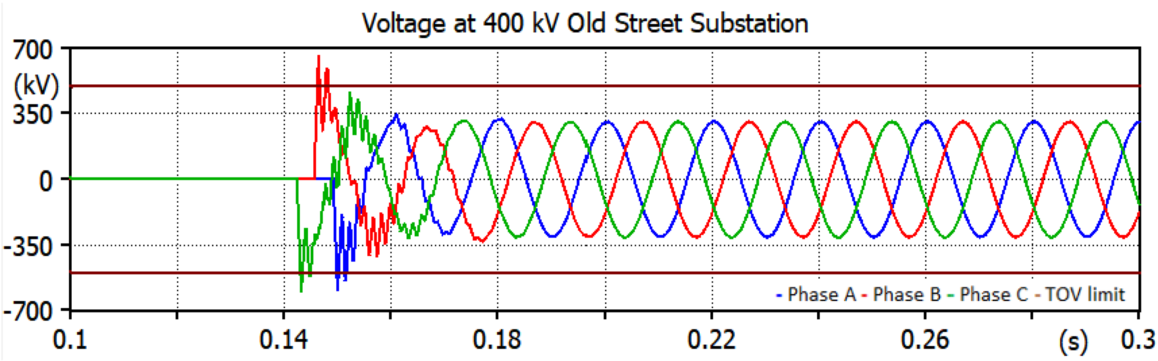

Figure 6-10: Voltage at 400 kV Old Street Substation – Worst Fault Clearing Event

- *400 kV Portan Substation*

Figure 6-11 and Figure 6-12 present the worst case TOV results for the 400 kV Portan substation for a **3-phase fault during an outage of Old Street 400 kV – Woodland 400 kV circuit**.

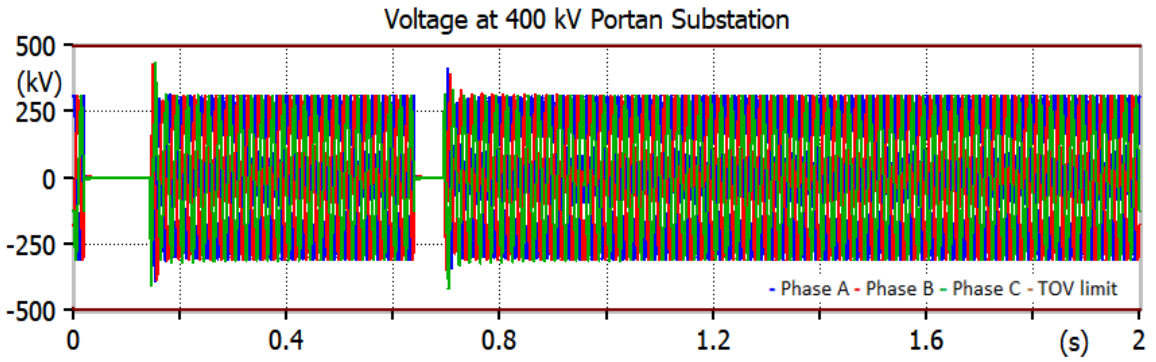

Figure 6-11: Voltage at 400 kV Portan Substation

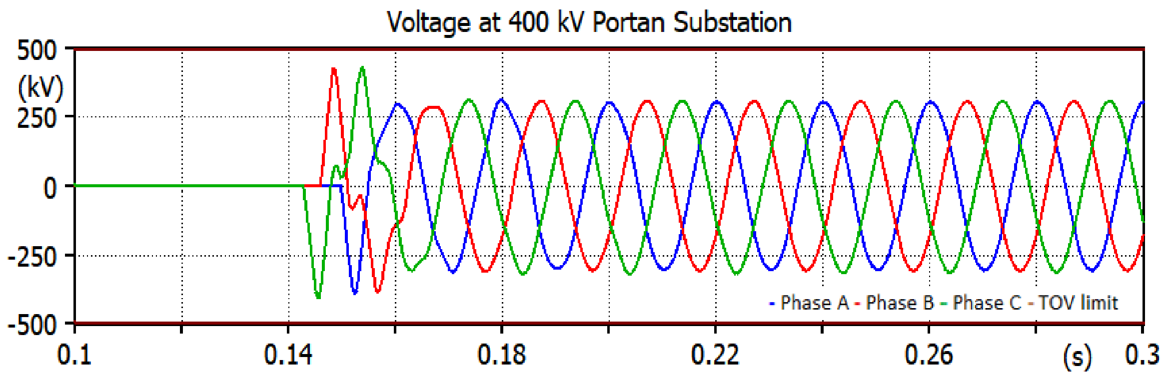

Figure 6-12: Voltage at 400 kV Portan Substation – Worst Fault Clearing Event

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- *400 kV Woodland Substation*

Figure 6-13 and Figure 6-14 present the worst case TOV results for the 400 kV Woodland substation for a **3-phase fault during an outage of Woodland 400 kV – Turleenan 400 kV circuit.**

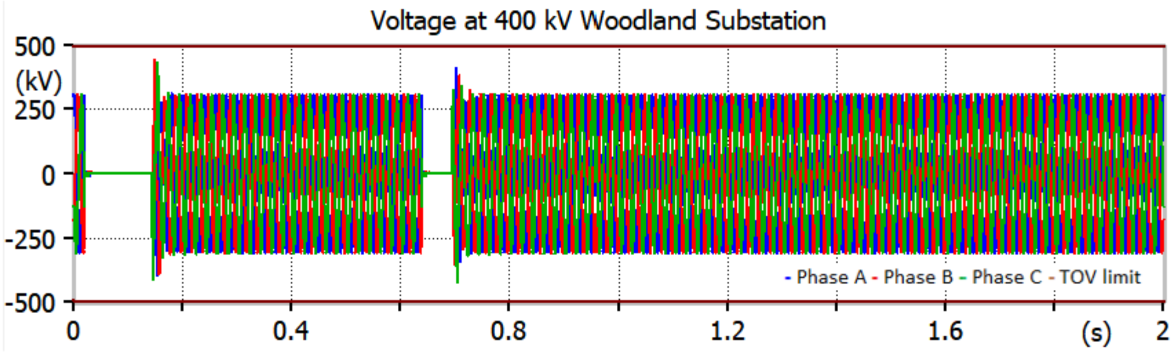

Figure 6-13: Voltage at 400 kV Woodland Substation

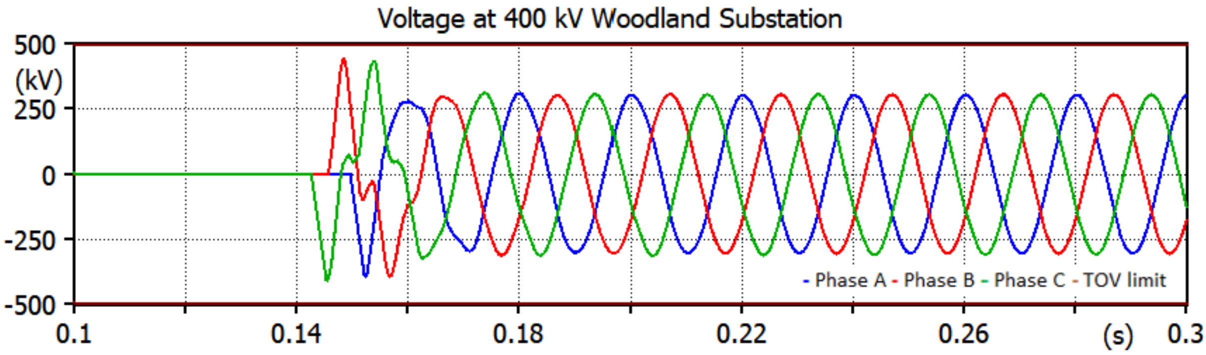

Figure 6-14: Voltage at 400 kV Woodland Substation – Worst Fault Clearing Event

Results for CP966_UGC400 (1c/ph) – all harmonic filters and revised reactive compensation

- *400 kV Coolnabacky Substation*

Figure 6-15 and Figure 6-16 present the worst case TOV results for the 400 kV Coolnabacky substation for a **3-phase fault during an outage of Dunstown 400 kV – Coolnabacky 400 kV circuit**.

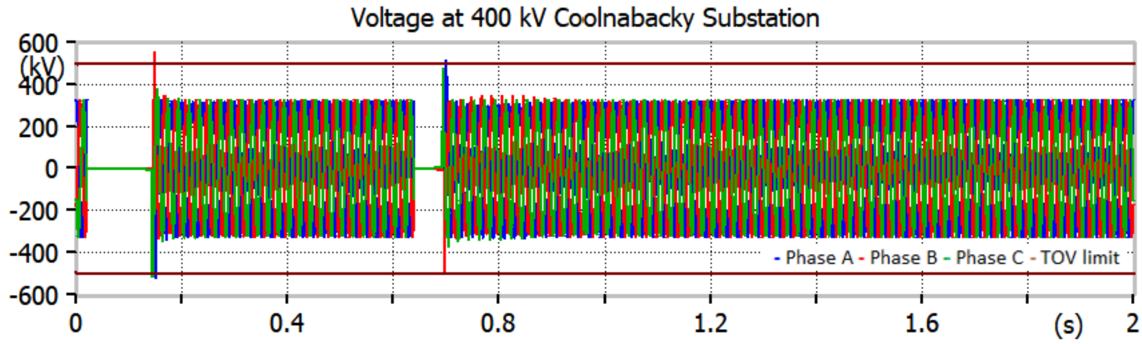

Figure 6-15: Voltage at 400 kV Coolnabacky Substation

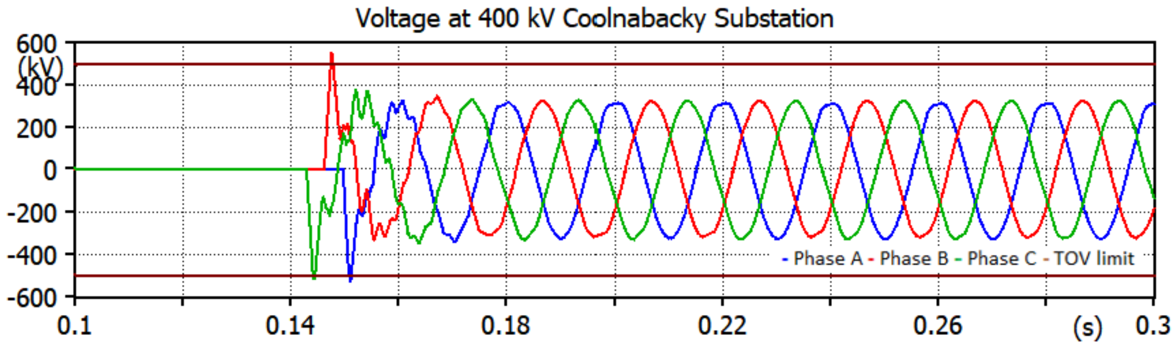

Figure 6-16: Voltage at 400 kV Coolnabacky Substation – Worst Fault Clearing Event

- *400 kV Dunstown Substation*

Figure 6-17 and Figure 6-18 Figure 5-19present the worst case TOV results for the 400 kV Dunstown substation for a **3-phase fault during an outage of Dunstown 400 kV – Coolnabacky 400 kV circuit**.

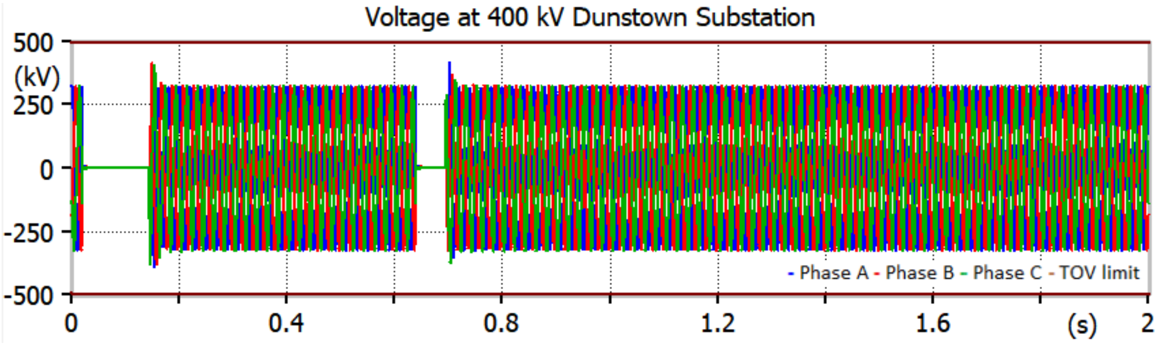

Figure 6-17: Voltage at 400 kV Dunstown Substation

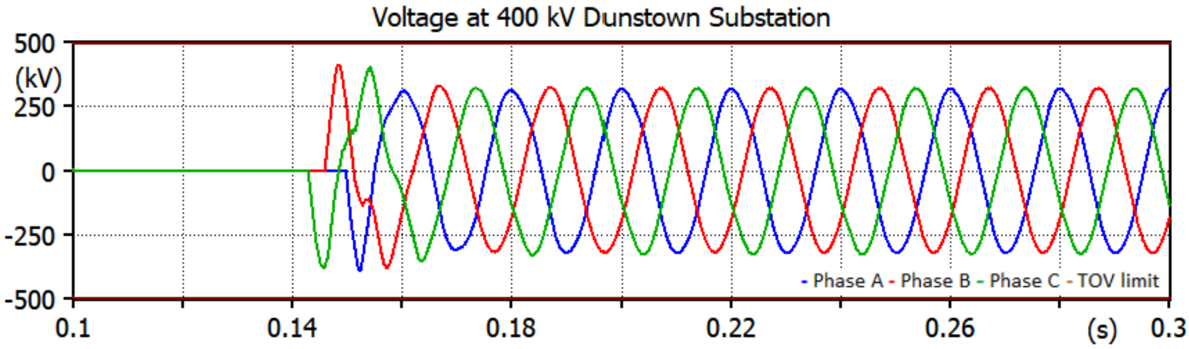

Figure 6-18: Voltage at 400 kV Dunstown Substation – Worst Fault Clearing Event

- *400 kV Old Street Substation*

Figure 6-19 and Figure 6-20 present the worst case TOV results for the 400 kV Old Street substation for a **3-phase fault during an outage of Old Street 400 kV – Moneypoint 400 kV circuit**.

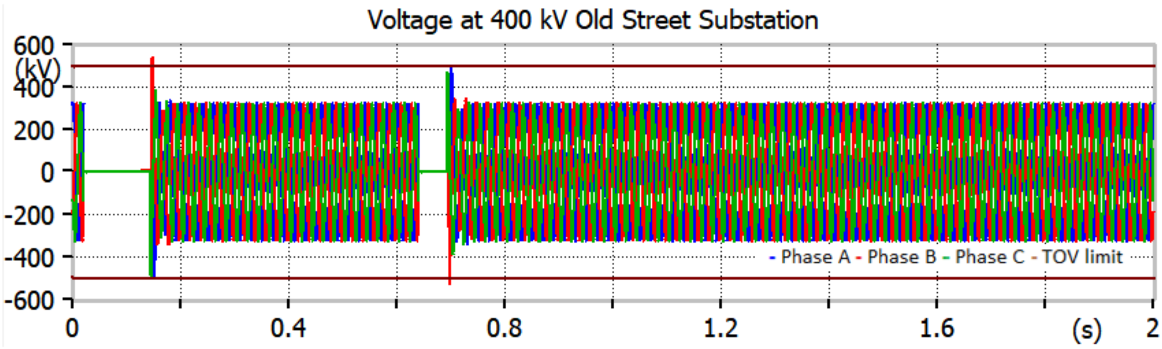

Figure 6-19: Voltage at 400 kV Old Street Substation

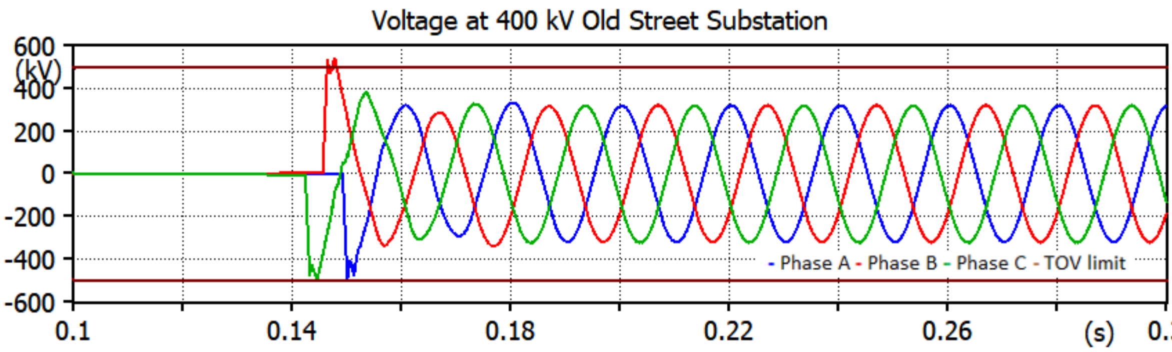

Figure 6-20: Voltage at 400 kV Old Street Substation – Worst Fault Clearing Event

- *400 kV Portan Substation*

Figure 6-21 and Figure 6-22 present the worst case TOV results for the 400 kV Portan substation for a **3-phase fault during an outage of Old Street 400 kV – Woodland 400 kV circuit**.

