HORSHAM SOLAR FARM
POWER QUALITY STUDY REPORT
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POWER GRID SOLUTIONS PTY LTD

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Executive Summary

Power Grid Solutions Pty Ltd (PGS) was engaged to undertake a power quality assessment for the Horsham Solar Farm (referred to in this report as HSF) following the requirements of the TNSP.

The scope of work covered in this report includes:

- Model preparation for power quality studies in PowerFactory V22 SP4;
- Evaluation of the generator's harmonic emissions;
- Evaluation of the generator's flicker emissions and voltage unbalance;
- Preliminary sizing of the required filter to reduce harmonic emissions to acceptable levels.

A summary of the power quality study's major findings is presented as follows:

- **Harmonic contribution:** several individual orders exceed allocated limits without shunt or harmonic filters in service. The 7/10/11/17/35/38/40/41/43/50th orders are expected to exceed the limits without filters in service.

- With the proposed shunt filters in service, all individual harmonic orders are expected to be below TNSP limits. Two options have been proposed as follows:

  - Option 1 is a 9 Mvar shunt filter tuned at the 17th order and a 1 Mvar shunt filter tuned at the 40th order. This option will meet both allocated and planning limits with and without consideration of the future background harmonic distortions.

  - Option 2 is a 5 Mvar shunt filter tuned at the 17th and a 5 Mvar shunt filter tuned at the 34.8th order. With this option, the 7th order marginally exceeds the allocated limit (0.19 vs 0.17) without considering future background harmonics. Considering future background harmonics, this option achieves compliance for both allocated and planning limits.

- **Flicker contribution**: the flicker contribution from HSF is expected to be below the specified limits. The short and long-term flicker disturbance factors are below TNSP flicker emission allocation limits of 0.35 and 0.25 for Pst and Plt respectively. The ***Automatic Access Standard*** is proposed.

- **Voltage unbalance:** HSF is not expected to contribute to negative sequence voltages. There may be a small contribution due to loading on the station auxiliary transformer (≤ 315 kVA). However, this is expected to be insignificant. The SMA-provided certificate states that individual inverter contributions will be less than 0.1%. This value is below the limit specified in Table S5.1a.1.

Abbreviations

Table 1: Abbreviations

Abbreviations	Description
HD	Harmonic Distortion
EMT	Electromagnetic Transient
FFT	Fast Fourier Transform
HSF	Horsham Solar Farm
NER	National Electricity Rules
POC	Point of Connection
SLD	Single Line Diagram
VTHD	Voltage Total Harmonic Distortion
TNSP	Transmission Network Service Provider

1 Introduction

1.1 Plant description

Power Grid Solutions Pty Ltd (PGS) has been engaged to undertake a power quality assessment for the Horsham Solar Farm (HSF) following the requirements of the TNSP.

The proposed HSF will comprise 36 x SMA 4200 UP PV inverters for a total installed capacity of 151.2 MVA.

Under favourable system operating conditions (at 35 °C) HSF will be capable of exporting 118 MW via the 220 kV Point of Connection (POC).

HSF will connect to the 220 kV POC via a single 220/33 kV 170 MVA, YNd11, Z= 16.8% power transformer.

1.2 Purpose

This report includes the following power quality studies:

- Harmonics assessment (total and HSF contribution)
- Flicker assessment
- Voltage unbalance assessment
- Preliminary shunt filter sizing within the 10 Mvar specified limit

The proposed simplified connection arrangement for HSF is shown in SLDs in **Appendices A**. A detailed model developed in DIgSILENT PowerFactory V22, SP4 package was used for the assessment. The SLD of this model is shown in **Appendix D**.

This report evaluates HSF harmonic voltage distortion, both total distortion and HSF contribution, flicker, and voltage unbalance; and makes recommendations based on modelling information provided by the Client and the TNSP emission limits.

1.3 Referenced documents and drawings

Table 2: Reference documents and drawings

Reference	Title	Rev.
[1]	NER – Version 199. Available at: https://energy-rules.aemc.gov.au/ner/468	-
[2]	SMA.Technical Guidelines for Power Generating Units and Systems, Part 3	-
[3]	SMA. Norton and Thevenin Harmonic Models for SC 4200 UP. File name" 200804_Norton_Thevenin_SC4200UP_all.pdf"	-
[4]	AS/NZS 61000.3.6:2012. Electromagnetic Compatibility (EMC) - Limits - Assessment of emission limits for distorting loads in MV and HV power systems.	-
[5]	AS/NZS 61000.3.7:2012. Electromagnetic Compatibility (EMC) - Limits - Assessment of emission limits for fluctuating loads in MV and HV power systems	-
[6]	ENA Guidelines for Power Quality: Harmonics. Recommendations for the application of the Joint Australian/New Zealand Technical Report TR IEC 61000.3.6:2012	-
[7]	IEC 61400 Part 21: Measurement and Assessment of Power Quality Characteristics of Grid Connected Wind Turbines, 2001.	-
[8]	MWTS_20230130_20230222_BackgroundHarmonics	-
[9]	20230221_Harmonic_Allocations_RE Horsham SF - Harmonics	-
[10]	20230207_HOTS_BESS_ Impedance Scans	-
[11]	IEC 60871-1:2014: Shunt capacitors for a.c. power systems having a rated voltage above 1 000 V	-
[12]	IEC 60076-6:2007: Power transformers - Part 6: Reactors	-
[13]	TransGrid. Harmonic Assessment Requirements Guide. Technical Report Version 1.0, TransGrid, January 2020.	-
[14]	SMA. Saturation curve (by calculation)_LV. Technical report, File name "Step-up_Transformer_Saturation_Curve.pdf", 07.06 2021.	-
[15]	Horsham Solar Farm and Bess (HOR DE-3001)	M
[16]	Horsham Solar Farm Single Line Diagram (HOR DE-3002)	D
[17]	20220926_HORSF_Cable_Aggr	-
[18]	DIgSILENT GmbH, Heinrich-Hertz-Strasse 9, 72810 Gomaringen / Germany. DIgSILENT PowerFactory Version 2022. User Manual, January 2022.	-
[19]	Network modelling for harmonic studies, Cigre, Reference:766, April 2019	-

2 Power system modelling and assumptions

2.1 Power quality assessment criteria

2.1.1 Harmonic voltage emission limits

Access standard requirements for harmonic voltage emission limits have been determined and provided by the TNSP and are shown in Table 3 [9].

Table 3: TNSP Individual harmonic and V_{THD} criteria for 220 kV network

Harmonic Order (h)	Planning limit (%V)	Allocated Limit (%V)	Harmonic Order (h)	Planning limit (%V)	Allocated Limit (%V)
2	1.40	0.10	**26**	0.23	0.10
3	2.00	0.10	**27**	0.20	0.10
4	0.80	0.10	**28**	0.23	0.10
5	2.00	0.17	**29**	0.70	0.11
6	0.40	0.10	**30**	0.22	0.10
7	2.00	0.17	**31**	0.66	0.11
8	0.40	0.10	**32**	0.22	0.10
9	1.00	0.10	**33**	0.20	0.10
10	0.35	0.10	**34**	0.22	0.10
11	1.50	0.27	**35**	0.58	0.10
12	0.32	0.10	**36**	0.21	0.10
13	1.50	0.27	**37**	0.55	0.10
14	0.30	0.10	**38**	0.21	0.10
15	0.30	0.10	**39**	0.20	0.10
16	0.28	0.10	**40**	0.21	0.10
17	1.20	0.18	**41**	0.50	0.10
18	0.27	0.10	**42**	0.21	0.10
19	1.07	0.18	**43**	0.47	0.10
20	0.26	0.10	**44**	0.20	0.10
21	0.20	0.10	**45**	0.20	0.10
22	0.25	0.10	**46**	0.20	0.10
23	0.89	0.13	**47**	0.43	0.10
24	0.24	0.10	**48**	0.20	0.10
25	0.82	0.13	**49**	0.42	0.10
-	-	-	**50**	0.20	0.10
-	**-**	-	**V_{THD}**	**-**	**0.35**

2.1.2 Flicker criteria

Access standard requirements for flicker have been determined and provided by the TNSP and are shown in Table 4 [9].

Table 4: TNSP flicker criteria for 220 kV network

	Limit
Pst	0.35
Plt	0.25

2.1.3 Voltage unbalance criteria

Access standard requirements for voltage unbalance have been provided in Table S5.1a.1 [1] and [9].

Table 5: Voltage unbalance criteria for 220 kV network

Nominal supply voltage (kV)	Maximum negative sequence voltage (% of nominal voltage)			
	No contingency event	Credible contingency event or protected event	general	Once per hour
	30 minute average	30 minute average	10 minute average	1 minute average
220 kV	0.5	0.7	1.0	2.0

2.2 Modelling data and assumptions

2.2.1 Network impedance

The network harmonic impedance scan data at the HSF 220 kV POC was provided by the TNSP [10].

To determine the maximum voltage distortion at the connection point, an iterative harmonic load flow calculation was performed to scan the area within the user-defined R/X impedance plan for each harmonic order and report the highest (worst) voltage distortion. Refer to **Appendix F** for the derived polygons used in the study.

2.2.2 DIgSILENT PowerFactory 2022 SP4

A detailed model was created to represent the HSF including all key components such as individual inverters and the MV collector reticulation system [15 & 16]. Details of modelling information are contained in the PowerFactory model and SLDs used for modelling are shown in **Appendices A and C.**

2.2.3 HSF grid connection

The NEM is represented as a Thévenin equivalent of the external network, comprising a constant harmonic voltage source applied in series with the source impedances that lie on the boundary of the harmonic impedance ranges.

- The future background harmonic spectrum was used for calculating emissions in the presence of background distortion.

- The external grid element was set to control the fundamental frequency voltage magnitude and phase angle at the POC to 1.00 p.u. and 0 degrees.

