Passive Harmonic Filter Design Study for a MV Network Connected BESS – A Case Study

K.Ozer, T.P.Rastall

Abstract*-- This paper discusses the application of MV passive harmonic filters which are used to ensure harmonic grid compliance of a 50MW Battery Energy Storage System (BESS) in the UK. The harmonic non-compliances were captured during the commissioning & post-commissioning measurements for various charging & discharging operation modes. The harmonic non-compliances against Engineering Recommendation (ER) G5 Issue 5 (G5/5) planning limits were measured at various harmonic orders between the 14th and 65th orders. To ensure an accurate harmonic filter design, a detailed harmonic measurement including various operation modes was conducted. The power system is modelled using DIgSILENT analysis tool and the studies are conducted on the created model. The model is validated based upon the site measurements. Prior to initiating the filter design, a root cause analysis was conducted to identify the reasons for harmonic non-compliance, such as the self-impedance of the BESS inverters and the amplification of background network impedance caused by the BESS plant. Considering not only harmonic compliance, but also a cost-effective filter in terms of manufacturing, a 5.0MVAR C-type harmonic filter is designed. A comparison of harmonic voltages and impedance sweeps was performed with and without the designed harmonic filter. Ultimately, full harmonic compliance was demonstrated in accordance with the ER G5/5 planning limits.

***Keywords*: grid compliance, harmonics in renewable systems, harmonic filter design, harmonic resonance, harmonic studies, power quality.**

I. INTRODUCTION

Installations of renewable energy and storage plants have been increasing dramatically for decades. These power plants are distributed throughout the power grid closer to loads. Increased penetration of Distributed Generation (DG) brings about new challenges and problems to the network operators in terms of power quality issues such as voltage regulation, power factor and harmonics. If DG sites do not comply with grid connection requirements, they may need to install power quality improvement equipment [1].

If DG sites fail to comply with harmonic voltage distortion limits, new users are responsible to ensure harmonic compliance in the United Kingdom [2]. Passive harmonic filters are considered the most cost-effective solution.

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The passive harmonic filters which consist of capacitors, reactors and resistors typically provide an alternative impedance path for harmonic currents and dampen the harmonic impedance profile.

Based upon the specific system impedance profile, the new users' harmonic emissions and the background voltage distortion, the filters need to be custom designed for each site. Designs without consideration of the above identified criteria possibly results in poor filter performance and over/ under rated filter designs.

Designing passive harmonic filters requires a special attention to system parameters, including the background network characteristics and details of the new user's power plant. Additionally, to ensure a cost-effective and efficient solution, it is recommended, wherever possible, to align the design parameters with components that are widely available in the market.

In this paper, a post-connection harmonic study is conducted for a 50MW BESS connected to the 33kV network to ensure a full harmonic compliance against the G5/5 planning limits in the UK. Based upon the post-connection harmonic measurements, harmonic non-compliance was detected at various harmonic orders between 14th and 65th orders. The BESS plant was required to solve the harmonic non-compliance issue.

Based upon the above, a thorough investigation was conducted to identify the possible root-cause(s) of the harmonic non-compliance. Considering the BESS was an operational site, a detailed harmonic site measurement was conducted for various operation modes - including idle, charging & discharging - to capture comprehensive behavior of the inverters. The site is modelled using DIgSILENT analysis tool and the model is validated based upon the site measurements. Furthermore, a passive harmonic filter is designed to ensure full compliance against the G5/5 planning limits.

II. DESCRIPTION OF THE SYSTEM UNDER STUDY

The BESS plant is connected to the Super Grid Transformer (SGT) 13kV tertiary via a 33/13kV step down transformer. The transformer is connected to the 13kV SGT tertiary winding via 100m, 3 parallel of 3x1c 1000mm2 CU, XLPE cable. The 33/13kV transformer is owned by Distribution Network Operator and therefore harmonic assessment point is at 33kV Point of Common Coupling (PCC).

The BESS plant is equipped with 19 off 3.8MW BESS inverters and their step-up transformers (0.66/0.66/33.0 kV, 3500/3500/7000kVA), giving the BESS plant a rated export & import capacity of 50MW.

III. SYSTEM DETAILS UNDER THE STUDY

The key site details used for the harmonic study are summarized in this section.

A. External Grid Harmonic Impedance Data

The DNO has provided two sets of harmonic impedance profiles as seen from the 13kV SGT tertiary terminal up to 100th harmonic order for the intact network operation cases. The DNO has also provided the upper and lower bound harmonic impedance at the 33kV grid transformer terminals in the form of an envelope, representing the possible network impedance values.

To investigate the compliance of the BESS plant under all network conditions, the analyses were completed for a range of network impedance scenarios. In addition to analyzing the upper and lower bound network impedance characteristics, various intermediate scenarios were explored. These scenarios were generated by calculating a weighted average between the upper and lower bounds, as illustrated below:

$$Z_i = (1-W_i) \text{ x } Z_{lower} + W_i \text{ x } Z_{upper}.$$

Sectionalized harmonic impedance envelopes were determined using linear interpolation. The background network operation scenarios are summarized in Table I.

TABLE I
EXTERNAL GRID HARMNONIC IMPEDANCE SWEEP CASES

Case Number	Case Description
D01	Summer Min Demand, the model was built up from 13kV SGT tertiary terminal.
D02	Winter Peak Demand, the model was built up from 13kV SGT tertiary terminal.
D03	Lower bound impedance sweep, R-X equivalent of background network was represented at the 33kV PCC.
D04	Intermediary (Wi=0.2) impedance sweep, R-X equivalent of background network was represented at the 33kV PCC.
D05	Intermediary (Wi=0.4) impedance sweep, R-X equivalent of background network was represented at the 33kV PCC.
D06	Intermediary (Wi=0.6) impedance sweep, R-X equivalent of background network was represented at the 33kV PCC.
D07	Intermediary (Wi=0.8) impedance sweep, R-X equivalent of background network was represented at the 33kV PCC.
D08	Upper bound impedance sweep, R-X equivalent of background network was represented at the 33kV PCC.

Given the 33kV BESS system's isolation from the transmission level via the SGT tertiary winding and grid transformer, the site's harmonic impedance profile is expected to closely resemble cases D01 and D02. Thus, weighted average method ensures a pessimistic study outcome.

B. Transformer Details

The grid and BESS transformer details are summarized in Table II.

TABLE II
TRANSFORMER DETAILS

ID	TX size [MVA]	Voltage [kV/kV]	Vector Group	U_k [%]	Copper losses [%]
DNO transformer	60.0	33/13	YNd1	12.2	207.7
BESS unit transformers	7.0	33/0.66/ 0.66	Dy11y11	6.0	20.4

C. Cable Details

The DNO side and BESS plant side cable details are summarized in Table III.