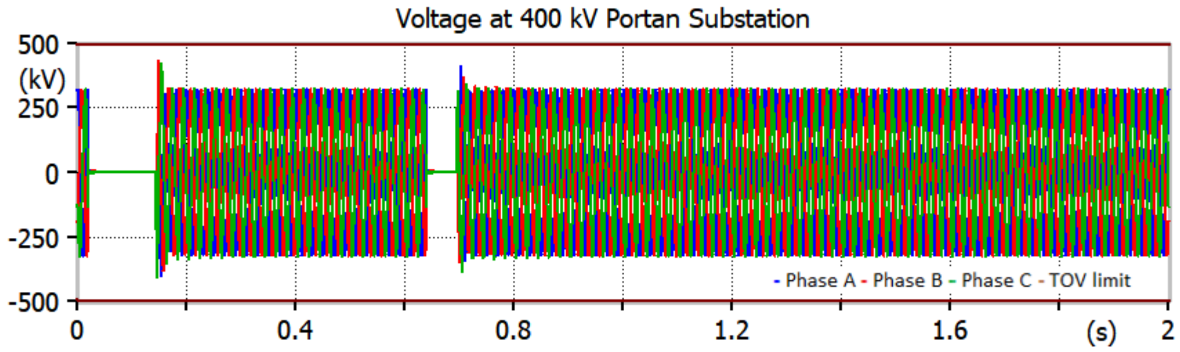

Figure 6-21: Voltage at 400 kV Portan Substation

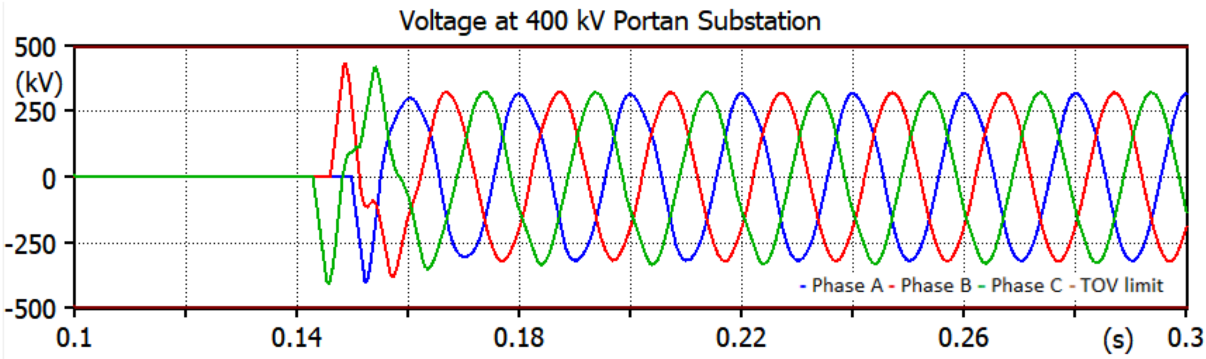

Figure 6-22: Voltage at 400 kV Portan Substation – Worst Fault Clearing Event

- *400 kV Woodland Substation*

Figure 6-23 and Figure 6-24 present the worst case TOV results for the 400 kV Woodland substation for a **3-phase fault during an outage of Woodland 400 kV – Turleenan 400 kV circuit**.

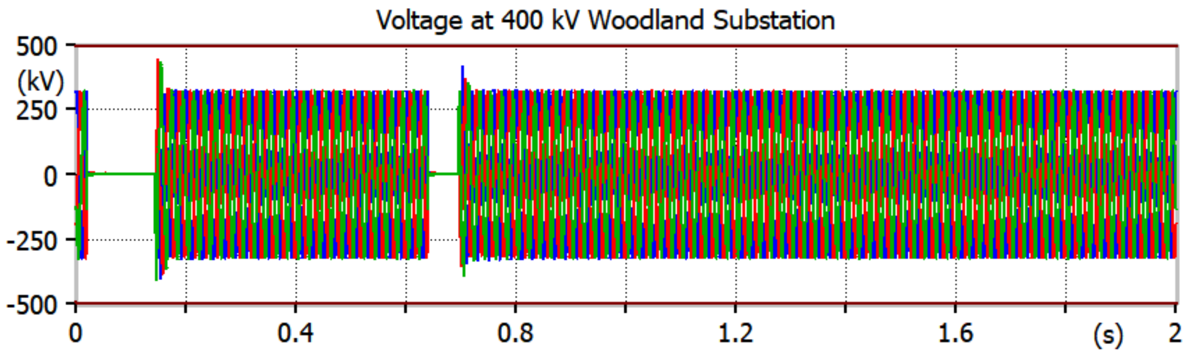

Figure 6-23: Voltage at 400 kV Woodland Substation

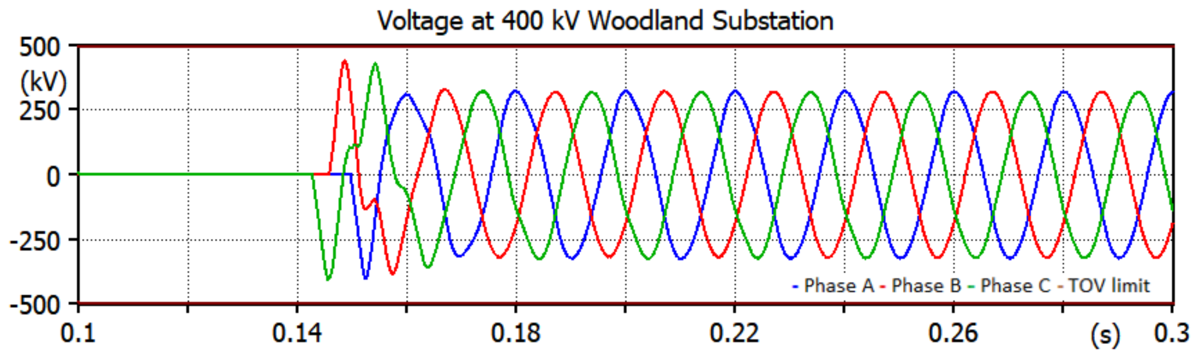

Figure 6-24: Voltage at 400 kV Woodland Substation – Worst Fault Clearing Event

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Results for CP966_UGC400 (2c/ph) – all harmonic filters and revised reactive compensation

- *400 kV Coolnabacky Substation*

Figure 6-25 and Figure 6-26 present the worst case TOV results for the 400 kV Coolnabacky substation for a **3-phase fault during an outage of Dunstown 400 kV – Coolnabacky 400 kV circuit**.

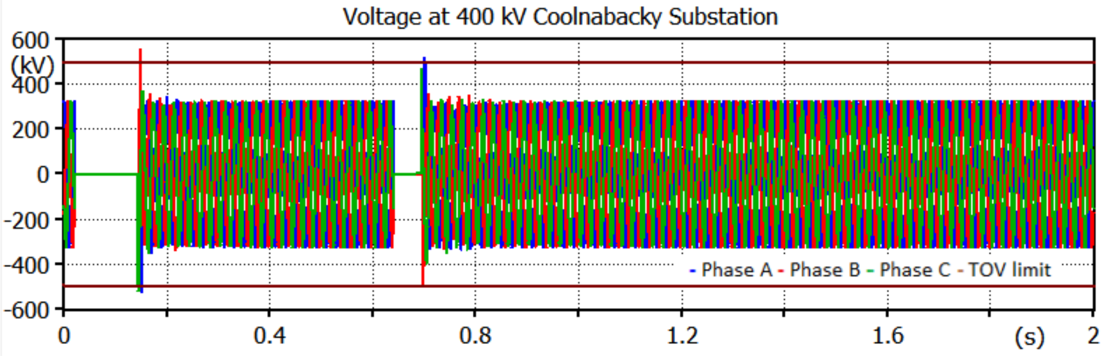

Figure 6-25: Voltage at 400 kV Coolnabacky Substation

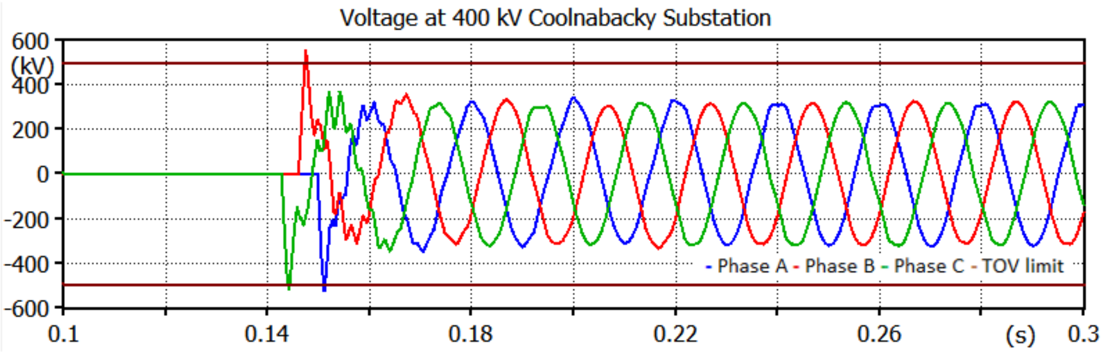

Figure 6-26: Voltage at 400 kV Coolnabacky Substation – Worst Fault Clearing Event

- *400 kV Dunstown Substation*

Figure 6-27 and Figure 6-28 Figure 5-19present the worst case TOV results for the 400 kV Dunstown substation for a **3-phase fault during an outage of Dunstown 400 kV – Coolnabacky 400 kV circuit**.

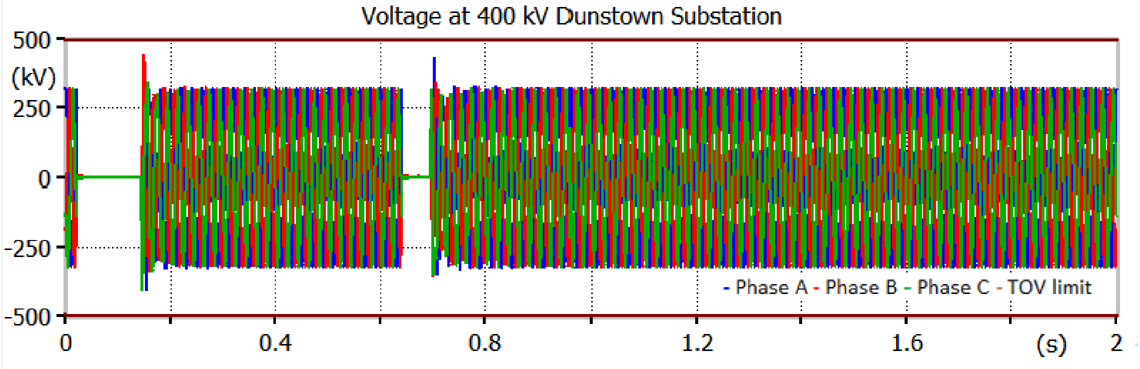

Figure 6-27: Voltage at 400 kV Dunstown Substation

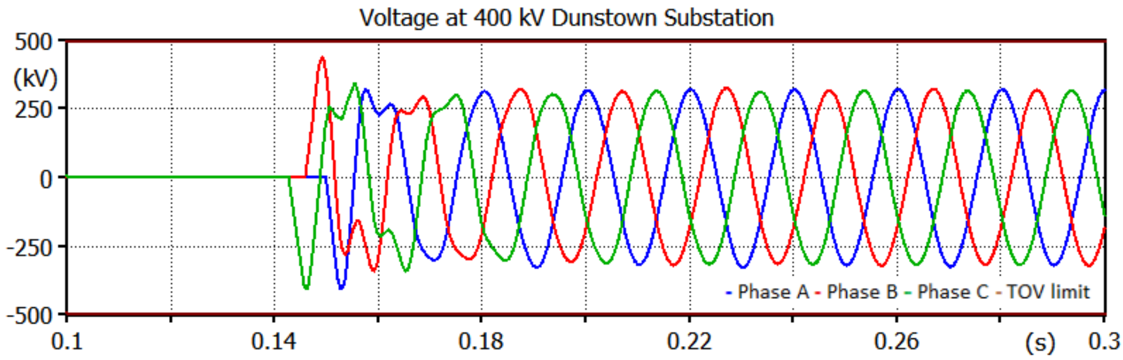

Figure 6-28: Voltage at 400 kV Dunstown Substation – Worst Fault Clearing Event

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- *400 kV Old Street Substation*

Figure 6-29 and Figure 6-30 present the worst case TOV results for the 400 kV Old Street substation for a **3-phase fault during an outage of Old Street 400 kV – Moneypoint 400 kV circuit.**

Figure 6-29: Voltage at 400 kV Old Street Substation

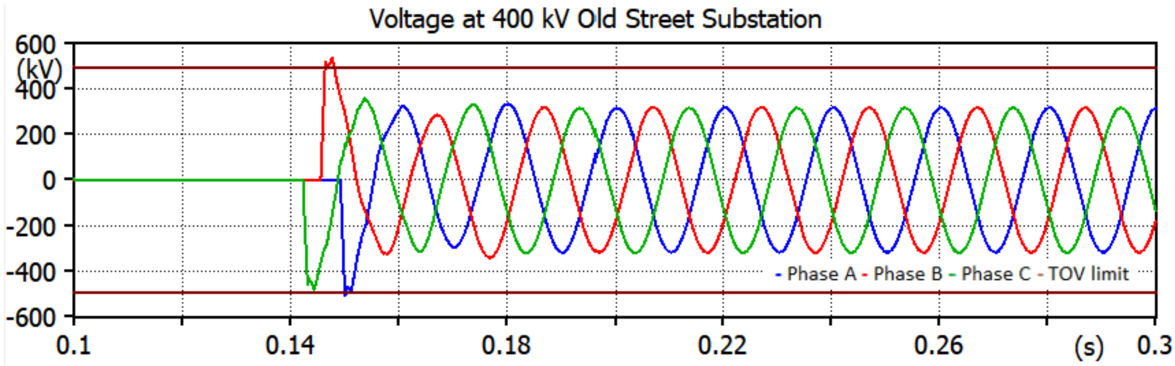

Figure 6-30: Voltage at 400 kV Old Street Substation – Worst Fault Clearing Event

- *400 kV Portan Substation*

Figure 6-31 and Figure 6-32 present the worst case TOV results for the 400 kV Portan substation for a **3-phase fault during an outage of Old Street 400 kV – Woodland 400 kV circuit**.

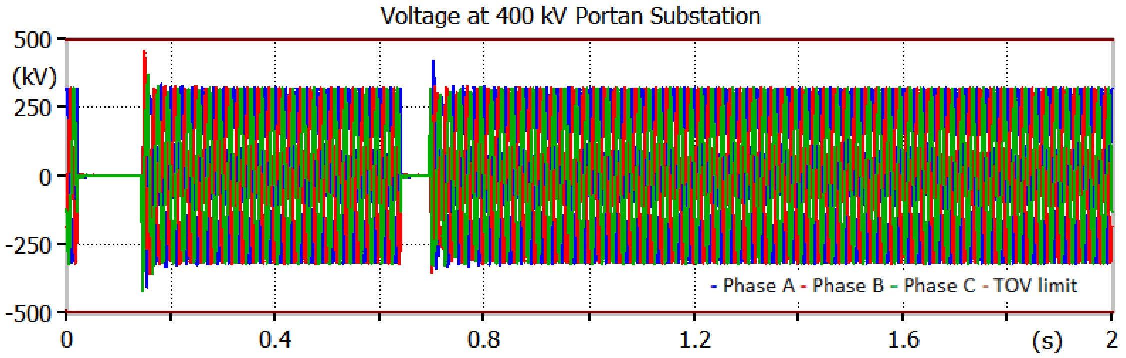

Figure 6-31: Voltage at 400 kV Portan Substation

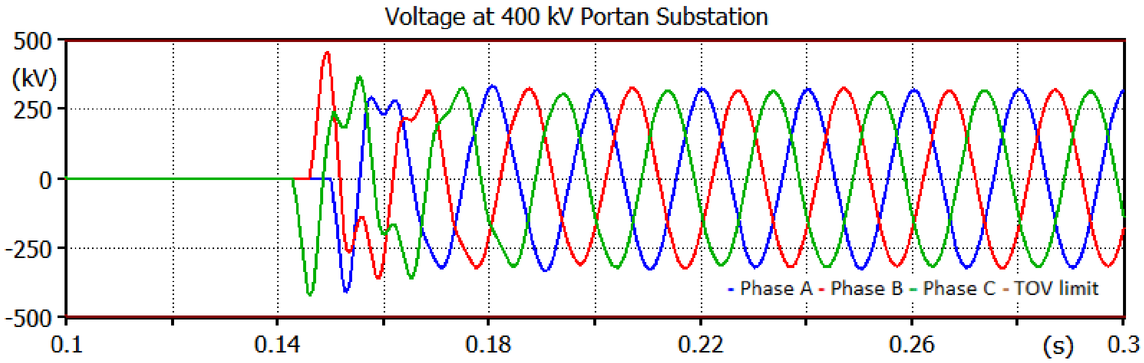

Figure 6-32: Voltage at 400 kV Portan Substation – Worst Fault Clearing Event

- *400 kV Woodland Substation*

Figure 6-33 and Figure 6-34 present the worst case TOV results for the 400 kV Woodland substation for a **3-phase fault during an outage of Woodland 400 kV – Turleenan 400 kV circuit**.

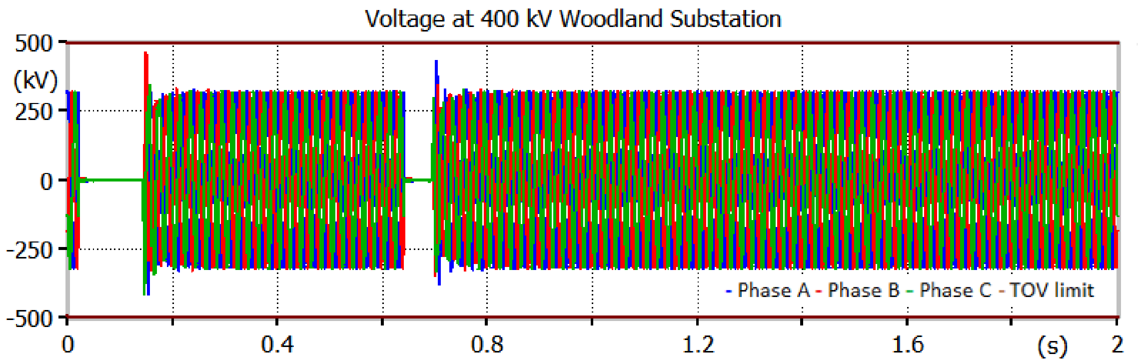

Figure 6-33: Voltage at 400 kV Woodland Substation

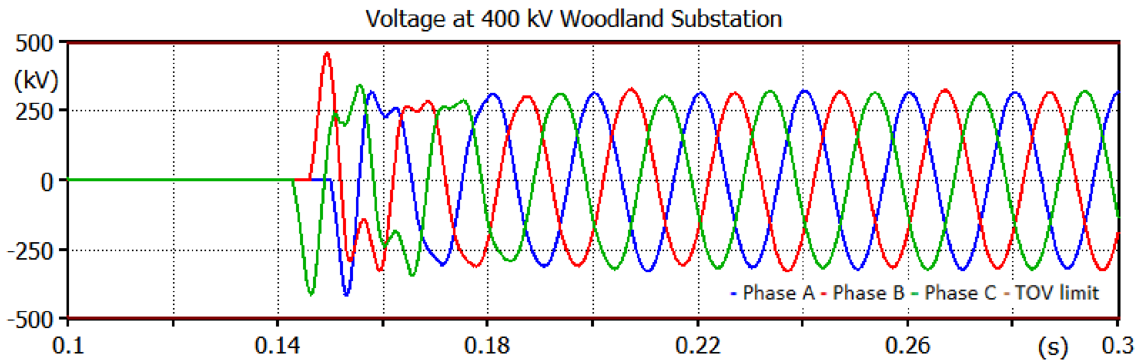

Figure 6-34: Voltage at 400 kV Woodland Substation – Worst Fault Clearing Event

6.3.2 Zero-Miss Phenomenon Analysis

A sensitivity study for the 400 kV (2 cable / phase) option was carried out considering the revised reactive compensation and the detailed harmonic solution proposed for that cable configuration. The energisation is set to happen at 0.095sec for scenario 1 detailed in Section 5.2 and the time domain simulation lasts for 1.3 seconds.