2.2.4 HSF interconnection transformer

The grid connection transformer was given as 170 MVA 220/33 kV YNdn11 with an impedance Z = 16.8%.

The main transformer's frequency-dependent winding resistance was modelled as per the guidelines provided in [19].

The main transformer is operating on the principal tap in the harmonic assessment.

2.2.5 Solar farm reticulation

The MV cables were provided by the Client [17]. However, the 220 kV short cable between the main transformer HV and the POC data was not available at the time of writing this report. Hence, PGS data from the *Cable Grid catalogue* was assumed, and 200 m was used as advised by the Client.

Cables' frequency-dependent resistances were modelled as per the guideline provided in [19].

2.2.6 Reactive plant and reactive power capability

Except for the 10 Mvar shunt filters proposed in this report, it is assumed there are no other reactive plants to be connected at the 33 kV bus.

2.2.7 PCU inverters and transformers

A Norton equivalent model of the inverter is required to consider the impact that the inverters have on the solar farm impedance and emissions.

Norton equivalent information was provided by SMA [3].

In using the Norton equivalent model it was further assumed that:

- The series impedance of the inverter transformer contributed to the dominant part of the source impedance during the testing;
- The inverter Norton impedances provided by SMA are correct;
- The background harmonic voltages in the 50 Hz supply system were low during the tests;
- The 33 kV Norton equivalent current spectra and impedance characteristics used in the analysis are provided in Table 8.

2.2.8 Transformer excitation harmonic currents

The main transformer excitation harmonic currents were calculated in the 50 Hz model of the solar farm using data provided by the Client. PCU transformer excitation currents were calculated based on SMA typical data and assumed flux density. It is anticipated that the proposed solution will be revised with Vendor supplied data at the R1 stage and before the procurement of the shunt filters:

- *Main Transformer*: an electromagnetic transient (EMT) analysis was performed in PSCAD with the highest expected 50 Hz voltages applied across the unloaded main transformer terminals, and a Fast Fourier Transform (FFT) was performed on the HV side current waveform. The magnitudes of the main transformer excitation currents in Table 11, were applied as an ideal current source connected to the POC and considered in phase with the inverter emissions according to [13].

- *PCU transformers*: similarly an EMT analysis was performed in PSCAD using data in Table 6 with the highest expected 50 Hz voltages applied across the unloaded inverter transformer terminals. 6x the magnitude of the inverter transformer excitation currents were applied in phase with the inverter emissions according to [13] per collector group.

Table 6: Transformer excitation data used in PSCAD modelling

Parameter	220/33 kV 170 MVA transformer	33/0.63 kV 4.2 MVA transformer
Configuration		
3 Phase Transformer MVA	170 MVA	4.2 MVA
Base Operation frequency	50 Hz	50 Hz
Winding #1 Type	Y	D
Winding #2 Type	Delta	Y
Positive sequence leakage Reactance	0.168 pu	0.065 pu
Ideal Transformer Model	No	No
Eddy Current losses	0.01 pu	0.01 pu
Copper losses	0.003529 pu	0.0127 pu
Saturation - to be validated with actual vendor data during R1 stage before the procurement of the shunt fitlers		
Saturation Enabled	Yes	Yes
Place Saturation on Winding	Middle	Middle
Hysteresis	Jiles_Atherton	Jiles_Atherton
Inrush Decay time constant	2.5 s	2.5 s
Time to release flux clipping	0.0 s	0.0 s
Air core reactance	0.3727 pu	0.0244 pu
Magnetising current	0.0436 %	1 %
Knee voltage	1.1 pu	1.1 pu
Remanant Flux Core 1	0.6	0.6
Remanant Flux Core 2	-0.3	-0.3
Remanant Flux Core 3	-0.3	-0.3
Nominal Flux Density (T)	1.9	1.72

Refer to **Appendix E** for PSCAD modelling details

2.3 Network fault levels

Table 7: 3 Ph Fault levels considered for the power quality model

Location	Bus ID	System Normal fault (MVA)		Minimum fault (MVA)	
		MVA	X/R	MVA	X/R
220 kV POC	HOTS BUS 1	1109	3.43	483	3.42

The above figures were provided by the Client

2.4 Minimum fault level for flicker assessment

For flicker assessment, the lowest fault level is calculated using the provided fault level at POC in **Section 2.3**

- The minimum 3 Phase fault level at the 220 kV POC is 483 MVAsc
- X/R corresponding to the minimum 3 Phase fault is 3.42

2.5 Study cases

Harmonic studies were undertaken for the proposed system configurations. The following methodology and sequencing were used in developing scenarios as shown in Table 7.

Table 8: Case studies for harmonic simulations

Case Study	Case Study Description
PQOC01	PV export without the shunt filters in service
PQOC02	PV export with the proposed shunt filters in service

220 kV POC simulated power flow results for PQOC01 to PQOC02 are documented in **Section 3.3.**

2.6 Inverter harmonic emissions

HSF will comprise 36 x 4.2 MVA SMA PV inverters. The harmonic emissions for a single PV inverter at 100% loading were provided and these are shown in Table 9 [2]. 100% harmonic loading represents the worst-case scenario. Tables 9 and 10 summarise the 33 kV Norton equivalent impedances used for the inverters [3].

Table 9: Inverter THD at 100% harmonic loading for one 4.2 MVA inverter

Harmonic Order (h)	100% Loading Limit (%) Day-time	Harmonic Order (h)	100% Loading Limit (%) Day-time
	-	**26**	0.05
2	0.08	**27**	0.03
3	0.05	**28**	0.05
4	0.08	**29**	0.05
5	0.21	**30**	0.04
6	0.03	**31**	0.04
7	0.21	**32**	0.10
8	0.09	**33**	0.02
9	0.02	**34**	0.03
10	0.10	**35**	0.05
11	0.15	**36**	0.01
12	0.02	**37**	0.02
13	0.12	**38**	0.03
14	0.03	**39**	0.01
15	0.04	**40**	0.02
16	0.04	**41**	0.03
17	0.02	**42**	0.01
18	0.02	**43**	0.02
19	0.04	**44**	0.02
20	0.03	**45**	0.01
21	0.02	**46**	0.03
22	0.03	**47**	0.02
23	0.02	**48**	0.00
24	0.02	**49**	0.03
25	0.03	**50**	0.04

Table 10: 33 kV Norton equivalent impedances for 4.2 MVA inverters

Harmonic Order (h)	R (Ω)	X (Ω)	Harmonic Order (h)	R (Ω)	X (Ω
1	-	-	**26**	104.70	260.18
2	2.00	188.78	**27**	97.66	347.11
3	2.12	287.17	**28**	91.96	426.89
4	2.39	390.80	**29**	87.25	501.01
5	2.97	502.23	**30**	83.31	570.56
6	4.12	624.96	**31**	79.97	636.38
7	6.32	764.06	**32**	77.12	699.10
8	10.53	927.34	**33**	74.65	759.22
9	18.67	1127.67	**34**	72.50	817.14
10	35.17	1388.04	**35**	70.61	873.17
11	71.38	1754.02	**36**	68.94	927.57
12	162.82	2329.96	**37**	67.46	980.56
13	461.73	3411.90	**38**	66.14	1032.31
14	2160.39	6104.44	**39**	64.95	1082.98
15	14329.12	-1234.04	**40**	63.88	1132.67
16	2401.60	-4413.20	**41**	62.91	1181.51
17	858.16	-2376.74	**42**	62.03	1229.57
18	472.44	-1473.38	**43**	61.22	1276.95
19	317.20	-967.59	**44**	60.49	1323.70
20	237.87	-637.88	**45**	59.81	1369.89
21	191.16	-400.56	**46**	59.19	1415.56
22	160.95	-217.58	**47**	58.62	1460.77
23	140.09	-69.23	**48**	58.09	1505.54
24	124.95	55.69	**49**	57.60	1549.93
25	113.55	164.03	**50**	57.14	1593.96

Table 11: 170 MVA Main and 4.2 MVA PCU transformers estimated excitation harmonic currents

Harmonic Order (h)	170 MVA Main Transformer ($I_{HV,h}$ / %)	4.2 MVA PCU Transformer ($I_{HV,h}$ / %)	Harmonic Order (h)	170 MVA Main Transformer ($I_{HV,h}$ / %)	4.2 MVA PCU Transformer ($I_{HV,h}$ / %)
1	-	-	**26**	0.00	0.000
2	13.40	3.880	**27**	0.00	0.000
3	10.60	1.000	**28**	0.00	0.000
4	1.47	0.074	**29**	0.00	0.000
5	1.26	0.388	**30**	0.00	0.000
6	1.29	0.400	**31**	0.00	0.000
7	0.45	0.221	**32**	0.00	0.000
8	0.49	0.205	**33**	0.00	0.000
9	0.59	0.160	**34**	0.00	0.000
10	0.16	0.142	**35**	0.00	0.000
11	0.30	0.036	**36**	0.00	0.000
12	0.21	0.010	**37**	0.00	0.000
13	0.04	0.020	**38**	0.00	0.000
14	0.23	0.086	**39**	0.00	0.000
15	0.00	0.000	**40**	0.00	0.000
16	0.00	0.000	**41**	0.00	0.000
17	0.18	0.000	**42**	0.00	0.000
18	0.00	0.000	**43**	0.00	0.000
19	0.00	0.000	**44**	0.00	0.000
20	0.14	0.000	**45**	0.00	0.000
21	0.05	0.000	**46**	0.00	0.000
22	0.00	0.000	**47**	0.00	0.000
23	0.00	0.000	**48**	0.00	0.000
24	0.00	0.000	**49**	0.00	0.000
25	0.00	0.000	**50**	0.00	0.000

3 Harmonic analysis

3.1 Harmonic modelling

Harmonic order entries as shown in Table 9 were used for each inverter. Impedance scans have been provided by the TNSP [10]. 100-2500 Hz polygons were determined from impedance scans. Each polygon represents 20 cases as described in [10]. The polygons are processed by the in-built impedance loci script in PowerFactory to determine the worst-case Harmonic Distortion (HD) at the 220 kV POC. **Appendix F** summarises the polygons used in the study.

