# SUMMARY OF SUB-WORKGROUP DISCUSSIONS ON APPORTIONMENT OF HARMONIC HEADROOM IN EREC G5 ISSUE 5

Report by Stage 3 Assessment Sub-Workgroup

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# 1 SUMMARY

The EREC G5 review workgroup was mandated to assess the suitability of first come first served methodology for setting harmonic limits. Different apportionment methods were considered. The proposed methodology within EREC G5 Issue 5 is deemed to best meet the need of the industry as a whole and the objectives set out in the terms of reference. The application of apportionment for all harmonics would lead to:

- a more consistent approach which is fair for all users.
- allowing Network Owners/Operators to manage harmonics more efficiently.
- a more detailed guideline in EREC G5 Issue 5 bringing more consistency between connections allowing users to begin their design work early, avoiding unnecessary delays in ordering equipment

# 2 BACKGROUND

EREC G5 Issue 5 (EREC G5/5) [1] was published for consultation on 13/03/2019. One comment on the apportionment of the harmonic headroom to derive the harmonic limits was received which disagreed with the approach. The comment is shown below for ease of reference.

> "We are not able to confirm agreement with the "apportionment of headroom" approach at this stage, because an objective justification for this change has not been provided with the consultation. The consultation paper does not include any detail of analysis of the benefits / lower costs to users and consumers that the workgroup calculates would come from adopting the method of "apportionment of headroom" as compared to remaining with the existing method.

The objective of this note is to explain the rational that was considered by the Stage 3 Assessment sub-workgroup of the G5 Work Group (WG) and used in their subsequent proposal to the main WG.

Stage 3 assessment applies to connection of equipment that fails Stage 2 (excluding those with an LV PCC) and those connecting to voltage levels of 33 kV and above.

The revision of the method for allocation of harmonic headroom prescribed in EREC G5 Issue 4-1 (EREC G5/4-1) [2] was one of the main items in the Terms of Reference of WG [3]. The reason for this was the proliferation of equipment with harmonic emission used by network users (users), which in turn made it difficult to accommodate all new users in a fair and timely manner without causing significant delays and thus additional cost.

# 3 EREC G5/4-1 APPROACH VERSUS EREC G5/5 METHODOLOGY

In this section the methodology in EREC G5/4-1 for Stage 3 assessment is presented and its shortcomings for new connections at medium, high and extra high voltage levels (respectively, MV, HV and EHV), which have large harmonic emitting equipment, will be discussed. These include but not limited to, large variable speed drives for gas pumping stations, small to large solar farms, super charging stations for vehicles, small to very large onshore and offshore wind farms, HVDC interconnectors and high speed/high power locomotives. Comparisons are made between the approach within EREC G5/4-1 and those proposed in EREC G5/5.

The WG identified, amongst others, four main areas that required particular attention when applying Stage 3 assessment.

## 3.1 Allocation of headroom to different capacity network users

It has been recognised by Network Owners/Operators (NO) that the methodology in EREC G5/4-1 would lead to, in some respect, unfair allocation of the harmonic headroom. For example, a user with small MVA connection size (load or generation) who happened to be the first in the connection queue would be given all the headroom available. On the other hand, the second user in the queue who might be a large HVDC interconnector or windfarm, would have no headroom available to them. Similarly, if a large MVA connection is first in the connection queue, they should be given all the headroom forcing

the next in the queue, who may be small size user, to be allocated no headroom and having to install filter, whom may have not otherwise been forced to do so if there were some small headroom available, thus disadvantaging the smaller user by imposing the mitigation cost.

### 3.2 Data requirement and exchange between connectee and Network Owner/Operator (NO)

Currently, according to EREC G5/4-1, the assessment for the first connectee should be completed before the process for the second begins. Usually the full data for harmonic assessment is available at later stages of connection process which in turn introduces delays in the assessment of subsequent connectees. It is the objective of the Equal Right (ER) or apportionment approach to address this issue related to the amount of data that is required to begin the harmonic assessment and to reduce the dependency of assessment on the data.

The delay in providing data to the NO would lead to delay in the connection process and thus ordering the equipment that would have a significant financial impact.

### 3.3 Concurrency of connections

While the number of polluting equipment in the supply system is increasing, it is usual that two or more network users apply for connection to the same node or electrically near each other, in a short period of time. This imposes the need for a versatile process which allows the harmonic limits for each connection to be determined fairly, in a timely manner and, if possible, independent of each other.