Figure 6-35 presents the current waveform at Dunstown 400 kV for energisation of the cable during zero crossing of voltage of phase A. The results indicate that there is a zero-miss phenomenon with the current DC offset being very slightly lower than the one presented in Section 5.2.3 due to the reduction (in %) in the revised reactive compensation.

Since the existence of the ZMP depends on the reactive compensation (in %) of the cable, it is expected that the other cable configurations will also result in slightly lower current DC offset than the one calculated in Section 5.1.4 due to the reduction (in %) in the revised reactive compensation. Hence, the initially presented results are still valid at this initial stage of the studies and further detailed analysis will need to be performed once the exact cable configuration and route are defined.

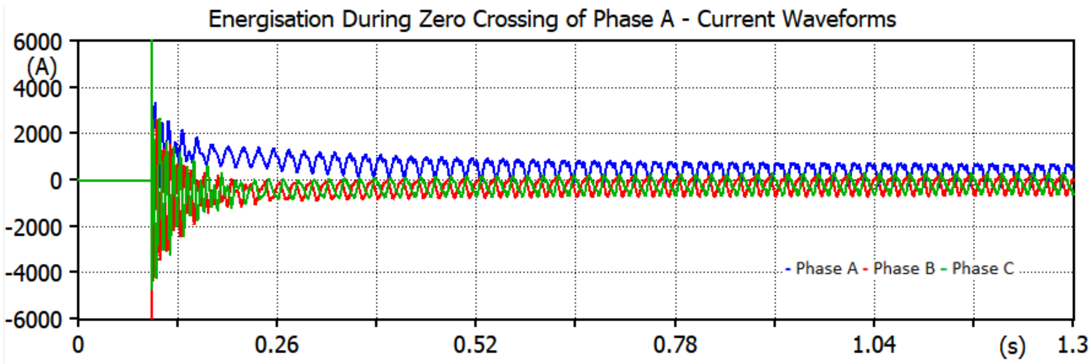

Figure 6-35: Current at Dunstown 400 kV for energisation during zero crossing of voltage of phase A

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7 Conclusions

This report details the reactive compensation, harmonic voltage distortion analysis and the TOV and ZMP studies carried out for the Capital Project 966 to investigate the impact of integration of either 220 or 400 kV UGC between the Woodland and Dunstown substations on the EirGrid network.

7.1 Reactive Compensation Requirements

Steady state load flow studies carried out in PSSE for all possible N-1 contingencies and under three different operating scenarios (SVLW, SVHW and WPHW) in order to determine the reactive compensation in the form of shunt reactors required to maintain a post contingency voltage limit for three different UGC options: 220kV, 400kV with a single cable per phase and 400kV with two cables per phase (effectively doubling the power transfer capability). Sensitivity analysis was carried out checking the level and location of reactive compensation required by varying the cable lengths and replacing it with overhead line. In most cases the compensation required is at both ends of the cable with specific details of the level given in Section 3. The final level of reactive compensation was then tested for each operating scenario and contingency to determine the pre- and post-contingency system voltages.

Brief summary of the results is shown in the table below.

	220 kV	400 kV 1-cable/phase	400 kV 2-cables/phase
Cable Length (%)	Compensation (%)	Compensation (%)	Compensation (%)
100.0%	81.6% (198 Mvar)	88.4% (558 Mvar)	99.6% (1258 Mvar)
75.0%	72.5% (132 Mvar)	70.5% (349 Mvar)	83.0% (839 Mvar)
50.0%	50.3% (61 Mvar)	45.3% (162 Mvar)	71.6% (543 Mvar)
25.0%	0.0%	21.3% (47 Mvar)	38.8% (196 Mvar)

The results indicate that for the full cable length a reactive compensation of above 80% is required for all the options but as the cable length reduces the level of compensation also reduces.

7.2 Harmonic Analysis

The reactive compensation determined during the steady state load flow studies were implemented in the PowerFactory frequency domain model in order to analyse the impact of the new 220 kV, 400 kV (1cable/ph) and 400 kV (2cable/ph) circuits on the harmonic distortions in the area. This was based on harmonic amplification studies performed for the nodes of interest and for a number of network contingencies and under the three operating scenarios (SVLW, SVHW and WPHW). Frequency scans were carried out in the 50 Hz to 2000 Hz range using the EirGrid HAST tool in order to establish likely resonance points.

For the determination of distortion levels, background harmonics calculated in a previous EirGrid project [6] were used. For the nodes of interest where there were not any calculated future background harmonic data it was considered to be identical to electrically close stations. For the harmonics where the calculated future background data was higher due to the assumptions considered in the previous EirGrid project, the 75 % of the PL was considered as the level of existing background for the calculations. It should be noted that the overall results depend heavily on the level of the assumed background distortion and depending on how these compare with the actual levels, the perceived level of issues may be more or do not exist at all.

Levels of harmonic distortions exceeding the EirGrid planning levels were observed for different cable lengths (100 %, 50%, 25%, 12.5%) for the 220 kV and 400 kV (1cable/ph) UGC options. Although there is some improvement with decreasing cable length, there is no cable length option that results in no harmonic breach. Similar levels of exceedance were also observed for the full cable length (100 % - the most onerous length investigated) for the 400 kV (2cable/ph) UGC option. In general, there were harmonic breaches in multiple substations which are getting higher and more complex in the 400 kV UGC. Indicative harmonic mitigation solutions were investigated for the full length of 220 kV, 400 kV (1cable/ph) and 400 kV (2cable/ph) UGC options.

Mitigation solutions with five, seven and eight C-type filters were established for the 220 kV, 400 kV (1cable/ph) and 400 kV (2cable/ph) options, respectively. A summary of these mitigation solutions along with the points they are connected is given in the next table.

	220kV		400kV (1cable/phase)		400kV (2cable/phase)	
Node	Size (Mvar)	Tuning (Hz)	Size (Mvar)	Tuning (Hz)	Size (Mvar)	Tuning (Hz)
DSN2	32	420	20	550	20	550
CLN4	10	550	-	-	-	-
WOO4	-	-	50	200	-	-
OST4	-	-	40	300	50	300
MAY2B	30	525	30	530	37	530
MAY2A	15	550	15	550	20	550
MAY1	5	525	5	550	5	550
BEL2	-	-	30	500	30	500
BEL2	-	-	-	-	30	180
WOO2	-	-	-	-	40	315

For the 220 kV option, the Maynooth substations are targeting more the local harmonic issues; whereas the remaining filters in Dunstown and Coolnabacky substations are targeting harmonic issues in local and nearby stations. For the 400 kV options, the filters in Maynooth and Belcamp substations are targeting more the local harmonic issues; whereas the remaining filters in Dunstown, Woodland and Old Street substations are targeting harmonic issues in local and nearby stations.

Following the implementation of the mitigation solutions, there were still a few harmonic breaches that can be resolved with the filter fine tuning during the design stage once the final level of UGC option has been decided.

7.3 Temporary Overvoltages and Zero-cross Miss Phenomenon

EMT studies were carried out in ATP in order to investigate the risk of TOV issues on the EirGrid network after the introduction of the proposed CP966 reinforcements and associated harmonic mitigation solutions. The frequency scans produced during the harmonic analysis studies in PowerFactory were analysed in order to identify the specific contingencies, network elements and nodes that there is a potential for TOV issues.

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The analysis showed that there is a risk of TOV exceeding 1.6 p.u voltage level for a very short duration for Coolnabacky and Old Street 400 kV substations with the response of the system and the calculated overvoltages to be very similar among the different UGC options. Therefore, once the full route details are known along with finalised mitigation for harmonic issues, EirGrid are recommended to review the TOV studies because the calculated overvoltages may be within the capability of existing surge arresters on the EirGrid system. It is believed that those overvoltages should not be a problem for the existing surge arresters due to the marginal exceedance and the very short duration but EirGrid are advised to confirm their specific capability from the equipment technical specification.

ZMP studies were also carried out in ATP in order to investigate whether the simultaneous energisation of the proposed cables and shunt reactors can result in a DC offset in the charging current of the cable and hence circuit breaker preventing its safe operation if a fault was to take place. The studies were performed by energizing the underground cables from one end while the other was maintained open and for different times that the circuit breaker closure is happening (energisation during zero crossing of the voltage and during peak of voltage). Due to the high reactive compensation requirements of both 220 kV and 400 kV UGC options, the ZMP analysis indicated that there is a current DC offset during energisation and a mitigation solution such as a pre-insertion resistor or a delayed reactor switching should be considered in the future. The phenomenon is more pronounced in the 400 kV UGC option when compared to the 220 kV UGC option due to the higher reactive compensation (in %) requirement.

7.4 Further Investigation and Sensitivity Checks

7.4.1 Reactive Compensation Requirements

Revised reactive compensation in the form of shunt reactors was determined for all possible N-1 contingencies for steady state conditions and for the contingency with the energisation of the cable from one end. This was done for the different operating scenarios (SVLW, SVHW, WPHW) and the three different UGC options: 220 kV, 400 kV (1 cable / phase) and 400 kV (2 cable / phase). Sensitivity analysis was carried out checking the level and location of reactive compensation required for different cable lengths.

Brief summary of the results is shown in the table below:

	220 kV	400 kV 1-cable/phase	400 kV 2-cables/phase
Cable Length (%)	Compensation (%)	Compensation (%)	Compensation (%)
100.0%	45.3% (110 Mvar)	45.9% (290 Mvar)	68.9% (870 Mvar)
75.0%	34.1% (62 Mvar)	34.4% (170 Mvar)	57.4% (580 Mvar)
50.0%	8.2% (10 Mvar)	11.2% (40 Mvar)	39.6% (300 Mvar)
25.0%	0.0%	0.0%	4.0% (20 Mvar)

The results indicate that for the full cable length the reactive compensation has reduced by at least 30% when compared with the initial levels. A maximum level of around 46% is required for the 220 kV and 400 kV (1c/ph) and of around 69% for the 400 kV (2c/ph).

7.4.2 Harmonic Analysis

The revised reactive compensation was implemented in the PowerFactory frequency domain model and the impact that the change in the reactive compensation has on the need for a harmonic filtering solution was analysed. The full cable length options of UGC220 and UGC400 (1 cable / phase) were assessed without any harmonic filters and the background harmonic amplification was reviewed for all the nodes of interest under the three operating scenarios (SVLW, SVHW and WPHW).

Comparing with the results for the initial reactive compensation requirements, similar levels of harmonic distortions exceeding the EirGrid planning levels were observed and the behaviour of the results was very similar with a few harmonic breaches observed only in the revised cases; whereas a few other harmonic breaches observed only in the revised case. Since there is a slight impact on the harmonic analysis as observed from the sensitivity studies for the 220 kV and 400 kV (1 cable / phase), the previously identified harmonic mitigation solutions can be used as the basis for designing the final solution at a later stage with the possibility of requiring some minor additional filtering solution. Those conclusions are expected to be also valid for the 400 kV (2 cable / phase) option.

A qualitative analysis for a potential underground cable reinforcement with 2 independent cable circuits concluded that a possible harmonic mitigation solution for this cable reinforcement is expected to consist primarily from the solution of the 2 cable / phase option plus one more filter in the 400 kV Woodland substation similar to the one proposed for the 1 cable / phase option.

7.4.3 Temporary Overvoltages and zero-cross Miss Phenomenon

EMT sensitivity studies were carried out for the 400 kV (1 cable / phase) to investigate the impact on the TOV analysis for the cases of either having no harmonic filters or considering the revised reactive compensation. TOV studies were also performed for the 400 kV (2 cable / phase) UGC option considering the proposed harmonic mitigation solution and the revised reactive levels. The analysis indicated that in all the cases there is a very similar risk to the initial studies of TOV exceeding 1.6 p.u voltage level for a very short duration for Coolnabacky and Old Street 400 kV substations. Those conclusions are expected to be also valid for the 220 kV UGC option.

ZMP studies were carried out for the revised reactive compensation for the 400 kV (2 cable / phase) UGC option and indicated that there is a current DC offset during energisation that is very slightly lower than the one calculated in the initial ZMP studies. This conclusion is expected to be valid for the other cable configurations due to the reduction (in %) in the revised reactive compensation for all the cable options.

7.5 Summary

The 220 kV, 400 kV (1 cable / phase) and the 400 kV (2 cable / phase) UGC options between the Woodland and Dunstown substations in the east of Ireland were brought forward from Step 2 of EirGrid's six-step approach and were studied in detail in this report. The 220 kV option is rated at 760 MVA; whereas the 400 kV (1 cable / phase) is rated at 1254 MVA which is below the rating of an equivalent 400 kV overhead line but is selected as the maximum possible rating achievable for a cable buried in a typical trench or road arrangement. The 400 kV (2 cable / phase) option is rated at 2509 MVA which exceeds the rating of an equivalent 400 kV overhead line but requires a larger strip of land or a second route. However, the 400 kV (2 cable / phase) option is found to be feasible from engineering investigations done in parallel with the studies in this report.

Brief summary of the three UGC options and their requirements in terms of reactive compensation, harmonic filtering, TOV and ZMP is shown in the table below. The requirements of the two 400 kV independent cable circuit solution are primarily similar to the 400 kV (2 cables / phase) option with the exception of the harmonic filtering where at least one more filter is expected to be necessary.

	Reactive Compensation Requirements (Mvar)		Harmonic Filtering Requirements (Number of filters)		ZMP Mitigation Requirements (Y/N)		TOV Mitigation Requirements	
UGC option (100% Cable Length)	Initial studies	Revised studies	Initial studies	Revised studies	Initial studies	Revised studies	Initial studies	Revised studies
220 kV	198	110	5	≥5[12]	Y	Y[13]	Possible[14]	Possible[15]
400 kV (1 cable/phase)	558	290	7	≥7[13]	Y	Y[14]	Possible[15]	Possible[15]
400 kV (2 cable/phase)	1258	870	8	≥8[13]	Y	Y[14]	Possible[15]	Possible[15]

The reactive compensation studies performed for the three UGC options (220kV, 400kV with a single cable per phase and 400kV with two cables per phase) identified that there is a high compensation requirement (> 80%) in all options for full cable length. Those levels were reduced considerably (by at least 30%) during revised reactive compensation studies. The option with two cables per phase at 400 kV results to 1258 Mvar of reactive compensation for the initial studies which is high but reduces to 870 Mvar following the revised studies.

Harmonic analysis studies for the 220 kV, 400 kV (1 cable/ph) and 400 kV (2 cable/ph) identified that there are harmonic breaches in the full cable length which are generally getting higher and more complex in the 400 kV (2 cable/ph) option. Harmonic breaches are also identified in all the different cable lengths analysed for the 220 kV and 400 kV (1 cable/ph). Mitigation solutions with C-type filters were established for the full length of all the cable options which resolve most of the breaches. Any remaining breaches can be resolved with the filter fine tuning during the design stage once the final level of UGC option has been decided. Sensitivity studies with the revised reactive compensation concluded that the mitigation solutions proposed are still applicable and there is possibility of requiring some minor additional filtering solution. The overall results depend heavily on the level of the assumed background distortion which is based on a previous EirGrid project [6] and depending on

[12] Qualitative analysis detailed in the relevant section indicates that there is a possibility of some additional filtering solution when compared to the initial studies

[13] Slightly improved results expected for the revised studies due to the reduction (in %) of the revised reactive compensation

[14] Small risk of TOV exceeding 1.6 p.u which may be within the capability of the existing surge arresters in the EirGrid system and should be reviewed as part of the detailed design.

how these compare with the actual levels, the perceived level of issues may be more or do not exist at all.

TOV analysis for the full length of the 220 kV, 400 kV (1 cable/ph) and 400 kV (2 cable/ph) with the reactive compensation and harmonic filters identified that there is a small risk of TOV exceeding 1.6 p.u voltage level for a very short duration for Coolnabacky and Old Street 400 kV substations with the calculated overvoltages being very similar among the different UGC options. Sensitivity studies for the revised reactive compensation and for cases with no harmonic filters indicated that the conclusions are very similar in terms of magnitude, duration and location for the TOV risk. This may be within the capability of the existing surge arresters in the EirGrid system and should be reviewed as part of the detailed design.

ZMP analysis indicated that there is a current DC offset during the energisation of both cables due to the high reactive compensation requirements (in %) which is slightly improving for the revised reactive compensation requirements due to the reduction (in %) in the calculated values. However, there are different countermeasures available and a mitigation solution such as a pre-insertion resistor or a delayed reactor switching should be considered in the future. The phenomenon is more pronounced in the 400 kV UGC options when compared to the 220 kV UGC option due to the higher reactive compensation (in %) requirement.