TABLE III
CABLE DETAILS

Type	Cable Ref.	Length (m)	R (ohm/ km)	X (ohm/ km)	C (uF/ km)
15kV - 9×1c 1000mm2, Cu	DNO Cable	90	0.127	0.121	0.259
33kV - 6×1c 630mm2, Cu	DNO Cable	180	0.051	0.090	0.647
3×1c 630mm2, Cu - BESS plant cable	C-06	35	0.042	0.097	0.320
	C-08	30			
3×1c 300mm2, Cu - BESS plant cable	C-16	20	0.079	0.102	0.370
	C-07	15			
3×1c 120mm2, Al - BESS plant cable	C-15	85	0.325	0.126	0.170
	C-14	25			
	C-01	125			
	C-02	115			
	C-03	100			
	C-04	90			
	C-05	80			
	C-09	75			
	C-10	60			
	C-11	50			
	C-12	65			
	C-13	80			

D. BESS Inverter Details

The details of the BESS inverters and harmonic impedance sweep (inverter Norton self-impedance) at the 0.66kV LV level are given in Table IV and Fig. 1 as per provided by inverter vendor. The impedance profile is applicable across the full operating range (0%–100%), encompassing both charging and discharging modes, as per discussions with the vendor. Furthermore, the BESS inverters operate at a switching frequency of 2950 Hz.

TABLE IV
BESS INVERTER DETAILS

Parameter	Details
Rated voltage [kV]	0.66
Rated power [kVA]	3800
Number of the inverters	19

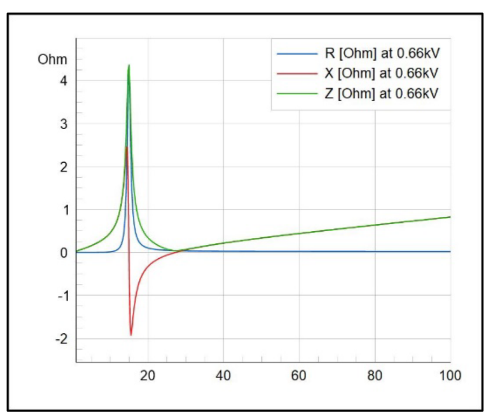

Fig. 1. Single BESS inverter self-impedance R-X-Z sweeps, 2nd to 100th harmonic order

E. Site Harmonic Measurement Details

Post-connection harmonic voltage measurements up to 100th harmonic order were carried out at the 33kV PCC. Considering the BESS plant was an operational site, a detailed harmonic site measurement was conducted for various operation modes - including idle, charging & discharging - to capture comprehensive behavior of the inverters and to ensure a robust harmonic filter design. The measurement details are summarized in Table V. Each measurement period spans a minimum duration of 60 minutes, except background harmonic measurement. The measurement was conducted over a continuous 7-day period. Data collected during this period is processed using 10-minute averaging to minimize the impact of transient variations and captures representative trends within the observed dataset in line with ER G5/5 [2].

TABLE V
HARMONIC MEASUREMENT DETAILS

Case ID	Operation Mode	Power Output [MW]	Explanation
I	Inverter LV circuit breakers OPEN	0	This test was done to investigate background harmonic distortion.
II	Idle	0	Inverters are in service, but no power export & import.
III	Import	1.0	Import operation mode at various power output levels
IV		10.0	
V		12.5	
VI		25.0	
VII		37.5	
VIII		50	
IX	Export	1.0	Export operation mode at various power output levels
X		10.0	
XI		12.5	
XII		25.0	
XIII		37.5	
XIV		50	

Although all harmonic orders up to the 100th were analyzed, only the measurement results of the most relevant harmonic orders are presented in Table VI and Table VII for the brevity. No additional harmonic non-compliances were observed up to the 100th h. order.

TABLE VI
HARMONIC MEASUREMENT RESULTS, CASES I-VIII

h	Harmonic measurement cases [%]							
	I	II	III	IV	V	VI	VII	VIII
8	0.04	0.08	0.14	0.10	0.22	0.14	0.13	0.17
10	0.04	0.15	0.15	0.10	0.21	0.14	0.14	0.15
14	0.04	0.09	0.17	0.08	0.22	0.13	0.14	0.22
16	0.02	0.27	0.24	0.11	0.35	0.12	0.21	0.35
17	0.06	0.44	0.56	0.37	0.82	0.24	0.69	1.75
18	0.03	0.12	0.16	0.11	0.25	0.40	0.21	0.14
19	0.06	0.35	0.11	0.06	0.34	0.14	0.34	0.46
20	0.03	0.14	0.10	0.12	0.34	0.34	0.19	0.25
56	0.02	0.05	0.04	0.06	0.04	0.04	0.05	0.04
57	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04
58	0.02	0.05	0.05	0.22	0.05	0.05	0.05	0.06
59	0.03	0.15	0.14	0.66	0.15	0.16	0.17	0.18
60	0.03	0.04	0.04	0.04	0.03	0.04	0.03	0.04
61	0.04	0.14	0.14	0.63	0.14	0.15	0.17	0.17
62	0.03	0.05	0.05	0.22	0.05	0.05	0.05	0.05
63	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
64	0.02	0.04	0.04	0.15	0.04	0.03	0.04	0.04

TABLE VII
HARMONIC MEASUREMENT RESULTS, CASES IX-XIV

h	Harmonic measurement cases [%]						
	IX	X	XI	XII	XIII	XIV	Max of cases I-XIV
8	0.08	0.08	0.18	0.12	0.11	0.14	0.22
10	0.12	0.08	0.21	0.15	0.12	0.15	0.21
14	0.06	0.06	0.12	0.07	0.11	0.12	0.22
16	0.20	0.08	0.45	0.13	0.23	0.37	0.45
17	0.27	0.33	0.68	0.25	0.38	0.69	1.75
18	0.11	0.13	0.46	0.26	0.80	0.24	0.80
19	0.26	0.08	0.46	0.12	0.74	0.29	0.74
20	0.08	0.07	0.09	0.12	0.14	0.11	0.34
56	0.00	0.16	0.04	0.04	0.05	0.05	0.16
57	0.04	0.04	0.04	0.04	0.04	0.04	0.04
58	0.00	0.22	0.06	0.06	0.06	0.05	0.22
59	0.00	0.20	0.14	0.13	0.13	0.14	0.66
60	0.00	0.03	0.04	0.04	0.04	0.04	0.04
61	0.00	0.21	0.13	0.12	0.13	0.14	0.63
62	0.00	0.20	0.05	0.06	0.05	0.05	0.22
63	0.00	0.04	0.04	0.04	0.04	0.04	0.04
64	0.00	0.15	0.03	0.03	0.04	0.04	0.15

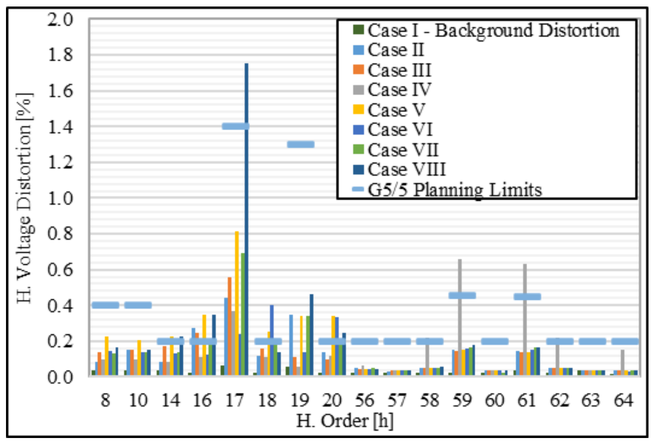

Fig. 2. Harmonic measurement results against G5/5 planning limits, Cases I-VIII

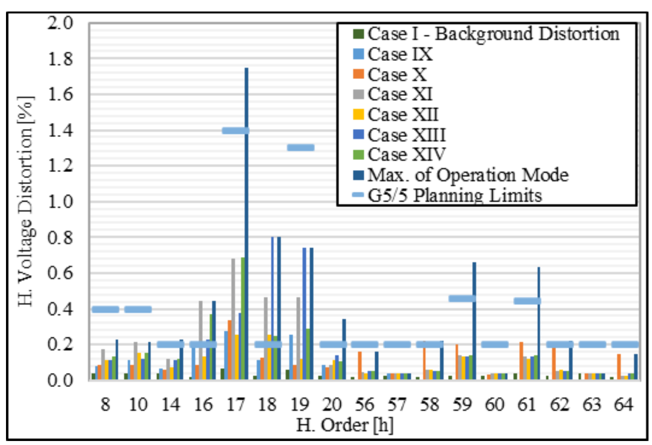

Fig. 3. Harmonic measurement results against G5/5 planning limits, Cases IX-XIV

The post-connection measurements reveal various instances of harmonic non-compliance. These exceedances do not correlate with the power export and import levels (0%-100%) of the BESS plant. In other words, maximum power output (100%) does not necessarily result in the highest harmonic distortion values at each harmonic order.

