Helping to Improve the **Performance of Electricity Networks**

BESS - EREC P28 Voltage Fluctuations Assessment

Northern Powergrid (NPg)

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1 Executive Summary

Northern Powergrid (NPg) has registered an NIA project [2] that will critically review the requirements in ENA Engineering Recommendation (EREC) P28 Issue 2 [1] and recommend improvements for assessment of Battery Energy Storage Systems (BESS). This Report documents the findings and recommendations from Workstream A of the project by Threepwood Consulting.

The detailed findings and analysis from each task of the project are presented in sections 4-6 of this Report. Notwithstanding, a summary of key findings and recommended changes to assessment of BESS has been collated into section 3 for convenience and to facilitate dissemination of key information to NPg stakeholders more easily. Other key recommendations arising from the review can be found in section 7.

The desktop review carried out identified key differences between EREC P28 Issue 2 and related IEC standards and DNO policies. Notwithstanding, P28 is generally aligned with the related IEC Standards – the key differences being the definition and assessment of step voltage change and the limits for Rapid Voltage Changes (RVCs).

The 3 % step voltage change limit in P28 has been accepted practice for many years to control the risk of excessively low system voltages – equipment immunity is not the main issue. A similar limit exists for frequent voltage changes in the IEC 61000 series of standards. At present, there is insufficient information to justify a change to the 3 % general limit for step voltage change in EREC P28. The assessment of BESS operation against this limit should be made clearer, in particular how the operation of tap-changers should be treated and that ramp voltage changes, i.e. voltage changes that take place over a period of time, should meet the same limit – shape factors only apply to flicker assessment and not to step voltage change assessment.

The current IEC flicker meter approach has been verified as still being valid now and for the foreseeable future. There is an incorrect assumption that modern, e.g. LED, lighting is immune to voltage fluctuation and that flicker assessments are no longer relevant. In practice, meeting the 3 % step voltage change limit will be the limiting factor when assessing BESS operation. Flicker is not expected to be an issue for certain BESS operating models, such as in the Balancing Mechanism (BM) and wholesale market, where ramp import / export changes are slower and less frequent compared with BESS operation to provide services to NGESO such as Frequency Response (FR) services. BESS providing Dynamic Regulation (DR) services are expected to produce the highest values of flicker. As system frequency changes can be complex and unpredictable, BESS providing FR services should be assessed using a representative power system model of the system, BESS controller and frequency time-series data.

Reductions in system inertia will probably result in greater volume, greater magnitude and increased frequency of occurrence of voltage fluctuations associated with BESS providing FR services than for the same operations at present. It is recommended that these intended reductions in minimum system inertia should be taken into account in P28 assessments to provide an element of future proofing as explained in section 4.4.10 and 6.2.4.

Simplified assessments for step voltage change and flicker have been identified and summarised in this report based on the maximum ramp rates and defined ramp times for

BESS operating to provide various services. This review has not identified any particular BESS operations that would provide the opportunity to exploit the higher than 3 % steady state voltage change limit for P28 compliance.

The application of voltage control (droop) within BESS control systems would require more detailed assessment of step voltage change and flicker than present but it could help with reducing the magnitude of step voltage changes and flicker compared with the constant power factor (pf) mode of control typically employed at present.

A comprehensive list of proposed clarifications and additional guidance associated with P28 has been identified to ensure that P28 is fit-for-purpose. These are lengthy and summarised in section 3.3 of this report. The most significant aspects are:

- clarification of how to assess BESS operation against the definition of step voltage change in P28 given that voltage changes occur across a finite period of time and can hence be best characterised as being a series of continuous ramps rather than discrete voltage change events; and
- clarification on how tap-changer operation should be treated.

It has been concluded that the text in DPC4.2.3.3 of the Distribution Code (DCode) should be removed or revised to avoid the perceived conflict with the provisions in EREC P28 Issue 2.

2 Introduction

2.1 Background & Purpose

Northern Powergrid (NPg) believes there are weaknesses in EREC P28 Issue 2 [1] and the current approach for assessing voltage fluctuations caused by Battery Energy Storage Systems (BESS).

NPg has registered an NIA project [2] that will critically review the requirements in EREC P28 Issue 2 and recommend improvements to clarify how best to assess t BESS for compliance with EREC P28 Issue 2.

Threepwood Consulting Limited (Threepwood) has been contracted by NPg to deliver Workstream A of the NIA project.

This Report documents Threepwood's findings and recommendations from Workstream A.

2.2 Scope

The scope of Workstream A covered the following high-level aspects.

- Task A.1: Desktop review
    - A desktop review of EREC P28 Issue 2, related IEC standards and DNO policies and practices in relation to the operation of BESS and how requirements compare and are applied.
    - The appropriateness of the 3 % voltage step limit in EREC P28 Issue 2 to BESS operation and how it relates to ramped voltage change.
    - How shape factors in EREC P28 Issue 2 apply to the assessment of voltage fluctuations.
    - Brief commentary on the following:
        - Current flicker meter approach to assessing flicker and its legacy relationship to incandescent light bulbs.
        - The Brunel University paper [11] published in 2023 "Assessment of Voltage Fluctuations for Battery Storage Systems Providing Frequency Response Services".
- Task A.2: Interpretation
    - How the requirements of EREC P28 Issue 2 should be interpreted for assessment of BESS.
    - How BESS voltage fluctuations should be assessed by NPg.
    - The feasibility of developing simplified and detailed assessment methodologies.
    - The effect of reactive power on voltage when BESS operates in voltage control mode (with a Q/V slope setting).

- Task A.3: Improvement
  - Identification of potential changes to EREC P28 Issue 2 to ensure it is fit for purpose in terms of assessing BESS voltage fluctuations.
  - How the existing text in the Distribution Code (DCODE) [3] relating to EREC P28 and voltage step change might be improved.

Task A.4: Findings and recommendations

- Produce a report [this Report] from the previous tasks.
- Obtain formal review comments from NPg.
- Prepare and deliver a presentation to the NPg project team and relevant stakeholders concerning the findings and recommendations from the review.

The detailed scope of work for each Task can be found in Appendix A.

2.3 Objectives

The overall objective for the project was to identify and recommend proposed changes to the assessment of voltage fluctuation caused by BESS operation with particular reference to ensuring compliance with EREC P28 Issue 2.

2.4 Approach and Convention

Threepwood prepared draft outputs from each Task, as it was completed, in the form of memos, which were submitted to NPg for comments.

Regular progress meetings, nominally every two weeks, were held with representatives from NPg, Threepwood and Aurora Consulting. This provided a platform for NPg to:

- check progress against the project programme;
- seek clarification and provide comments on Threepwood's draft outputs;
- coordinate the work being carried out by Threepwood and Aurora Consulting.

NPg comments received on the draft outputs were reviewed and addressed by Threepwood before being incorporated into this Report as part of Task A.4.

The detailed findings and analysis from each workstream of the project are presented in sections 4-6 of this Report. A summary of key findings has been collated into section 3 for convenience.

The Report has been structured this way to enable transparency of the work carried out in each Task of the project whilst allowing NPg to easily distill and disseminate the key information more easily from section 3.

A number of terms and abbreviations have been used throughout this Report. These are listed in section 8.

Unless stated otherwise in this Report, the term 'EREC P28' or 'P28' refers to the current ENA EREC P28 Issue 2 [1]. The previous version has been referred to as ENA EREC P28 Issue 1 [8].

3 Summary of Findings

The key findings from each main task of the project are summarised below. Detailed analysis and findings are presented in the later sections of this Report.

3.1 Desktop Review

3.1.1 EREC P28 Issue 2

The potential for BESS operation to cause voltage fluctuations, i.e. step voltage changes, rapid voltage changes and flicker, including as a consequence of providing frequency response services, is acknowledged in P28. It is clear from the review that all various types of BESS operation are intended to be assessed, except possibly where the BESS provides frequency support under abnormal system frequencies.

There are a number of high-level generic considerations/requirements in clause 8.9 of P28 that apply to BESS. However, these do not provide sufficient detailed guidance for assessment. Whilst it is clear that P28 applies to all customer's equipment that may cause voltage fluctuations, there are no explicit specific requirements for assessment of BESS stated in P28.

It is clear from this review that BESS operation, including the voltage fluctuations associated with power changes (whether these changes occur over a long period of time or effectively instantaneously), is required to be assessed against the 3 % step voltage change limit in P28. There is no guidance on whether the operation of tap-changers during long duration voltage changes can be used to assist with compliance with the step voltage change limit in P28.

Shape factors cannot be used for the assessment of step voltage changes or RVCs. They can only be used for assessment of flicker.

It is believed that the shape factor (*F*) of 0.2 for flicker assessment of ramp voltages can be applied to voltage ramps lasting greater than 1 s. This is not currently clear in EREC P28.

There are a number of opportunities to update and improve the guidelines for assessing BESS given its predomination since EREC P28 Issue 2 was last published.

3.1.2 IEC 61000-3-7

This document does not mention any requirements or provide any guidance for BESS and no revisions of the document are planned. As such it is considered to have little bearing on the development of policy for P28 assessment of BESS.

A review of this document leads to a question of whether and when the DNO might permit exceedances in the 3 % step voltage limit for BESS operation such as during BESS responses to infrequent and exceptional changes in system frequency. However, the 3 % step voltage limit in P28 is accepted industry good practice and should be met in most circumstances.

The definition of RVC in EREC P28 is similar and aligned to that in IEC 61000-3-7.

The application of shape factors as described in P28 is identical to that in IEC Standards, where shape factors only apply to assessment of flicker. They do not apply to assessment of RVCs or step voltage changes. As such they cannot be used to increase the general limit of 3 % for ramp type voltage changes.

Shape factors are not suitable for assessing flicker arising from unpredictable complex voltage fluctuations, which should be assessed using a flickermeter algorithm. Such complex voltage fluctuations could arise from BESS providing frequency response services.

3.1.3 Distribution Code Review Panel P28 Working Group Outputs

An ENA Engineering Report (EREP) 28 is currently being drafted by the Distribution Code Review Panel (DCRP) P28 Working Group, which will provide guidance on the application of EREC P28 Issue 2 to BESS operation. This will include worked examples of BESS assessments. No revision of the P28 requirements are being proposed by the DCRP P28 Working Group at present.