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9 Document History

Revision	Date	Description of changes
0	11-11-2019	Issued for Client Review
1	07-02-2020	Included initial comments and further studies
2	12-03-2020	Final report including comments

Revision	Date	Author	Peer Review	Approved
0	11-11-2019	Michail Bitos	Zia Emin	Zia Emin
1	07-02-2020	Michail Bitos	Zia Emin	David Mills
2	12-03-2020	Michail Bitos	David Mills	Zia Emin

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Appendix A Contingencies Considered

The following table presents the contingencies considered and tested in PSSE during the model review

Short Name	Type	Description	Additional Action
CDU2-CDU1-1	3 Winding Transformer Trip	Corduff 220 / 110 kV Transformer 1	
CDU2-CDU1-2	3 Winding Transformer Trip	Corduff 220 / 110 kV Transformer 2	
CLN4-CLN1B-1	3 Winding Transformer Trip	Coolnabacky 400 / 110 kV Transformer 1	Coolnabacky 110 kV bus-section closed
DSN4-DSN2-1	3 Winding Transformer Trip	Dunstown 400 / 220 kV Transformer 1	
DSN4-DSN2-2	3 Winding Transformer Trip	Dunstown 400 / 220 kV Transformer 2	
MAY2A-MAY1A-1	3 Winding Transformer Trip	Maynooth A 220 / 110 kV Transformer 1	Maynooth 110 kV Bus-section Closed
MAY2A-MAY1A-2	3 Winding Transformer Trip	Maynooth A 220 / 110 kV Transformer 2	Maynooth 110 kV Bus-section Closed
MAY2B-MAY1B-1	3 Winding Transformer Trip	Maynooth A 220 / 110 kV Transformer 1	Maynooth 110 kV Bus-section Closed
MAY2B-MAY1B-2	3 Winding Transformer Trip	Maynooth A 220 / 110 kV Transformer 2	Maynooth 110 kV Bus-section Closed
OST4-OST2-1	3 Winding Transformer Trip	Oldstreet 400 / 220 kV Transformer 1	
WOO4-WOO2A-1	3 Winding Transformer Trip	Woodland A 400 / 220 kV Transformer 1	Woodland 220 kV Bus-section closed
WOO4-WOO2B-1	3 Winding Transformer Trip	Woodland B 400 / 220 kV Transformer 1	Woodland 220 kV Bus-section closed
WOO4-WOO2C-1	3 Winding Transformer Trip	Woodland C 400 / 220 kV Transformer 1	Woodland 220 kV Bus-section closed
PRN4-Fshunt-1	Capacitor Trip	Portan 400 kV Capacitor	
BEL2-FIN2A-1	Circuit Trip	Belcamp to Finglas 220 kV	
BEL2-SHL2-1	Circuit Trip	Belcamp to Shellybanks 220 kV	
CDU2A-FIN2A-1	Circuit Trip	Corduff to Finglas 220 kV	
CDU2A-HUN2B-1	Circuit Trip	Corduff to Hunstown B 220 kV	
CDU2B-WOO2A-1	Circuit Trip	Corduff to Woodland 220 kV	
CDU2-CLE2-1	Circuit Trip	Corduff to Clonee 220 kV	
CDU2-CRU2-1	Circuit Trip	Corduff to Cruiserath 220 kV Circuit 1	CDU2-CRU2-2 has the same circuit parameters
CKM2-DSN2-1	Circuit Trip	Carrickmines to Dunstown 220 kV	
CLN4-MP4-1	Circuit Trip	Coolnabacky to Moneypoint 400 kV	
CTB2-MAY2A-1	Circuit Trip	Castlebagot to Maynooth A 220 kV	Maynooth 220 kV Bus-section Closed

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CTB2-MAY2B-1	Circuit Trip	Castlebagot to Maynooth B 220 kV	Maynooth 220 kV Bus-section Closed
DSN2-KLS2-1	Circuit Trip	Dunstown to Kellis 220 kV	
DSN2-MAY2A-1	Circuit Trip	Dunstown to Maynooth A 220 kV	
DSN2-MAY2B-1	Circuit Trip	Dunstown to Maynooth B 220 kV	Maynooth 220 kV Bus-section Closed
DSN2-TH2-1	Circuit Trip	Dunstown to Turlough Hill 220 kV	
DSN2-WOO2C-1	Circuit Trip	Dunstown to Woodland 220 kV	Not Applicable to BC or UGC400, Woodland bus-section closed
DSN4-CLN4-1	Circuit Trip	Dunstown to Coolnabacky 400 kV	
DSN4-WOO4-1	Circuit Trip	Dunstown to Woodland 400 kV	Not Applicable to BC or UGC220
FIN2A-HUN2A-1	Circuit Trip	Finglas to Hunstown A 220 kV	
FIN2B-NW2-1	Circuit Trip	Finglas to North Wall 220 kV	
INT2-MAY2A-1	Circuit Trip	Intel to Maynooth A 220 kV	Maynooth 220 kV Bus-section Closed
MAY2A-SH2-1	Circuit Trip	Maynooth A to Shannonbridge 220 kV	Maynooth 220 kV Bus-section Closed
MAY2B-GOR2-1	Circuit Trip	Maynooth B to Gorman 220 kV	Maynooth 220 kV Bus-section Closed
MAY2B-TH2-1	Circuit Trip	Maynooth B to Turlough Hill 220 kV	Maynooth 220 kV Bus-section Closed
NW2-PB2B-1	Circuit Trip	North Wall to Poolbeg North 220 kV	
OST4-MP4-1	Circuit Trip	Oldstreet to Moneypoint 400 kV	
OST4-WOO4-1	Circuit Trip	Oldstreet to Woodland 400 kV	
WOO2-CLE2-1	Circuit Trip	Woodland to Clonee 220 kV	
WOO2-INT2-1	Circuit Trip	Woodland to Intel 220 kV	
WOO2-ORL2-1	Circuit Trip	Woodland to Oriel 220 kV	
WOO4-PRN4-1	Circuit Trip	Woodland to Portan 400 kV	
WOO4-TLE4-1	Circuit Trip	Woodland to Turleenan 400 kV	
CKM2-SSHUNT-1	Reactor Trip	Carrickmines 220 kV Reactor	
PB2B-Sshunt	Reactor Trip	Poolbeg North 220 kV Reactor	

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Appendix B Included Models

The following sections set out the models which are submitted along with this report.

B.1 PSSE Model Details

Included with this report is the PSSE 2030 system model after the review and updates detailed in this report. The following PSSE case files are included:

- CP966_PSPF020_SLD.sld – PSSE slider produced to represent the nodes of interest for the CP966 project
- SNV2030LowW_30snv_33_dc_Scenario Updated_BC(No ND).sav – PSSE case for SV LW
- SNV2030HighW_30snv_33_dc_Scenario Updated_BC(No ND).sav – PSSE case for SV HW
- WP2030HW_30w_33_dc_Scenario 0_95%SW Updated_BC(No ND).sav – PSSE case for WP HW

B.2 PowerFactory Model Details

Included with this report is an extract of the PowerFactory model that will be used for the cable integration studies as part of capital project 966.

- PowerFactory Model: AIM 2019-MODEL-RELEASE v1.0(JI7867).pfd

B.2.1 Study Cases

- CP966.IntCase – Validated PowerFactory model prior to inclusion of UGC options
- CP699_UGC220.IntCase – Includes 220 kV UGC option
- CP699_UGC220_Fil.IntCase – Includes harmonic filters for 220 kV UGC option
- CP966_UGC400(1c).IntCase – Includes 400 kV UGC option with 1 core / phase
- CP966_UGC400(1c)_Fil.IntCase – Includes harmonic filters 400 kV UGC option with 1 core / phase
- CP966_UGC400(2c).IntCase – Includes 400 kV UGC option with 2 cores / phase
- CP966_UGC400(2c)_Fil.IntCase – Includes harmonic filters 400 kV UGC option with 2 cores / phase

B.2.2 Operational Scenarios

- SV_LW.IntScenario – Summer valley demand with low wind generation dispatch
- SV_HW.IntScenario – Summer valley demand with high wind generation dispatch
- WP_HW.IntScenario – Winter peak demand with high wind generation dispatch

B.3 ATP Model Details

Included with this report is an extract of the ATP model that will be used for the cable integration studies as part of capital project 966.

- FS_SV_BASE_N1_DevA_220kVUGC.acp – Includes 220 kV UGC option and mitigation solution
- FS_SV_BASE_N1_DevA_220kVUGC_ZMP.acp – ZMP analysis for 220 kV UGC option
- FS_SV_BASE_N1_DevA_400kVUGC.acp – Includes 400 kV (1c/ph) UGC option and mitigation solution
- FS_SV_BASE_N1_DevA_400kVUGC_ZMP.acp – ZMP analysis for 400 kV (1c/ph) UGC option
- FS_SV_BASE_N1_DevA_400kVUGC2c.acp – Includes 400 kV (2c/ph) UGC option and mitigation solution
- FS_SV_BASE_N1_DevA_400kVUGC2c_ZMP.acp – ZMP analysis for 400 kV (2c/ph) UGC option

Appendix C Capital Project 966 Technical Data

C.1 PSSE Technical Data

The original PSSE models of the new UGC were compared with the cable manufacturers datasheet assuming the standard EirGrid flat installation arrangement [14,15]. During the review it was apparent that the base PSSE model data did not reflect the selected UGC and so was updated accordingly. Table 9-1 compares the original PSSE model data with that calculated from the manufacturer's datasheets with the selected values shown in green.

Table 9-1: Project cables parameters comparison between PSSE and datasheets

Reinforcement ID	**CP966_UGC220**		**CP966_UGC400**	
From	Dunstown 220 kV		Dunstown 400 kV	
To	Woodland 220 kV		Woodland 400 kV	
Cable Type	2500mm Cu/XLPE/Pb (NKT Cables, 2012)		2500mm Cu/XLPE/Al (Eckstein, 2017)	
Length (km)	60		60	
Cables Per Phase	1		2	
Source	Original	Updated	Original	Updated
PSSE Nominal Voltage (kV)	220	220	380	380
Circuit R (pu on 100 MVA)	0.0022	**0.0015**	0.001	0.0002
Circuit X (pu on 100 MVA)	0.0083	**0.0269**	0.0068	0.0046
Circuit B (pu on 100 MVA)	1.1926	**2.4268**	4.9562	12.6295
Rate A (MVA)	570	**760**	1944	2509
Rate B (MVA)	570	**760**	1944	2509
Rate C (MVA)	570	**760**	1944	2509
Source	PSSE	Datasheet	PSSE	Datasheet
Cable R (Ω / km)	0.0177	0.0118	0.0481	0.0118
Cable L (mH / km)	0.2131	0.6900	1.0418	0.7000
Cable C (µF / km)	0.1307	0.2660	0.0910	0.2320

C.1.1 Additional Reinforcements as Part of 220 kV UGC Option

As part of the CP966_UGC220 reinforcement there are also uprates required to the existing circuits listed below. These were included as part of the model review with the values shown in green in the following table implemented.

Table 9-2: CP966_UGC220 additional uprate circuit PSSE parameters

From	Cashla 220 kV		Killonan 220 kV	
To	Prospect 220 kV		Shannonbridge 220 kV	
Length (km)	88.54		89.7	
Source	Original	Uprated	Original	Uprated
Nominal Voltage (kV)	220	220	220	220
R (pu on 100 MVA)	0.0103	0.0103	0.01436	0.0104
X (pu on 100 MVA)	0.0767	0.0767	0.0795	0.0776
B (pu on 100 MVA))	0.1158	0.1157	0.120346	0.117

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Rate A (MVA)	392	434	269	434
Rate B (MVA)	392	434	269	434
Rate C (MVA)	431.2	477.4	295.9	477.4

Additionally, to avoid thermal overloading of the new 220 kV cable as part of the CP966_UGC220 option it is necessary to run the Woodland 220 kV busbar split. This is modelled in the PSSE model with the following running arrangement (Figure 9-1):

- WOO4204 – Supplies Woodland 220 kV system
- WOO4201 – Connected to new CP966_UGC220 cable from Dunstown 220 kV
- WOO4202 – Hot standby transformer for loss of WOO4204

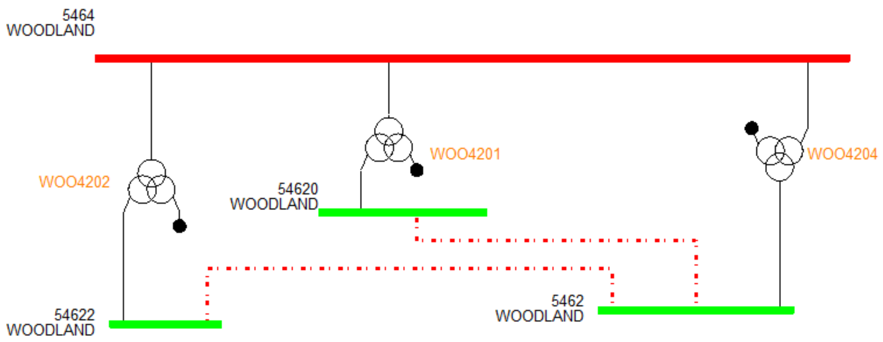

Figure 9-1: Woodland 220 kV PSSE Normal Running Arrangement after CP966_UGC220 reinforcement

C.2 PowerFactory Technical Data

The PowerFactory model was updated to represent the CP966 reinforcements with the option of either the 220 or 400 kV UGC. The detailed models of the cables were based on the technical datasheets. The following modifications were made to represent the cable options.

C.2.1 CP966_UGC400

- 60 km Dunstown – Woodland 400 kV UGC[15] - 2 cables per phase

C.2.2 CP966_UGC220

- 60 km Dunstown – Woodland 220 kV UGC[16]
- Uprating of the Cashla – Prospect 220 kV overhead line[17]
- Uprating of the Killonan – Shannonbridge 220 kV overhead line
- Woodland 220 kV station is operated “split” in order to prevent thermal overloading of the new 220 kV cable for an unplanned loss of a circuit.

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[15] Cable system = Dunstown-Woodland 400 kV Cable.TypCabsys with cable type = NKT 2500 sq mm 380 kV Cu XLPE Al Pe.TypCab

[16] Cable system = Dunstown-Woodland 220 kV Cable.TypCabsys with cable type = NKT 2500 sq mm 220 kV Cu XLPE 20.TypCab

[17] OHL conductor type = 220 kV 600 SCA Curlew.TypCon

Appendix D System Voltages Without Reactive Compensation

The following sections show the resulting overvoltages that can be expected on the system for the 220 and 400 kV underground cable options without any reactive compensation (D.1 - D.3) and with the revised reactive compensation levels detailed in section 6.1 (D.4 - D.6). An explanation of the specific meanings of the components of the individual graphs is included in section 3.

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D.1 Results for CP966_UGC220 Without Reactive Compensation

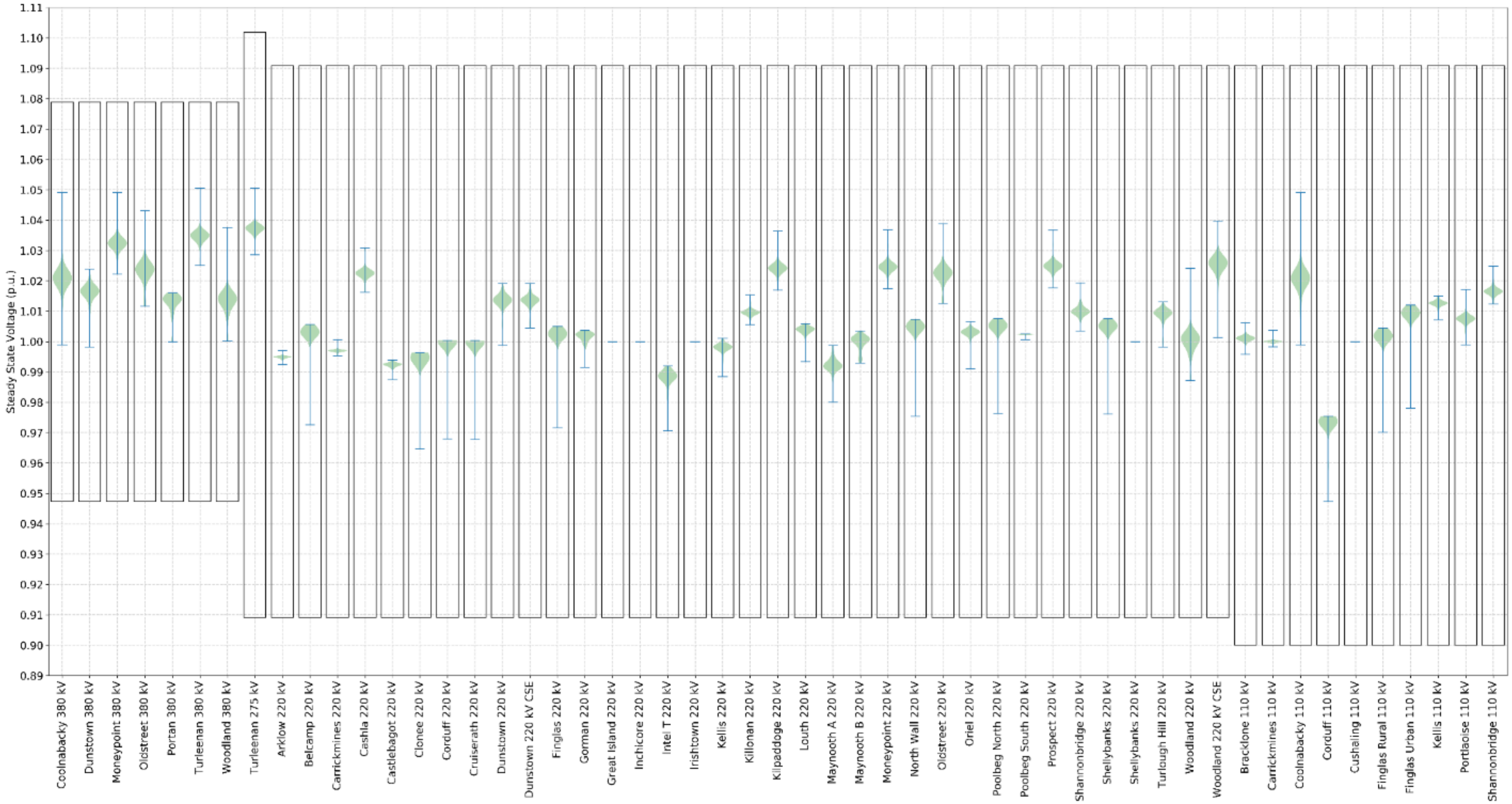

Figure D-1: CP966_UGC220 post-contingency steady state voltages compared against EirGrid limits for operating scenario SV LW with no reactive compensation