IV. HARMONIC AND HARMONIC FILTER DESIGN STUDY METHODOLOGY

To ensure a robust harmonic filter, the design is based on the maximum harmonic distortions observed across various operating modes. The study methodology is summarized in this section. It should also be noted that the

A. Background harmonic distortion representation

P95 harmonic data, which is the level of harmonic distortion that is associated to the probability of occurrence 95% of the time, measured at the 33kV PCC while the BESS inverters were physically switched out. This measurement was conducted over a continuous 7-day period

A harmonic current source was connected at the 33kV PCC to represent the measured harmonic background voltage at the 33kV PCC for the provided harmonic impedance envelope – intact, upper bound, lower bound and intermediary scenarios (Wi = 0.2, 0.4, 0.6 and 0.8). The background harmonic voltage distortions were tuned to match with the measured values for each study case.

B. Calculation of harmonic voltage distortions

The methodology presented in ER G5/5 for a Stage 3 harmonic assessment has been used to calculate the harmonic voltages in this assessment. The procedure followed is outlined below [2]:

- The base network has both background harmonics and BESS plant harmonic sources represented.
- The existing background voltage distortion is modified because of the addition of new emitting equipment into the network. The following equation is applied to calculate the effect of the new harmonic impedance into the existing background distortion.

$$V_{h\,bg\,Post} = V_{h\,bg\,Pre}\, x \frac{|Z_{h\,PCC\,Post}|}{|Z_{h\,PCC\,Pre}|}$$

Where:

$|Z_{h\,PCC\,Post}|$: the modules of the self-impedance at the PCC after the new user is connected.

$|Z_{h\,PCC\,Pre}|$: the modules of the self-impedance at the PCC before the new user is connected.

$V_{h\,bg\,Pre}$: the existing background voltage distortion before the connection.

$V_{h\,bg\,Post}$: the modified background voltage distortion after connection of the new user.

- In line with CIGRE 766, the harmonic current of the individual BESS inverters is added up arithmetically up to 100th harmonic order. The site measurement also supports this approach [3].
- At each selected corresponding busbar, $V_{h\,bg\,Post}$ and V_{hc} were combined to give the predicted harmonic voltages 'V_{hp}' based upon the equation below [2].

$$V_{hp} = \sqrt[\alpha]{{V_{h\,bg\,Post}}^{\alpha} + {V_{hc}}^{\alpha}}$$

Where:

$V_{h\,bg\,Post}$: Modified background voltage distortion resulted by the connection of the new user.

V_{hc}: Incremental increase in harmonic voltage distortion.

V_{hp}: Predicted harmonic voltage distortion.

α: Summation exponent – See Table VIII.

TABLE VIII
AGGREGATION EXPONENTS

Summation exponent (α)	Harmonic order [h]
1.0	h < 5
1.4	5 <= h <=10
2.0	h >10

- Harmonic current injections from the BESS inverters are tuned to match the highest harmonic measurement data. The harmonic currents were then injected at the LV side of each BESS transformer. The minimum P95 background measurement data is used to calculate harmonic current injections from the BESS inverters. This calculation is done based upon the intact background network configuration.
- After calculation of harmonic current injection from the BESS inverters, the maximum P95 background measurement data is then used to calculate V_{hp} for entire external grid impedance sweeps (Cases D01-D-08) to ensure a pessimistic approach and a robust harmonic filter design.
- The predicted harmonic voltage distortions (V_{hp}) are compared to G5/5 planning limits with and without designed harmonic filter.

C. Component modelling

The following modelling methods and PowerFactory | DIgSILENT software package settings are used:

- The cables are all modelled as distributed parameters with skin effect approximated as a square-root function against harmonic order [3], [4].
- The transformer skin effects are used in line with the specified model in Electra 164 (CIGRE JTF 36.05.02/14.03.03). The parameters are used (a0 = 0.85, a1 = 0.075, a2 =0.075, b = 1.4) in the frequency dependent equation - Rs(h) = Rt x (a0 + a1xhb +a2xh2). This was decided based upon the harmonic measurements of BESS inverters disconnected & connected. This ensures an adequate level of modelling & damping [3].
- The BESS inverters were modelled in this assessment as Norton equivalents – a parallel impedance with a harmonic current injection source at the LV levels.
- Harmonic injections from all sources were assumed to be positive sequence components at all frequencies.

V. LIMITATION OF THE STUDY

One of the core limitations of a harmonic analysis is the representation of background harmonic voltage distortion. The background harmonic distortion is represented as a constant harmonic voltage across the entire impedance sweeps - it is uncertain that the measured background harmonic voltage distortion reflects to each background impedance profile.

VI. Harmonic Filter Design

Various filter options were connected to the 33kV BESS Switchboard and tested against all study cases (D01-D08) to ensure the mitigation of individual harmonic voltage distortions at the 33kV PCC. In addition to achieving harmonic compliance, the proposed filter design also considers cost-effectiveness in terms of manufacturing and optimized harmonic filter losses to reduce operational costs. The parameters of the designed filter are given in Table IX [4], [5].

TABLE IX
DESIGNED HARMONIC FILTER PARAMATERS

Filter Parameters	Values
Filter Arrangement	C-type
Size [MVAR]	5.0
Tuning frequency [Hertz]	240
Filter Q factor(i) [R/X at 240 Hertz]	0.55
Tuning Reactor Q factor(i) [X/R at 50 Hertz]	131.8
R [Ω]	26.09
Cmain [μF]	14.62
Cauxiliary [μF]	322.11
L [mH]	31.46

(i): These may vary depending on the type of software used.

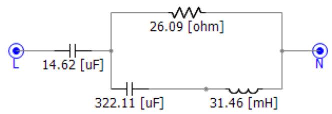

Fig. 4. Harmonic filter simplified electrical schematic

VII. Harmonic Study Results

Harmonic voltage distortion and harmonic impedance assessment results are demonstrated separately in this section.

A. Harmonic voltage distortion results

Predicted harmonic voltage distortion (V_{hp}) results against the G5/5 planning limits for all cases are tabulated in Table X and Table XI. The results include without & with filter connections. Although all harmonic orders up to the 100th were analyzed, only the most relevant harmonic distortion results are presented for brevity. All other harmonic distortion results comply with G5/5 limits.