The following points are the initial conclusions from the DCRP P28 Working Group:

1. The 3 % step voltage limit in P28 has its basis in long established engineering practice to prevent unacceptably low voltages as opposed to lack of immunity of customer equipment either to lower voltages or to the magnitude of step changes in voltage.
2. The ‘expected depression of around 10 %’, stated in DPC 4.2.3.3 of the DCode, is not a general increase in the allowable step voltage change. The basis of this 10 % figure was to recognise that the unpredictability of the ‘point of wave’ switching when energising one or more transformers associated with infrequent events meant that voltage step changes could be planned which would be expected to result in a maximum voltage change of around 10 %.
3. Any BESS site capable of changing power from export to import, and vice versa, within the operating time of the DNOs tap-changer(s) should conform to the 3 % step voltage change limit for all power changes between defined and agreed limits which may be up to 100% of the BESS rating. This includes voltage changes associated with ramped power changes.
4. BESS Power Park Controllers should be accurately modelled, as using incorrectly set-up models can result in oscillatory type modelling responses that produce high flicker severity values. It is important that Power Park Controllers are correctly set up on site.
5. Representative 1 s system frequency data should be sufficient for modelling BESS frequency responses and determining flicker severity, in particular, for Dynamic Response (DR) frequency response services. Frequency data with 20 ms granularity does not deviate significantly from the trend line of the 1 s interval data.

6. Statistical analysis of frequency time-series data[1] shows that:
    a. Dynamic Regulation (DR) and Dynamic Moderation (DM) should be assessed as being a normal operating condition (given that they occur more than 5% of the time).
    b. System frequency is outside of the 50 Hz ±0.2 Hz band for approximately 1 % of the time. Consequently, Dynamic Containment (DC) operation could be deemed a very infrequent event (given it occurs for less than 5% of the time), where the DNO could exercise some discretion in terms of the consequent voltage changes complying with the flicker and step voltage change limits in EREC P28.
7. There might be justification to exclude the operation of BESS providing frequency response services to NGESO, such as DC, when responding to frequencies outside the 49.8 Hz to 50.2 Hz band on the basis that such events are rare and are an immediate operational response to a fault condition. The latest NGED guidelines for assessing BESS [9] do not require BESS to meet flicker severity limits in EREC P28 for these events.
8. Different BESS sites that are providing the same frequency response service(s) could result in coincident power and hence voltage changes, and guidance is required on how such coincidences need to be assessed, including what summation coefficient(s) should be used to assess flicker at the PCC.
9. When carrying out P28 assessments, foreseeable reductions in system inertia, and the associated increase in the use by NGESO of frequency services should be considered to ensure BESS will remain compliant.

3.1.4 DER Technical Forum Outputs

The application of P28 has been discussed at the ENA DER Technical Forum. There have been discussions that the magnitude of step voltage change caused by BESS operation can be mitigated by requiring the BESS to operate at an optimum power factor, approaching pf = 1.0, whilst recognising that BESS power changes might need to be constrained for the range of power factor operation required in the DCode [3] and EREC G99 [10].

3.1.5 Comparison of DNO Policies & Practices

Shape factors associated with ramp voltage changes, particularly those with a duration greater than or equal to 1 s, if suitably spaced, means flicker is unlikely to be a problem. This includes voltage ramps arising from BESS trading in the Balancing Mechanism (BM) and wholesale markets.

Ramp voltage changes with shorter ramp times (less than 0.5 s) approximate closer to a step voltage change and could result in flicker if repeated frequently enough. Frequent ramp

[1] Source: Figure 4 from NGED Guidance Note [9].

voltage changes caused by BESS providing frequency response services, in particular DR, are most likely to result in the highest flicker of all BESS operations.

NGED has recently refined its guidance [9] on modelling BESS for flicker. This is believed to be the most up-to-date of the DNOs. This includes useful guidance on what frequency data should be used, how BESS controllers should be set up for accurate modelling and how flicker severity results should be extrapolated for future reductions in system inertia.

Maximum power swings from full import to full export and vice versa have been found to be valid when BESS is providing FR services. Although such magnitudes of power swings are improbable for BESS providing purely FR services, due to the slow nature of changes to system frequency, they cannot be ruled out. The probability of such swings increases when the BESS is providing stacked services. However, there might be scope for DNOs to assess BESS compliance with EREC P28 limits for smaller power swings, where the BESS operator can assure that such power swings will not be exceeded.

Two DNOs (ENWL and NGED) do allow step voltage changes of up to 6 % at the POC or the lower voltage busbar of Bulk Supply Points, which allow for coincident BESS operation. Notwithstanding, the 3 % limit applies at the PCC to the operation of each individual BESS.

In practice, BESS providing FR services will be practically constrained by the need to comply with the 3% step voltage change limit rather than flicker limits due to the typically slow ramp nature of the power changes and consequently the voltage changes.

3.1.6 Current Flickermeter Approach

Whilst the origins of the IEC Flickermeter are in the perceptibility of changes to the luminance of a 230 V 60 W incandescent lamp, testing and compliance against IEC 61547 ensures that modern lighting, such as LED lighting, will not result in flicker that is worse than that of an incandescent lamp under similar conditions.

P_{st}, as measured by the IEC Flickermeter, has become a widely accepted measure of supply voltage quality and can be used to compare the severity of voltage fluctuations caused by differing equipment and installations irrespective of the type of lighting.

Due to the variety of lamp types and their differing responses to voltage fluctuations (including RVCs) it is not true to say that modern lighting is immune from flicker effects. In some cases, particularly during high frequency voltage fluctuations, modern lighting can be more sensitive to voltage fluctuations. Therefore, it is likely that the IEC Flickermeter and flicker severity limits for equipment and installations connected to public electricity systems will continue to be used in the foreseeable future.

In future, it might be possible to accept greater percentage voltage fluctuations and rates of change in voltage fluctuations than at present, where the sensitivity of the predominant lighting is well understood and less than that for incandescent lamps for all voltage fluctuations. However, implementing any wholesale changes to planning levels for flicker at a distribution network level is likely to be challenging.

3.2 Interpretation

3.2.1 Voltage Fluctuations

EREC P28 refers to three types of voltage fluctuation: rapid voltage changes, flicker and step voltage changes. These are explained in the following section.

3.2.2 Rapid Voltage Changes (RVCs)

As defined in EREC P28, for a voltage change to be classed as a RVC event, the voltage needs to change from one steady state voltage to another in a short period of time (i.e. less than or equal to 2 s).

BESS operations that produce fast ramp changes in the r.m.s. voltage from one steady state to another within a short time frame (i.e. less than or equal to 2 s) should be assessed as an RVC, e.g. energisation of BESS transformer(s) and very infrequent fast power ramps not associated with FR services.

Slow ramp voltage changes (i.e. greater than 2 s) should be assessed as step voltage changes.

It is not expected that BESS providing FR services will produce RVCs. Under normal system conditions the rate of change of power, and hence voltage, is governed by the rate of change of system frequency which changes relatively slowly and tends not to reach steady state.

Even fast power changes associated with other services provided by BESS operations, such as arbitrage, are not expected to produce voltage changes that have an RVC characteristic, i.e. an initial voltage dip or voltage swell that exceeds the steady state voltage change limit of 3 %. No examples have become apparent in Workstream A of the project.

In reality, it is not expected that BESS operations will produce a voltage characteristic that can exploit the higher (i.e. higher than 3%) voltage change limits in Figure 5, 6 and 7 [of EREC P28]. This is particularly the case for BESS connected at lower voltages, i.e. 33 kV and below, where the X/R ratio is lower. As such, the 3 % limit for steady state voltage changed will be the limiting factor for assessment.

3.2.3 Flicker

The flicker assessment requirements and flicker limits in EREC P28 are similar to those in IEC Standards. No change in these assessment requirements or limits is warranted for BESS operations.

Frequent large voltage step changes or frequent large slow ramp voltage changes can cause flicker and should be subject to a flicker assessment.

Flicker should not be an issue for BESS providing BM or wholesale market services given the relatively infrequent (once every several minutes) and slow ramp voltage changes involved.

BESS providing FR services, in particular DR, are most likely to result in greater flicker levels compared with other types of BESS operations. However, DR generally results in slow ramp changes in voltage over several seconds. Due to the ramp nature of these voltage changes it is not expected that flicker severity would exceed the Stage 2 flicker limit of P_{st} = 0.5 for normal operations.

Due to the complex and unpredictable nature of voltage changes resulting from BESS providing FR services, a detailed assessment of voltage changes should be carried out using an accurate power system model of the distribution network, BESS controller and representative 1 s frequency data where flicker severity is derived from an IEC flickermeter conforming to the requirements of IEC 61000-4-15 [17].

A simplified Stage 2 assessment of compliance with flicker limits could be introduced for BESS based on the maximum stated power change per second, i.e. ramp rate in MW/s, declared by the BESS operator (and included as an operational condition in the connection agreement), where the resultant ramp voltage change for a maximum ramp time of 1.6 s should be less than 2.25 % (see 5.3.1 of this Report). It is not deemed feasible to carry out a simplified Stage 3 assessment of flicker.

For BESS operations that result in repetitive ramp type voltage changes, the equivalent step voltage change for simplified assessment using the P_{st} flicker curves can be derived from the shape factor curve in Figure B.2.5 [EREC P28]. A shape factor of 0.2 can be used for ramps with rise times greater than or equal to 1 s.

Fast voltage ramps with rise and fall times less than 0.5 s approximate to rectangular voltage changes and should be assessed as such.

For a BESS providing stacked services, flicker for each service might need to be assessed individually.

Where the network at the PCC contains one or more BESS installations providing FR services then the worst case P_{st} from each BESS should be summated using Equation 1 in EREC P28. In the absence of any contrary data about the degree of coincidence then it should be assumed in the first instance that voltage changes are coincident and a summation exponent of $\alpha = 1$ should be used, i.e. directly added together.

3.2.4 Step Voltage Change

The basis of the 3 % limit for step voltage change is long established engineering practice to prevent unacceptably low voltages. The limit is not due to any equipment immunity issue, although larger step voltage changes could adversely impact the performance of motors (see 5.4.2). Any change in this limit would be difficult to justify based on current information.

The 3 % limit in EREC P28 should be applied to step voltage changes (i.e. change in steady stage voltage occurring in a period of time greater than 2 s) and also fast ramp voltage changes (i.e. change in steady stage voltage occurring in a period of time less than or equal to 2 s). Shape factors should not be applied to ramps for step voltage change assessment or rapid voltage change assessment and cannot be used to increase the general limit of 3 % for step voltage changes or rapid voltage changes.

In the context of BESS, the 3 % limit refers to the difference between the highest r.m.s. voltage and lowest r.m.s. voltage caused by the BESS operation in the time before tap-changer operation (see Figure 7).

The operation of tap-changers would mitigate the step voltage change caused by the BESS operation and could be considered in the assessment for step voltage change associated with slow ramp power changes lasting longer than 90 seconds. 90 seconds is typically the fastest operational time for a network operator transformer tap changer.