3.2 Harmonic compliance assessment

3.2.1 Summation of harmonic emissions from inverters

Modelling and analysis of voltage distortion at POC are conducted using PowerFactory following [4,5,6]. The following equation is used for the summation of harmonics from all connected inverters. This analysis is performed automatically within PowerFactory software.

$$U_h = \sqrt[\alpha]{\sum_{i=1}^{\mathbb{N}_{\omega t}} U_{hi}^{\alpha}} \qquad (1)$$

where

N_{wt}	*is the number of inverters connected;*
U_h	*is the magnitude of the various individual emission levels (order h) to be combined;*
U_{hi}	*is the emission level of the i-inverter*
α	*is the summation exponent for harmonics: an exponent equal to 1 for harmonic < 5th order and 1.4 for harmonics from 5th to 10th; and equal to 2 for harmonics > 10th order.*

For the ***worst-case scenario*** alpha was set to 1 for all harmonic orders, i.e. harmonics are added scalarly (arithmetically) rather than vectorially.

3.2.2 Evaluation methodology

Harmonic emissions are apportioned such that when all sources of emissions are connected to the power system, the planning levels L_h at the POC must not be exceeded. By separating the new distorting loads from other loads and allocating the value of E_h, and summating all contributions from other sources expressed at the POC as pre-connection distortion $U_{Ext,h}$, the following equation applies:

$$L_h \geq \sqrt[\alpha]{U_{Ext,h}^{\alpha} + E_h^{\alpha}} \qquad (2)$$

The summation exponent alpha is described in Section 7 of the “General summation law” in [4], and its selection is guided by the degree to which individual harmonic voltages vary randomly in terms of magnitude and phase.

Figure 3 represents the harmonic contribution of the new generator and the contribution of all other sources of harmonics.

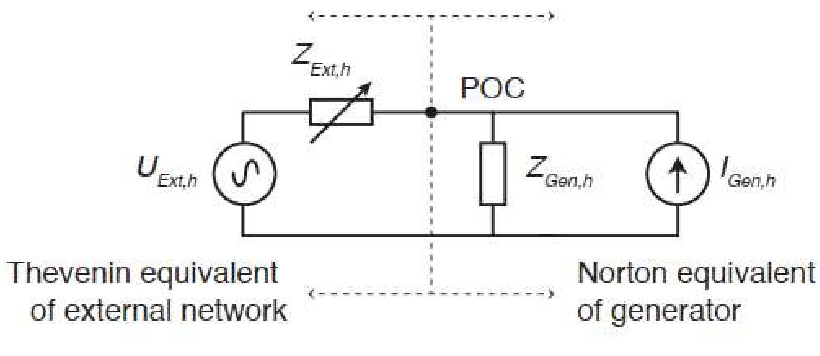

Figure 1: External network and generator representation

The contribution of the new generator is calculated via Ohm's law:

$$V_{1,h} = I_{Gen,h} \frac{Z_{Ext,h} Z_{Gen,h}}{Z_{Ext,h}+Z_{Gen,h}} \qquad (3)$$

The contribution of all external sources to distortion at the POC is given by:

$$V_{2,h} = U_{Ext,h} \frac{Z_{Gen,h}}{Z_{Ext,h}+Z_{Gen,h}} \qquad (4)$$

Where

$I_{Gen,h}$	*Is the ideal current source*
$Z_{Gen,h}$	*is the generator Norton equivalent shunt impedance*
$U_{Ext,h}$	*is the external network of the complete supply system up to the POC*
$Z_{Ext,h}$	*Is the external network Thevenin equivalent impedance of the complete supply system up to the POC*

The total harmonic voltage at the POC is then calculated as the sum of the contributions from internal and external sources via the summation law calculated at the POC [4].

3.2.3 Future background harmonic distortions

The future background harmonic distortion spectrum used in the analysis is shown in Table 12. 2-14th orders were determined from the provided data [9]. These are represented by the 95% percentile values. 15-50th orders were assigned as per [4], 50% of the corresponding planning limit.

Table 12: Future background harmonic distortion

Harmonic Order (h)	Harmonic distortion	Harmonic Order (h)	Harmonic distortion (%)
1	-	**26**	0.1165
2	0.5005	**27**	0.1000
3	0.2433	**28**	0.1139
4	0.1977	**29**	0.3517
5	0.7095	**30**	0.1117
6	0.1040	**31**	0.3290
7	0.3407	**32**	0.1097
8	0.1224	**33**	0.1000
9	0.1241	**34**	0.1079
10	0.0909	**35**	0.2914
11	0.1777	**36**	0.1064
12	0.0727	**37**	0.2757
13	0.1895	**38**	0.1050
14	0.0720	**39**	0.1000
15	0.1500	**40**	0.1038
16	0.1394	**41**	0.2488
17	0.6000	**42**	0.1026
18	0.1328	**43**	0.2372
19	0.5368	**44**	0.1016
20	0.1275	**45**	0.1000
21	0.1000	**46**	0.1007
22	0.1232	**47**	0.2170
23	0.4435	**48**	0.0998
24	0.1196	**49**	0.2082
25	0.4080	**50**	0.0990

3.2.4 Harmonic load flow studies

The maximum generator emission was calculated in the presence of the future background harmonic distortions for a given configuration, by traversing the harmonic impedance polygons in steps between vertices, with voltage distortion outcome generated for each step and recording the highest value:

- The impedance polygons are traversed with a 5 Ω step size using PowerFactory's built-in impedance loci script.
- All collector groups are in service. An outage of collector group scenarios is excluded as the HSF will operate with all collector groups in service.
- The total harmonic voltage value is calculated for all scenarios at all impedance points for each harmonic order.
- The HSF emissions are calculated by subtracting the applied future background harmonic distortions from the total harmonic voltage value.

3.2.5 Application of the limits

In the absence of future background harmonic distortion: $U_{Ext,h} = 0$, therefore

$$V_{POC,\,h} = V_{1,h} \leq E_h \qquad (5)$$

In the presence of future background harmonic distortion:

$$V_{POC,\,h} = \sqrt[\alpha]{v_{1,h}^{\alpha} + v_{2,h}^{\alpha}} \qquad (6)$$

The contribution to voltage distortion at the POC of the generator must not exceed the emission limits as shown below:

$$\Delta V_{POC,\,h} = \sqrt[\alpha]{V_{POC,h}^{\alpha} - U_{Ext,h}^{\alpha}} \leq E_h \qquad (7)$$

3.3 Voltage harmonic distortion results

Simulations were performed for inverters generating at the following load levels for the cases described in **Section 2.5.**

Table 13: Generation for harmonics study cases (grid voltage set to 1.0 pu)

Case Study	Case Study Description	PV MW / Mvar Inverter dispatch	POC MW	POC Mvar
PQOC01	PV export day-time without the filter banks in service	3.294 / -0.867	118	46.61
PQOC02	PV export day-time with filter banks in service	3.318 / -1.122	118	46.61

Table 14 summarises the worst-case results of harmonic distortion without and with the proposed filter banks.

Amplification factor plots are shown in Figure 2 with and without the proposed filter.

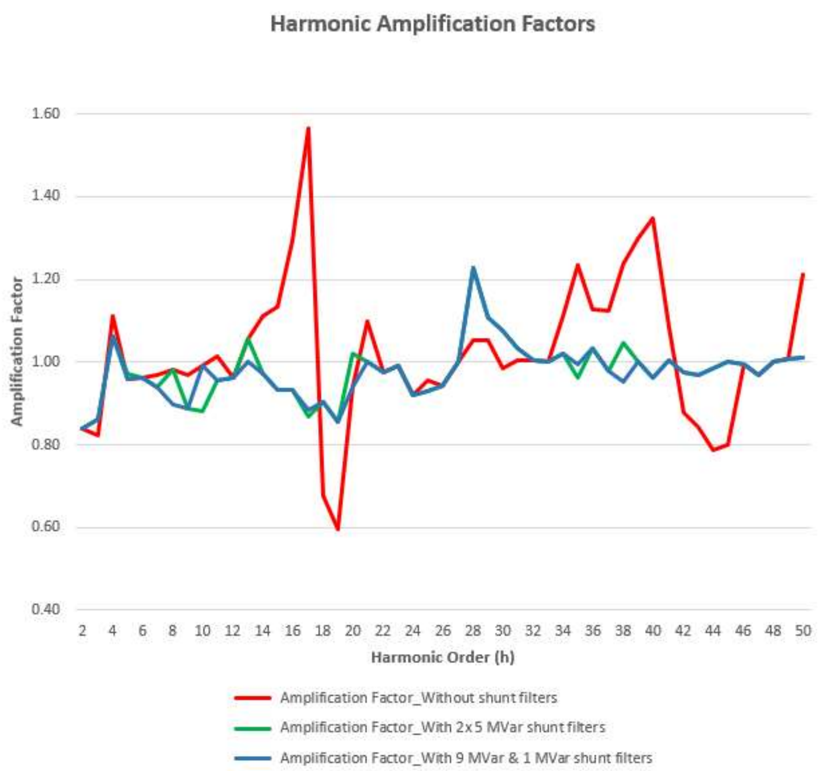

Figure 2: Amplification factors for the worst-case scenario

Table 14:Harmonic distortion with and without the proposed 9 MVar & 1 MVar shunt filters (Optio 1)