TABLE X
STUDY RESULTS, CASES D01-D08 WITHOUT HARMONIC FILTER

h	G55	Harmonic study results [%]						
		D01& D02	D03	D04	D05	D06	D07	D08
THD	3.70	2.57	1.23	1.70	2.16	2.67	3.16	3.43
8	0.40	0.28	0.12	0.17	0.21	0.25	0.27	0.30
10	0.40	0.22	0.11	0.15	0.19	0.23	0.25	0.28
14	0.20	0.22	0.09	0.13	0.18	0.23	0.28	0.33
16	0.20	0.45	0.11	0.20	0.31	0.44	0.61	0.81
17	1.40	1.75	0.36	0.69	1.18	1.79	2.35	2.58
18	0.20	0.80	0.19	0.40	0.62	0.69	0.66	0.61
19	1.30	0.74	0.39	0.67	0.74	0.71	0.66	0.63
20	0.20	0.34	0.27	0.35	0.35	0.34	0.33	0.32
56	0.20	0.16	0.13	0.15	0.16	0.18	0.19	0.19
57	0.20	0.04	0.03	0.03	0.03	0.03	0.03	0.03
58	0.20	0.22	0.17	0.19	0.21	0.22	0.23	0.23
59	0.45	0.66	0.50	0.55	0.59	0.61	0.63	0.64
60	0.20	0.04	0.02	0.02	0.02	0.02	0.02	0.02
61	0.45	0.63	0.45	0.48	0.50	0.52	0.52	0.53
62	0.20	0.22	0.15	0.15	0.16	0.16	0.16	0.16
63	0.20	0.04	0.03	0.03	0.03	0.03	0.02	0.02
64	0.20	0.15	0.10	0.11	0.11	0.11	0.11	0.11

TABLE XI
STUDY RESULTS, CASES D01-D08 WITH HARMONIC FILTER

h	G55	Harmonic study results [%]						
		D01& D02	D03	D04	D05	D06	D07	D08
THD	3.70	1.14	0.86	1.18	1.45	1.68	1.87	2.03
8	0.40	0.28	0.13	0.20	0.26	0.30	0.33	0.35
10	0.40	0.22	0.11	0.16	0.19	0.22	0.23	0.24
14	0.20	0.12	0.07	0.09	0.11	0.11	0.11	0.11
16	0.20	0.12	0.08	0.10	0.11	0.11	0.11	0.11
17	1.40	0.31	0.22	0.28	0.30	0.30	0.30	0.30
18	0.20	0.13	0.10	0.12	0.13	0.13	0.13	0.13
19	1.30	0.23	0.19	0.22	0.22	0.22	0.22	0.22
20	0.20	0.16	0.14	0.15	0.15	0.15	0.15	0.15
56	0.20	0.02	0.02	0.02	0.02	0.02	0.02	0.02
57	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00
58	0.20	0.02	0.02	0.02	0.02	0.02	0.02	0.02
59	0.45	0.05	0.05	0.05	0.05	0.05	0.05	0.05
60	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00
61	0.45	0.05	0.05	0.05	0.05	0.05	0.05	0.05
62	0.20	0.02	0.02	0.02	0.02	0.02	0.02	0.02
63	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00
64	0.20	0.01	0.01	0.01	0.01	0.01	0.01	0.01

The worst results of the study Case D01-D08 against the G5/5 planning limits are demonstrated in Table XII and Fig. 5.

TABLE XII
WORST STUDY RESULTS, WITHOUT & WITH HARMONIC FILTER

h	G55 limits	Worst harmonic study distortion results	
		Without harmonic filter	With harmonic filter
THD	3.70	3.43	2.03
8	0.40	0.30	0.35
10	0.40	0.28	0.24
14	0.20	0.33	0.12
16	0.20	0.81	0.12
17	1.40	2.58	0.31
18	0.20	0.86	0.13
19	1.30	0.79	0.23
20	0.20	0.36	0.16
56	0.20	0.19	0.02
57	0.20	0.04	0.00
58	0.20	0.24	0.02
59	0.45	0.71	0.05
60	0.20	0.05	0.00
61	0.45	0.67	0.05
62	0.20	0.23	0.02
63	0.20	0.04	0.00
64	0.20	0.16	0.01

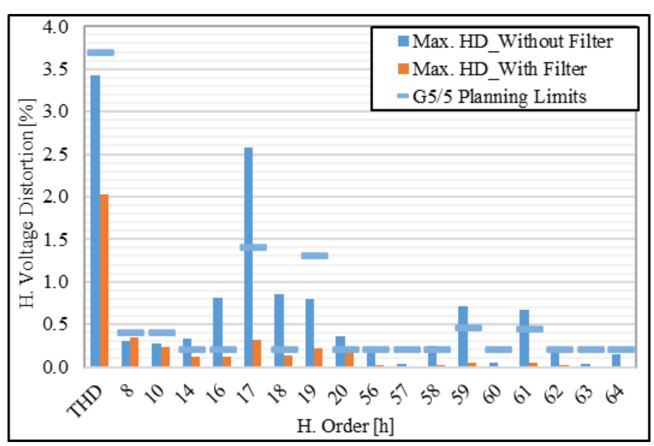

Fig. 5. Worst harmonic study results against G5/5 planning limits, Without & with harmonic filter

B. *Harmonic impedance assessment results*

Harmonic impedance sweeps are presented in this section. The impedance sweeps at the 33kV PCC both prior to and after the 33kV BESS plant connection without & with the designed harmonic filter were obtained from the model and analyzed to identify resonance magnitudes and frequencies at which they occur. The results of these scans are illustrated in the following graphs.