The current NPg method of fixing taps (or disabling AVC) for assessing the step voltage change caused by slow power ramps and also a RVC caused by fast power ramps is believed to be appropriate.

There is a possibility of mitigating large step voltage changes caused by BESS operation by implementing fast-tap tap-changer settings where these are configurable in modern AVC relays. However, it is recognised that the 'fast-tap' feature, although available in modern AVC relays, it is not currently widely implemented across DNOs.

The completion of the tap-changer operation should signify the commencement of a new observation period for assessing step voltage changes.

Maximum power swings from full import to full export and vice versa have been found to be possible when BESS is providing FR services. The probability of power swings from full import to full export and vice versa increases when the BESS is providing stacked services. Therefore, in the absence of assurance to the contrary, assessment of step voltage change should be assessed for a power swing from full import to full export and vice versa. Allowance might be made where import/export power contracted under FR services is less than the BESS capacity and the BESS Operator provides assurance this will not be exceeded.

Care needs to be exercised when assessing BESS, which is absorbing or exporting a constant or variable value of reactive power (Q). This will impact on the assessment of step voltage change, particularly where the X/R ratio of the distribution network is large. The extent of voltage changes should be assessed for the range of P & Q values for both import and export to determine the magnitude of the worst-case step voltage change. The range of P and Q values that need to be considered will be site specific.

3.2.5 Effect of Reactive Power on Voltage

A BESS exporting reactive power tends to increase the voltage at the PCC whilst importing reactive power tends to decrease the voltage at the PCC.

There is an opportunity to require the BESS to operate in voltage control (droop) mode according to a Q/V slope. This could mitigate the magnitude of the step voltage change at the output terminals caused by changes in real power (P) by exporting/importing reactive power (Q). Applying this operating mode could be a solution where the output of the BESS is significantly constrained because of the 3 % step voltage limit. The voltage droop characteristic is a linear relationship between the operating voltage at the busbar being controlled and the amount of Q being exported or imported by the BESS and might require dynamic modelling of the BESS and the relevant part of the network.

However, there are concerns around multiple BESS controllers fighting each other and transformer tap-changer AVCs not working correctly. Anecdotal feedback from DNOs that implement this mode of control suggests that injecting Q at local distribution network level can be somewhat unpredictable in terms of managing the voltage of the wider power system and its application should be carefully considered before being implemented.

BESS operating in voltage droop control mode should reduce the magnitude of the voltage change for a given real power change. It should not affect the frequency of voltage changes. It would affect the assessment of all three categories of voltage fluctuations within the scope of EREC P28.

For distribution systems with large X/R ratios and high fault levels, voltage changes are almost entirely dependent on changes in Q rather than by changes in P. The relative impact of changes in P on voltage change increases for systems with lower X/R ratios, i.e. 'weaker' systems, where changes in Q have less of an effect.

3.2.6 Simplified & Detailed Assessment Methodology

3.2.6.1 Step Voltage Changes

The maximum voltage change for the aggregated maximum change of % of contracted power change at unity pf can be simply calculated using the system X/R ratio and short-circuit current. This can then be expressed as a percentage of the nominal system voltage (V_n). This can be used for simplified assessment of step voltage change.

Such a simplified approach to step voltage change assessment is feasible where a maximum power ramp rate can be defined, which would equate to a maximum voltage step voltage change of 3 % when calculated over a defined period for the ramp.

3.2.6.2 Flicker

A simplified assessment of flicker compliance for BESS providing FR services is believed to be feasible based on stated maximum rates of change of system frequency and minimum ramp times determined from NGESO's Frequency Response Delivery Requirement Curves (see Figure 17). Maximum permitted values of % voltage changes for flicker compliance can be determined from Figure B.1.2 in EREC P28 for Stage 2 flicker assessments and from Figure B.1.1 in EREC P28 for Stage 3 flicker assessments.

Detailed assessment might be required for accurate flicker severity of BESS providing FR services, where a simplified assessment shows the flicker severity is close to the required limit.

For BESS providing other services such as arbitrage, which does not involve frequent changes in power and hence voltage, compliance with flicker limits is not anticipated to be a problem. A simplified assessment could involve agreeing a limit on the number of power changes (and hence voltage changes) per minute. Figure B.1.2 and Figure B.1.1 of EREC P28, as appropriate, could then be used to determine the maximum % voltage change permitted. This could then be equated to a maximum change in power and power ramp rate not to be exceeded. A detailed assessment could involve assessing the output from a BESS model which calculates the power changes and consequent voltage changes based on operating parameters defined by the BESS operator. This would be similar to the detailed assessment for FR services but where the input data to the model is different.

3.2.6.3 Rapid Voltage Changes

Assessment of RVC, if relevant, would have to be assessed by a detailed study of the voltage change characteristic.

3.2.6.4 Limitations of a Simplified Assessment

A simplified methodology will not be possible where the BESS is providing stacked services. Indeed, a BESS providing stacked services might be required to switch from significant import to significant export. In the absence of information to the contrary the assessment should assume a worst case from maximum export to maximum import within the 1 s FR response time.

NOTE: NPg has stated that the majority of BESS connection applications received request all of the possible services/operating options to be considered. Engagement with BESS operators and developers would make it clear that assessment for all possible options might result in an unnecessary pessimistic result compared with only assessing what services they intend to actually use. This approach might be more advantageous to them in terms of meeting the limits in EREC P28.

3.3 Improvements

3.3.1 Recommended Changes to EREC P28

The potential changes identified in this section apply to both EREC P28 and its accompanying guidance document (EREP 28), which is currently being drafted. No distinction is drawn between the two documents.

3.3.2 Scope

The scope of EREC P28 should be clarified to explicitly include BESS, particularly the assessment of those services typically provided by BESS, such as FR, BM, wholesale market etc.

It is suggested that assessments of so-called ‘post-fault frequency response services’, in particular assessment of DC for system frequencies outside the range of 49.8 Hz and 50.2 Hz, are excluded from EREC P28 flicker assessments given this is an immediate operational response to a fault condition, which is allowed to be excluded from P28 requirements as set out in clause 6.1.6 of P28.

3.3.3 Terms & Definitions

A number of new terms and definitions relating to BESS and associated operations could be added to EREC P28 to improve its interpretation. These are detailed in section 6.2.2 of this Report.

The followings existing terms and definitions in EREC P28 could be improved.

- Normal operating condition - to clarify the application of this term to the distribution system, the transmission system, users' plant and control systems.
- Step voltage change - to clarify that the 3 % limit refers to the difference between the highest r.m.s. voltage and lowest r.m.s. voltage caused by the BESS operation in the time before the tap-changer operates. This includes a limit on aggregated voltage rise or aggregated voltage fall over the same period.
- Figure 5 requires a note to be added to clarify that the envelope between +3 % and - 3 % only applies to a specific RVC event with a definite start and finish. It does not apply to continuous voltages changes caused by BESS operation, particularly when providing FR services. This is to make clear that BESS voltage cannot ramp from +3 % to - 3 % in the time before the tap-changer operates and vice versa, as this would exceed the 3 % step voltage change limit.

It is suggested that the term 'steady state voltage' is defined and the definition clarifies whether a 0.2 % voltage change within 1 s (according to IEC 61000-3-3 [16]) or 0.5 % voltage change within 1 s (according to IEC 61000-3-7 [5]) should be used.

3.3.4 Definition of Step Voltage Change

EREC P28 should be revised to clarify the definition of step voltage change in relation to assessment of BESS. There is confusion how this relates to 'voltage step changes' in the IEC 61000 series of Standards and other forms of voltage change, such as ramps, that are not instantaneous and can last in the window until the tap-changer operates.

Potential clarifications to the definition of step voltage change in EREC P28 for assessing BESS should be as follows.

- The 3 % limit applies to any form of voltage change, occurring across any timeframe, meeting the definition in EREC P28, including voltage changes occurring in a finite period of time, not just rectangular or square wave instantaneous voltages changes.
- The 3 % limit mitigates the risk of excessively low system voltages that might breach the lower statutory voltage limit. Immunity of customer equipment is not the main consideration.
- The 3 % limit represents the "maximum permitted change in r.m.s. voltage when expressed as a percentage of the nominal system voltage (V_n), when measured between any two points in the time period after all generating unit (including BESSs) automatic voltage regulator (AVR) and static VAR compensator (SVC) actions and transient decay (typically 5 seconds after the fault clearance or system switching) have taken place, but before any other automatic or manual tap-changing and switching actions have commenced."

- Automatic or manual tap-changing refers to the operation of those tap-changers that will reduce he magnitude of the voltage change caused by BESS operation.
- The voltage in the time/observation period before the tap-changer operates does not need to reach steady state.
- Alignment with IEC 61000-3-3 [16], where a voltage that does not exceed 0.2 % in one second is deemed to be in ‘steady state’.

For clarity, there is insufficient information to justify a change to the 3 % general limit for step voltage change in EREC P28. The consequence of increasing this limit would require more detailed investigation and evaluation at an industry level, i.e., via ENA.

3.3.5 Assessment of Step Voltage Change

The following potential changes to current DNO assessment practices associated with BESS operation, in terms of step voltage change, should be considered.

- Recognition that compliance with the 3 % step voltage limit for large power swings over several seconds will generally be the limiting factor rather than flicker or RVC limits.
- Add a figure/illustration (similar to Figure 7) which clarifies the permissible voltage changes (i.e., to comply with the 3 % limit) over time in relation to the point that the tap-changer operates.
- Allow the operation of the tap-changer within the assessment for slow ramp voltage changes, where the voltage change event resets at the point when the tap-changer operation is completed.
- Ramp voltage changes should be assessed as step voltage changes in terms of compliance against the 3 % general limit.
- Shape factors should not be applied to step voltage changes or RVCs when assessing compliance against the 3 % general limit.
- Make clear the initial tap delay and operation time of the relevant automatic tap-changer determines the time/observation period for the assessment of the step voltage change. This time is expected to be specific to each voltage level and possibly individual site. Alternatively, a default time/observation period, say 120 s, could be considered for simple assessment. This is believed to be the worst-case (i.e. the longest) operating time for 33 kV and 132 kV tap-changers.
- The completion of the tap-changer operation should signify the end of one observation period and the commencement of a new observation period.
- For BESS providing stacked services a simplified assessment of step voltage change based on a worst-case power swing from 100 % full export to 100 % full import and vice versa should be undertaken.
- For BESS providing BM and/or wholesale market/arbitrage services only, propose a simplified assessment of step voltage change based on the maximum stated power change per second (i.e., ramp rate in MW/s) and the maximum ramp time declared

by the BESS operator, where the BESS operator agrees to this constraint in the Connection Agreement. Otherwise, the BESS should be assessed based on a worst-case power swing from 100 % full export to 100 % full import and vice versa.