Assessment Criteria			Without future background harmonics		With future background harmonics			
			PQOC01	PQOC02	PQOC01	PQOC01	PQOC02	PQOC02
n	Allocated Limits (%)	Planning Limits (%)	Total & HSF Emissions	Total & HSF Emissions	Total Emissions	HSF Emissions Contribution	Total Emissions	HSF Emissions Contribution
2	0.10	1.40	0.02	0.03	0.43	0.00	0.43	0.00
3	0.10	2.00	0.05	0.04	0.22	0.00	0.22	0.00
4	0.10	0.80	0.03	0.03	0.24	0.04	0.23	0.03
5	0.17	2.00	0.11	0.11	0.72	0.01	0.72	0.01
6	0.10	0.40	0.02	0.02	0.11	0.01	0.11	0.01
7	0.17	2.00	0.18	0.17	0.47	0.13	0.44	0.10
8	0.10	0.40	0.05	0.05	0.16	0.04	0.15	0.03
9	0.10	1.00	0.02	0.01	0.13	0.01	0.12	0.00
10	0.10	0.35	0.14	0.10	0.22	0.13	0.16	0.07
11	0.27	1.50	0.29	0.17	0.45	0.27	0.27	0.09
12	0.10	0.32	0.04	0.02	0.11	0.04	0.08	0.01
13	0.27	1.50	0.23	0.11	0.41	0.22	0.24	0.05
14	0.10	0.30	0.04	0.02	0.12	0.05	0.08	0.01
15	0.10	0.30	0.06	0.02	0.22	0.07	0.15	0.00
16	0.10	0.28	0.07	0.02	0.24	0.10	0.14	0.00
17	0.18	1.20	0.07	0.01	1.01	0.41	0.53	0.00
18	0.10	0.27	0.06	0.01	0.14	0.01	0.12	0.00
19	0.18	1.07	0.08	0.03	0.36	0.00	0.47	0.00
20	0.10	0.26	0.03	0.02	0.14	0.01	0.13	0.00
21	0.10	0.20	0.01	0.01	0.11	0.01	0.11	0.01
22	0.10	0.25	0.01	0.01	0.12	0.00	0.12	0.00
23	0.13	0.89	0.00	0.00	0.44	0.00	0.44	0.00
24	0.10	0.24	0.00	0.00	0.12	0.00	0.12	0.00
25	0.13	0.82	0.01	0.01	0.39	0.00	0.39	0.00
26	0.10	0.23	0.03	0.02	0.12	0.00	0.11	0.00
27	0.10	0.20	0.03	0.02	0.12	0.02	0.11	0.01
28	0.10	0.23	0.09	0.06	0.20	0.09	0.17	0.06
29	0.11	0.70	0.04	0.03	0.41	0.06	0.41	0.06
30	0.10	0.22	0.03	0.01	0.14	0.03	0.12	0.01
31	0.11	0.66	0.01	0.01	0.34	0.01	0.34	0.01
32	0.10	0.22	0.04	0.02	0.15	0.04	0.12	0.01
33	0.10	0.20	0.01	0.00	0.11	0.01	0.10	0.00
34	0.10	0.22	0.03	0.01	0.14	0.03	0.11	0.00
35	0.10	0.58	0.14	0.04	0.48	0.19	0.30	0.01
36	0.10	0.21	0.05	0.01	0.15	0.04	0.11	0.00
37	0.10	0.55	0.09	0.02	0.34	0.06	0.27	0.00
38	0.10	0.21	0.11	0.03	0.21	0.11	0.13	0.03
39	0.10	0.20	0.05	0.01	0.16	0.06	0.10	0.00
40	0.10	0.21	0.13	0.02	0.27	0.17	0.11	0.01
41	0.10	0.50	0.15	0.03	0.33	0.08	0.25	0.00
42	0.10	0.21	0.05	0.01	0.13	0.03	0.10	0.00
43	0.10	0.47	0.11	0.02	0.23	0.00	0.24	0.00
44	0.10	0.20	0.08	0.01	0.13	0.03	0.11	0.01
45	0.10	0.20	0.03	0.00	0.11	0.01	0.10	0.00
46	0.10	0.20	0.07	0.01	0.14	0.04	0.11	0.01
47	0.10	0.43	0.08	0.02	0.23	0.01	0.22	0.00
48	0.10	0.20	0.00	0.00	0.10	0.00	0.10	0.00
49	0.10	0.42	0.08	0.02	0.24	0.03	0.21	0.00
50	0.10	0.20	0.10	0.00	0.21	0.11	0.12	0.02

Table 15:Harmoni distortion with 5 MVar & 5 MVar shunt filters (Option 2)

Assessment Criteria			Without future background harmonics		With future background harmonics			
			PQOC01	PQOC02	PQOC01	PQOC01	PQOC02	PQOC02
n	Allocated Limits (%)	Planning Limits (%)	Total & HSF Emissions	Total & HSF Emissions	Total Emissions	HSF Emissions Contribution	Total Emissions	HSF Emissions Contribution
2	0.10	1.40	0.02	0.03	0.43	0.00	0.43	0.00
3	0.10	2.00	0.05	0.04	0.22	0.00	0.22	0.00
4	0.10	0.80	0.03	0.03	0.24	0.04	0.23	0.03
5	0.17	2.00	0.11	0.11	0.72	0.01	0.73	0.02
6	0.10	0.40	0.02	0.03	0.11	0.01	0.11	0.01
7	0.17	2.00	0.18	0.19	0.47	0.13	0.46	0.12
8	0.10	0.40	0.05	0.06	0.16	0.04	0.16	0.04
9	0.10	1.00	0.02	0.02	0.13	0.01	0.12	0.00
10	0.10	0.35	0.14	0.10	0.22	0.13	0.16	0.07
11	0.27	1.50	0.29	0.16	0.45	0.27	0.25	0.07
12	0.10	0.32	0.04	0.02	0.11	0.04	0.08	0.01
13	0.27	1.50	0.23	0.10	0.41	0.22	0.25	0.06
14	0.10	0.30	0.04	0.02	0.12	0.05	0.08	0.01
15	0.10	0.30	0.06	0.02	0.22	0.07	0.14	0.00
16	0.10	0.28	0.07	0.02	0.24	0.10	0.14	0.00
17	0.18	1.20	0.07	0.01	1.01	0.41	0.52	0.00
18	0.10	0.27	0.06	0.01	0.14	0.01	0.12	0.00
19	0.18	1.07	0.08	0.02	0.36	0.00	0.48	0.00
20	0.10	0.26	0.03	0.01	0.14	0.01	0.13	0.00
21	0.10	0.20	0.01	0.01	0.11	0.01	0.11	0.01
22	0.10	0.25	0.01	0.01	0.12	0.00	0.12	0.00
23	0.13	0.89	0.00	0.00	0.44	0.00	0.44	0.00
24	0.10	0.24	0.00	0.00	0.12	0.00	0.11	0.00
25	0.13	0.82	0.01	0.01	0.39	0.00	0.38	0.00
26	0.10	0.23	0.03	0.02	0.12	0.00	0.11	0.00
27	0.10	0.20	0.03	0.02	0.12	0.02	0.11	0.01
28	0.10	0.23	0.09	0.05	0.20	0.09	0.17	0.06
29	0.11	0.70	0.04	0.03	0.41	0.06	0.42	0.07
30	0.10	0.22	0.03	0.01	0.14	0.03	0.12	0.01
31	0.11	0.66	0.01	0.01	0.34	0.01	0.34	0.01
32	0.10	0.22	0.04	0.02	0.15	0.04	0.12	0.01
33	0.10	0.20	0.01	0.00	0.11	0.01	0.10	0.00
34	0.10	0.22	0.03	0.01	0.14	0.03	0.11	0.00
35	0.10	0.58	0.14	0.03	0.48	0.19	0.29	0.00
36	0.10	0.21	0.05	0.01	0.15	0.04	0.11	0.00
37	0.10	0.55	0.09	0.02	0.34	0.06	0.27	0.00
38	0.10	0.21	0.11	0.02	0.21	0.11	0.13	0.03
39	0.10	0.20	0.05	0.01	0.16	0.06	0.11	0.01
40	0.10	0.21	0.13	0.01	0.27	0.17	0.11	0.01
41	0.10	0.50	0.15	0.02	0.33	0.08	0.25	0.00
42	0.10	0.21	0.05	0.00	0.13	0.03	0.10	0.00
43	0.10	0.47	0.11	0.02	0.23	0.00	0.24	0.00
44	0.10	0.20	0.08	0.01	0.13	0.03	0.11	0.01
45	0.10	0.20	0.03	0.00	0.11	0.01	0.10	0.00
46	0.10	0.20	0.07	0.01	0.14	0.04	0.11	0.01
47	0.10	0.43	0.08	0.01	0.23	0.01	0.22	0.00
48	0.10	0.20	0.00	0.02	0.10	0.00	0.10	0.00
49	0.10	0.42	0.08	0.02	0.24	0.03	0.21	0.00
50	0.10	0.20	0.10	0.02	0.21	0.11	0.11	0.01

3.3.1 Shunt filter sizing

9 Mvar and 1 MVar shunt filters are proposed as the preferred option to reduce individual harmonic emissions below the TNSP emissions limits. The components of the proposed filter banks are summarised in Tables 16 and 17.