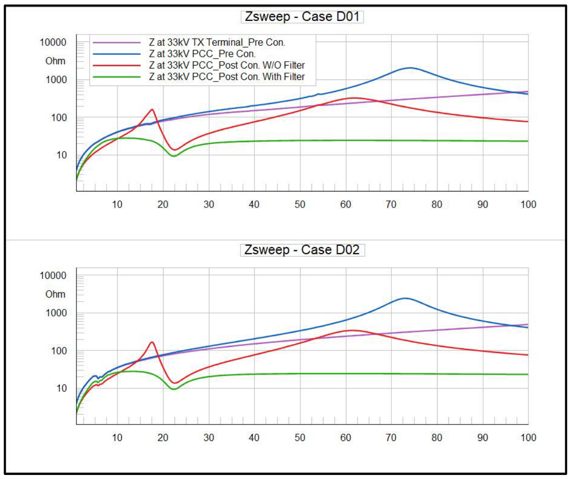

Fig. 6. Impedance sweeps, Study cases D01-D02, Summer & Winter demand

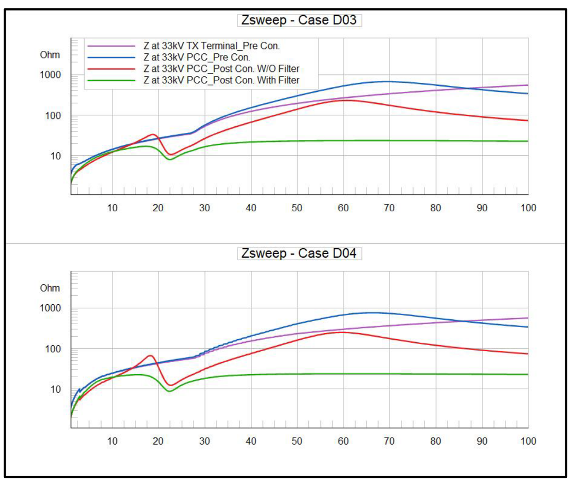

Fig. 7. Impedance sweeps, Study cases D03-D04, Lower bound & Wi=0.2

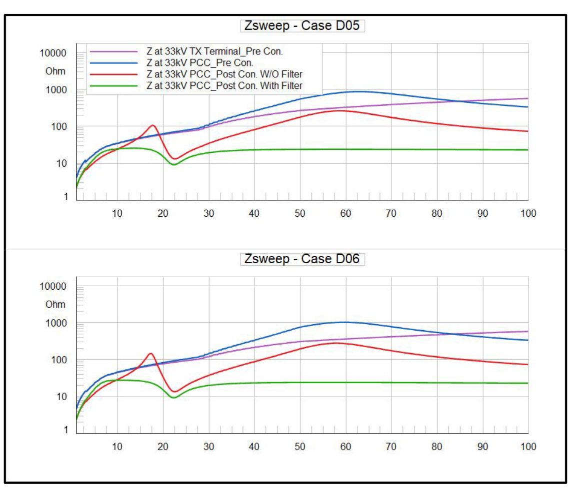

Fig. 8. Impedance sweeps, Study cases D05-D06, Wi=0.24& Wi=0.6

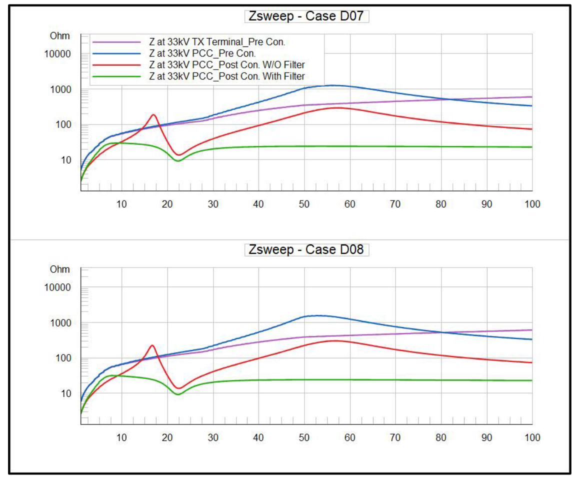

Fig. 9. Impedance sweeps, Study cases D07-D08, Wi=0.8 & Upper bound

VIII. CONCLUSIONS AND RECOMMENDATIONS

It was found that the BESS plant does not comply with the G5/5 planning limits because of the various non-compliances between 14th - 20th and 55th - 65th harmonic orders.

Two local resonances were identified: one between the 14th and 20th harmonic orders, and the other between the 50th and 70th harmonic orders. The resonances 14th-20th and 50th-70th h. orders are caused by inverter self-impedance and short 33kV cable capacitances, respectively.

No direct correlation was found between harmonic distortions at different orders against various power export and import levels (0%-100%) of the BESS plant. In other words, maximum power output (100%) does not necessarily result in the highest harmonic distortion values at each harmonic order. Therefore, considering various outputs of the BESS inverters are essential for harmonic studies.

A 33kV, 5.0MVAr C-type harmonic filter tuned to 240Hz with quality factor of 0.55 is recommended to ensure compliance against G5/5 planning limits. The parallel resonances are adequately dampened with the installation of the designed filter. To minimize power losses at the fundamental frequency, a C-type filter design is recommended. The filter is currently under manufacturing. Upon commissioning, post-connection harmonic measurements will be performed to assess the effectiveness of the designed filter.

The quality factor and tuning frequency of the designed filter were optimized not only to ensure compliance but also to prevent the amplification of source impedances provided by the DNO across the 2nd to 100th harmonic orders

Overall, the system is well isolated from the transmission level via the SGT tertiary winding and grid transformer. However, the local system is sensitive to capacitances, whether in the inverter internal filter or the 33kV cables, due to poor damping elements. Therefore, it is recommended to model the inverter self-impedance and 33kV cable details with high accuracy. Failure to accurately represent these elements may result in an inability to capture harmonic exceedances during simulation studies conducted at the system design stage.

IX. Appendix

A. System Details

The simplified site electrical schematic is illustrated in Fig. 10. The site includes 10 BESS transformers and 19 BESS inverters. However, to maintain clarity and conciseness in this technical paper, not all individual components are represented in the simplified schematic.