Under current G5/4-1 if two connectees are connecting in close electrical proximity the second cannot complete their harmonic studies until the first has finished theirs. This could lead to a delay in the project. The EREC G5 WG attempt was to improve the situation. This required a method which allows the design of both parties to run in parallel and managing the resultant risk. The sub-workgroup considered the basis of apportionment method used in IEC 61000-3-6 [4] and proposed a method that is versatile and deemed fair to all users. The adopted approach minimises the need for data from the user which makes it possible to determine the limits for users at early stages of the connection process.

Appendix A provide a comparison between first come-first served (FCFS) and apportionment methodologies with respect to impact on the number of harmonic filter that may be required and time line and thus delay on projects.

### 3.4 Current practice according to EREC G5/4-1 for determining harmonic limits on the modification of background

Although EREC G5/4-1 is clear about how to assess a harmonic polluting plant which emits harmonic current or voltage but it is not so in describing how to estimate the effect of a resonant plant and therefore how to set harmonic limits on the amplification of the background harmonic levels.

Under EREC G5/4-1 the amount of the harmonic headroom each customer can have is allocated on a first come-first served basis. The sub-workgroup concluded that this approach did not help with the above concurrency and data requirement issues and was potentially disadvantaging some users. Alternatives were considered and a list of options, including first come-first served, were prepared and analysed. A summary of the available options is shown in Appendix B.

EREC G5/4-1 is based on the assessment of the harmonic impact of a new user' equipment due to harmonic emission from the equipment. This is explicitly shown in Figure 1 of EREC G5/4-1, part of which is shown in Fig 1 below for illustration.

Therefore, assessment is based on the data provided by new users. In addition to the harmonic current emission data, the new user must provide any other network data related to their installation that impacts the harmonic currents at the point of entry to the network. This additional data includes transformer, cables, shunt compensation etc, as these significantly impact the amount of harmonic current that are finally injected into the supply system. As per EREC G5/4-1 and ETR 122 [5], the network surrounding the point of common coupling (PCC) that the connection is made, should be modelled to include susceptible remote nodes. After including the new user network into the model the assessment can then begin and harmonic limits derived.

EREC G5/4-1 and more so ETR 122 elaborate on the impact of cable capacitance and shunt capacitor banks in the vicinity of the PCC that may cause resonance conditions which lead to increase in system impedance, which in turn cause higher distortion for a given harmonic current injection. However, they do not explicitly state that the resonance conditions or change in impedance at the PCC after the new

user's installation is connected may affect the network background harmonic levels. This is a real effect that has been managed by NOs by issuing limits on either the amplification factor or issuing total limits, using the context of G5/4-1 resonance conditions.

As said above, the concept of total limit has been used by NOs to manage the total impact of users but this has not been defined in EREC G5/4-1 and therefore has led to inconsistency in application of this engineering recommendation. The main question has been, what limit should be given for harmonics that the customer equipment does not inject any current but users need to know how much of the headroom they are allowed to use at those harmonics. For example, consider a situation where a new user injects the 5$^{th}$ and 7$^{th}$ harmonics with defined magnitudes. The connection is at 132 kV. The self-impedance of the network seen by the new customer is shown by the red trace in Fig 2 below, which was obtained from a real 132 kV network. As it can be seen the impedances at the 5$^{th}$ and 7$^{th}$ harmonics are respectively around 150 Ω and 100 Ω. The 5$^{th}$ harmonic voltage level at the busbar exceeds the planning level after considering the new user and therefore, filter had to be used. It is well known that reducing the network impedance magnitude at a given range of frequencies by means of passive filters, would create a parallel resonance between the network and equivalent impedance of the new user plant including harmonic filter, which always occur below the tune frequency of the filter. For example, in Fig 2, the green trace shows the impedance of the PCC after a D-Type filter was considered. The impedance at the 5$^{th}$ harmonic, the filter tuned frequency, reduced to about 65 Ω, which implies an attenuation of 57% compared to the case without the filter, which was enough to make the customer compliant at the 5$^{th}$ harmonic. Note that this is a real system design. The modification factor at the 7$^{th}$ harmonic is below unity and therefore the 7$^{th}$ harmonic voltage level would also reduce. However, the impedance at around the 3$^{rd}$ and 4$^{th}$ harmonics would increase. The amount by which the new impedance increases at frequencies below the filter tune frequency depends on the filter design and its component values but largely on the amount of damping, i.e. resistance, that is added to the filter, which in turn depends on how much of the headroom can be used. In this context, the amount of headroom that can be used determines the type and complexity of the filter. Therefore, it is essential that limits are specified even for harmonics that the network user does not emit any harmonic current, to allow mitigation to be designed. Note that harmonic filters are designed according to the harmonic limits, thus the information about how much of the headroom at other frequencies can be utilised by the filter designer must be known before the design begins.