Table 16: 9 Mvar & 1 Mvar, 17th and 40th shunt filter components (Option 1)

Description	17th shunt filter	40th shunt filter	Unit
Reactive power at 33 kV system	9	1	Mvar
The inductance of the reactor L	1.34	2.17	mH
The resistance Rs	17.86	100.89	Ω
The capacitance C	26.22	2.92	μF
Tuned frequency	850	2000	Hz
Quality factor	0.4	0.27	-

Table 17: 2x 5 Mvar, 17th and 40th shunt filter components (Option 2)

Description	17th shunt filter	34.8th shunt filter	Unit
Reactive power at 33 kV system	5	5	Mvar
The inductance of the reactor L	2.41	0.57	mH
The resistance Rs	18.37	20.88	Ω
The capacitance C	14.56	14.60	μF
Tuned frequency	850	1740	Hz
Quality factor	0.7	0.3	-

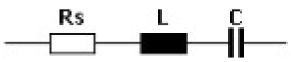

Figure 3: Proposed Shunt filter structure

3.3.2 Shunt filter component ratings

The shunt filter component ratings are determined according to [11] and [12] considering the worst-case harmonic emissions and in the presence of potential background harmonics; and fundamental frequency overvoltage.

Based on expected harmonics for the worst-case scenario, the calculated maximum component stress levels are summarised in Table 17. These values are based on the maximum individual harmonic distortion for each harmonic frequency independent of the operating scenario applied on each filter circuit simultaneously.

The proposed filter has been assessed for the worst-case scenario considering the following tolerances and allowances on the key filter and network components:

- Main power transformer impedance variation: ±10%
- 220 kV transmission line and 33 kV collector feeder length variation: ±10%
- 33 kV collector bus maximum voltage: 1.10 pu
- Filter capacitance variation: ±2%
- Filter inductance variation: ±1%
- Filter resistance variation: ±5%

Table 18: 9 Mvar & 1 MVar Shunt filter components ratings

Filter component	Description	9 Mvar 17th Shunt filter	1 Mvar 40th Shunt filter	Unit
Capacitor C	Phase–phase voltage	45	45	kV
Reactor L	RMS current	172	19.25	A
Power Dissipation (RLC)	Power rating per phase	528	37.37	kW

Table 19: 2 x 5 MVar Shunt filter components ratings

Filter component	Description	5 Mvar 17th Shunt filter	5 Mvar 34.8th Shunt filter	Unit
Capacitor C	Phase–phase voltage	45	45	kV
Reactor L	RMS current	96	96	A
Power Dissipation (RLC)	Power rating per phase	168	190	kW

Table 20: 9 Mvar and 1 MVar shunt filter components stress levels

Frequency [Hz]	9 x MVar 17th Shunt filter		1 x MVar 40th Shunt filter	
	Uc [kV]	Reactor Current [A]	Uc [kV]	Reactor Current [A]
50	20.86	171.82	20.94	19.22
100	0.06	0.95	0.06	0.11
150	0.03	0.72	0.03	0.08
200	0.03	0.94	0.03	0.11
250	0.09	3.82	0.10	0.46
300	0.01	0.68	0.02	0.08
350	0.04	2.40	0.05	0.30
400	0.01	0.96	0.02	0.12
450	0.01	1.01	0.02	0.13
500	0.01	0.79	0.01	0.11
550	0.02	1.57	0.02	0.22
600	0.01	0.65	0.01	0.09
650	0.02	1.75	0.02	0.25
700	0.01	0.63	0.01	0.09
750	0.01	1.17	0.01	0.18
800	0.01	1.10	0.01	0.17
850	0.03	4.12	0.04	0.65
900	0.01	0.85	0.01	0.14
950	0.02	3.01	0.03	0.49
1000	0.00	0.68	0.01	0.11
1050	0.00	0.42	0.00	0.07
1100	0.00	0.29	0.00	0.05
1150	0.00	0.60	0.00	0.10
1200	0.00	0.14	0.00	0.03
1250	0.00	0.65	0.01	0.12
1300	0.00	0.22	0.00	0.04
1350	0.00	0.24	0.00	0.04
1400	0.00	0.36	0.00	0.07
1450	0.00	1.07	0.01	0.20
1500	0.00	0.33	0.00	0.06
1550	0.00	0.98	0.01	0.19
1600	0.00	0.33	0.00	0.07
1650	0.00	0.30	0.00	0.06
1700	0.00	0.32	0.00	0.07
1750	0.00	0.87	0.01	0.18
1800	0.00	0.33	0.00	0.07
1850	0.00	0.83	0.01	0.18
1900	0.00	0.32	0.00	0.07
1950	0.00	0.30	0.00	0.07
2000	0.00	0.31	0.00	0.07
2050	0.00	0.76	0.00	0.17
2100	0.00	0.31	0.00	0.07
2150	0.00	0.72	0.00	0.17
2200	0.00	0.31	0.00	0.07
2250	0.00	0.31	0.00	0.07
2300	0.00	0.32	0.00	0.08
2350	0.00	0.67	0.00	0.16
2400	0.00	0.31	0.00	0.08
2450	0.00	0.65	0.00	0.16
2500	0.00	0.32	0.00	0.08

Table 21: 2x 5 Mvar shunt filters components stress levels

Frequency [Hz]	5 x MVar 17th Shunt filter		5 x MVar 34.8th Shunt filter	
	Uc [kV]	Reactor Current [A]	Uc [kV]	Reactor Current [A]
50	20.88	95.55	20.81	95.45
100	0.06	0.59	0.06	0.59
150	0.04	0.48	0.03	0.47
200	0.04	0.70	0.04	0.67
250	0.15	3.36	0.14	3.11
300	0.02	0.65	0.02	0.59
350	0.11	3.55	0.10	3.09
400	0.05	1.72	0.04	1.46
450	0.03	1.13	0.02	0.93
500	0.05	2.29	0.04	1.84
550	0.05	2.71	0.04	2.14
600	0.01	0.81	0.01	0.63
650	0.05	3.16	0.04	2.45
700	0.01	0.83	0.01	0.64
750	0.02	1.45	0.02	1.13
800	0.02	1.38	0.01	1.08
850	0.04	3.18	0.03	2.53
900	0.01	0.85	0.01	0.69
950	0.03	2.63	0.03	2.18
1000	0.01	0.84	0.01	0.71
1050	0.01	0.51	0.00	0.45
1100	0.00	0.44	0.00	0.39
1150	0.01	0.58	0.01	0.54
1200	0.00	0.19	0.00	0.18
1250	0.01	0.67	0.01	0.66
1300	0.00	0.48	0.00	0.49
1350	0.00	0.38	0.00	0.40
1400	0.00	0.59	0.00	0.64
1450	0.01	1.15	0.01	1.27
1500	0.00	0.56	0.00	0.64
1550	0.01	1.03	0.01	1.21
1600	0.01	1.13	0.01	1.36
1650	0.00	0.38	0.00	0.47
1700	0.00	0.49	0.00	0.63
1750	0.01	1.02	0.01	1.34
1800	0.00	0.30	0.00	0.40
1850	0.00	0.70	0.01	0.96
1900	0.00	0.48	0.00	0.67
1950	0.00	0.27	0.00	0.38
2000	0.00	0.37	0.00	0.54
2050	0.00	0.72	0.01	1.08
2100	0.00	0.27	0.00	0.41
2150	0.00	0.58	0.00	0.91
2200	0.00	0.36	0.00	0.57
2250	0.00	0.26	0.00	0.42
2300	0.00	0.48	0.00	0.79
2350	0.00	0.54	0.00	0.91
2400	0.00	0.15	0.00	0.25
2450	0.00	0.63	0.00	1.10
2500	0.00	0.57	0.00	1.01

3.3.3 S5.1.6 Voltage harmonic or voltage notching distortion compliance assessment

(a) *Automatic access standard*: the *Network Service Provider* must allocate emission limits no more onerous than the lesser of the acceptance levels determined in accordance with either of stage 1 or the stage 2 evaluation procedures defined in AS/NZS 61000.3.6:2001.

(b) *Minimum access standard*: subject to clause S5.1.6(c), the determination by the *Network Service Provider* of acceptable emission limits must be undertaken in consultation with the party seeking *connection* using the Stage 3 evaluation procedure defined in AS/NZS61000.3.6:2001.

(c) In respect of each new *connection* at a level of performance below the *automatic access standard* the *Network Service Provider* must include provisions in the relevant *connection agreement* requiring the *Network User* if necessary to meet the *system standards* or allow connection of other *Network Users* to either upgrade to the *automatic access standard* or fund the reasonable cost of the works necessary to mitigate their effect of connecting at a standard below the *automatic access standard*.

(d) If for existing customer *connections* the level of harmonic *voltage* distortion is, or may be, exceeded as a result of a proposed new *connection*, the *Network Service Provider* must, if the cause of that excessive level cannot be remedied by enforcing the provisions of existing *connection agreements*, undertake all works necessary to meet the technical standards in this schedule or to permit a proposed new *connection* within the *automatic access standard* defined in clause S5.3.8 and the requirements stated in this clause.

Without shunt or harmonic filters in service, 7/10/11/17/35/38/40/41/43/50th orders are expected to exceed the limits. Option 1 will meet both allocated and planning limits with and without future background harmonics considered. Without background harmonics considered Option 2 will marginally exceed the allocated limits for the 7th order.

With the proposed shunt filters in service, all the emissions at all individual harmonic orders are expected to be within the allocated and planning limits provided by the TNSP in Table 3 when the system is operational.

HSF will meet the ***Automatic Access Standard*** for voltage harmonics or voltage notching distortion.

4 Voltage fluctuation

4.1 Emission level

The emission level from a fluctuating load is the flicker level that would be produced in the power system if no other fluctuation load was present. The process of determining the flicker emission from a fluctuating load is specified in [5], [6] and [7].

Two quantities are commonly used to characterise the flicker severity:

- P_{st} – short term where one value is obtained for each 10 min period
- P_{lt} – long term where one value is obtained for each 2 h period

Emission limits at the POC are allocated amongst customers according to the following equations:

$$E_{Psti} = L_{PstiHV}.\sqrt[3]{\frac{S_i}{S_{tHV}}} \qquad (8)$$

$$E_{Plti} = L_{PltiHV}.\sqrt[3]{\frac{S_i}{S_{tHV}}} \qquad (9)$$

where

$E_{Psti} = P_{sti}$	*is the emission limit for user i;*
L_{PstiHV}	*Is the planning level in HV systems;*
S_i	*Is the agreed power of user i;*
S_{tHV}	*is the part of the total supply capacity of the HV substation which is devoted to the HV users*

The flicker emission allocation for HSF set by the TNSP is summarised in **Section 2.1.2**. Pst and Plt limits are 0.35 and 0.25 respectively.