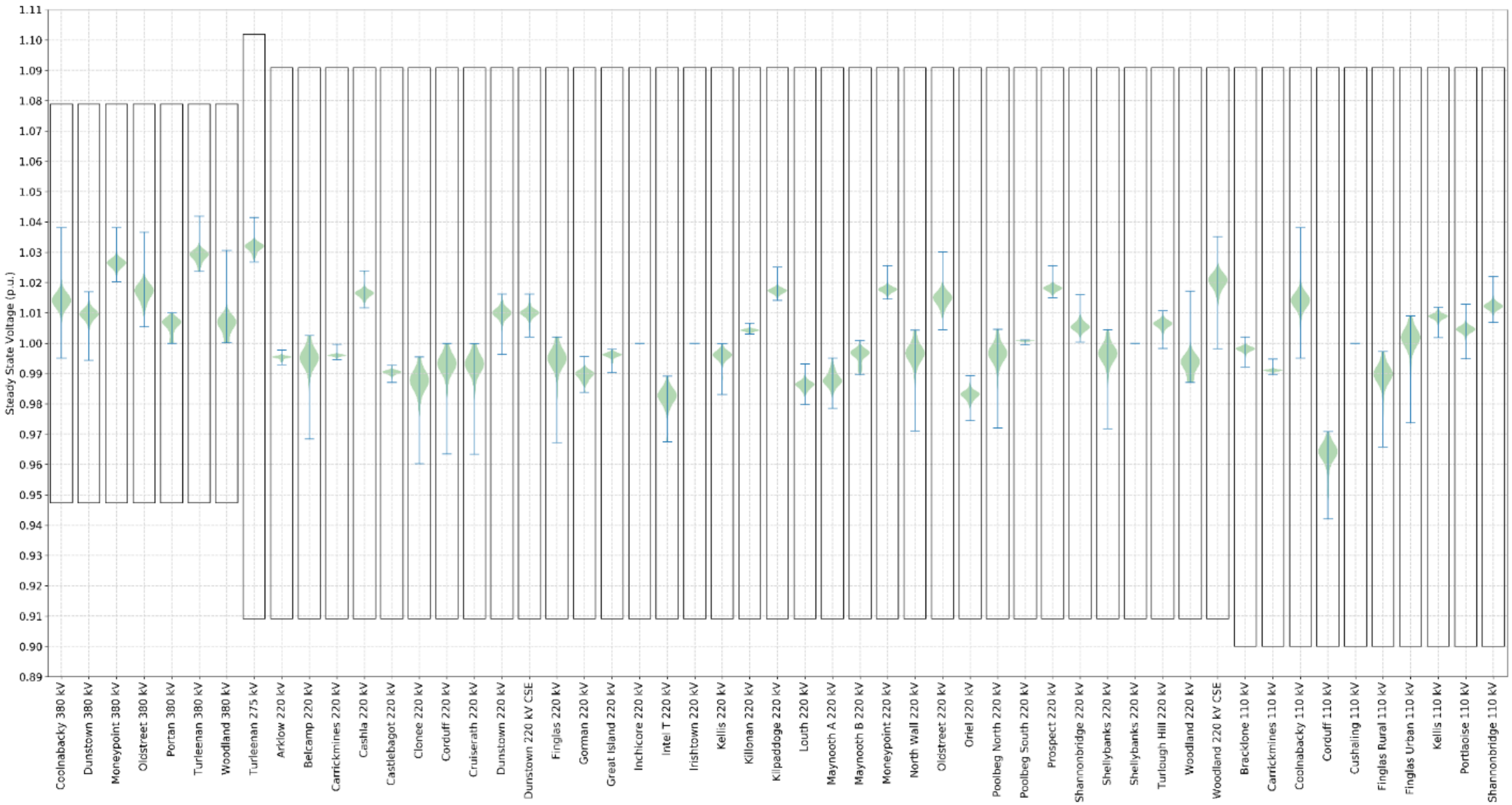

Figure D-2: CP966_UGC220 post-contingency steady state voltages compared against EirGrid limits for operating scenario SV HW with no reactive compensation

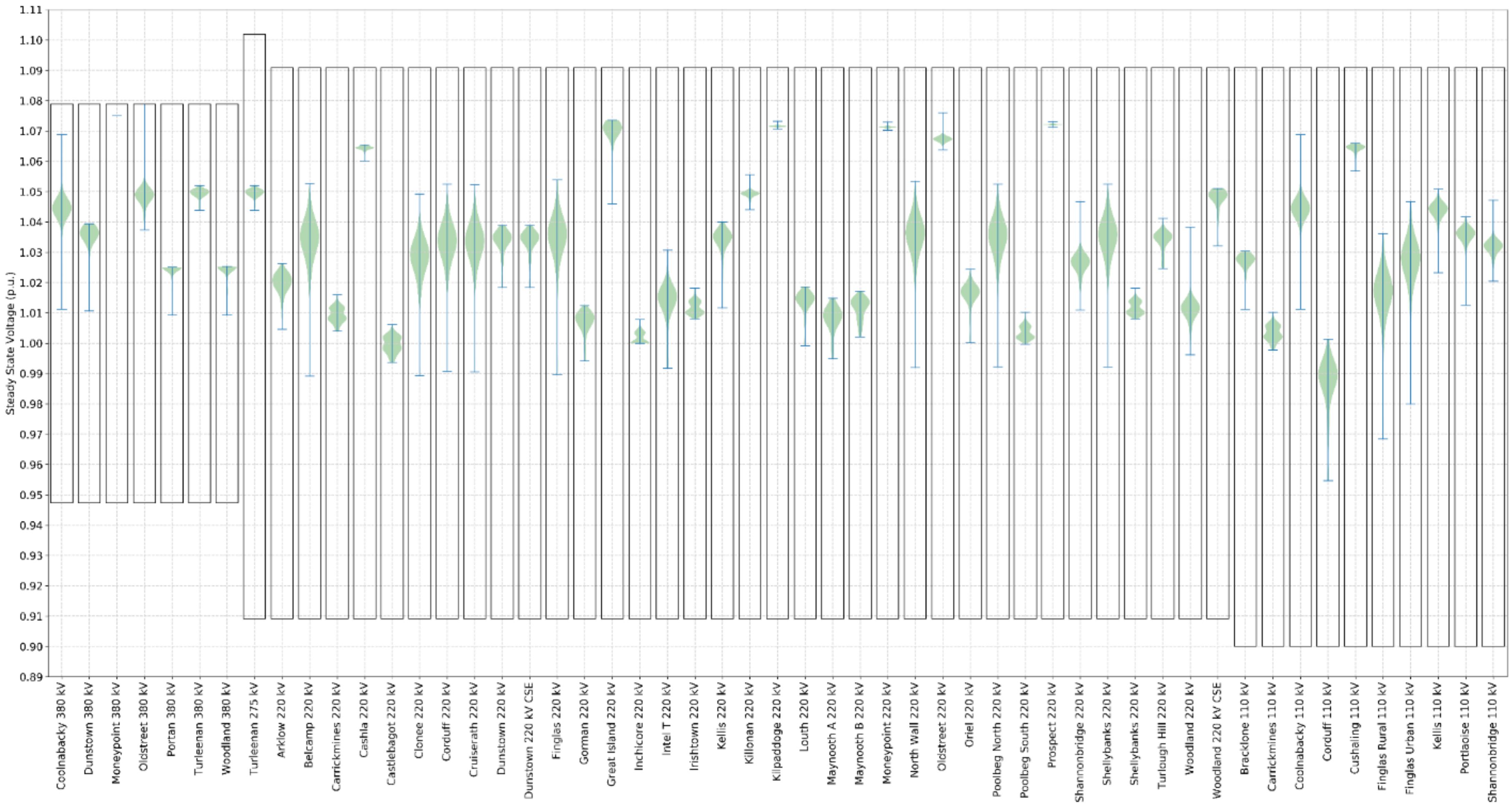

Figure D-3: CP966_UGC220 post-contingency steady state voltages compared against EirGrid limits for operating scenario WP HW with no reactive compensation

D.2 Results for CP966_UGC400 1 Cable / Phase Without Reactive Compensation

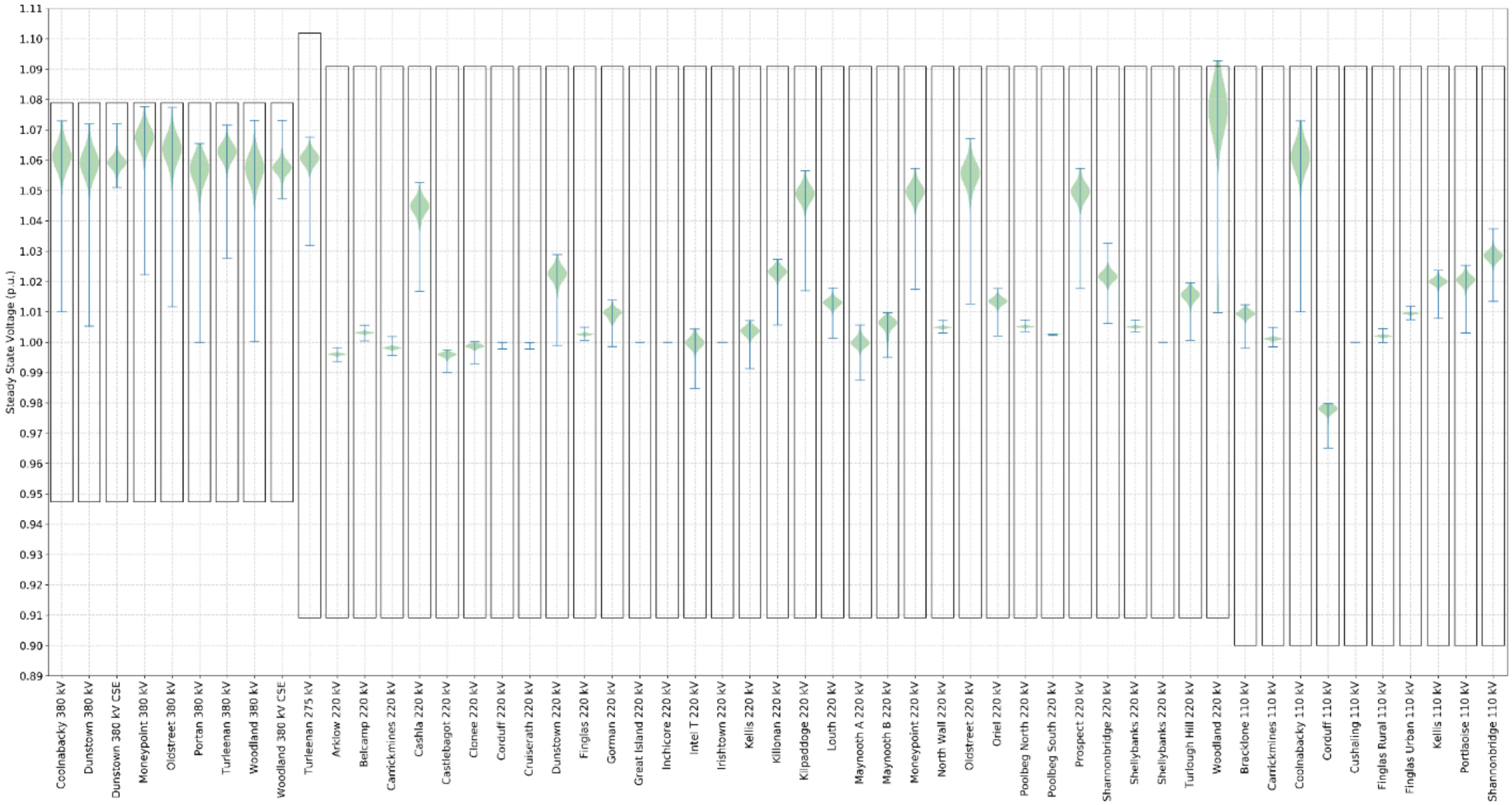

Figure D-4: CP966_UGC400, 1 cable / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario SV LW with no reactive compensation

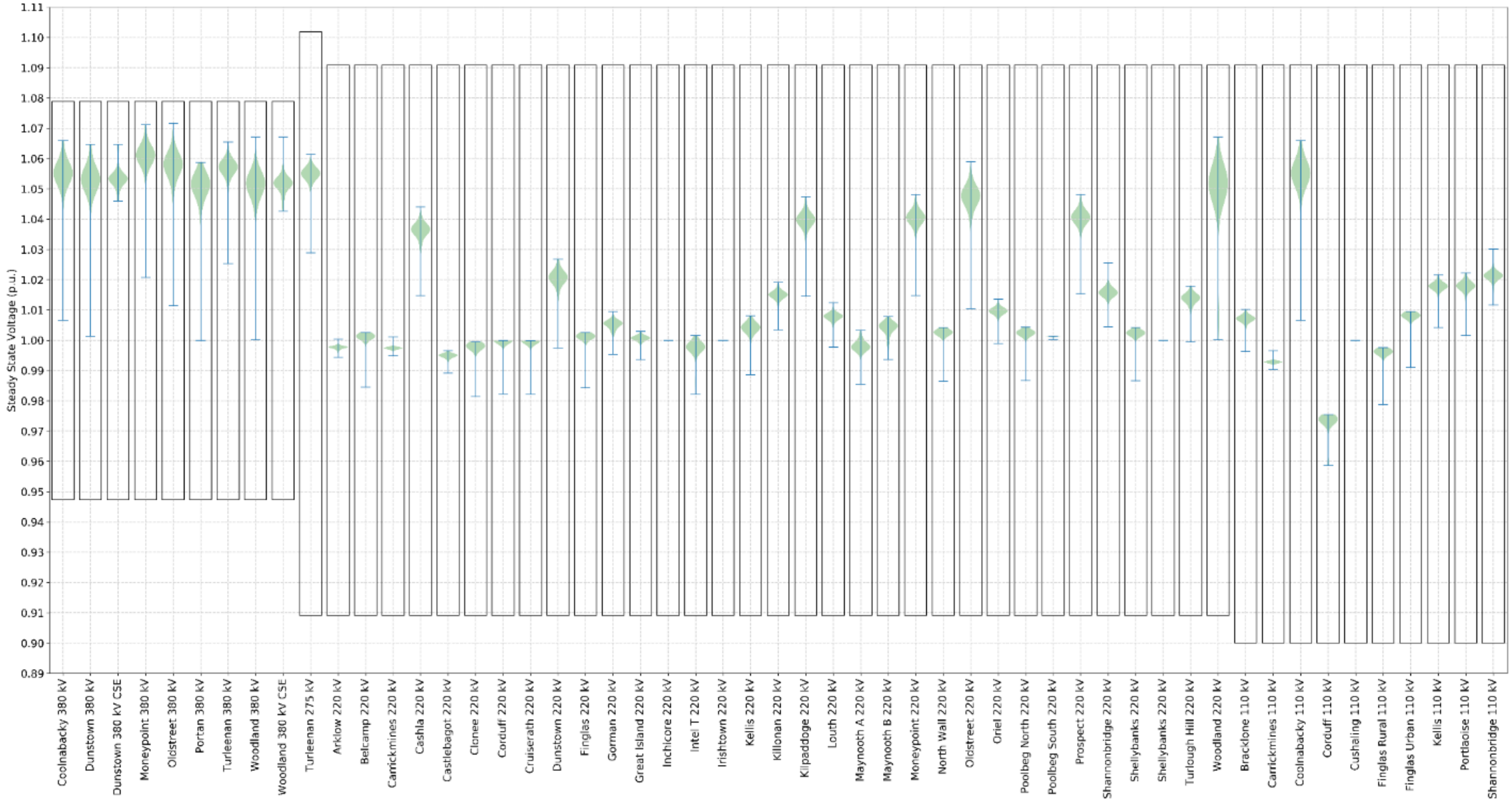

Figure D-5: CP966_UGC400, 1 cable / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario SV HW with no reactive compensation

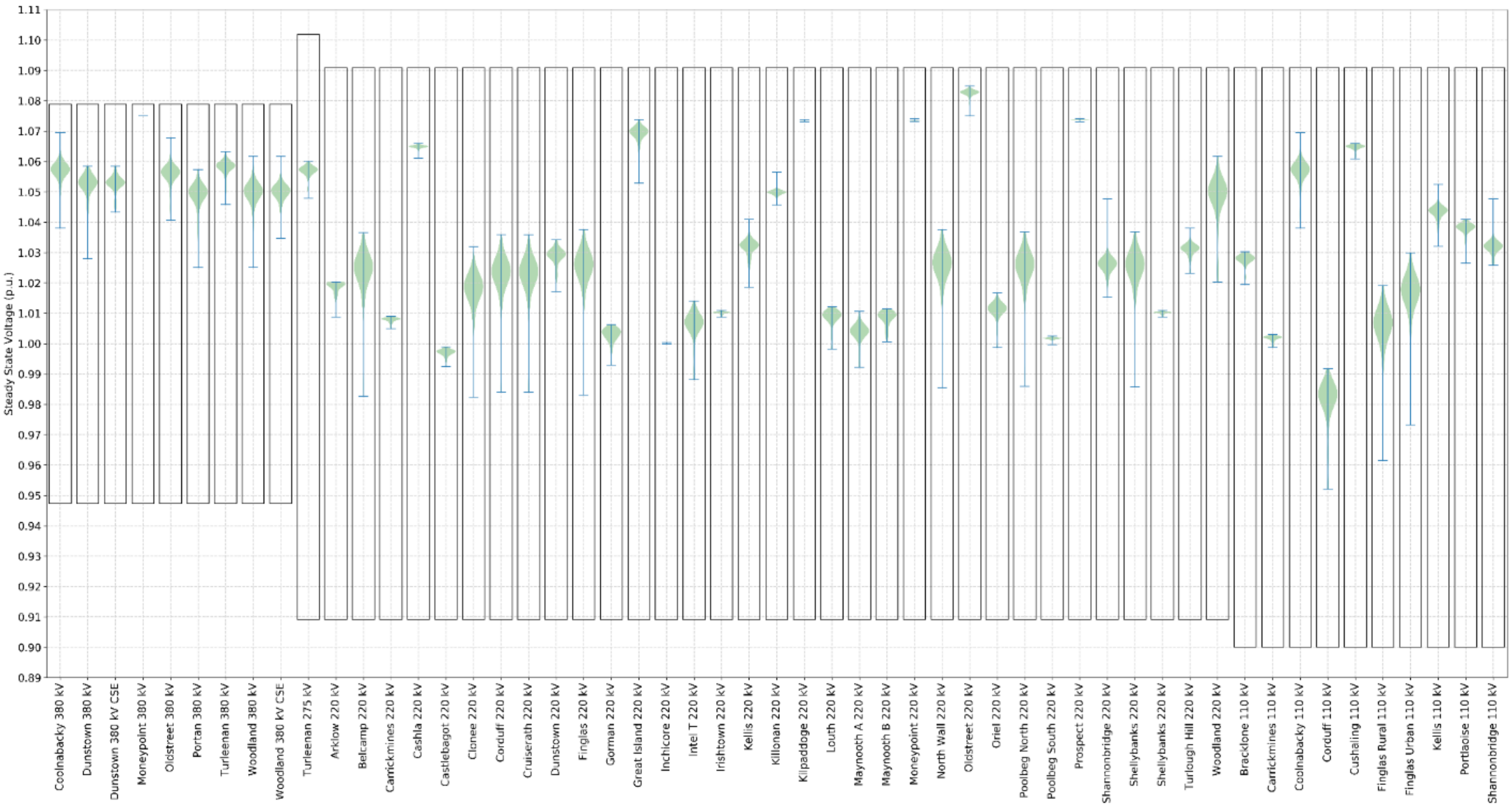

Figure D-6: CP966_UGC400, 1 cable / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario WP HW with no reactive compensation