3.3.6 Assessment of Flicker

No changes in the flicker emission limits in EREC P28 for BESS operation are proposed.

A simplified Stage 2 flicker assessment could be introduced in EREC P28 for a BESS based on the maximum stated power change per second, i.e. ramp rate in MW/s, declared by the BESS operator, where the resultant ramp voltage change for a maximum ramp time of 1.6 s should be less than 2.25 % (see 5.3.1 of this Report).

Clarification should be provided on the application of shape factors to simplified flicker assessment of ramp voltage changes and that they do not apply to the assessment of step voltage changes or RVCs. Also that a shape factor (*F*) of 0.2 can be applied to voltage ramps greater than 1 s.

For BESS providing different or stacked services, flicker should be assessed for each service/operating cycle provided and the worst flicker severity determined.

3.3.7 Detailed Assessment of Flicker Severity

There is potential to include specific guidance in EREC P28 regarding how to assess a BESS that provides FR services.

This should state that flicker caused by BESS providing FR services, or services where the power can change frequently and unpredictably, should normally be subject to detailed assessment; simplified assessment of flicker in this case is not appropriate.

Clarification should be provided that BESS providing only DM or DC services are not likely to produce significant flicker because the system frequency is within ±0.1 Hz of the nominal system frequency for the majority of the time.

Requirements should be included for conducting a detailed assessment of flicker severity (see 6.2.6), which is likely to be worst for the DR service, using a representative static model of the power system. The requirements for modelling the BESS controller (to reflect the actual controller set-up and operation) and the application of representative system frequency data (historical or synthesised data, potentially reflecting an expected increase in utilisation of DR services in the future, with 1 s resolution) should be provided to ensure consistency of assessment.

Where more than one BESS is providing, or may be providing, the same FR services, as assessed at the PCC, that it is more appropriate for flicker severity to be summated using a summation exponent of $\alpha = 1$, i.e. directly added together, unless the BESS operators can otherwise demonstrate that the summation exponent of $\alpha = 1$ is too onerous. This approach might be used when more than one BESS are connected to electrically adjacent parts of the network.

3.3.8 Assessment of RVC

No changes to the limits, assessment methodology or definition of RVC in EREC P28 are proposed in relation to the assessment of BESS. However, guidance on EREC P28 could make clear that RVC assessments of BESS are not normally required except for the energisation of the transformer connecting the BESS to the distribution network or for very infrequent fast power ramps, lasting no longer than 2 s, which result in a steady-state voltage change. Otherwise it is not envisaged that BESS operation will produce voltage fluctuations with an RVC characteristic. RVC assessments should only be carried out where the resultant voltage change has an RVC characteristic fitting the voltage envelopes in Figure 5, 6 and 7 of EREC P28.

3.3.9 Control Modes

There is potential to provide greater clarity in EREC P28 regarding the different control modes for BESS and their impact on voltage fluctuations. This includes constant power factor control mode, constant reactive power control mode and voltage control (droop) mode with a defined Q/V slope.

The simplified and detailed EREC P28 assessment methodology for each mode of operation should be explained including how to assess the change in voltage caused by the import/export of reactive power (Q) as well as of active power (P).

Guidance should be included on how BESS connected at 132 kV, and possibly 33 kV, operating in voltage control mode with a defined Q/V slope (voltage droop control) can reduce the magnitude of voltage fluctuation by locally injecting/absorbing Q.

Guidance should also be provided on assessing any potential interaction with the voltage control mechanisms of other BESS installations, generator installations and network operator tap-change control schemes.

3.3.10 System Inertia

There could be a requirement for EREC P28 assessments to also consider the effect on step voltage change and flicker for the predicted minimum value of system inertia of 102 GVAs compared with the current value of 140 GVAs. This would provide an element of future proofing of designs.

3.3.11 Improved Guidance

In addition to the recommended changes documented above, improved guidance on the following could be included.

- The operating characteristics of the BESS and performance requirements for FR, BM, wholesale market, arbitrage and STOR.
- How services may be stacked and how scenarios of stacked services should be assessed.
- How to assess coincidence of BESS providing FR services including the worst-case assumption to arithmetically sum P_{st} values.

- Mitigation of step voltage change by reducing rate of power change for BESS providing BM, wholesale market and arbitrage.
- How export limiting schemes could be applied to BESS to meet step voltage change limits.
- Worked examples of simplified and detailed assessment of flicker and step voltage change.
- Application of static and dynamic power system modelling of BESS for assessment.
- Definition of those 'very infrequent events' associated with BESS operation where exceedance in limits could be acceptable.
- Explanation of the role of maximum power ramp rates in FR services and in assessing flicker and step voltage change.

3.3.12 Distribution Code Text

When EREC P28 Issue 2 was published in 2019, the text in DPC4.2.3.3 of the DCode [Issue No.39] was modified to align it with the new recommendations. Notwithstanding, stakeholders perceive a conflict in requirements between the two documents.

There is doubt whether the term 'voltage step change' used in the DCode has the same meaning as 'step voltage change' in EREC P28. The author can confirm it is intended to have the same meaning.

There is confusion regarding the application of the 3 % general limit stated in the DCode. The author confirms this applies to any step voltage change caused by the user's equipment and not just during its connection or disconnection.

The term 'very infrequent events' is not defined in the DCode or in EREC P28. However, Table 4 in EREC P28 does state the maximum number of occurrences for very infrequent events.

The text "…expected depression of around ±10%." in the DCode is somewhat vague compared with the clear envelopes for RVC in clause 5 of EREC P28. It would seem better to simply refer to the RVC envelopes in EREC P28 for accuracy. For clarity, this is not a general increase in the allowable step voltage change.

In summary, it is believed that the requirements DPC4.2.3.3 of the DCode are adequately covered by EREC P28 Issue 2, if interpreted correctly. Therefore, it is recommended that the text in DPC4.2.3.3 is either reviewed or removed in its entirety. Reliance should be placed on the fact that EREC P28 is listed in Annex 1 of the DCode as a 'Qualifying Standard' and, therefore, the technical requirements in EREC P28 form part of the DCode.

4 Workstream A.1 Findings

4.1 Introduction

This section relates to workstream A.1 of the project carried out by Threepwood. It captures the findings from the initial desktop review carried out by Threepwood.

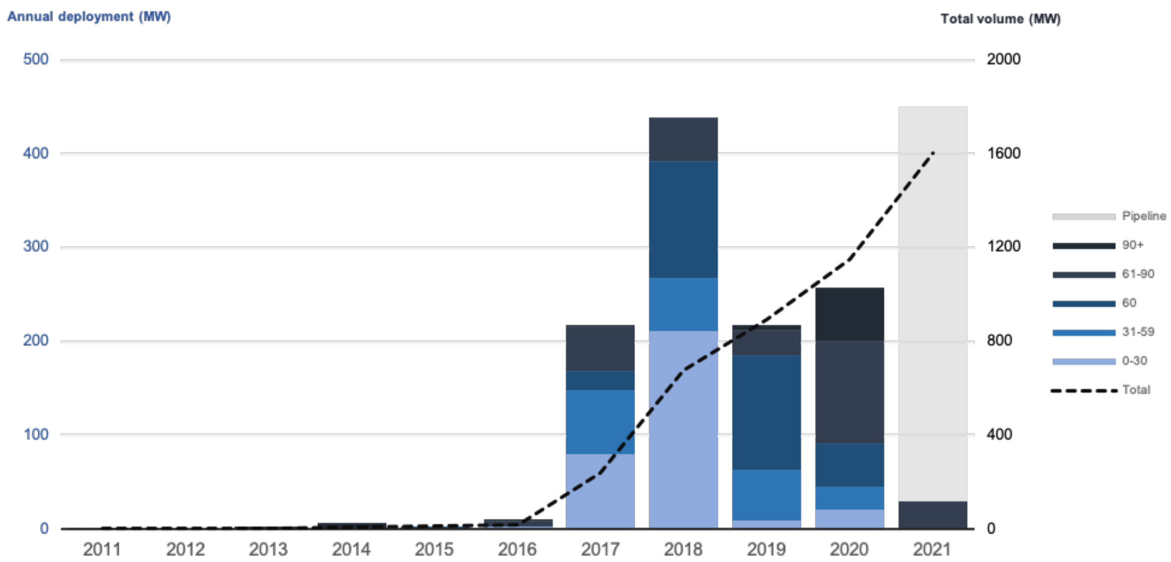
4.2 Desktop Review of EREC P28 Issue 2 Concerning BESS Assessment

The latest version of ENA EREC P28 Issue 2 [1] (published in 2019) was reviewed with respect to requirements for BESS assessment. The key findings are discussed below (see sections 4.2.1 to 4.2.7).

4.2.1 Scope

It is clear that the connection of BESS to distribution networks is within the scope of EREC P28 Issue 2 (subsequently referred to as 'P28') given that its operation causes voltage fluctuations. The scope of P28 explicitly includes energy storage installations, which are defined as operating flexibly as load or generation.

Specific requirements for assessing the voltage fluctuations from energy storage installations are covered in clause 8.9 of P28. Interestingly, there is no specific reference to 'Battery Energy Storage Systems' or 'BESS' in this clause or elsewhere in the document. Although P28 was published in 2019, it was drafted earlier and at that time BESS was not a term that was commonly used in industry documents. Consequently, the specific requirements for energy storage installations in this clause are somewhat generic and non-prescriptive.



NOTE: Assets categorised by duration of rated output in minutes.

Figure 1 – BESS Deployments Between 2011 and 2021

P28 alludes to the potential of energy storage to cause rapid power swings and significant voltage fluctuations when changing between importing and exporting electrical power. However, the nature and severity of those power swings that need to be assessed is not mentioned. This is believed to be a key gap in P28.

4.2.2 Frequency Response

Reference is made to the frequency response function but not to any specific frequency response services or the difference in power response to frequency variations for different frequency response services. It should be noted that the new frequency response services defined by National Grid ESO, i.e. Dynamic Containment (DC), Dynamic Moderation (DM), Dynamic Regulation (DR), post-date the publication of P28 in 2019. At the time P28 was being drafted, procuring frequency response services was in its infancy which explains why it was not covered in any detail in the document.

It is worth noting that the current frequency response services procured by NGESO are DC, DM and DR each with defined performance characteristics, NGESO may revise the characteristics in the future and hence the requirements and guidance in P28 and EREP 28 need to be sufficiently future proof.