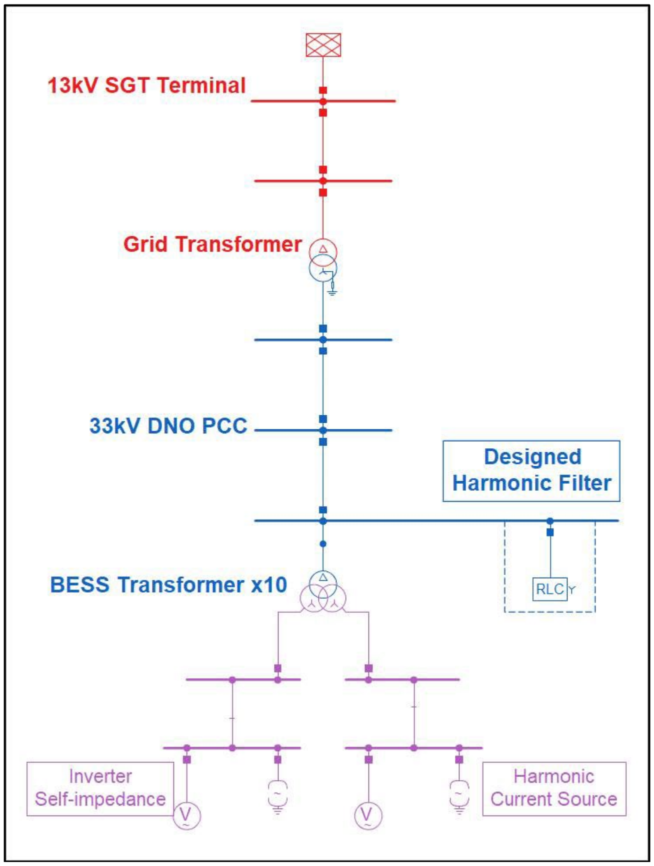

Fig. 10. Simplified site electrical schematic

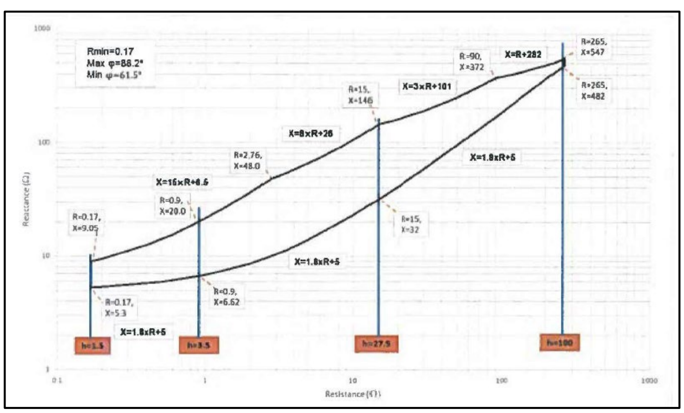

Fig. 11. External grid harmonic impedance envelope

TABLE XIIII
BESS Inverter Norton Equivalent Details

H. Order	Current	Norton Impedance		H. Order	Current	Norton Impedance	
	I[A]	R [Ohm]	X [Ohm]		I[A]	R [Ohm]	X [Ohm]
2	14.56508	0.00050	0.05900	52	0.86172	0.02450	0.35820
3	2.46746	0.00050	0.09000	53	0.87717	0.02430	0.36910
4	13.62578	0.00070	0.12280	54	0.40744	0.02420	0.37980
5	0.00000	0.00090	0.15860	55	1.04172	0.02400	0.39040
6	11.04106	0.00140	0.19840	56	3.11370	0.02390	0.40090
7	0.00000	0.00240	0.24420	57	0.44571	0.02380	0.41140
8	15.64004	0.00420	0.29870	58	3.77359	0.02370	0.42180
9	4.22969	0.00780	0.36680	59	10.65707	0.02350	0.43210
10	10.46236	0.01510	0.45650	60	0.22210	0.02340	0.44240
11	26.76079	0.03100	0.58430	61	9.37499	0.02330	0.45260
12	6.43270	0.07100	0.78690	62	3.05279	0.02320	0.46270
13	17.88332	0.19990	1.16450	63	0.21530	0.02320	0.47280
14	9.44147	0.88530	2.02820	64	2.23212	0.02310	0.48280
15	3.05490	4.34950	-0.22650	65	0.71377	0.02300	0.49280
16	9.30300	0.99420	-1.55150	66	0.10420	0.02290	0.50280
17	24.43909	0.37110	-0.91950	67	0.51351	0.02280	0.51270
18	10.58422	0.20630	-0.61330	68	0.45409	0.02280	0.52250
19	18.44741	0.13900	-0.43950	69	0.10983	0.02270	0.53230
20	13.99800	0.10430	-0.32660	70	0.00000	0.02260	0.54210
21	3.84613	0.08380	-0.24620	71	0.26071	0.02260	0.55190
22	11.27755	0.07060	-0.18510	72	0.35993	0.02250	0.56160
23	12.70703	0.06140	-0.13630	73	0.00000	0.02250	0.57130
24	7.02787	0.05480	-0.09600	74	0.31913	0.02240	0.58100
25	16.72182	0.04970	-0.06160	75	0.42287	0.02240	0.59060
26	24.52898	0.04580	-0.03160	76	0.35311	0.02230	0.60020
27	17.22893	0.04270	-0.00490	77	0.37040	0.02230	0.60980
28	24.16875	0.04020	0.01920	78	0.46647	0.02220	0.61930
29	18.92953	0.03810	0.04120	79	0.00000	0.02220	0.62890
30	10.43024	0.03640	0.06160	80	0.49907	0.02210	0.63840
31	10.98734	0.03490	0.08060	81	0.52907	0.02210	0.64780
32	6.35178	0.03370	0.09860	82	0.55000	0.02210	0.65730
33	3.23226	0.03260	0.11550	83	0.57083	0.02200	0.66680
34	3.97748	0.03160	0.13170	84	0.59165	0.02200	0.67620
35	3.49145	0.03080	0.14720	85	0.00000	0.02200	0.68560
36	2.32338	0.03010	0.16210	86	0.63340	0.02190	0.69500
37	2.84438	0.02940	0.17650	87	0.65403	0.02190	0.70440
38	2.62065	0.02880	0.19050	88	0.67495	0.02190	0.71370
39	1.95889	0.02830	0.20400	89	0.69573	0.02180	0.72310
40	2.19888	0.02780	0.21720	90	0.71621	0.02180	0.73240
41	1.91566	0.02740	0.23010	91	0.73706	0.02180	0.74170
42	1.64789	0.02700	0.24270	92	0.93594	0.02180	0.75100
43	1.68315	0.02670	0.25510	93	0.52064	0.02170	0.76030
44	1.57996	0.02630	0.26720	94	0.79946	0.02170	0.76950
45	1.39236	0.02600	0.27920	95	0.33199	0.02170	0.77880
46	1.32998	0.02580	0.29090	96	1.20669	0.02170	0.78800
47	1.11799	0.02550	0.30250	97	0.86150	0.02160	0.79730
48	1.13381	0.02530	0.31390	98	1.29610	0.02160	0.80650
49	0.91577	0.02510	0.32520	99	0.90267	0.02160	0.81570
50	1.10476	0.02490	0.33630	100	1.40633	0.02160	0.82490
51	0.45101	0.02470	0.34730				