D.3 Results for CP966_UGC400 2 Cables / Phase Without Reactive Compensation

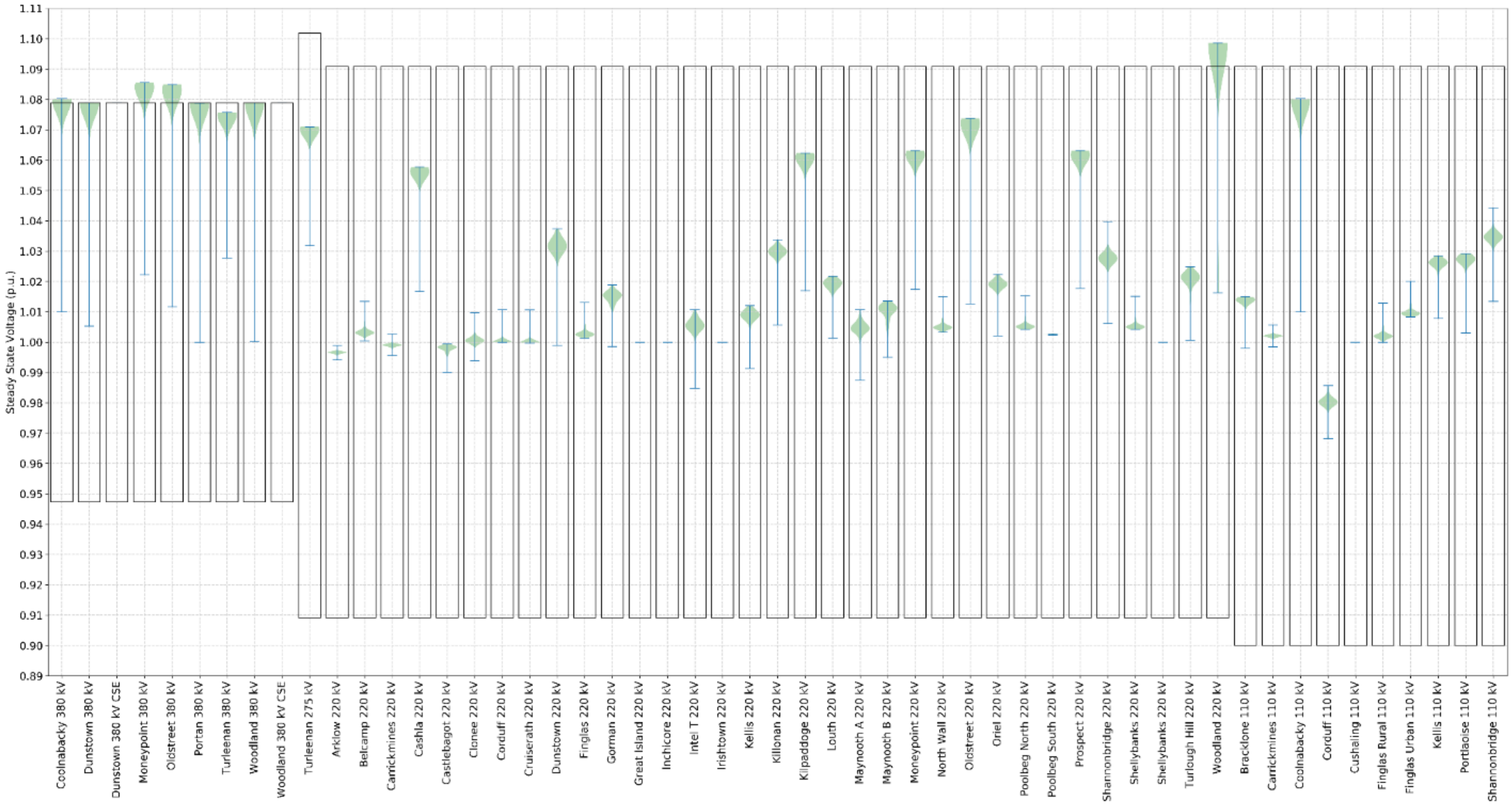

Figure D-7: CP966_UGC400, 2 cables / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario SV LW with no reactive compensation

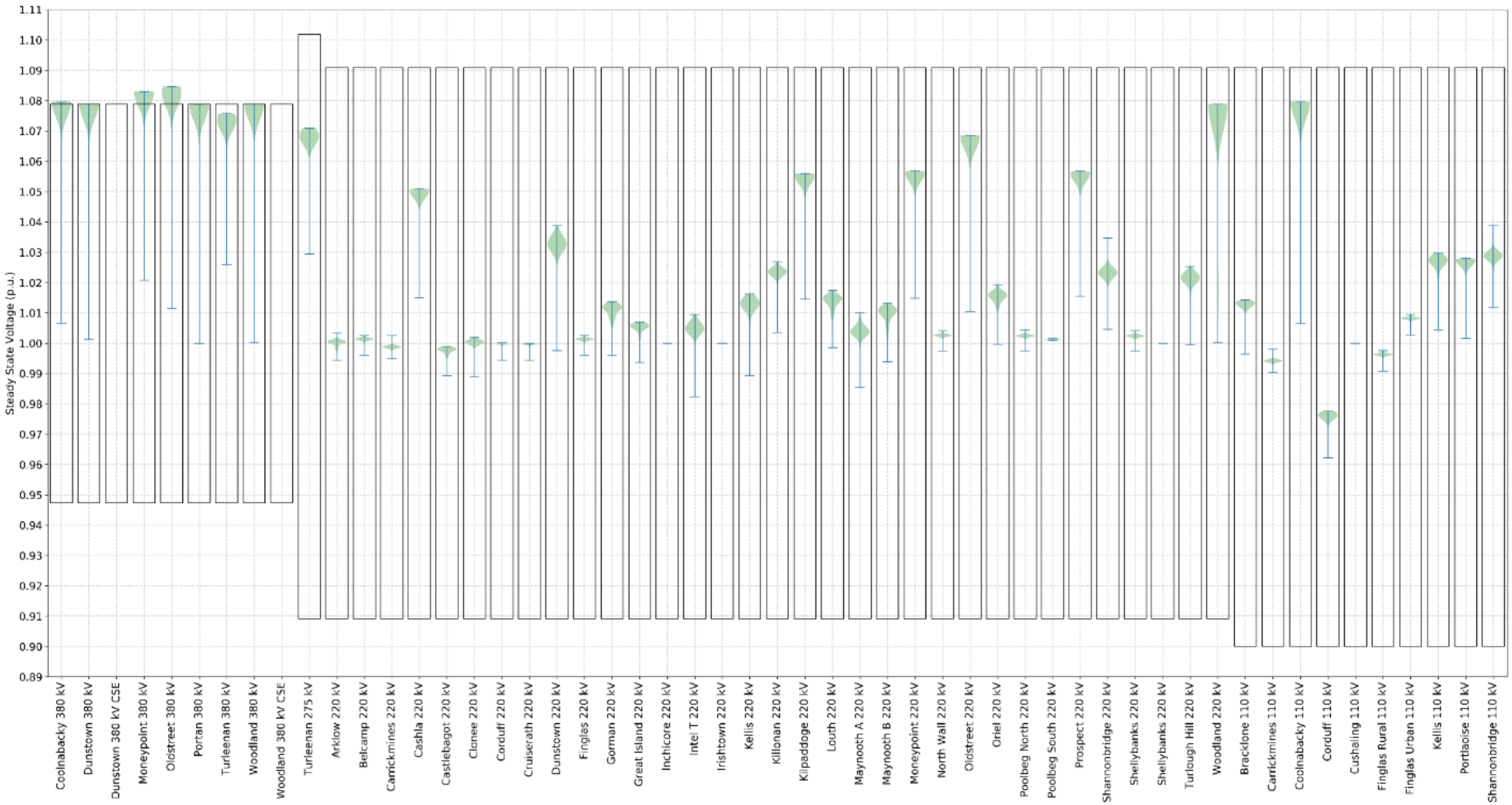

Figure D-8: CP966_UGC400, 2 cables / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario SV HW with no reactive compensation

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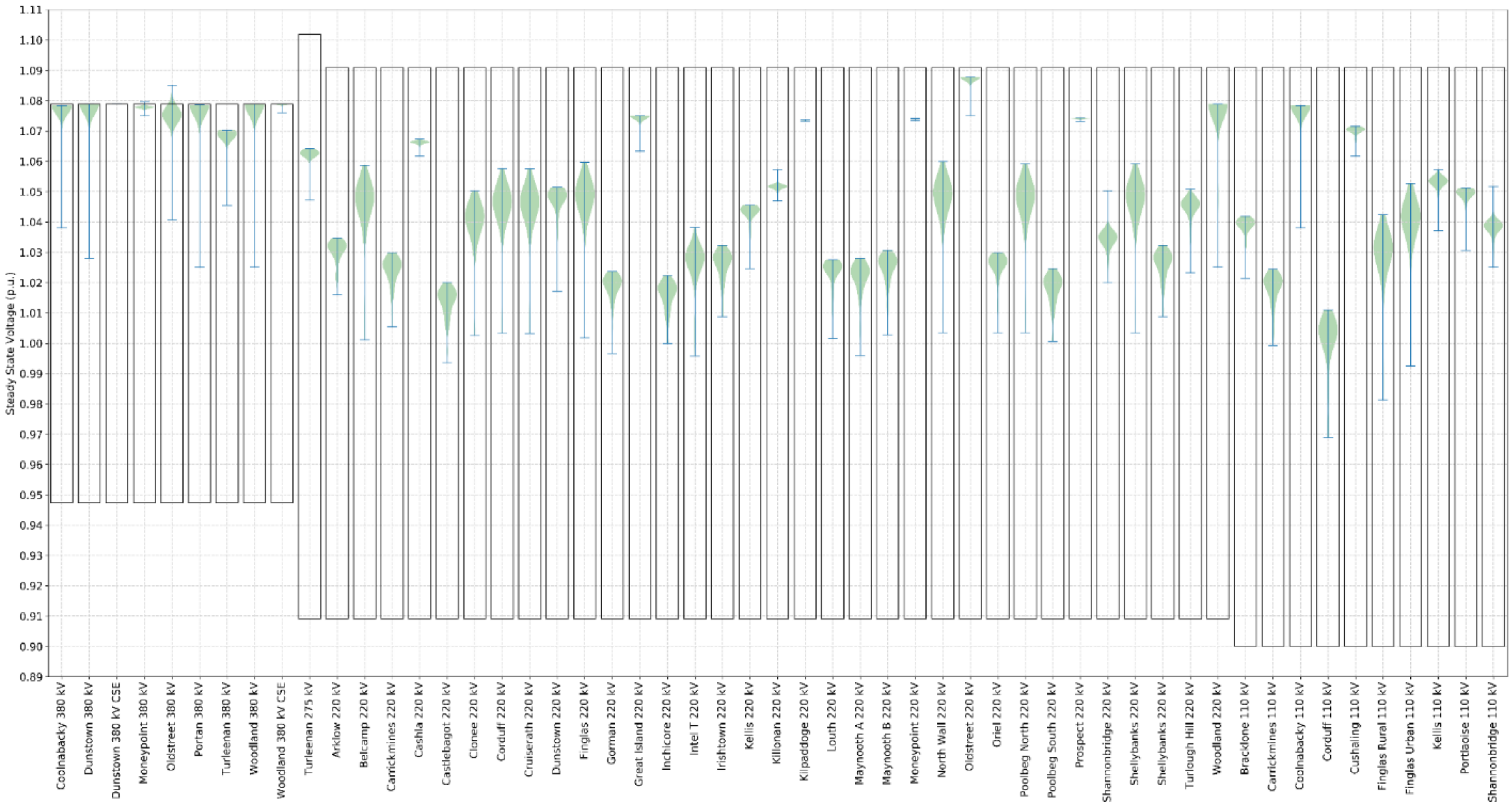

Figure D-9: CP966_UGC400, 2 cables / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario WP HW with no reactive compensation

D.4 Results for CP966_UGC220 With Revised Reactive Compensation

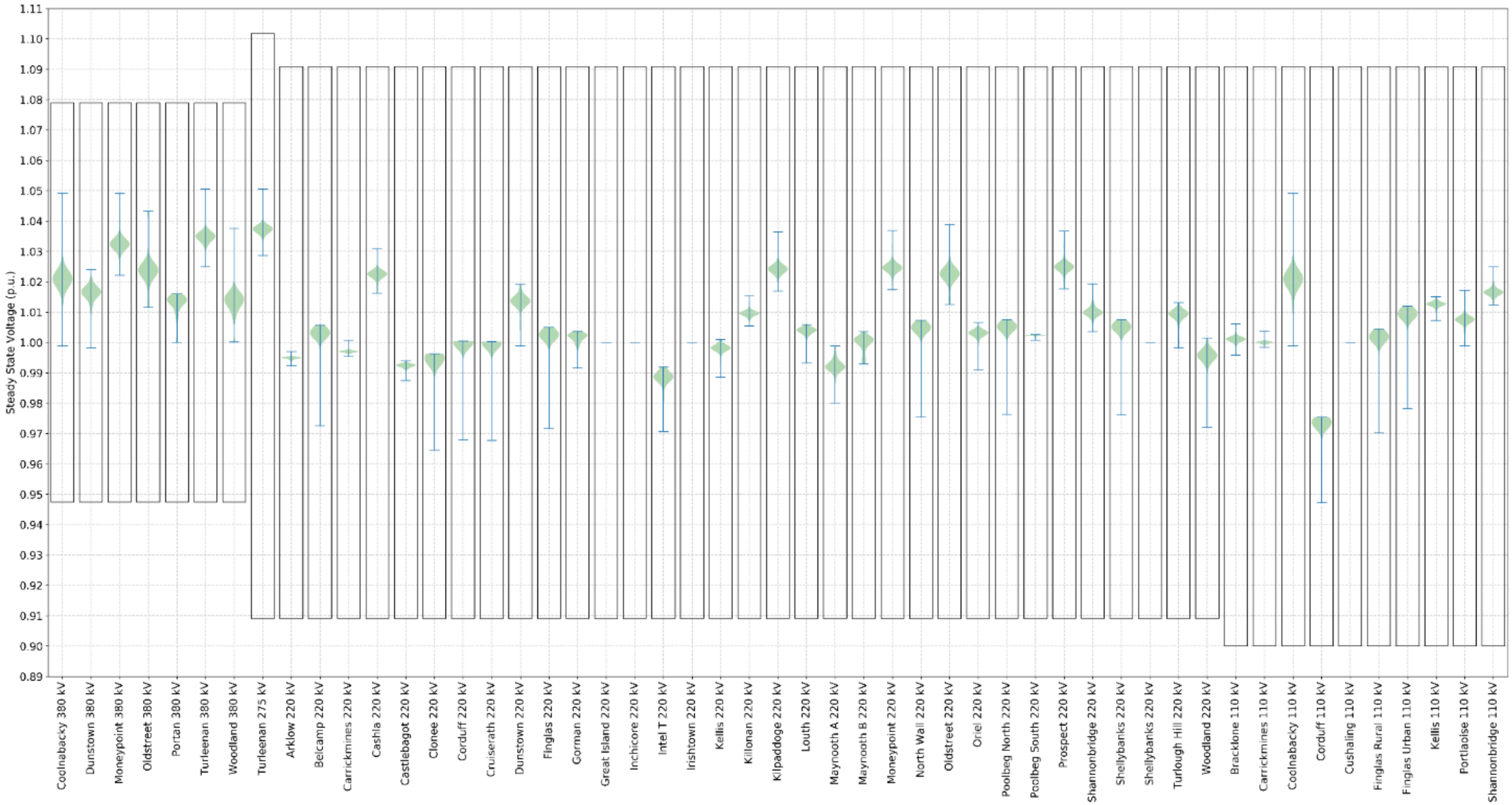

Figure D-10: CP966_UGC220 post-contingency steady state voltages compared against EirGrid limits for operating scenario SV LW with revised reactive compensation (section 6.1)

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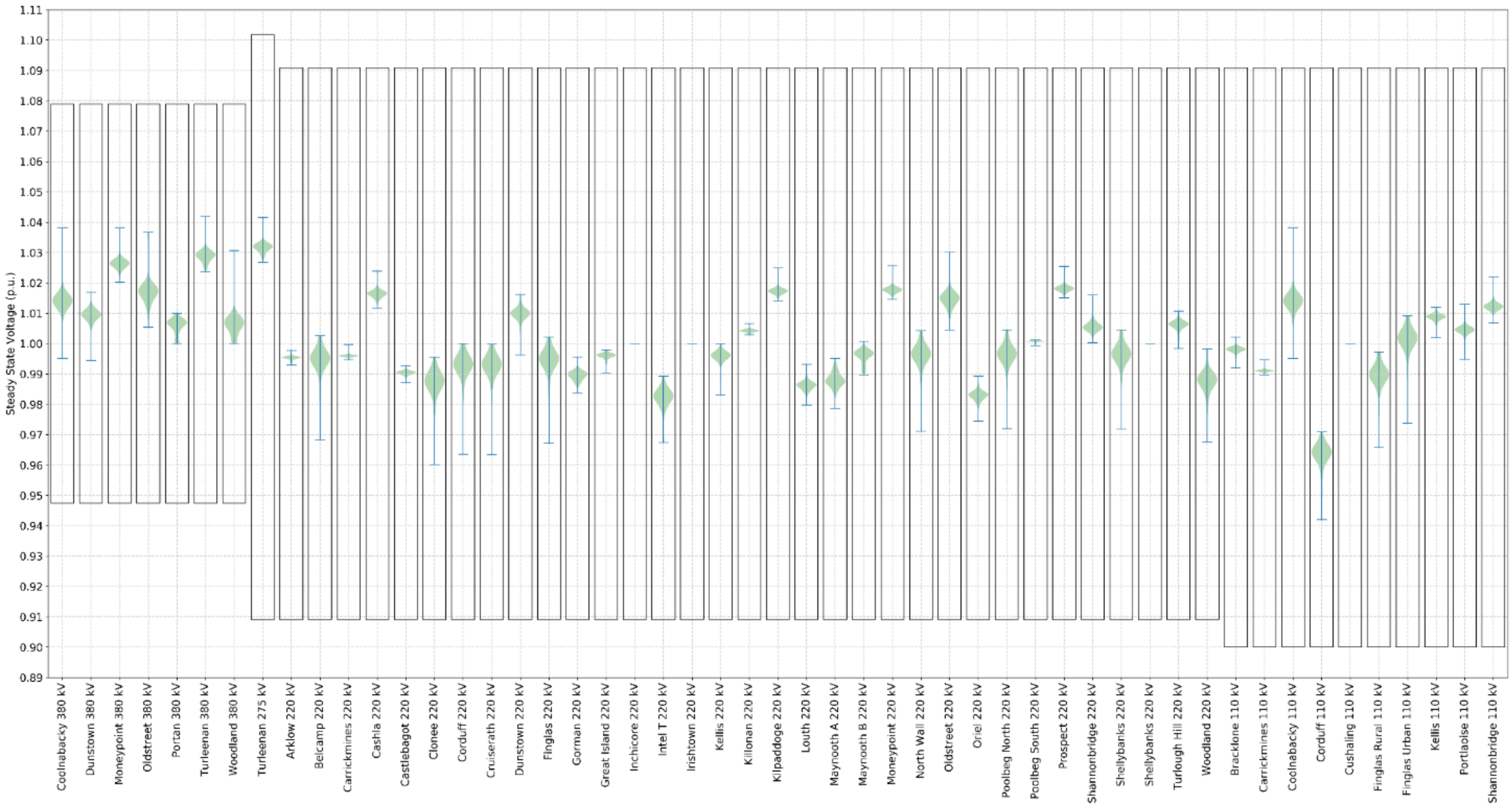