4.2 Flicker calculation

For the HSF the key source of voltage fluctuation will be caused by the fluctuation of power generated from the solar farm. The variation of solar irradiance and cloud shading is dependent on the climate and is site-specific. In the absence of site measurements, an empirical method can be used to estimate the flicker contribution from the HSF.

4.3 Cloud shading

The flicker severity caused by a single step in voltage change can be calculated using the flicker time t_f as per the below equation:

$$t_f = 2.3\,(100\ d\ F)^3 \qquad (10)$$

where

d	*is relative voltage change;*
F	*is shape factor (for a step voltage change $F = 1$).*

The flicker severity is evaluated as the cubic root of the sum of the flicker times within a given interval divided by the duration of this interval according to equations 11 & 12:

$$P_{st} = \sqrt[3]{\frac{\sum t_f}{10min}} \qquad (11)$$

$$P_{lt} = \sqrt[3]{\frac{\sum t_f}{120min}} \qquad (12)$$

Since the 220 kV, POC bus will be controlled by the SMA power plant controller in reactive power control mode at a specific voltage setpoint, the variation in active power output due to clouds or a change in irradiance does not cause a change in voltage at the POC. The relative voltage change factor d in equation (10) is 0, hence resulting in flicker time being 0, consequently P_{st} = 0 & P_{lt} = 0.

4.4 Flicker calculation

SMA provided a certificate test report for SC4200 UP Inverters according to [2]. In the test report, the flicker coefficients were provided for different network conditions and active power output as shown in Table 20 for the worst-case results.

Table 22: SC4200 UP inverters flicker coefficients calculated for different network impedance, phase angle and active power level

Grid Impedance Angle	30^0	50^0	70^0	85^0
Maximum Coefficient, $C(\psi_k)$	2.88	2.53	1.93	1.36
Max short-term flicker, Pst	0.14	0.13	0.10	0.07

The flicker coefficient is calculated using equation 8 according to [7]:

$$c(\psi_k) = P_{st,fic} \cdot \frac{S_{k,fic}}{S_n} \qquad (13)$$

where

$P_{st,fic}$ *is the flicker emission value on the fictitious grid for each 10 min time series;*

S_n *is the rated apparent power of the wind turbine;*
09

$S_{k,fic}$ *is the short-circuit apparent power of the fictitious grid.*

Using equation 13, the worst-case P_{st} for the solar farm is calculated to be 0.09336. This is based on the following:

S_n = *4.2 MVA, single inverter rating*
$S_{k,fic}$ = 483 *MVAsc, the lowest short circuit level at POC*
X/R = *3.42 at PoC*
Angle = *Arctan(X/R) = 73.70*
$C(\psi_k)$ = *1.789 (interpolated value between 70 and 85 Degrees using maximum values (1.93 & 1.36)*
$P_{st,fic}$ = *1.789 / (483/4.2) = 0.0156 (individual inverter Pst)*
$P_{st,fic}$ *total* = *sqrt(36*0.0156*^{2}*) = 0.09336*

According to [7], the flicker coefficient for continuous operation is the same as for short-term (10 min) and long-term periods (2 h). Consequently P_{st} = P_{lt} = 0.09336

4.5 Flicker compliance assessment

Based on the above analysis, the flicker contribution from HSF is expected to exceed the specified limits. The long-term flicker disturbance factor for P_{lt} is below the allocation limit of 0.25. The short-term flicker disturbance factor P_{st} is also below the limit of 0.35. The ***Automatic Access Standard*** is proposed for flicker.

5 Voltage Unbalance

5.1 Voltage unbalance compliance assessment

The PV inverters should be designed to balance the voltage generated, and when not generating, balance the current drawing in each phase to limit the negative sequence voltage at the POC to the limits provided in Table 5.

With the maximum auxiliary load from the auxiliary transformer < 315 kVA, any current drawn when not generating is not expected to introduce any significant levels of voltage unbalance, and any single-phase auxiliary loads are expected to be appropriately distributed across phases. This must be considered during detailed design.

A quantitative assessment has not been performed. This performance must be confirmed during commissioning.

SMA has provided a statement for voltage unbalance to confirm that unbalance below the TNSP limits is achievable at the POC. Refer to **Appendix B.**

HSF will be able to meet the ***Automatic Access Standard*** of voltage unbalance.

6 Conclusions and recommendations

PGS has undertaken a power quality assessment for the HSF. Major findings and recommendations of the studies are summarised below:

- **Harmonic contribution:** several individual orders exceed allocated and planning limits without a filter in service.

- Harmonic filters are required to reduce emissions for individual harmonic orders to below TNSP limits:

    - A 9 Mvar shunt filter tuned at the 17th order and a 1 Mvar shunt filter tuned at the 40th order have been proposed to meet both allocated and planning limits with and without consideration of the future background harmonic distortions.

- **Flicker contribution**: the flicker contribution from HSF is expected to be below the specified limits. The short and long-term flicker disturbance factors are below TNSP flicker emission allocation limits of 0.35 and 0.25 for Pst and Plt. The ***Automatic Access Standard*** is proposed

- **Voltage unbalance:** HSF is not expected to contribute to negative sequence voltages. There may be a small contribution due to loading on the station auxiliary transformer (≤ 315 kVA). However, this is expected to be insignificant. SMA certificate states that individual inverter contributions will be less than 0.1%. This value is below the limit specified in Table S5.1a.1. Refer to **Appendix B** for further details.

Proposed future work to be done during the R1 stage:

- Revise the main transformer excitation curve based on the actual manufacturer-provided curve.
- Revise estimated excitation harmonic currents for the main transformer.
- Revise filter design parameters based on the above inputs before the procurement of the filter.

Appendix A: Single Line Diagrams & Cable schedule

REFER TO PDF ATTACHMENT

Appendix A – HSF Single Line Diagram and MV Cable Schedule (Client-provided data)

Appendix B: SMA statement

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Description of the behavior of the Sunny Central UP and Sunny Central Storage UP (-XT) inverters in case of grid imbalances

The SC XXXX UP and SCS XXXX UP(-XT) inverters operate with a negative sequence system regulation to avoid unsymmetrical currents. In case of unsymmetrical grid voltage, the negative sequence system regulation adjusts the currents after approximately 1s back to symmetry in steady-state operation.

The reactive current contribution is calculated by each generating unit using sequence components of voltage and is determined for each sequence component separately when the positive sequence component falls outside the lower or upper voltage level for commencing the reactive current contribution, according to the following formula:

$$I_{qVRT} = (V_{meas} - db) \times K \times I_{nominal} + I_{q\,prefault}$$

Where

- I_{qVRT} = sequence component of reactive current contribution during disturbance
- V_{meas} = sequence component of voltage measured at the generating unit terminals
- db = lower or upper boundary of voltage at which the reactive current contribution commences
- K = rate at which reactive current is applied ($\%I_{nominal}$) and is equal for both positive and negative sequence components
- $I_{nominal}$ = maximum continuous current of each generating unit
- $I_{nominalq\,prefault}$ = sequence component of reactive current before the disturbance

If $I_{qVRT} + I_{total\,prefault} > I_{nominal}$, then I_{qVRT} is prioritized

In the event of an asymmetrical grid fault, the generating system has facilities capable of keeping voltage increase below 10% of the nominal voltage in the phases unaffected by the fault.

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With a symmetrical grid voltage and symmetrical impedances (transformer, cables etc.) the negative sequence current of the generating system does not lead to negative sequence voltages higher than 0.1% at the connection point for the symmetrical disturbances listed in S5.2.5.5.

Yours sincerely

SMA Solar Technology AG

i. V. Carsten Wendt	i. A. Daniel Greger
Head of PM Central Power Conversion	Product Manager Inverter
BU Large Scale & Project Solutions	BU Large Scale & Project Solutions

Appendix C: HSF PowerFactory Model Data

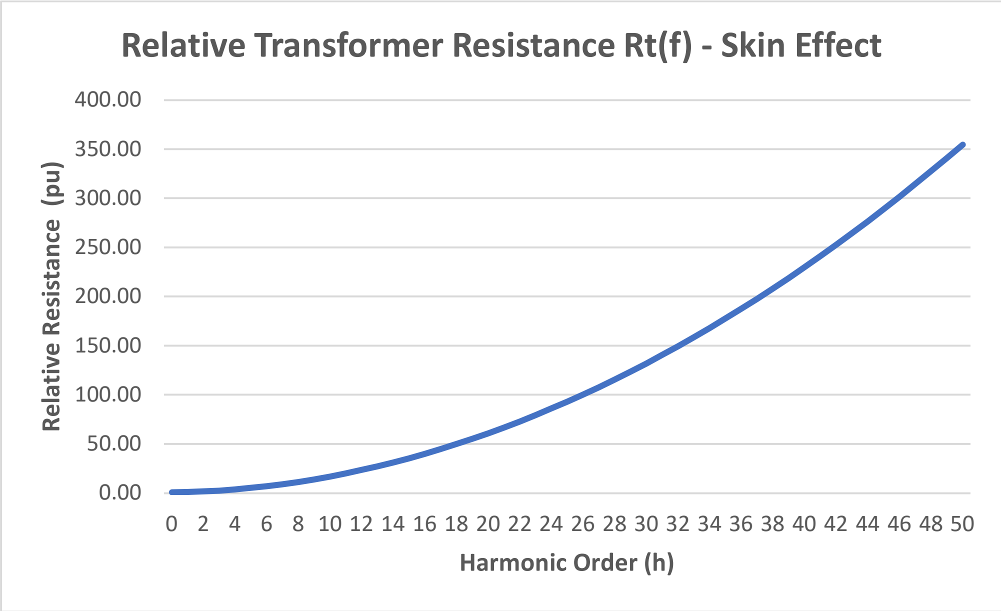
PowerFactory - 220/33 kV 170 MVA transformer frequency-dependent model