Fig 1- Extract from Figure 1 in G5/4-1

Fig 2- Impedance of PCC for a 132 kV Busbar

EREC G5/4-1 does not provide any guidance for setting limits for harmonics that need to be managed, due to the impact on the background harmonic levels, but users do not have any current/voltage emission and are essential for users in meeting the harmonic specification.

One solution can be, contrary to G5/4-1, to specify the headroom up to the planning level for all other harmonics that the new user does not have any current/voltage emission. Note that it is "contrary to EREC G5/4-1" because the procedure in this engineering recommendation is based on the concept of "what the user" needs. Setting the limits for harmonics at which the customer has no emission at the planning level is based on the assumption that this effect is local and therefore the remote nodes are not affected. The counter argument to this is that the next customer is likely to cause the harmonic levels to exceed the planning level. This also applies to any modification, such as installing new cables or passive reactive power compensators, the NO will install in the network in the vicinity of the customer as there is no margin available for the NO or other users to utilise. The allowance up to the planning level may be used by inexperience filter designers to arrive at a poor and inefficient design, at expense of other users and NOs.

The other solution may be to give the user a portion of the harmonic headroom to allow the user to design a suitable filter. Then the question is how much of the headroom should be consistently given. This leads to the apportionment methodology that had been adopted by IEC 61000-3-6 and has been proposed in revised EREC G5/5.

## 4 APPORTIONMENT OF HARMONIC HEADROOM

The G5 sub-workgroup on Stage 3 assessment considered apportionment of the harmonic headroom to be most suitable for today's fast changing power system.

The sub-workgroup considered several different apportionment techniques, including that recommended in IEC 61000-3-6 [4]. This is summarised in Appendix B. Costs and benefits of each method were discussed. The criteria that were used to select a method were:

I. Availability of data and minimum reliance on data from user.

II. Practicality of applying the method, e.g. a balance between details of the analysis, amount of data required, required and achievable accuracy and demand on personnel resources.

III. To be fair and consistent to all new users, present and future.

IV. A small portion of the headroom to always remain for future connection and network expansion/modification by utilities.

It was the view of the sub-workgroup that FCFS would not be fit for use in todays' power system as it would lead to delays in projects and uncertainty in harmonic level management by NOs because of future connections and network expansion/modification.

After considering many possible apportionment methods, the sub-workgroup concluded that the one contained in the version of G5/5 published for consultation meets many of the requirements.

## 5 PARALLEL BETWEEN THERMAL CAPABILITY AND HARMONIC HEADROOM

It has been argued that, similar to utilising thermal capacity of the network at a given point for connecting a new user, all of the harmonic headroom should be given to the first in the queue, and any subsequent user, when they apply for connection, must pay for mitigation if there is no capacity, i.e. headroom, available. It may be said that in thermal case, all the equipment, such as circuit breakers and cables, in user's installation are standard and reinforcement is done in the network by the NOs to create the capacity for the new user. Part of the cost is paid for by the new user and the rest is shared by other network users, if the reinforcement does not fall in the "enabling work" category. Considering wider networks, maintaining thermal capacity on the networks is fundamental role of the NOs and reinforcements benefit more than one user and therefore the cost associated with those reinforcements are distributed amongst all users according to Use of System Charges methodologies. Considering harmonics, the cost of mitigation, in the form of harmonic filter, is always met by the new user only. The NOs have no mandate to install harmonic filters, i.e. reinforce the network, for users and therefore the cost of mitigation cannot be socialised amongst the network users and thus cannot be recovered.

Furthermore, the thermal impact of a new user is directly related to the 50 Hz demand/generation of the new plant whereas the harmonic impact somehow is related to the quality of equipment and design of

new user network. A low quality harmonic performance can consume/generate the same amount of MVA power at 50 Hz as a high quality device or two networks with different behaviour within the capacitive range for harmonic frequencies, e.g. controlled by shunt inductive equipment, would export/import the same amount of MVA rating.