Figure D-11: CP966_UGC220 post-contingency steady state voltages compared against EirGrid limits for operating scenario SV HW with revised reactive compensation (section 6.1)

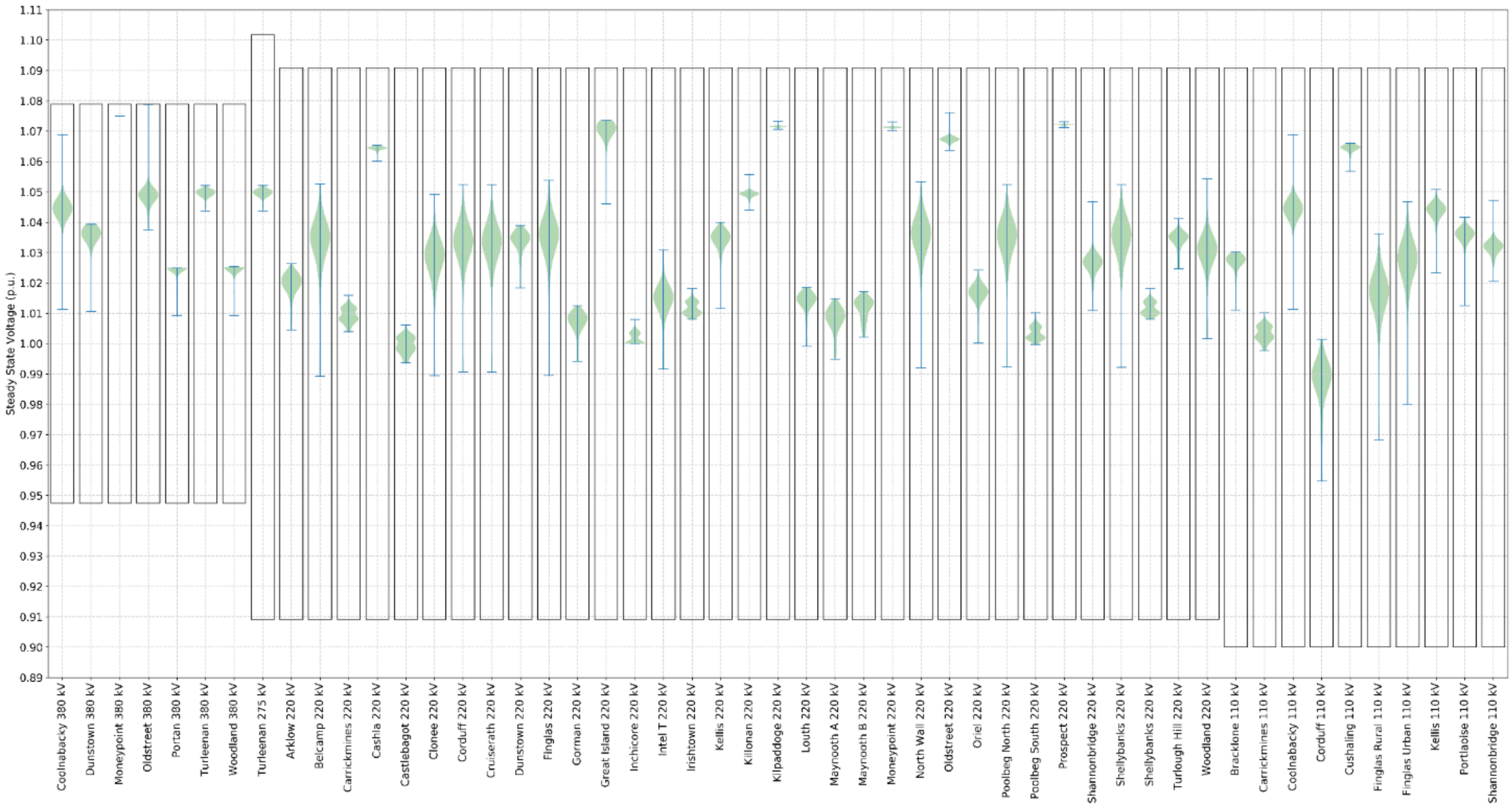

Figure D-12: CP966_UGC220 post-contingency steady state voltages compared against EirGrid limits for operating scenario WP HW with revised reactive compensation (section 6.1)

D.5 Results for CP966_UGC400, 1 Cable / Phase With Revised Reactive Compensation

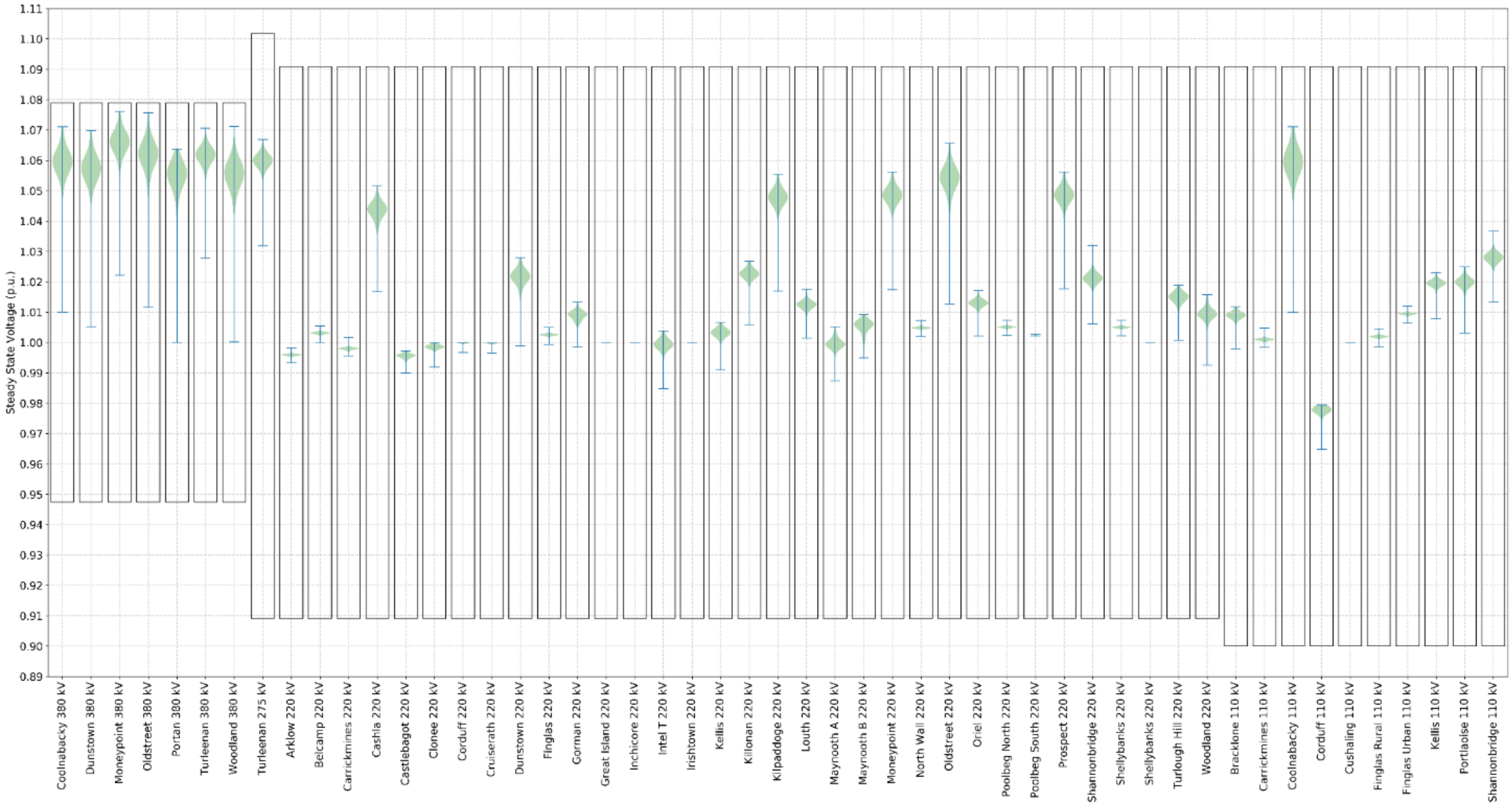

Figure D-13: CP966_UGC400, 1 cable / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario SV LW with revised reactive compensation (section 6.1)

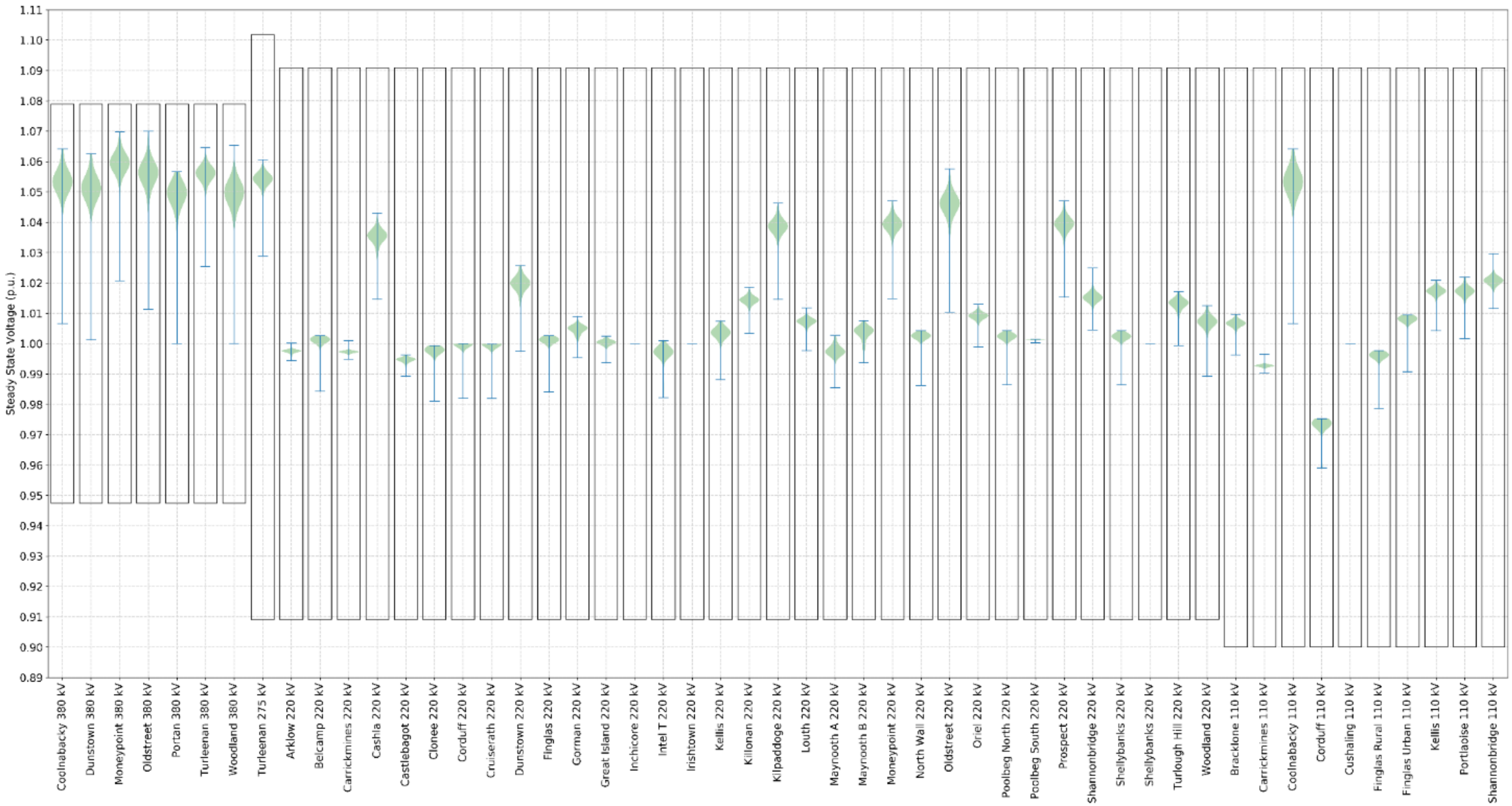

Figure D-14: CP966_UGC400, 1 cable / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario SV HW with revised reactive compensation (section 6.1)

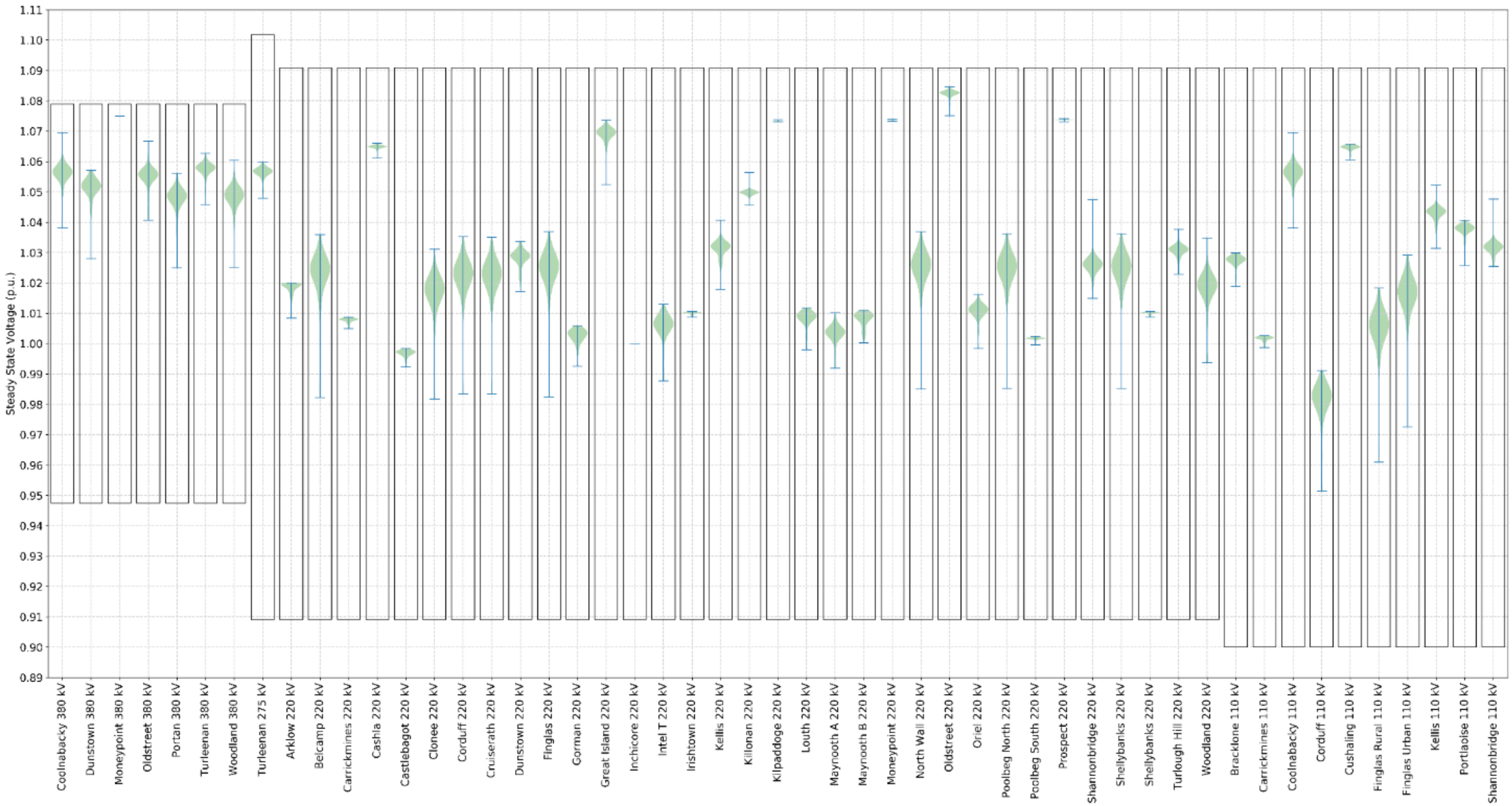

Figure D-15: CP966_UGC400, 1 cable / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario WP HW with revised reactive compensation (section 6.1)

D.6 Results for CP966_UGC400, 2 Cables / Phase With Revised Reactive Compensation