4.2.3 Step Voltage Change

P28 specifically mentions the potential for energy storage installation to cause step voltage changes of significant magnitude and very high probability of coincident power swings from other energy storage installations. Although there is no specific mention of assessment against the 3 % step voltage limit, this requirement does apply to BESS in the same way as any other customer equipment/installations that cause voltage fluctuations, e.g. clause 8.6.2 of P28 regarding simultaneous switching of electric vehicle (EV) charging connections. Whilst the very high probability of coincident power swings is mentioned, no information is provided on how to assess these from a step voltage change aspect.

There is a requirement in clause 8.9 of P28 that any system that can cause large step changes in load or generation should be assessed as a complete system of generation, load and energy storage. Reference is made to ENA EREC G100 [23] in this respect. A cursory review of ENA EREC G100 shows that step voltage changes associated with a change from state 1 to state 2 operation of customer limitation schemes (CLS) need to be assessed in accordance with P28. P28 should clarify this and make clear that tripping of a BESS when operating at full import and full export should be assessed against the step voltage change limits in P28.

4.2.4 Flicker

Also, there is no explicit reference to any flicker summation exponent to be used when assessing coincidence of flicker from BESS operation. Reference to Table 8 in P28 suggests that a flicker summation exponent of $\alpha = 1$ should be used when there is a very high occurrence of coincident voltage fluctuations such as when multiple motors are started at the same time. This might also be appropriate to BESS, which provide similar power responses when operating in the same market, such as when providing dynamic FR.

NOTE: Flicker summation exponents apply to the addition of either P_{st} or P_{lt} from various sources using Equation 1 and Equation 2 in P28, such as summating at the point of common coupling (PCC). A higher value of the exponent represents less probability of coincidence, whereas a value of 1 represents a very high probability of occurrence, where flicker severity is arithmetically added together.

Clause 8.9 of P28 also mentions the potential for flicker caused by energy storage providing voltage control/reactive power support as these can result in small frequent voltage fluctuations. The BM service can be inferred but is not explicitly referred to in P28. P28 recognises that energy storage used to balance load to generation can result in increased flicker levels.

4.2.5 Assessment of Ramping

Ramping of power changes is recommended in clause 8.9, where significant changes in power occur frequently. Ramping power changes, instead of instantaneously changing power, will reduce flicker severity.

The definition of step voltage change in P28 means that ramp changes need to be assessed against step voltage change limits. However, P28 does not provide guidance on how a slow ramp voltage change that occurs over a longer period than tap-changer operation should be treated. Compliance of BESS with step voltage change limits could be improved if the effect of the tap-changer is considered. The Electronics MDPI Article [11] demonstrates how specific times for tap-changer operation at different system voltages could be modelled.

4.2.6 Charging & Discharging Rates

Clause 8.9 of P28 states that charging and discharging rates of energy storage systems should be limited so as to comply with the voltage fluctuation limits. There is no mention of the charging or discharging characteristic. It is believed that charging and discharging rates will be in MW. Therefore, there should be no voltage fluctuation for a constant charging/discharging rate. This should be clarified in any revision of P28.

4.2.7 Interpretation of Relevant Limits, Definitions and Terms from EREC P28

The three types of voltage fluctuation to be assessed in EREC P28 Issue 2 are:

- Step voltage change.
- Rapid voltage change (RVC).
- Flicker.

The definition of a step voltage change was introduced into the last revision of P28 [1]. There is no equivalent definition in IEC Standards, however the term ‘step change’ is used in the context of an instantaneous rectangular voltage change. The definition in P28 encompasses these instantaneous voltage step changes but also other types of voltage characteristics such as ramp voltage changes. The purpose of the definition is to bound the magnitude of voltage changes caused by customer equipment that occur, after the operation of any fast acting voltage compensation equipment but before the operation of tap-changers. This is to prevent unacceptably low voltages.

The definition of a RVC in P28 is similar and aligned to that in IEC 61000-3-7 [5]. RVCs are short duration changes in steady state voltage that occur over several cycles but no longer than 2 seconds.

NOTE: According to IEC 61000-3-3 [16], the voltage should be deemed to be in a steady state condition if it does not vary by more than ±0.2 % of nominal system voltage over a 1 s period.

RVCs are typically associated with motor starting, transformer energisation and similar events, where the maximum voltage rise or depression might be greater than the steady state voltage change. The characteristic of RVCs means that higher values of short duration voltage changes are less likely to cause disturbance to customers.

Flicker is defined as the impression of unsteadiness of visual sensation induced by a light stimulus whose luminance fluctuates with time. It is important to note that the cause of the change in luminance is not stated and flicker is not exclusively the result of changes in supply voltage. Flicker limits are intended to limit the frequency of repetitive voltage changes so they are not an annoyance to other customers connected to the same part of the network.

The requirement in P28 is for the various limits to be applicable in 'normal operating conditions'. The interpretation of 'normal operating conditions' could be improved generally and specifically how it relates to BESS, in particular whether it includes BESS providing DC frequency response services to the ESO, when the system frequency is outside normal limits of 50 Hz ±0.2 Hz (see clause 6.1.6 of P28). DM, DR, arbitrage and BM services are deemed to be pre-fault services and within the 'normal operating conditions' scope of EREC P28.

The definition of step voltage change is believed to be suitable and applicable to BESS related voltage fluctuations. However, the following clarifications are required.

- What observation time should be chosen for assessing step voltage changes associated with BESS providing FR services given voltages tend to constantly change and do not tend to reach steady state values.
- Whether fast tap settings on tap-changers can be used to mitigate step voltage changes associated with BESS.
- How the interaction between ramp voltage changes occurring over a time period greater than 1 s and the correction of the voltage by tap-changers needs to be considered.

In P28 it is not made clear whether the shape factor for ramp voltage changes can be used for voltage changes where the time between steady state voltages is greater than 1 s. Based on this review it is believed that they can be.

Clarity could be provided of what constitutes a RVC for BESS operation. There is believed to be limited scope for voltage fluctuations caused by BESS providing FR services to be assessed as being RVCs given the slower ramp voltage characteristics (see 5.2).

A significant gap in P28 in terms of its application to BESS is the impact that modelling at different power factors (for export and import) and for different control modes (e.g. constant power factor control, voltage control etc.) can have on the magnitude of the step voltage change and RVC. This review has identified this as a developing area, in particular power factor control operation and the change in the import/export of reactive power during significant voltage changes.

The definition of the flickermeter in P28 could be improved with reference to the new Light Flickermeter and its difference compared to the IEC Flickermeter referred to in the current issue of P28.

The addition of the following definitions, similar to those in NPg document IMP/001/007/001 [14], would improve P28 and/or its proposed accompanying EREP document.

- Agreed Export/Import Capacity.
- Power Rating (kW or MW).
- Energy Rating (kWh or MWh).
- Import/Export Limiting Scheme.

4.3 Desktop Review of IEC 61000-3-7 Concerning BESS Assessment

This document has the status of an IEC technical report and was last published on 22/02/2008. It has a stability date of 2024, which means its content will remain unchanged up to this date and, at this date, it will be either reconfirmed, withdrawn, replaced by a revised edition or amended.

It comes under the governance of BSI Committee GEL/210. A check of the stated work of this Committee confirms that there is no work in progress on this document.

IEC 61000-3-7 primarily focuses on limiting flicker and RVCs. Interestingly, instantaneous step voltage changes fall under the definition of RVC in the document. It is apparent that this definition is intended to cover infrequent short duration voltage changes that occur as a result of inrush currents, start-up and switching equipment, i.e. where the timescales are less than or equal to 2 seconds. This is consistent with the definition of RVC in P28 Issue 2 [1].

Clause 10.2 states that: “Under normal circumstances, the value of rapid voltage changes is limited to 3 % of nominal supply voltage in MV systems.” The accompanying note states: “Current practice in many companies is that the value of 3 % corresponds in general to rapid voltage changes that may occur twice per hour or more.” Indicative planning levels for RVC for MV systems are provided in Table 6. These are no greater than 6 %. However, it should be noted that:

- The values relate to the maximum voltage change expressed as a percentage of nominal voltage.
- These values are planning levels for the system at the PCC and not limits for individual emissions from installations. There are currently no emission standards for MV equipment.

There are no references to BESS or energy storage in IEC 61000-3-7. This is not surprising given the last update to IEC 61000-3-7 in 2008, predates the application of BESS.

4.4 DCRP P28 Working Group Outputs

4.4.1 General

The DCRP P28 Working Group was reconstituted early in 2023 triggered by BESS stakeholder comments on the application of P28 to assessment of BESS. The membership of the Working Group includes NPg and the author [of this Report]. So far, several meetings of the Working Group have been held.

A key objective for the Working Group is to draft an ENA Engineering Report (EREP) which will provide guidance on the application of P28 Issue 2. This will follow a similar structure and approach to the revision of Engineering Technical Report (ETR) 122 [29] for the application of EREC G5/5 [6]. A key element will be to provide worked examples of assessments, including but not limited to those for BESS connections. Providing guidance on assessing RVCs associated with transformer energisation is another key element.

For clarity, the Working Group do not believe any changes will be required to P28 Issue 2 in terms of its application to BESS. They believe the proposed EREP will provide the necessary explanation of requirements.

4.4.2 BESS Stakeholder Questions

A key agenda item has been to prepare a response to BESS stakeholder comments on the way DNOs apply P28. These questions revolve around the following.

- The conflation of step voltage change and flicker.
- The basis and appropriateness of the 3 % voltage step limit.
- The recognition and application of requirements in IEC Standards.
- Whether there should be any recognition of system management issues in P28 for significant frequency excursions.
- The perceived greater flexibility of the Distribution Code (DCode) [3].

4.4.3 Scope of Frequency Response Services

The DCRP P28 Working Group believes that DM and DR frequency response services are ‘pre-fault’ services and are therefore wholly within the scope of P28[2].

In addition, the Working Group has proposed that any ‘post-fault’ frequency response services, namely DC, do not need to meet voltage fluctuation limits in P28 when operating outside the 49.8 Hz - 50.2 Hz range. Within this frequency range, DC does provide a

[2] In this context ‘pre-fault’ means the services are responding to frequency changes under normal system operation conditions. ‘Post-fault’ means the services are responding to frequency changes in large-loss, low inertia scenarios, such as those following a major fault, either loss of load or loss of generation.

response, albeit less than DM and DR services, which need to be subject to P28 assessment. Clause 5.3.3 of P28 states for coincident RVCs that: *"The requirement to prevent co-incident RVCs exceeding the limits in Table 4 at the PCC does not apply to: a) fault clearance operations; or b) immediate operations in response to fault conditions*." In addition, clause 6.1.6 states that "*voltage fluctuations are not expected to conform to planning levels under abnormal conditions or whilst steps are taken to maintain/restore supplies to customers, where otherwise supplies would be interrupted"*.