Therefore, it is believed that a direct connection between the thermal policy and harmonic performance cannot be drawn.

## 6 CONCLUSIONS

The G5 review workgroup was mandated to assess the suitability of first come-first served methodology for setting harmonic limits against the objective set out in the terms of reference for the workgroup.

First come-first served approach recommended in G5/4-1 was analysed. It was deemed by the members to be inadequate for setting the harmonic limits for today's power system harmonic management considering the large number of harmonic polluting equipment being connected to the network.

Different apportionment methods were considered. It was deemed necessary to devise a method that was fair, consistent, did not increase substantially the need or cost of harmonic mitigation and was based on historical data from existing large number of connections of harmonic emitting equipment.

The method proposed by the Stage 3 assessment sub-workgroup of G5 WG is similar to first come-first served but with a difference that instead of allocating all of the headroom, 50% of headroom is allocated to the first in the connection queue for voltages at 132 kV and below and for voltages above 132 kV the headroom is apportioned according to the MVA size of the connection with a bias towards smaller connection, i.e. the rate of increase in apportionment multiplier is faster for the smaller connection and then it flattens at 66% for the highest connections recorded so far in the network.

The scale of apportionment (i.e. the multiplier M used in the apportionment calculation) was consulted upon in the EREC G5/5 consultation. No comments were received on these values and therefore were considered to be accepted.

The application of apportionment for all harmonics would lead to:

- A more consistent approach which is fair for all users.
- Allowing NOs to manage harmonics more efficiently.
- More detailed guideline in EREC G5/5 brings more consistency between connections.
- A harmonic specification that can be determined at early stages of the connection process which in turn allows users to begin their design work early, avoiding unnecessary delays in ordering equipment.

## 7 REFERENCES


[1] Engineering Recommendation G5 Issue 5," Harmonic voltage distortion and the connection of harmonic sources and/or resonant plant to transmission systems and distribution networks in the United Kingdom", Draft for consultation, 2019.

[2] Engineering Recommendation G5/4-1,"Planning levels for harmonic voltage distortion and the connection of non-linear equipment to transmission systems and distribution networks in the United Kingdom", October 2005.

[3] EREC G5 review, Terms of Reference; http://www.energynetworks.org/assets/files/electricity/engineering/g5_cop_wg/G5_CoP_WG.ToRs.30Jan14.pdf

[4] IEC TR 61000-3-6,"Electromagnetic compatibility (EMC)- Part 3-6: Limits-Assessment of emission limits for the connection of distorting installations for MV, HV and EHV power systems", Edition 2, 2008.

[5] ENA Engineering Technical Report (ETR) 122,"Guide to the application of engineering recommendation G5/4 in the assessment of harmonic voltage distortion and connection of non-linear equipment to the electricity supply system in the UK", December 2002.

# 8 APPENDICES

## 8.1 Appendix A

### 8.1.1 Impact on Number of Filters

Filter requirements based on First Come-First Served (FCFS) and Equal Right (ER) approaches is shown in Table below.

It can be concluded that FCFS may lead to the minimum number of filters being required. This generally may lead to lower overall aggregated cost. It will put all the cost on the subsequent customers in the queue. In practice, vast majority of users have needed to install a harmonic filter.

ER will spread filter cost more evenly amongst market participants. It may result in more filters than FCFS and therefore may result in additional cost of filters.

Note that a big portion of a passive harmonic filter cost is switchgear, mechanical and civil works costs. The size of filter electrical components does not greatly impact the filter total cost.

Table A. 1 illustrates comparison between FCFS and ER. Note that the application of FCFS recommended in G5/4-1 in practice has led to nearly all users at HV and EHV voltage levels to have installed harmonic filters. Also note that the main cost of harmonic filters is associated with civil and mechanical works and circuit breaker. The cost of filter electrical components such as capacitor banks, inductor and/or resistor form smaller portion of the total filter cost.

| | First Come First Serve | Equal Right |
|---|---|---|
| **Multiple Customers Aggregated impact above Planning Levels** | | |
| **Multiple Customers Aggregated impact Below Planning Levels** | | |
| **Single Customers Aggregated impact above Planning Levels** | | |
| **Single Customers Aggregated impact below Planning Levels** | | |