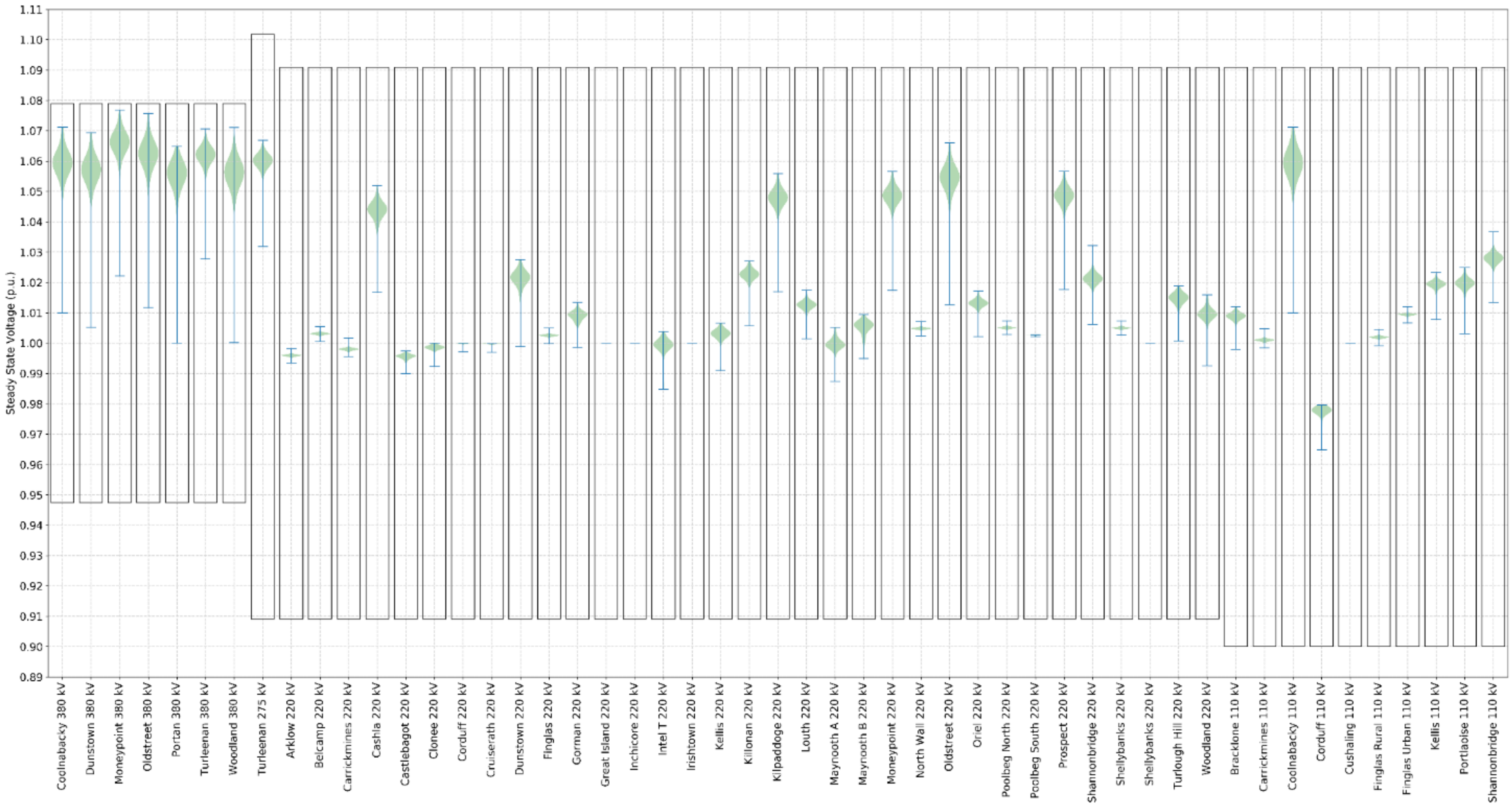

Figure D-16: CP966_UGC400, 2 cables / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario SV LW with revised reactive compensation (section 6.1)

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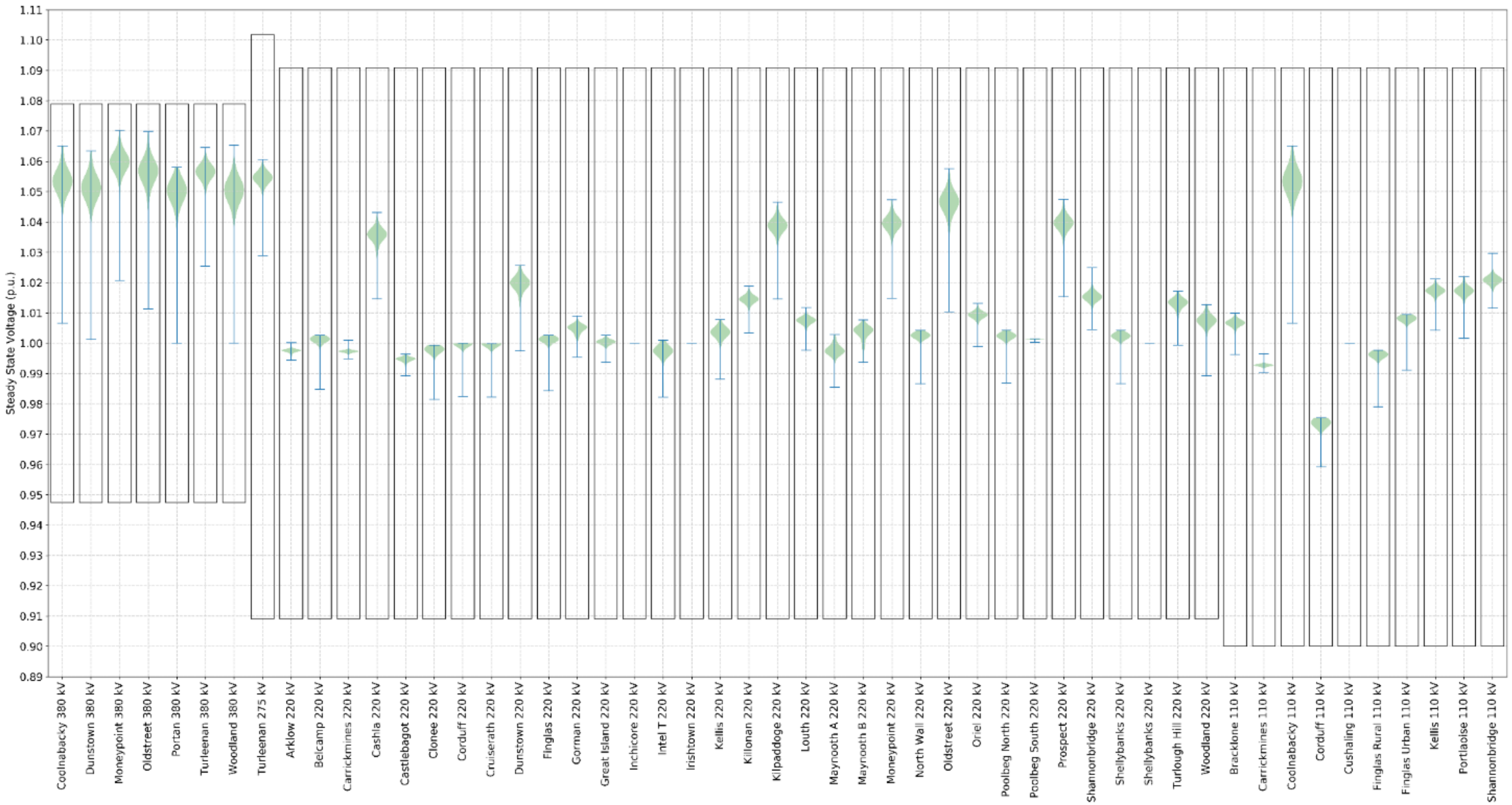

Figure D-17: CP966_UGC400, 2 cables / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario SV HW with revised reactive compensation (section 6.1)

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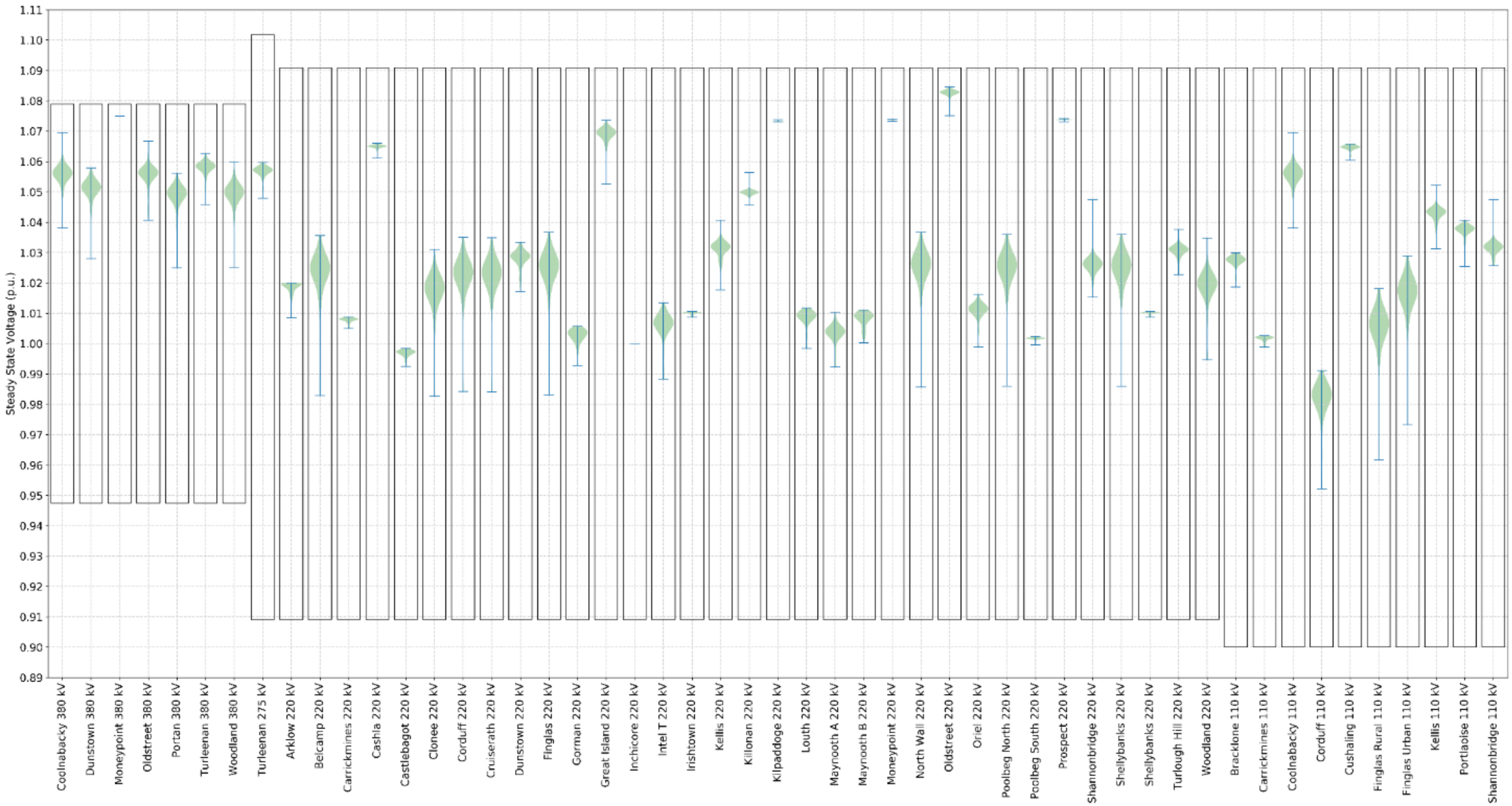

Figure D-18: CP966_UGC400, 2 cables / phase post-contingency steady state voltages compared against EirGrid limits for operating scenario WP HW with revised reactive compensation (section 6.1)

Appendix E Background Harmonic Distortion Data

Table 9-3 presents the background harmonic distortion data used for the harmonic analysis studies.

Table 9-3: Background Harmonic Distortion Data

Backgr.	CLE2	CDU2	CDU1	DSN4	DSN2	FIN2	GOR2	KLS2	CLN4	MAY2A	MAY2B	MAY1	OST4	PRN4	CTB2	CTB1	WOO4	WOO2	BEL2	CKM2	TH2
2	0.27	0.29	0.21	0.20	0.20	0.29	0.23	0.15	0.20	0.27	0.27	0.27	0.25	0.25	0.28	0.28	0.25	0.25	0.31	0.20	0.20
3	0.49	0.48	0.32	0.43	0.43	0.48	0.48	0.44	0.43	0.46	0.46	0.46	0.46	0.46	0.48	0.48	0.46	0.46	0.65	0.43	0.43
4	0.22	0.21	0.23	0.23	0.23	0.21	0.18	0.18	0.23	0.23	0.25	0.23	0.23	0.23	0.26	0.26	0.23	0.23	0.58	0.23	0.23
5	1.29	1.31	0.93	1.09	1.09	1.31	1.38	1.02	1.09	1.50	1.50	1.50	1.08	1.08	1.50	1.50	1.08	1.08	1.50	1.09	1.09
6	0.21	0.23	0.22	0.12	0.12	0.23	0.15	0.14	0.12	0.15	0.22	0.15	0.17	0.17	0.21	0.21	0.17	0.17	0.30	0.12	0.12
7	0.91	0.75	1.16	0.62	0.62	0.75	0.64	0.59	0.62	1.20	1.35	1.20	1.50	1.50	1.50	1.50	1.50	1.50	0.81	0.62	0.62
8	0.30	0.25	0.20	0.11	0.11	0.25	0.13	0.11	0.11	0.14	0.14	0.14	0.18	0.18	0.09	0.09	0.18	0.18	0.19	0.11	0.11
9	0.39	0.12	0.29	0.06	0.06	0.12	0.06	0.05	0.06	0.12	0.13	0.12	0.07	0.07	0.06	0.06	0.07	0.07	0.36	0.06	0.06
10	0.17	0.14	0.04	0.03	0.03	0.14	0.14	0.03	0.03	0.06	0.06	0.06	0.12	0.12	0.05	0.05	0.12	0.12	0.26	0.03	0.03
11	0.19	0.17	0.59	0.16	0.16	0.17	0.17	0.20	0.16	0.27	0.33	0.27	0.15	0.15	0.27	0.27	0.15	0.15	0.22	0.16	0.16
12	0.06	0.04	0.07	0.17	0.17	0.04	0.05	0.07	0.17	0.19	0.21	0.19	0.06	0.06	0.08	0.08	0.06	0.06	0.09	0.17	0.17
13	0.49	0.11	0.25	0.10	0.10	0.11	0.09	0.14	0.10	0.14	0.13	0.14	0.19	0.19	0.13	0.13	0.19	0.19	0.14	0.10	0.10
14	0.13	0.05	0.04	0.06	0.06	0.05	0.04	0.13	0.06	0.08	0.12	0.08	0.07	0.07	0.06	0.06	0.07	0.07	0.17	0.06	0.06
15	0.23	0.10	0.10	0.03	0.03	0.10	0.04	0.03	0.03	0.06	0.06	0.06	0.06	0.06	0.04	0.04	0.06	0.06	0.14	0.03	0.03
16	0.08	0.11	0.03	0.02	0.02	0.11	0.02	0.02	0.02	0.08	0.04	0.08	0.04	0.04	0.03	0.03	0.04	0.04	0.08	0.02	0.02
17	0.20	0.90	0.22	0.07	0.07	0.90	0.14	0.08	0.07	0.14	0.07	0.14	0.16	0.16	0.10	0.10	0.16	0.16	0.12	0.07	0.07
18	0.11	0.19	0.07	0.03	0.03	0.19	0.06	0.05	0.03	0.12	0.05	0.12	0.11	0.11	0.04	0.04	0.11	0.11	0.07	0.03	0.03
19	0.15	0.36	0.20	0.05	0.05	0.36	0.13	0.12	0.05	0.18	0.13	0.18	0.22	0.22	0.13	0.13	0.22	0.22	0.27	0.05	0.05
20	0.03	0.19	0.09	0.03	0.03	0.19	0.03	0.03	0.03	0.09	0.06	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.03	0.03
21	0.04	0.15	0.04	0.03	0.03	0.15	0.03	0.03	0.03	0.11	0.10	0.11	0.08	0.08	0.06	0.06	0.08	0.08	0.06	0.03	0.03
22	0.04	0.18	0.11	0.03	0.03	0.18	0.04	0.18	0.03	0.08	0.10	0.08	0.17	0.17	0.08	0.08	0.17	0.17	0.05	0.03	0.03
23	0.11	0.67	0.27	0.08	0.08	0.67	0.08	0.14	0.08	0.08	0.10	0.08	0.67	0.67	0.10	0.10	0.67	0.67	0.09	0.08	0.08

24	0.06	0.18	0.09	0.05	0.05	0.18	0.06	0.10	0.05	0.11	0.12	0.11	0.15	0.15	0.06	0.06	0.15	0.15	0.07	0.05	0.05
25	0.08	0.25	0.12	0.08	0.08	0.25	0.07	0.09	0.08	0.10	0.10	0.10	0.05	0.05	0.06	0.06	0.05	0.05	0.07	0.08	0.08
26	0.04	0.08	0.06	0.04	0.04	0.08	0.04	0.06	0.04	0.06	0.06	0.06	0.04	0.04	0.04	0.04	0.04	0.04	0.08	0.04	0.04
27	0.04	0.12	0.05	0.03	0.03	0.12	0.03	0.04	0.03	0.05	0.06	0.05	0.07	0.07	0.03	0.03	0.07	0.07	0.10	0.03	0.03
28	0.03	0.05	0.03	0.03	0.03	0.05	0.10	0.03	0.03	0.04	0.04	0.04	0.13	0.13	0.02	0.02	0.13	0.13	0.17	0.03	0.03
29	0.10	0.10	0.10	0.07	0.07	0.10	0.36	0.09	0.07	0.09	0.09	0.09	0.38	0.38	0.05	0.05	0.38	0.38	0.53	0.07	0.07
30	0.03	0.05	0.03	0.04	0.04	0.05	0.03	0.03	0.04	0.02	0.05	0.02	0.09	0.09	0.03	0.03	0.09	0.09	0.10	0.04	0.04
31	0.06	0.05	0.05	0.05	0.05	0.05	0.15	0.03	0.05	0.06	0.10	0.06	0.11	0.11	0.04	0.04	0.11	0.11	0.38	0.05	0.05
32	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.03	0.02	0.04	0.04	0.01	0.01	0.04	0.04	0.16	0.02	0.02
33	0.03	0.04	0.02	0.03	0.03	0.04	0.09	0.03	0.03	0.04	0.06	0.04	0.05	0.05	0.04	0.04	0.05	0.05	0.11	0.03	0.03
34	0.02	0.02	0.04	0.02	0.02	0.02	0.15	0.03	0.02	0.03	0.06	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.15	0.02	0.02
35	0.11	0.10	0.15	0.05	0.05	0.10	0.35	0.08	0.05	0.12	0.15	0.12	0.10	0.10	0.12	0.12	0.10	0.10	0.37	0.05	0.05
36	0.02	0.02	0.06	0.02	0.02	0.02	0.07	0.02	0.02	0.10	0.11	0.10	0.02	0.02	0.03	0.03	0.02	0.02	0.16	0.02	0.02
37	0.09	0.09	0.35	0.05	0.05	0.09	0.22	0.03	0.05	0.12	0.17	0.12	0.08	0.08	0.06	0.06	0.08	0.08	0.40	0.05	0.05
38	0.03	0.03	0.12	0.02	0.02	0.03	0.07	0.02	0.02	0.04	0.05	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.16	0.02	0.02
39	0.02	0.03	0.08	0.03	0.03	0.03	0.06	0.02	0.03	0.04	0.04	0.04	0.03	0.03	0.02	0.02	0.03	0.03	0.15	0.03	0.03
40	0.02	0.02	0.04	0.03	0.03	0.02	0.05	0.02	0.03	0.04	0.05	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.15	0.03	0.03

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