In summary, it could be interpreted that the DC response outside the 49.8 Hz to 50.2 Hz frequency band is an immediate operational response to a fault condition and that P28 should not apply.

4.4.4 Basis & Appropriateness of the 3 % Step Voltage Limit

The DCRP P28 Working Group believes that the 3 % step voltage change limit is still valid for BESS given it is well established and referenced in International Standards such as IEC 61000-3-3 [16] and IEC 61000-3-11 [25].

Engineering Recommendation P28 Issue 1 [8] first mentioned the 3 % limit in the context of being accepted practice for many years to control the risk of excessively low system voltages. For context, the relevant extract is as follows:

> A 3% general limit on the allowable magnitude of voltage changes, regardless of shape, caused by fluctuating loads has been the accepted practice for many years to control the risk of excessively low system voltages. For this reason this general limit is retained even though voltage changes in excess of 3%, if of sufficiently low frequency, may not give rise to flicker severity levels (P_{st}) in excess of the limits in this Recommendation.

This document predates the first issue of IEC 61000-3-3 and IEC 61000-3-11. The text in P28 Issue 1 makes clear this limit relates to the magnitude of voltage changes, regardless of shape or duration, caused by fluctuating loads. There is no suggestion the limit is imposed because of the lack of immunity of customer equipment either to lower voltages or to the magnitude of step changes in voltage.

The DCRP P28 Working Group has recognised the impact that the response of tap-changers can have on limiting excessive voltage changes, which could take the voltage outside statutory limits. It has also recognised that P28 clause 6.2 does allow for larger changes in step voltage where special circumstances apply: *"In certain cases, where special circumstances apply, the system/network operator may, at its discretion, allow larger step voltage changes to occur, e.g. continuous process plant where larger motors are only started once in several months."* The Working Group has made clear that this allowance is not expected to be given for all generation types due to operation models being designed to meet certain frequency services/market signals. However, there might be scope to allow step voltage changes greater than 3 % where any response provided by the BESS is exceptional.

The Working Group believes that any BESS capable of changing from 100 % export to 100 % import, and vice versa, should conform to the 3 % step voltage change limit. The Working Group are looking for operational data from BESS operators together with associated information concerning commercial contracts to ensure P28 assessments are appropriate.

However, there is a desire to identify realistic changes in power output for the various services provided by BESS and to ensure assessment criteria recognises this.

4.4.5 The Recognition and Application of Requirements in IEC Standards.

The DCRP P28 Working Group has confirmed in its proposed response to BESS stakeholders that the limits and requirements in P28 do and should continue to recognise and follow relevant International Standards. Any changes to requirements in P28 that include any deviation from International Standards would need to be carefully assessed and evaluated.

4.4.6 System Management Aspects

The DCRP P28 Working Group has confirmed that overall system management aspects are beyond the scope of P28. However, it does consider voltage fluctuations due to the combined effect of multiple installation which individually are within the scope of P28 as being within the scope of P28., e.g. coincident voltage fluctuations caused by BESS providing frequency response services whose response might be synchronised in time. Notwithstanding, it does make clear that extreme post-fault actions, including National Grid ESO actions during extreme system frequency events, are excluded.

4.4.7 The Perceived Greater Flexibility of The Distribution Code (DCode)

The DCRP P28 Working Group has made clear that the 'expected depression of around 10 %', stated in DPC 4.2.3.3 is not a general increase in the allowable step voltage change. The basis of this 10 % figure was to recognise the unpredictability of the 'point of wave' switching when energising multiple transformers associated with infrequent events, such as after commissioning. This wording in the DCode was intended to be compatible with the latest revision of P28. Furthermore, the Working Group does not believe that the 10 % value stated in the DCode for 'very infrequent events' will apply to the BESS FR services because the DCode specifically refers to its application to post fault switching, post maintenance switching, or carrying out commissioning tests.

4.4.8 Frequency Time Series Data and System Frequency Events

The DCRP P28 Working Group has also concluded that standard frequency data sets should be used when carrying out flicker assessment of BESS providing FR services, which are representative of frequency variations 95 % of time. System frequency information has been requested from National Grid ESO. Indeed National Grid ESO representation on the Working Group is being sought.

The DCRP P28 Working Group has reviewed frequency data from National Grid ESO. This data is available from https://www.nationalgrideso.com/data-portal/system-frequency-data which holds the historic system frequency data for Great Britain at a 1 second resolution. The DCRP P28 Working Group believes this 1 second data will be sufficient for BESS assessment, except where there might be a risk of the BESS controller causing an oscillatory response.

Figure 2 below confirms that DR would be responding to ramp type changes, not instantaneous changes, in frequency (50 Hz ± 0.1 Hz). These can occur quite often with ramps times typically of several seconds.

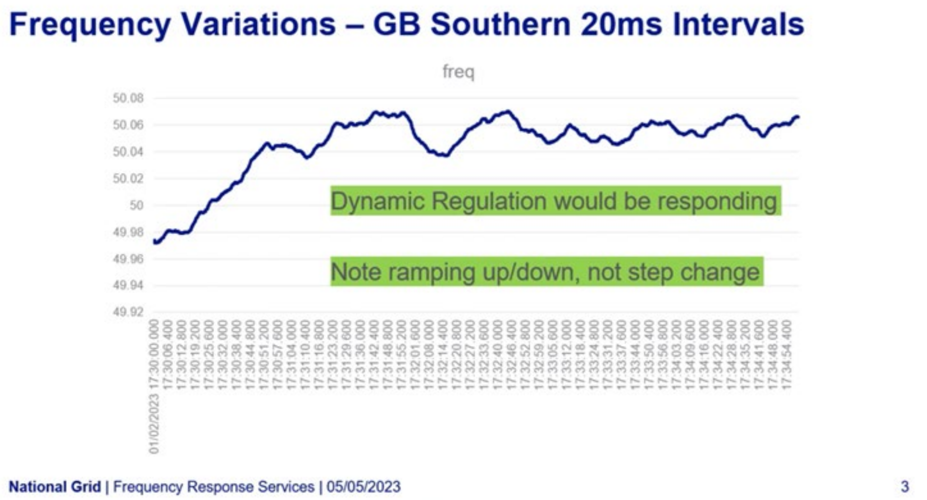


Figure 2 – Extract of Frequency Variations Over a 5 Minute Period

The frequency variations from the August 2019 low frequency event were analysed - see Figure 3. This shows a fast frequency drop (i.e. 0.9 Hz drop over 25 s) that would have resulted in a DC frequency response of 100 % of the contracted power to be exported by the BESS providing this service - and also potentially 100 % of contracted power to be exported from BESS providing DR and DM services.

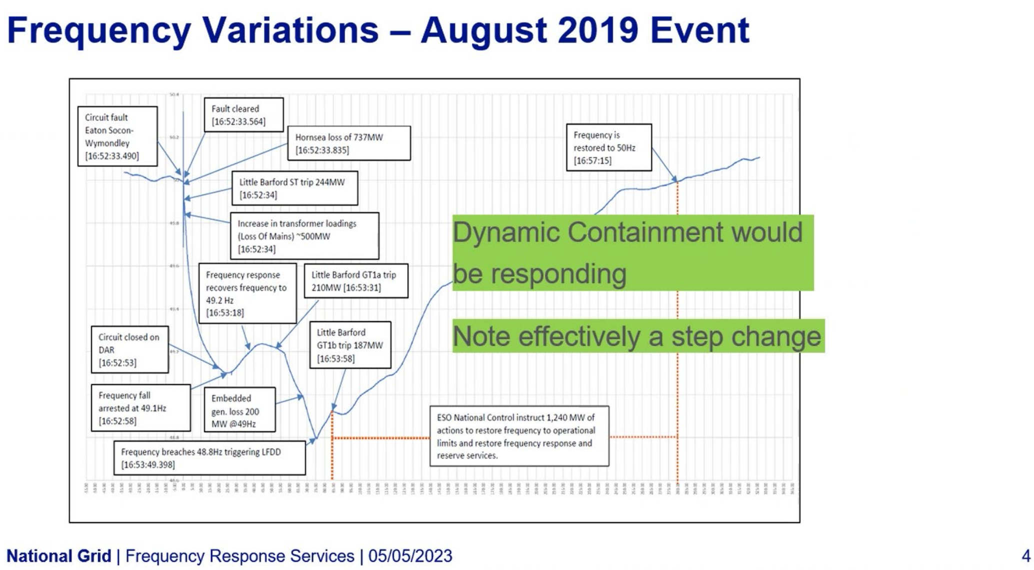


Figure 3 – Timeline of Frequency Variations for the August 2019 Major System Event

The time for the frequency to drop from 49.8 Hz to 49.5 Hz was less than 5 s. This would have resulted in any BESS providing DC-L going from 5 % of contract power export to 100 % of contracted power export in this time period. It is clear that this would have effectively been a step change in power output and hence voltage rise.

NOTE: The conclusion above only relates to the period of maximum response associated with DC and 100 % of the contracted DC power response. Prior to the system event, a BESS might have been importing power depending upon the other services it was contracted to provide in addition to DC. In which case, the power swing could have been greater from import to 100 % export.

The frequency drop from 49.9 Hz to 49.8 Hz happened in less than 1 s, which would have resulted in any BESS providing DM going from 5 % contracted power export to 100 % contracted power export in this time. Similarly, this would have effectively been a step change in power output and hence voltage rise.

This raises some points regarding the assessment of BESS:

- Infrequent national frequency events can result in FR services providing a step power response causing a significant step voltage change.
- As DC could be deemed to be a 'post fault service', where the most significant response occurs for large frequency variations (i.e. in the frequency band 0.2 Hz to 0.5 Hz which is outside the nominal operational frequency range), then it could be argued that the 3 % limit for step voltage changes should not apply for these extremely infrequent system wide fault events.
- However, the response by DM in the 0.1 Hz to 0.2 Hz band could result in an equally severe step change in voltage, which would need to be assessed against the 3 % step voltage change limit in EREC P28.
- Events such as the 2019 event do not appear to cause large frequency swings; in this case there was a step fall in frequency followed by a slow ramped increase in frequency.
- There might be a credible scenario where a BESS was fully importing whilst the frequency was in the deadband before the system event. This could have created a power swing from full import to full export.

4.4.9 Modelling

The DCRP P28 Working Group has recognised that there are different approaches to modelling used by connectees and DNOs. The Working Group intends to define minimum acceptable criteria that can satisfactorily represent the DNO network and that can accurately mimic the BESS control system on the customer's hardware.