**Filter size: a+b+c=d**
**Filter cost: a+b+c>d**

Table A. 1- FCFS vs ER Methods

### 8.1.2 Delays in Start of Connection Process

For concurrent connections and connections with a short time between them in the electrically same area, using FCFS will result in a delay in the second connection equal to the length of the time for the first user to design and finalise their network and filter. For HV and EHV voltage level connections it is expected for this delay to be of the order of one to two years. The cost of this delay is hard to quantify but is expected to be greater than the cost difference in filter requirements, considering that the main cost of filters are associated with civil and mechanical works and circuit breaker. Surveys of users in recent years has shown that the users prefer to receive the harmonic specification, i.e. limits and loci, as early in the project as possible. One user has quoted that harmonic specification is always on their list of high risk items because of the possible delay and uncertainty it may cause. Table A. 2 illustrates the timeline for determining the harmonic specification for new users.

Table A. 2- Illustration of Delay in Connection Process

## 8.2 Appendix B

Apportionment

The Stage 3 sub-workgroup of G5 WG considered several different apportionment methods, including those recommended by IEC 61000-3-6. Advantage and disadvantage of each were assessed considering their practical implication and need for data. A summary of the discussions is given below.

There are two parameters that needed be decided for selecting a method of apportionment. Firstly, one need decide whether to have equal capacity or equal percentage. Once this has been decided one can then select a method for the apportionment itself.

The two methods of equal amount and equal percentage are demonstrated in Table B. 1 (The use of 50% in the example would be determined by the choice of apportionment and may depend on the connection).

Equal amount would be the preferred method if perfect knowledge of all future connections was available. The NO would then be able to apportion all the headroom fairly to all parties. However as perfect knowledge of future connection is not available, this method risk using up all the headroom and blocking a future customer from connecting.

The equal percentage method always keeps some headroom back and gives a fair percentage of the remaining headroom to the next customer. This will always benefit the first customer to apply but this is already the case with the current fist come first served and with other methods of allocating network capacity (e.g. thermal capacity).

Therefore, this sub work group recommend using an equal percentage approach to allocating harmonic headroom.

Fig B. 1 to Fig B. 4 illustrates different apportionment methods and the parameters that needed to calculate the apportionment multiplier.

Table B. 1- Illustration of Equal Amount and Equal Percentage

| **Apportionment methodology** | Comments | Ease of use (user) [1-5] | Ease of use (NO) [1-5] | Limits justifiable/ defensible | Limits based on size of connection | Limits based on network capacity | Implementable | Number of connections allowable |
|---|---|---|---|---|---|---|---|---|
| Number of connections (equal amount) | Decide how many connections reasonably could be connected at a site and head room is apportioned as H/N | 1 | 1 | N | N | N | Y | Fixed |
| Number of connections (equal percentage) | Decide on a percentage (e.g. 50%) every connection get that percentage of the remaining headroom. | 1 | 1 | Y | N | N | Y | All of them |
| SL | Headroom is apportioned based on size of connection. The amount apportioned per MVA is specified by voltage level and is chosen based on historic data. | 1 | 3 | Y | Y | N | Y | Fixed or all |
| SL/Nc | Headroom is apportioned based on size of connection and capacity of network. Nc is difficult to calculate at 132kV and above. This also gives small amounts of headroom or need to be scaled. | 3 | 2 | M | Y | Y | Y/N | |
| SL/Ssc | Headroom is apportioned based on size of connection and uses Ssc as an approximation of the capacity of network. Needs to be scaled. | 3 | 3 | M | Y | Y | Y | Fixed or all |
| SL/Nc-Cc | Headroom is apportioned based on size of connection and capacity of network minus what is already connected. | 4 | 5 | N/ Y | Y | Y | Y/N | Fixed up to capacity of network |
| SL/THD | Head room is apportioned based on size of connection and remaining THD headroom. | 4 | 4 | Y | Y | Y | Y | |
| First come first served | Fist applicant gets all the headroom. | 1 | 1 | Y | N | N | Y | 1 |

Table B. 2- Apportionment Parameters and Methods

1 Fixed percentage apportionment method

Fig B. 1- Fixed Percentage Apportionment

2 Variable percentage with capped

Fig B. 2- Variable Percentage with Cap

3 Scaled connection size w.r.t. fault level

Fig B. 3- Scaled Connection Size w.r.t. Fault Level

4 Scaled connection size only

Fig B. 4- Scaled Connection Size