B. Harmonic Study Results

TABLE IX

HARMONIC AMPLIFICATION FACTOR, $Z_{H\ POST}$ (WITHOUT FILTER) / $Z_{H\ PRE}$

H. Order	Study Case IDs / Amplification Factor (Zpost / Zpre)																
	D01	D02	D03	D04	D05	D06	D07	D08	H. Order	D01	D02	D03	D04	D05	D06	D07	D08
2	0.55	0.55	0.64	0.59	0.55	0.51	0.48	0.45	52	0.33	0.50	0.48	0.40	0.33	0.27	0.21	0.17
3	0.58	0.55	0.70	0.64	0.58	0.54	0.50	0.46	53	0.34	0.51	0.48	0.41	0.34	0.27	0.22	0.18
4	0.59	0.54	0.74	0.66	0.59	0.54	0.49	0.45	54	0.34	0.52	0.48	0.41	0.34	0.28	0.22	0.19
5	0.59	0.57	0.76	0.67	0.59	0.53	0.48	0.44	55	0.34	0.53	0.48	0.41	0.34	0.28	0.23	0.20
6	0.59	0.64	0.78	0.67	0.59	0.53	0.48	0.44	56	0.34	0.54	0.48	0.41	0.34	0.28	0.23	0.20
7	0.61	0.65	0.80	0.69	0.61	0.54	0.49	0.45	57	0.33	0.55	0.47	0.40	0.33	0.28	0.23	0.21
8	0.63	0.64	0.81	0.71	0.63	0.57	0.52	0.48	58	0.33	0.55	0.47	0.39	0.33	0.27	0.24	0.22
9	0.66	0.66	0.83	0.74	0.66	0.60	0.55	0.51	59	0.32	0.54	0.45	0.38	0.32	0.27	0.24	0.22
10	0.69	0.69	0.85	0.76	0.69	0.64	0.59	0.54	60	0.31	0.52	0.44	0.37	0.31	0.26	0.24	0.23
11	0.73	0.72	0.87	0.80	0.73	0.68	0.63	0.59	61	0.30	0.49	0.42	0.35	0.30	0.26	0.24	0.23
12	0.78	0.77	0.90	0.84	0.78	0.74	0.69	0.65	62	0.29	0.45	0.40	0.34	0.29	0.25	0.23	0.23
13	0.85	0.84	0.93	0.89	0.85	0.81	0.78	0.75	63	0.27	0.40	0.38	0.32	0.27	0.25	0.23	0.23
14	0.94	0.95	0.97	0.96	0.94	0.93	0.92	0.90	64	0.26	0.35	0.36	0.30	0.26	0.24	0.23	0.23
15	1.09	1.13	1.03	1.06	1.09	1.12	1.16	1.20	65	0.26	0.30	0.34	0.29	0.26	0.24	0.23	0.23
16	1.33	1.48	1.10	1.20	1.33	1.48	1.64	1.82	66	0.25	0.25	0.32	0.28	0.25	0.23	0.23	0.23
17	1.71	**2.23**	1.19	1.42	1.71	**2.00**	**2.13**	**1.95**	67	0.24	0.21	0.30	0.26	0.24	0.23	0.23	0.23
18	**1.80**	2.09	**1.29**	**1.63**	**1.80**	1.55	1.19	0.92	68	0.24	0.17	0.29	0.25	0.24	0.23	0.22	0.23
19	1.06	0.93	1.29	1.35	1.06	0.77	0.58	0.46	69	0.23	0.14	0.27	0.25	0.23	0.22	0.22	0.23
20	0.54	0.45	0.99	0.77	0.54	0.40	0.31	0.25	70	0.23	0.12	0.26	0.24	0.23	0.22	0.22	0.23
21	0.30	0.25	0.60	0.42	0.30	0.23	0.18	0.15	71	0.22	0.10	0.25	0.23	0.22	0.22	0.22	0.23
22	0.20	0.16	0.39	0.27	0.20	0.15	0.12	0.10	72	0.22	0.08	0.24	0.23	0.22	0.22	0.22	0.23
23	0.18	0.15	0.35	0.25	0.18	0.15	0.12	0.10	73	0.22	0.08	0.24	0.23	0.22	0.22	0.22	0.22
24	0.21	0.17	0.38	0.27	0.21	0.16	0.14	0.11	74	0.22	0.08	0.23	0.22	0.22	0.22	0.22	0.22
25	0.23	0.19	0.42	0.30	0.23	0.19	0.16	0.13	75	0.22	0.08	0.23	0.22	0.22	0.22	0.22	0.22
26	0.26	0.22	0.45	0.34	0.26	0.21	0.18	0.15	76	0.22	0.08	0.23	0.22	0.22	0.22	0.22	0.22
27	0.29	0.24	0.48	0.36	0.29	0.23	0.19	0.16	77	0.22	0.09	0.22	0.22	0.22	0.22	0.22	0.22
28	0.30	0.25	0.49	0.38	0.30	0.25	0.21	0.17	78	0.22	0.09	0.22	0.22	0.22	0.22	0.22	0.22
29	0.30	0.27	0.48	0.37	0.30	0.25	0.21	0.18	79	0.22	0.10	0.22	0.22	0.22	0.22	0.22	0.22
30	0.30	0.28	0.47	0.37	0.30	0.25	0.21	0.18	80	0.22	0.11	0.22	0.22	0.22	0.22	0.22	0.22
31	0.31	0.29	0.46	0.37	0.31	0.26	0.22	0.19	81	0.22	0.11	0.22	0.22	0.22	0.22	0.22	0.22
32	0.31	0.30	0.46	0.37	0.31	0.26	0.22	0.19	82	0.22	0.12	0.22	0.21	0.22	0.22	0.22	0.22
33	0.31	0.31	0.45	0.37	0.31	0.26	0.22	0.19	83	0.22	0.13	0.22	0.21	0.22	0.22	0.22	0.22
34	0.31	0.32	0.45	0.37	0.31	0.26	0.22	0.19	84	0.22	0.13	0.21	0.21	0.22	0.22	0.22	0.22
35	0.31	0.33	0.44	0.37	0.31	0.26	0.22	0.19	85	0.22	0.14	0.21	0.21	0.22	0.22	0.22	0.22
36	0.31	0.34	0.44	0.37	0.31	0.26	0.22	0.19	86	0.22	0.14	0.21	0.21	0.22	0.22	0.22	0.22
37	0.31	0.35	0.44	0.37	0.31	0.26	0.22	0.19	87	0.22	0.15	0.21	0.21	0.22	0.22	0.22	0.22
38	0.31	0.36	0.44	0.37	0.31	0.26	0.22	0.19	88	0.22	0.15	0.21	0.21	0.22	0.22	0.22	0.22
39	0.31	0.37	0.44	0.37	0.31	0.26	0.22	0.18	89	0.22	0.16	0.21	0.22	0.22	0.22	0.22	0.22
40	0.31	0.37	0.44	0.37	0.31	0.26	0.22	0.18	90	0.22	0.16	0.21	0.22	0.22	0.22	0.22	0.22
41	0.31	0.38	0.44	0.37	0.31	0.26	0.22	0.18	91	0.22	0.16	0.21	0.22	0.22	0.22	0.22	0.22
42	0.31	0.39	0.44	0.37	0.31	0.26	0.21	0.18	92	0.22	0.17	0.22	0.22	0.22	0.22	0.22	0.22
43	0.31	0.40	0.44	0.37	0.31	0.26	0.21	0.17	93	0.22	0.17	0.22	0.22	0.22	0.22	0.22	0.22
44	0.31	0.41	0.45	0.37	0.31	0.26	0.21	0.17	94	0.22	0.17	0.22	0.22	0.22	0.22	0.22	0.22
45	0.31	0.42	0.45	0.38	0.31	0.26	0.21	0.17	95	0.22	0.18	0.22	0.22	0.22	0.22	0.22	0.22
46	0.31	0.43	0.45	0.38	0.31	0.26	0.21	0.16	96	0.22	0.18	0.22	0.22	0.22	0.22	0.22	0.22
47	0.32	0.44	0.46	0.38	0.32	0.26	0.20	0.16	97	0.22	0.18	0.22	0.22	0.22	0.22	0.22	0.22
48	0.32	0.45	0.46	0.39	0.32	0.26	0.20	0.16	98	0.22	0.18	0.22	0.22	0.22	0.22	0.22	0.22
49	0.32	0.46	0.46	0.39	0.32	0.26	0.20	0.15	99	0.22	0.19	0.22	0.22	0.22	0.22	0.22	0.22
50	0.32	0.47	0.47	0.39	0.32	0.26	0.20	0.15	100	0.22	0.19	0.22	0.22	0.22	0.22	0.22	0.22
51	0.33	0.48	0.47	0.40	0.33	0.26	0.21	0.16	**Max**	**1.80**	**2.23**	**1.29**	**1.63**	**1.80**	**2.00**	**2.13**	**1.95**