The resistance modelling accounts for skin effect. The frequency dependency of the resistance is calculated using Equation 3.15. The recommended values for the coefficients are given in Table 3-5 with the condition that $a_0 + a_1 + a_2 = 1$ [1].

$$R_s(h) = R_t \cdot (a_0 + a_1 h^b + a_2 h^2) \qquad \text{Equation 3.15}$$

Table 3-5 Values for Coefficients a_0, a_1 a_2 and b (requirement: $a_0 + a_1 + a_2 = 1$)

	a_0	a_1	a_2	b
Small system transformer	0.85 – 0.90	0.05 – 0.08	0.05 – 0.08	0.9 – 1.4
Large system transformer	0.75 – 0.80	0.10 – 0.13	0.10 – 0.13	0.9 – 1.4



$a_0 = 0.75$, $a_1 = 0.12$, $a_2 = 0.13$, $b = 1.4$

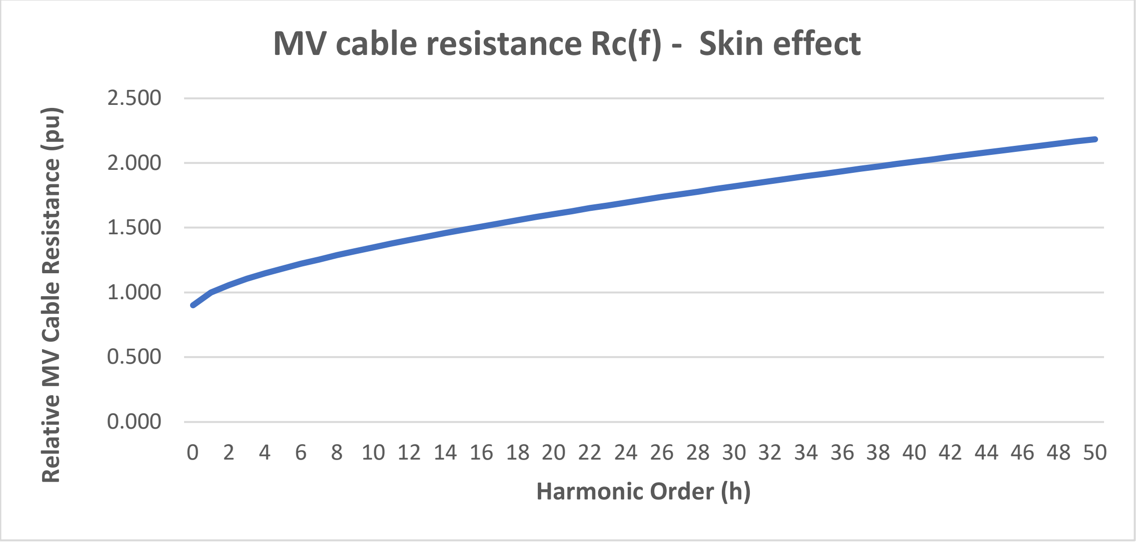
Order (h)	Relative Transformer resistance Rt(f)	Order (h)	Relative Transformer resistance Rt(f)
0	0.75		
1	1.00	26	100.12
2	1.59	27	107.63
3	2.48	28	115.41
4	3.67	29	123.46
5	5.14	30	131.78
6	6.90	31	140.37
7	8.95	32	149.23
8	11.28	33	158.36
9	13.88	34	167.75
10	16.76	35	177.41
11	19.92	36	187.34
12	23.36	37	197.54
13	27.07	38	208.01
14	31.06	39	218.74
15	35.32	40	229.74
16	39.85	41	241.01
17	44.66	42	252.55
18	49.73	43	264.35
19	55.08	44	276.42
20	60.70	45	288.76
21	66.60	46	301.36
22	72.76	47	314.23
23	79.19	48	327.37
24	85.90	49	340.77
25	92.87	50	354.44

PowerFactory - HV cable frequency-dependent model

$$R(f_h) = R_{nom}\left((1-a) + a\left[\frac{f_h}{f_1}\right]^b\right) \qquad (1)$$

where

R_{nom}	*is a.c resistance at nominal frequency per unit length*
f_1	*is the nominal network frequency (50 Hz)*
a , b	*are terms used to match the correct d.c resistance (a = 0.0985, b = 0.6562 provide acceptable representation of skin effect)*



Order (h)	Relative MV cable resistance Rc(f)	Order (h)	Relative MV cable resistance Rc(f)
0	0.9015		
1	1	26	1.736990934
2	1.056728733	27	1.757940374
3	1.104045779	28	1.778624679
4	1.146129032	29	1.799056501
5	1.184704629	30	1.819247474
6	1.220697206	31	1.83920833
7	1.254674683	32	1.858948992
8	1.287017307	33	1.878478661
9	1.317995358	34	1.897805886
10	1.347809602	35	1.91693863
11	1.376614309	36	1.935884327
12	1.404531248	37	1.954649927
13	1.431658658	38	1.973241941
14	1.458077246	39	1.991666483
15	1.483854338	40	2.009929299
16	1.509046835	41	2.028035799
17	1.533703379	42	2.045991087
18	1.557865958	43	2.063799982
19	1.581571137	44	2.081467041
20	1.604851007	45	2.098996581
21	1.627733924	46	2.116392692
22	1.650245101	47	2.133659259
23	1.672407084	48	2.150799973
24	1.694240137	49	2.167818344
25	1.715762556	50	2.184717718

PowerFactory - Main Power transformer

Name	Primary busbar	Secondary busbar	Power [MVA]	Primary Voltage [kV]	Secondary Voltage [kV]	Uk [%]	X/R ratio	Vector group
MAIN TX	TX_132kV	TX_33kV	170	220	33	16.8037033	47.605545	YNd11

PowerFactory - HV and MV cables

Name	Busbar i	Busbar j	Type	Length [km]	R [Ω/km]	X [Ω/km]	B1 [µS/km]
220kV Feeder	220kV_PoC	TX_132kV	220 kV 1C CU_630sqmm	0.20000	0.03930	0.10800	45.55309
SF UG	TX_33kV	Shunt Filters	33 kV 1C AL_185sqmm	0.05000	0.21100	0.14500	63.46017
MAIN_TX_MV_UG	TX_33kV	33 kV PV Collection Switchboard	33 kV 1C AL_630sqmm	0.03000	0.06290	0.12300	103.35840
PV1_1-2	PCU1_RMU	PCU2_RMU	33 kV 1C AL_185sqmm	0.01500	0.21100	0.14500	63.46017
PV1_2-3	PCU2_RMU	PCU3_RMU	33 kV 1C AL_185sqmm	0.23300	0.21100	0.14500	63.46017
PV1_3-4	PCU3_RMU	PCU4_RMU	33 kV 1C AL_185sqmm	0.01500	0.21100	0.14500	63.46017
PV1_3-5	PCU3_RMU	PCU5_RMU	33 kV 1C AL_300sqmm	0.03200	0.12900	0.13600	76.02654
PV1_5-6	PCU5_RMU	PCU6_RMU	33 kV 1C AL_185sqmm	0.01500	0.21100	0.14500	63.46017
PV1_5-SUB	33 kV PV Collection Switchboard	PCU5_RMU	33 kV 1C AL_630sqmm	2.06600	0.06290	0.12300	103.35840
PV2_11-12	PCU12_RMU	PCU11_RMU	33 kV 1C AL_185sqmm	0.01500	0.21100	0.14500	63.46017
PV2_12-15	PCU15_RMU	PCU12_RMU	33 kV 1C AL_300sqmm	0.22700	0.12900	0.13600	76.02654
PV2_14-15	PCU15_RMU	PCU14_RMU	33 kV 1C AL_185sqmm	0.01500	0.21100	0.14500	63.46017
PV2_15-SUB	33 kV PV Collection Switchboard	PCU15_RMU	33 kV 1C AL_630sqmm	1.60000	0.06290	0.12300	103.35840
PV2_9-10	PCU9_RMU	PCU10_RMU	33 kV 1C AL_185sqmm	0.01500	0.21100	0.14500	63.46017
PV2_9-11	PCU9_RMU	PCU11_RMU	33 kV 1C AL_185sqmm	0.03200	0.21100	0.14500	63.46017
PV3_16-17	PCU17_RMU	PCU16_RMU	33 kV 1C AL_185sqmm	0.01500	0.21100	0.14500	63.46017
PV3_17-18	PCU18_RMU	PCU17_RMU	33 kV 1C AL_185sqmm	0.23000	0.21100	0.14500	63.46017
PV3_18-19	PCU18_RMU	PCU19_RMU	33 kV 1C AL_185sqmm	0.01500	0.21100	0.14500	63.46017
PV3_18-20	PCU20_RMU	PCU18_RMU	33 kV 1C AL_300sqmm	0.03000	0.12900	0.13600	76.02654
PV3_20-SUB	33 kV PV Collection Switchboard	PCU20_RMU	33 kV 1C AL_630sqmm	1.32600	0.06290	0.12300	103.35840
PV4_13-22	PCU22_RMU	PCU13_RMU	33 kV 1C AL_185sqmm	0.47700	0.21100	0.14500	63.46017
PV4_20-21	PCU20_RMU	PCU21_RMU	33 kV 1C AL_185sqmm	0.01500	0.21100	0.14500	63.46017