The DCRP P28 Working Group is aware that incorrect set-up of the BESS controller can cause frequent small power changes that can result in high flicker P_{st} values. An example of a BESS connected at 11 kV with a 3.75 MVA connection agreement was tabled where the voltage ramp change was 1.8 % in 1 s, which resulted in a P_{st} >4. Subsequent investigations found that repetitive ramping up and down in power and the consequential voltage changes was due to an oscillatory response caused by the BESS controller. National Grid Electricity Distribution (NGED) has presented a proposal for a standard BESS controller set-up, which can be used for any modelling of BESS. This is incorporated in the NGED Guidance Note for BESS [9] discussed below.

4.4.10 System Inertia

The DCRP P28 Working Group are cognisant of the future reductions in system inertia, due to the reduction in the numbers of synchronous generators connected to the system. They believe it is necessary to future proof P28 compliance assessments and ensure that the assessment methodology takes this into account. This is also incorporated in the NGED Guidance Note for BESS [7] (see 4.6.2 below).

4.4.11 Coincident Voltage Changes

The DCRP P28 Working Group believe the voltage changes caused by BESS, that are providing the same frequency response service to NGESO, will be coincident and that guidance needs to be provided on their assessment.

4.4.12 BESS Services

The DCRP P28 Working Group are considering whether Short-Term Operating Reserve (STOR) services should be included. STOR is intended to replace generation after the largest loss. It is understood that BESS with an export capacity of greater than 3 MW can participate in the STOR market. However, fast-responding assets such as BESS are not likely to participate in this service as they can earn more revenue from providing frequency response, or trading in the wholesale markets and the BM. Also providing a STOR service requires a response for a minimum of 2 hours at a likely significant power, which would be outside the energy storage capacity of many BESS.

4.4.13 ENA DER Technical Forum

Electricity North West Limited (ENWL) has presented some findings on how power factor (pf) of the BESS can affect step voltage. In particular, how implementing pf control on the BESS can reduce step voltage change. Traditionally ENWL has assumed the BESS to be operating at unity power factor (i.e. imports and exports MW only). ENWL has demonstrated that the reduced voltage drop and rise caused by BESS importing/exporting reactive power (as appropriate) under maximum import and export conditions would create more voltage headroom at the Grid Supply Point (GSP).

NPg's policy requires the BESS initial assessments to be carried out assuming a lagging pf = 0.95 when exporting [3] and when importing. This will generate a pessimistic volt change. NPg's position of applying a lagging pf =0.95 for BESS when exporting is contrary to most UK DNOs which model the BESS using a pf = 0.95 leading.

[3] This policy is based on the requirements in the Distribution Code [3] and EREC G99 [10].

NOTE: Where there is an issue with a BESS connection complying with step voltage change limits at pf = 0.95, NPg allow the BESS to be assessed at its intended operating pf but reserve the right for the BESS to be compliant for operation at pf = 0.95 if required to operate at this pf in future.

The DER Technical Forum has been discussing a proposal for setting maximum power ramp rates as a means of limiting risk for the DNO. In this way, any assessment would not be dependent on the type of service being provided by the BESS. For example, a case where a BESS has been assessed on the basis of arbitrage (which generally involves slower ramp rates) and deemed compliant but the BESS operator subsequently changes to providing frequency response services with faster ramp rates. Whilst studying/setting a maximum ramp rate has merits, this would need to be accompanied by a maximum ramp time at the maximum ramp rate to limit the step voltage change.

4.5 Comparison of Policies & Practices

4.5.1 Shape Factors

P28 Issue 2 introduced the concept of 'shape factors' to facilitate a simplified assessment of P_{st} for periodic and non-repetitive voltage changes. These shape factors, and their application, are identical to those in IEC/TR 61000-3-7 [5]. It is important to clarify that shape factors do not apply to assessment of RVC or step voltage change. As such they cannot be used to increase the general limit of 3 % for ramp type voltage changes.

Shape factors are only applicable for simplified assessment of repetitive voltage fluctuations. This could include assessment of simple predictable ramp changes associated with BESS trading in the Balancing Mechanism or wholesale market. These types of ramp changes, potentially at the beginning and end of half-hour trading periods, are not expected to create any significant flicker.

Shape factors are not suitable to be used for complex voltage fluctuations, which should be assessed using a flickermeter algorithm. Such complex voltage fluctuations could arise from BESS providing frequency response services.

The term 'shape factor' (or F) is not defined in P28 Issue 2. However, it represents a multiplication factor (between 0 and 1) of the maximum voltage change (d_{max}).

It is important to derive an equivalent step voltage change for use with the P_{st} flicker curves in P28 Issue 2 to determine the maximum number of voltage fluctuations of that shape (i.e. magnitude and profile) permitted in a minute.

An example of motor starting, taken from Figure 10 of P28, is shown in Appendix C, Example of the Application of Shape Factors.

Shape factors are useful for converting repetitive ramp changes into equivalent rectangular repetitive changes for flicker assessment. For example a ramp change of 1 % voltage over 1 s is less severe than an instantaneous 1 % voltage change.

If we take the following example for a 20 MW BESS to be connected to a 33 kV substation busbar that is performing a DM frequency response service. This example is to illustrate simplified flicker assessment and not step voltage change assessment.

For the scenario where the BESS is neither importing/exporting and the frequency drops to 49.75 Hz. This requires the BESS to deliver 100 % of export (i.e. 20 MW within 1 s).

In this case:

The change in steady state voltage (*Vsteadystate*) has been calculated to be 2.5 %.

Assuming this is a ramp voltage change over 1 s (within the maximum time for delivery) then a Stage 2 assessment can be carried out as follows.

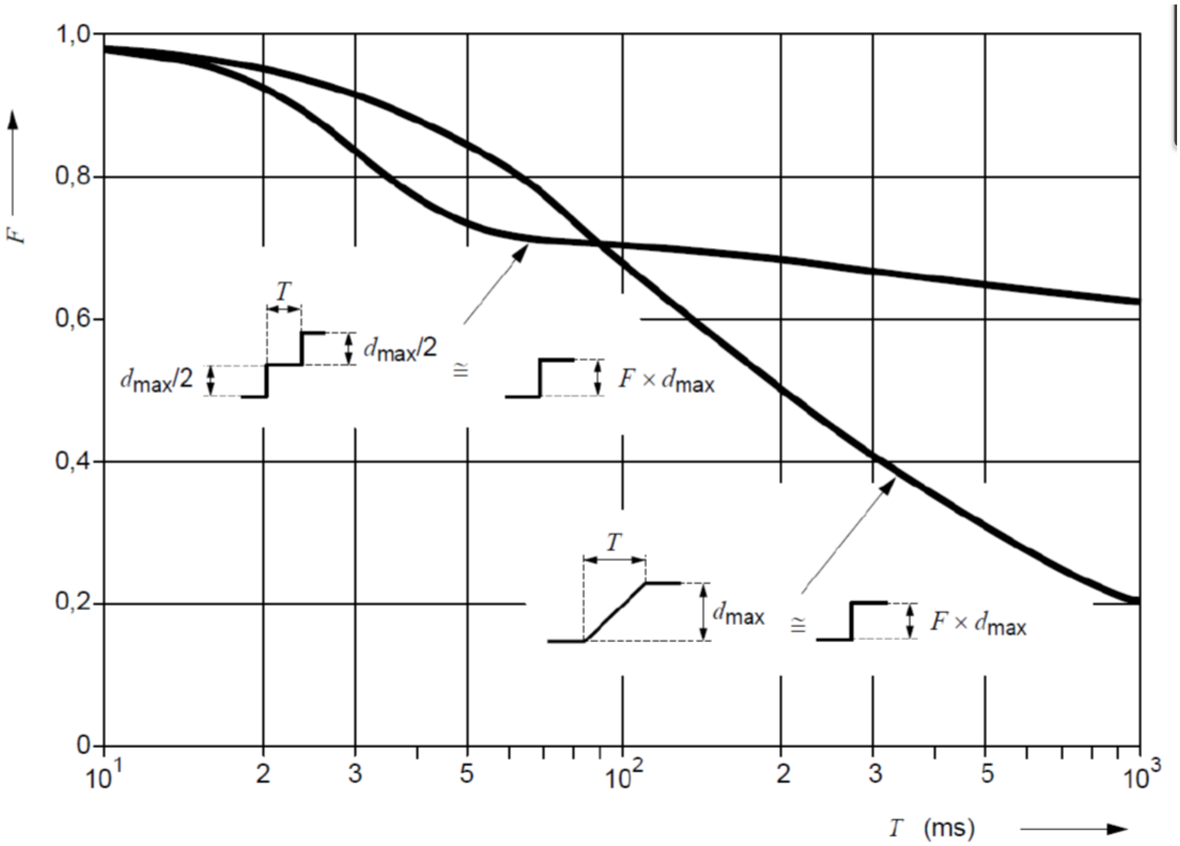


Figure 4 — Extract from Figure B.2.5 in EREC P28 Issue 2

With reference to Figure 4:

Assuming Ramp 1 takes 1 s

The shape factor $F = 0.2$

The value of $d_{max} = 2.5$ %

The equivalent step voltage change is F x d_{max}

= 0.2 x 2.5 % = 0.5 %

With reference to Figure B.1.1 [EREC P28 Issue 2]:

Using the calculated step voltage change of 0.5 %

The maximum number of these voltage changes per minute for P_{st}= 1 is 400

For a P_{st} = 0.5 the maximum number of these changes per minute is 0.5 x 400 = 200

This equates to one change every 0.3 s

In practice, a BESS alternating between a full DM response and providing no response every 0.3 seconds is very unlikely. Hence flicker is unlikely to be an issue for this BESS providing a DM service.

For the scenario where the power is ramping by 5 % every second. This equates to a power change of 1 MW per second. A calculation based on the Site A Data[4] shows that a 5 % power change results in a voltage change of 0.23 %.

It should be noted that the x-axis in Figure 4 only goes up to one second. Although not explicitly stated IEC/TR 61000-3-7, it can be implied that a shape factor of 0.2 can be extrapolated for ramps greater than one second. This is supported by the fact that a voltage ramp change over 1 second would be less onerous in terms of flicker severity than a ramp voltage change over a time period less than 1 second.

On this basis it is considered feasible to define ramp rate limits, which can be applied to assessment of defined voltage ramps such as those created by BESS trading in the BM and wholesale markets.