TABLE X

HARMONIC AMPLIFICATION FACTOR, $Z_{H\ POST}$ (WITH FILTER) / $Z_{H\ PRE}$

H. Order	Study Case IDs / Amplification Factor (Zpost / Zpre)																
	D01	D02	D03	D04	D05	D06	D07	D08	H. Order	D01	D02	D03	D04	D05	D06	D07	D08
2	0.57	0.57	0.66	0.62	0.57	0.54	0.51	0.48	52	0.04	0.06	0.07	0.05	0.04	0.03	0.02	0.02
3	0.65	0.62	0.76	0.70	0.65	0.60	0.57	0.53	53	0.04	0.06	0.06	0.05	0.04	0.03	0.02	0.02
4	0.71	0.66	0.82	0.76	0.71	0.66	0.62	0.58	54	0.03	0.06	0.06	0.05	0.03	0.03	0.02	0.02
5	0.75	0.71	0.86	0.81	0.75	0.70	0.66	0.62	55	0.03	0.05	0.06	0.04	0.03	0.03	0.02	0.02
6	0.78	0.80	0.89	0.83	0.78	0.73	0.68	0.63	56	0.03	0.05	0.05	0.04	0.03	0.02	0.02	0.02
7	0.78	0.84	0.89	0.84	0.78	0.72	0.66	0.60	57	0.03	0.05	0.05	0.04	0.03	0.02	0.02	0.02
8	0.77	0.81	0.89	0.84	0.77	0.69	0.62	0.56	58	0.03	0.04	0.05	0.04	0.03	0.02	0.02	0.02
9	0.74	0.79	0.88	0.82	0.74	0.65	0.58	0.51	59	0.03	0.04	0.05	0.04	0.03	0.02	0.02	0.02
10	0.70	0.74	0.87	0.80	0.70	0.61	0.53	0.46	60	0.03	0.04	0.04	0.04	0.03	0.02	0.02	0.02
11	0.67	0.69	0.85	0.77	0.67	0.57	0.49	0.42	61	0.03	0.03	0.04	0.03	0.03	0.02	0.02	0.02
12	0.63	0.63	0.84	0.74	0.63	0.53	0.45	0.38	62	0.03	0.03	0.04	0.03	0.03	0.02	0.02	0.02
13	0.59	0.59	0.82	0.71	0.59	0.49	0.41	0.35	63	0.03	0.03	0.04	0.03	0.03	0.02	0.02	0.02
14	0.56	0.54	0.80	0.68	0.56	0.45	0.38	0.32	64	0.03	0.03	0.04	0.03	0.03	0.02	0.02	0.02
15	0.52	0.49	0.78	0.65	0.52	0.42	0.34	0.29	65	0.03	0.02	0.04	0.03	0.03	0.03	0.02	0.03
16	0.48	0.44	0.76	0.62	0.48	0.38	0.31	0.26	66	0.03	0.02	0.04	0.03	0.03	0.03	0.03	0.03
17	0.43	**0.39**	0.73	0.57	0.43	**0.34**	**0.27**	**0.23**	67	0.03	0.02	0.04	0.03	0.03	0.03	0.03	0.03
18	**0.38**	0.33	**0.69**	**0.51**	**0.38**	0.29	0.23	0.19	68	0.03	0.02	0.04	0.03	0.03	0.03	0.03	0.03
19	0.31	0.27	0.62	0.43	0.31	0.24	0.19	0.16	69	0.03	0.01	0.04	0.03	0.03	0.03	0.03	0.03
20	0.24	0.20	0.50	0.34	0.24	0.18	0.15	0.12	70	0.03	0.01	0.04	0.03	0.03	0.03	0.03	0.03
21	0.17	0.14	0.37	0.24	0.17	0.13	0.10	0.09	71	0.03	0.01	0.04	0.03	0.03	0.03	0.03	0.03
22	0.13	0.11	0.28	0.18	0.13	0.10	0.08	0.07	72	0.03	0.01	0.04	0.03	0.03	0.03	0.03	0.03
23	0.13	0.11	0.27	0.18	0.13	0.10	0.08	0.07	73	0.03	0.01	0.04	0.03	0.03	0.03	0.03	0.04
24	0.15	0.12	0.29	0.20	0.15	0.12	0.09	0.08	74	0.04	0.01	0.04	0.04	0.04	0.04	0.04	0.04
25	0.17	0.14	0.32	0.23	0.17	0.13	0.11	0.09	75	0.04	0.01	0.04	0.04	0.04	0.04	0.04	0.04
26	0.18	0.15	0.35	0.24	0.18	0.14	0.12	0.10	76	0.04	0.01	0.04	0.04	0.04	0.04	0.04	0.04
27	0.19	0.15	0.36	0.26	0.19	0.15	0.12	0.10	77	0.04	0.01	0.04	0.04	0.04	0.04	0.04	0.04
28	0.19	0.16	0.35	0.25	0.19	0.15	0.12	0.10	78	0.04	0.02	0.04	0.04	0.04	0.04	0.04	0.04
29	0.18	0.16	0.32	0.23	0.18	0.14	0.12	0.10	79	0.04	0.02	0.04	0.04	0.04	0.04	0.04	0.04
30	0.17	0.16	0.29	0.22	0.17	0.13	0.11	0.09	80	0.04	0.02	0.04	0.04	0.04	0.04	0.04	0.04
31	0.16	0.15	0.27	0.20	0.16	0.13	0.10	0.09	81	0.04	0.02	0.04	0.04	0.04	0.04	0.05	0.05
32	0.15	0.15	0.25	0.19	0.15	0.12	0.10	0.08	82	0.05	0.02	0.04	0.04	0.05	0.05	0.05	0.05
33	0.14	0.15	0.23	0.18	0.14	0.11	0.09	0.08	83	0.05	0.03	0.05	0.05	0.05	0.05	0.05	0.05
34	0.13	0.14	0.21	0.16	0.13	0.10	0.09	0.07	84	0.05	0.03	0.05	0.05	0.05	0.05	0.05	0.05
35	0.12	0.14	0.20	0.15	0.12	0.10	0.08	0.07	85	0.05	0.03	0.05	0.05	0.05	0.05	0.05	0.05
36	0.11	0.13	0.19	0.14	0.11	0.09	0.07	0.06	86	0.05	0.03	0.05	0.05	0.05	0.05	0.05	0.05
37	0.11	0.13	0.17	0.13	0.11	0.08	0.07	0.06	87	0.05	0.03	0.05	0.05	0.05	0.05	0.05	0.05
38	0.10	0.12	0.16	0.13	0.10	0.08	0.06	0.05	88	0.05	0.03	0.05	0.05	0.05	0.05	0.05	0.05
39	0.09	0.12	0.15	0.12	0.09	0.07	0.06	0.05	89	0.05	0.04	0.05	0.05	0.05	0.05	0.06	0.06
40	0.09	0.11	0.14	0.11	0.09	0.07	0.05	0.04	90	0.06	0.04	0.05	0.06	0.06	0.06	0.06	0.06
41	0.08	0.11	0.13	0.10	0.08	0.06	0.05	0.04	91	0.06	0.04	0.06	0.06	0.06	0.06	0.06	0.06
42	0.08	0.11	0.13	0.10	0.08	0.06	0.05	0.04	92	0.06	0.04	0.06	0.06	0.06	0.06	0.06	0.06
43	0.07	0.10	0.12	0.09	0.07	0.05	0.04	0.03	93	0.06	0.04	0.06	0.06	0.06	0.06	0.06	0.06
44	0.07	0.10	0.11	0.08	0.07	0.05	0.04	0.03	94	0.06	0.05	0.06	0.06	0.06	0.06	0.06	0.06
45	0.06	0.09	0.10	0.08	0.06	0.05	0.04	0.03	95	0.06	0.05	0.06	0.06	0.06	0.06	0.06	0.06
46	0.06	0.09	0.10	0.07	0.06	0.04	0.03	0.02	96	0.06	0.05	0.06	0.06	0.06	0.06	0.06	0.06
47	0.05	0.08	0.09	0.07	0.05	0.04	0.03	0.02	97	0.06	0.05	0.06	0.06	0.06	0.06	0.07	0.07
48	0.05	0.08	0.09	0.07	0.05	0.04	0.03	0.02	98	0.07	0.05	0.06	0.07	0.07	0.07	0.07	0.07
49	0.05	0.08	0.08	0.06	0.05	0.03	0.02	0.02	99	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.07
50	0.04	0.07	0.08	0.06	0.04	0.03	0.02	0.02	100	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.07
51	0.04	0.07	0.07	0.05	0.04	0.03	0.02	0.02	**Max**	**0.78**	**0.84**	**0.89**	**0.84**	**0.78**	**0.73**	**0.68**	**0.63**

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