Name	Busbar i	Busbar j	Type	Length [km]	R [Ω/km]	X [Ω/km]	B1 [µS/km]
PV4_22-26	PCU26_RMU	PCU22_RMU	33 kV 1C AL_300sqmm	0.43000	0.12900	0.13600	76.02654
PV4_26-27	PCU26_RMU	PCU27_RMU	33 kV 1C AL_185sqmm	0.11000	0.21100	0.14500	63.46017
PV4_26-SUB	33 kV PV Collection Switchboard	PCU26_RMU	33 kV 1C AL_630sqmm	1.39000	0.06290	0.12300	103.35840
PV4_7-8	PCU8_RMU	PCU7_RMU	33 kV 1C AL_185sqmm	0.25700	0.21100	0.14500	63.46017
PV4_8-13	PCU13_RMU	PCU8_RMU	33 kV 1C AL_185sqmm	0.16000	0.21100	0.14500	63.46017
PV5_23-24	PCU23_RMU	PCU24_RMU	33 kV 1C AL_185sqmm	0.01500	0.21100	0.14500	63.46017
PV5_23-25	PCU25_RMU	PCU23_RMU	33 kV 1C AL_185sqmm	0.03000	0.21100	0.14500	63.46017
PV5_25-28	PCU28_RMU	PCU25_RMU	33 kV 1C AL_185sqmm	0.23500	0.21100	0.14500	63.46017
PV5_28-36	PCU36_RMU	PCU28_RMU	33 kV 1C AL_300sqmm	0.33300	0.12900	0.13600	76.02654
PV5_30-36	PCU36_RMU	PCU30_RMU	33 kV 1C AL_185sqmm	0.01000	0.21100	0.14500	63.46017
PV5_36-SUB	33 kV PV Collection Switchboard	PCU36_RMU	33 kV 1C AL_630sqmm	0.61800	0.06290	0.12300	103.35840
PV6_29-32	PCU32_RMU	PCU29_RMU	33 kV 1C AL_185sqmm	0.36300	0.21100	0.14500	63.46017
PV6_31-32	PCU32_RMU	PCU31_RMU	33 kV 1C AL_185sqmm	0.16700	0.21100	0.14500	63.46017
PV6_32-33	PCU32_RMU	PCU33_RMU	33 kV 1C AL_185sqmm	0.15500	0.21100	0.14500	63.46017
PV6_32-34	PCU34_RMU	PCU32_RMU	33 kV 1C AL_300sqmm	0.32100	0.12900	0.13600	76.02654
PV6_34-35	PCU35_RMU	PCU34_RMU	33 kV 1C AL_400sqmm	0.33900	0.10100	0.13100	83.88052
PV6_35-SUB	33 kV PV Collection Switchboard	PCU35_RMU	33 kV 1C AL_630sqmm	0.22000	0.06290	0.12300	103.35840

PowerFactory - Solar Farm Inverters

Name	Busbar	Power [MVA]	Voltage [kV]
PCU1-INV	PCU1_RMU	4200	33
PCU10-INV	PCU10_RMU	4200	33
PCU11-INV	PCU11_RMU	4200	33
PCU12-INV	PCU12_RMU	4200	33
PCU13-INV	PCU13_RMU	4200	33
PCU14-INV	PCU14_RMU	4200	33
PCU15-INV	PCU15_RMU	4200	33
PCU16-INV	PCU16_RMU	4200	33
PCU17-INV	PCU17_RMU	4200	33
PCU18-INV	PCU18_RMU	4200	33
PCU19-INV	PCU19_RMU	4200	33
PCU2-INV	PCU2_RMU	4200	33
PCU20-INV	PCU20_RMU	4200	33
PCU21-INV	PCU21_RMU	4200	33
PCU22-INV	PCU22_RMU	4200	33
PCU23-INV	PCU23_RMU	4200	33
PCU24-INV	PCU24_RMU	4200	33
PCU25-INV	PCU25_RMU	4200	33
PCU26-INV	PCU26_RMU	4200	33
PCU27-INV	PCU27_RMU	4200	33
PCU28-INV	PCU28_RMU	4200	33
PCU29-INV	PCU29_RMU	4200	33
PCU3-INV	PCU3_RMU	4200	33
PCU30-INV	PCU30_RMU	4200	33
PCU31-INV	PCU31_RMU	4200	33
PCU32-INV	PCU32_RMU	4200	33
PCU33-INV	PCU33_RMU	4200	33
PCU34-INV	PCU34_RMU	4200	33
PCU35-INV	PCU35_RMU	4200	33
PCU36-INV	PCU36_RMU	4200	33
PCU4-INV	PCU4_RMU	4200	33
PCU5-INV	PCU5_RMU	4200	33
PCU6-INV	PCU6_RMU	4200	33
PCU7-INV	PCU7_RMU	4200	33
PCU8-INV	PCU8_RMU	4200	33
PCU9-INV	PCU9_RMU	4200	33

Appendix D: HSF PowerFactory Model and power flow results

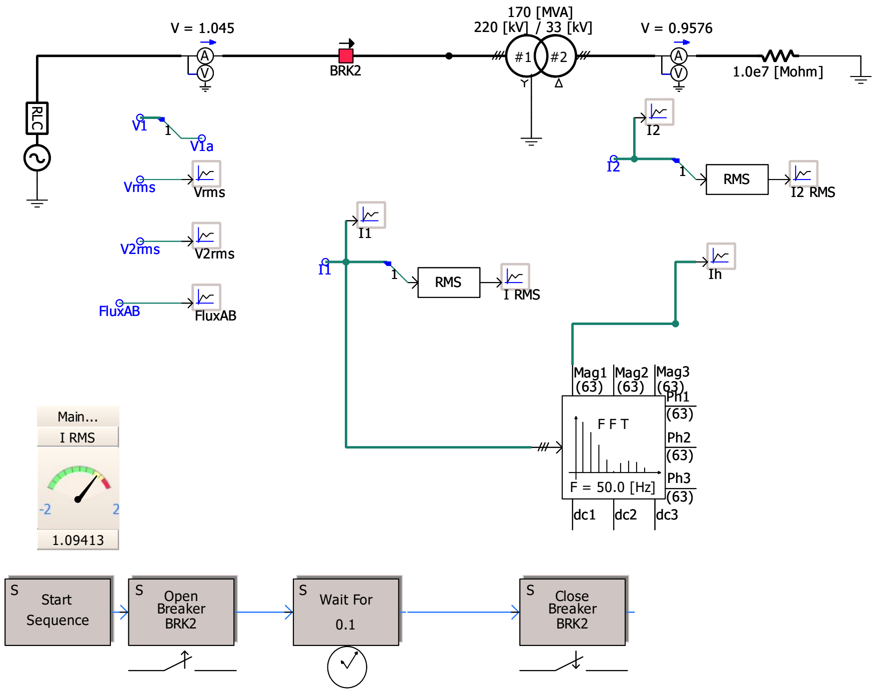
REFER TO PDF ATTACHMENTS

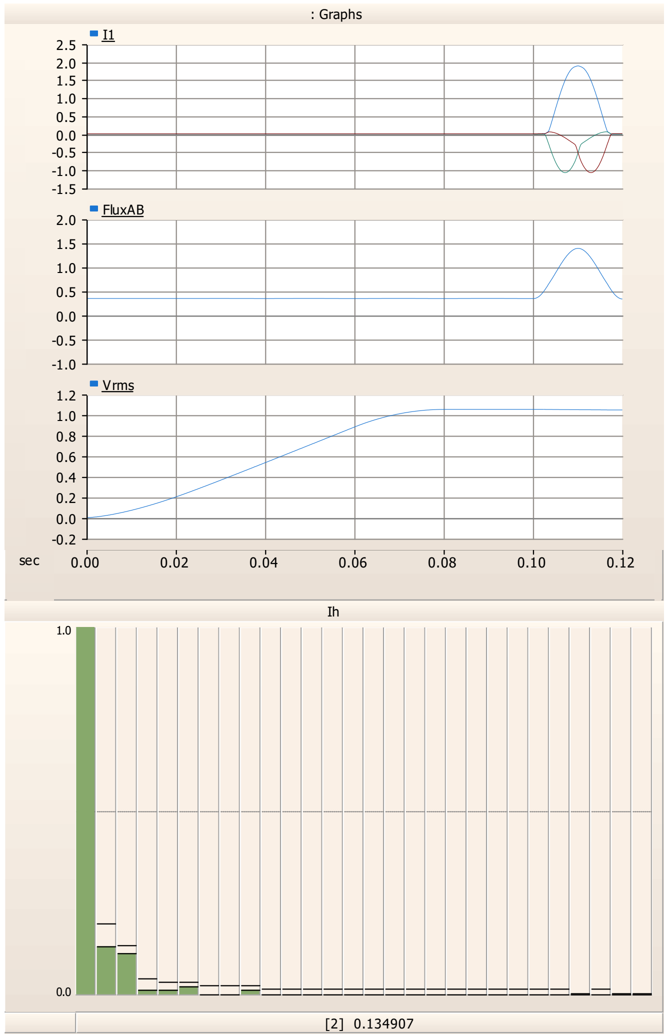
Appendix D1 – HSF Powerfactory Single Line Diagram

Appendix D2 – HSF Powerfactory Power Flow – Without shunt filters

Appendix D3 – HSF Powerfactory Power Flow – With shunt filters

Appendix E: PSCAD transformer excitation model





Note – it is strongly advised to update the excitation models once Vendor data is available during R1 & before the procurement of the shunt filters

Appendix F: Horsham PV impedance range plots

100-2500 Hz polygons have been created from the original TNSP-provided data and each polygon represents all 20 operational scenarios. These have been processed by the in-built impedance loci script in PowerFactory to determine the worst-case HD at the 220 kV POC.

REFER TO PDF ATTACHMENT

Appendix F – Horsham impedance range plots