Using a similar approach as above with reference to Figure B.1.1 [EREC P28 Issue 2]

Assuming the double ramp takes 2 s (i.e. 1 s rise followed by 1 s fall)

The shape factor F = 0.4[5]

The value of d_{max} = 0.23 %

The equivalent step voltage change is F x d_{max}

= 0.4 x 0.23 % = 0.1 %

With reference to Figure B.1.1 [EREC P28 Issue 2]

For a step voltage change of 0.1 %

The maximum number of these voltage changes per minute for P_{st} = 1 is approximated to be 600

For a P_{st} = 0.5 the maximum number of these changes per minute is 0.5 x 600 = 300

This equates to a minimal time interval of 0.2 s between voltage changes

Similarly, frequent small changes in BESS power are unlikely to result in flicker issues.

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[4] Site A is a BESS installation connected to the NPg 132 kV distribution system. Data from Site A over a specific operating period was provided including BESS power changes, the type of service being provided by the BESS at specific times, e.g. FR service, system frequency at specific times and the state of charge.

[5] See double ramp in Figure B.2.1 of P28.

4.5.2 Summary from Technical Paper (Brunel University)

Key points from Threepwood's review of the Brunel University paper published in 2023 "Assessment of Voltage Fluctuations for Battery Storage Systems Providing Frequency Response Services" [11] are summarised below. A detailed commentary is provided in Appendix D Commentary on Technical Paper (Brunel University) [of this Report].

System frequency changes slowly when the system is operating normally and therefore BESS power output changes will be ramped. Consequently, system frequency changes will not normally result in the BESS power output changing from full export to full import in a short time (<1 s). However, this extreme of power swing might occur when the BESS is providing other services in addition to frequency response services.

The resultant voltage fluctuations from the modelled BESS appear as ramp voltage changes over several seconds. This is consistent with slow frequency changes. Large step voltage changes do not appear to be a characteristic of BESS when providing frequency response services under normal system conditions. This might not be the case for rare national system frequency events such as the one experienced in August 2019.

Lower system inertia in future will result in faster and more frequent frequency changes than at present and consequently greater voltage fluctuations for the same frequency changes[6]. This raises the question whether foreseeable reduction in system inertia should be part of P28 assessments. This is discussed further in section 5.3.2 of this Report.

Given the slow frequency changes together with the associated slow BESS voltage changes and the probability that the voltage does not reach steady state, the operation of on-load tap-changers would mitigate the step voltage change of the BESS. Automatic Voltage Control (AVC) with fast tap settings[7], i.e. threshold and time delay, of on-load tap-changers connected to the same busbar are relevant and should be considered when assessing voltage fluctuations against the 3 % limit.

Understanding the BESS controller set-up is important for accurately modelling voltage fluctuations. However, for all current frequency response services, the required BESS power response is based on the BESS power, the system frequency and the voltage and hence the controller set-up will be similar lending itself to the application of a generic controller for modelling. A real life example has illustrated how a BESS controller, if not set-up correctly, could cause a local oscillatory frequency/power feedback loop where the BESS exported large amounts of active power that caused a local change in phase angle and hence a change in measured frequency, which the BESS controller then reacted to by importing large

[6] Minimum system inertia is planned to be reduced from 140 GVAs down to 102 GVAs in the coming years (i.e. a 40 % decrease which will lead to greater number of frequency variations, which will probably be larger, together with the consequential voltage variation).

[7] Fast tap settings are not currently stated in NPg policy nor in ENA Engineering Report 126 [12].

amounts of active power. BESS controllers need to respond to frequency quickly but not so quick as to result in such oscillatory responses.

Coincident voltage changes from BESS (providing similar FR services) connected to the same busbar or network is likely. Slight differences in the controller set-up and type of FR services being provided will mitigate these voltage changes somewhat. As such, the use of the flicker summation exponent of 3, which is generally referred to in P28, might not be appropriate for simplified assessment of flicker for BESS providing FR (see 4.2.4).

4.6 Critical Review of DNO Policies & Practices

4.6.1 NPg Policies & Practices

The following comments arise from Threepwood's critical review of NPg IMP/001/007 [13].

- The policy requires normal operation of connected DG, including BESS, to comply with the limits stated in P28.
- It recognises that limits on power ramping up/down might be required to comply with limits in P28.
- It also recognises that system transformer tap-changers have a role to play with ensuring voltage remains within limits. This is compatible with P28, which states that a voltage event is after generator Automatic Voltage Regulator (AVR) and Static Voltage Compensator (SVC) actions but before transformer tap-changing and switching actions have commenced. Assessment will require knowledge of NPg AVC settings, including any fast tap threshold and fast tap time delay, to check compliance.

  NOTE: Whilst the 'fast tap' feature is available in modern AVC relays, it is not currently widely implemented across DNOs although it has the potential to mitigate against step voltage changes caused by BESS operation.
- Designing a step voltage change of 10 % of nominal voltage is mentioned. This is intended for re-energisation of transformers post fault and aligns with the relaxation in the DCode [3] and P28.
- The most onerous conditions described are compatible with those for generators in P28. It is noted that the worst-case step voltage change for an (exporting only) generation installation is likely to occur when the metering circuit-breaker trips on full export.
- There is recognition of realistic minimum demand rather than an absolute minimum.
- There is recognition of assessment for different power factor operating ranges - consistent with ENA EREC G99 [10].

The following comments arise from a review of IMP/001/007/001 [14].

- Reference is made to stacking of services with the assumption that stacked services do not interfere with one another. This is National Grid ESO's requirement for BESS providing FR services. Stacked services could effectively result in a more onerous voltage fluctuation as output changes from one service to another (e.g. arbitrage importing to frequency response exporting). This is currently reflected in the study of maximum power swing from full import to full export and vice versa.
- Section 3.1.1 recognises the need for the DNO to understand the services provided by the storage development over its lifetime as this may alter the import/export response and hence the voltage fluctuation caused by the installation. This is consistent with good practice and ahead of thinking in the DCRP P28 Working Group.
- BESS is clearly defined in terms of its response time and capacity. Also there is helpful background information in terms of explaining Export Limitation Schemes (ELS), discharge rates and depth of discharge. There is an opportunity to use these definitions and include this information in P28.
- The System Operator frequency services described in section 3.1.4 do not reflect current frequency response services and need to be updated.
- The document recognises that BESS ramp rates will be more severe and can cause large step voltage changes where the response times are measured in seconds and not minutes (i.e. frequency response services compared with reserve services).
- Assessment of power factor is discussed in section 3.1.6 of the document. It is recognised that it is ideal for the BESS to operate at the same power factor as the network. However, network power factor is not always known and BESS is usually allowed to operate between 0.95 lagging and unity power factor. Assessments, including step changes, are required to be carried out at full import capacity and full export capacity (MW and MVAr) at 0.95 lagging power factor, which will produce a larger voltage drop than at unity power factor and represents a worst-case condition. There is an allowance for non-compliance against the power factor range 0.95 lagging to unity (e.g. because of the need for additional equipment). However, NPg reserves the right to ask the BESS to reduce output, where required, should the BESS operator be required to operate at a lower pf in future.
- Section 3.1.6 of the document requires the reactive characteristics of long circuits to be taken into account where to BESS Point of Supply (POS) if supplied via a long circuit (> 10 km). This is considered to be reasonable.
- There is an error in section 3.1.7.1 where the ELS should be reworded to be '…planned availability of 99.9% or greater.'
- Footnote 47 discusses the application of shape factors to BESS, stating that it is not envisaged they would apply to BESS. Whilst this is likely to be the case, the DR frequency response service could result in repetitive ramp up/down power characteristics, where a maximum ramp rate and recurrence could be defined to facilitate a simplified assessment of flicker compliance. The interpretation of shape factors and allowance for ramping in Appendix 3 is considered to be correct.

- For Stage 2 Assessment a statement is made that: "Although a ramped up/down voltage change of greater than 3% could lead to an equivalent step voltage change of 3% or less, such a connection shall not be permitted." This statement requires clarification to confirm that shape factors do not apply to ramp voltage changes when assessing step voltage changes.
- In section 3.3.2.2.1 for Step Voltage Change the 'aggregate 3 % rule', where the aggregate of the step voltage changes should not exceed 3 % before the operation of the tap-changer, is believed to align with the intent of the 3 % step voltage change limit in P28. Clarity is required in P28 for BESS operation, to ensure that the difference between the highest voltage and the lowest voltage caused by BESS operation before the tap-changer does not exceed 3 %. This is to reflect the fact that the voltage might be continuously varying.
- NPg's approach to P28 assessment is summarised in Appendix F NPg Approach to P28 Assessment [of this Report]. Threepwood's key observations are:
  - The simplified assessment of step voltage change is valid where the BESS power swing from full export to full import occurs within the operation time of the tap-changer (typically 90 s – 120 s). There might be scenarios where time for the power swing exceeds this time, in which case the operation of the tap-changer should be taken into account.
  - Initial modelling of step voltage change with pf = 0.95 lagging for both full import and full export will give the worst-case voltage change particularly for networks with a high X/R ratio and low fault level. This is at odds with other DNO policies and might unduly constrain BESS.
  - Use of export limiting schemes to limit step voltage change, where necessary, for N-1 conditions is consistent with the intent of P28.

4.6.2 National Grid Electricity Distribution (NGED) Policies & Practices

The following comments arise from Threepwood's critical review of NGED's design policies related to BESS.

Similar to NPg:

- NGED requires P28 assessments to be carried out at the most onerous operating condition specified in P28.
- NGED imposes a step voltage change limit of 3% for Fast Frequency Response (FFR) from full export to full import and vice versa. However, NGED does not specify a power factor that this must be carried out at.
- The definitions of step voltage change are identical.

Unlike NPg:

- NGED allows frequent operational switching (i.e. voltage changes) up to 3 % step voltage change at a frequency dictated by the P28 flicker limits. NPg limits this to an aggregate of 3% over the tap-changer initial tap delay.

- NGED has different step voltage change limits for DNO operations. For example, a 6% step voltage change at the busbar is allowed for FFR events, whereas this is limited to 3% for individual customers. This allows for coincident power swings from BESS.
- NGED assess single installations based on a pf = 0.95 lead for export and pf = 1.0 for import at the POC.

NGED have issued a Guidance Note for the Flicker Assessment of BESS (dated 21/08/2023) providing pre-fault FR services (i.e. Dynamic Regulation and Dynamic Moderation) [9]. The key points from the Guidance Note are as follows:

- Assessment of DC frequency response (outside the 49.8 Hz to 50.2 Hz band) is excluded as it is considered a post-fault service.
- NGED requires the BESS Power Park Controller to be modelled to be the same as that provided by the manufacturer and to have the same configurable settings to match those to be applied in practice.
- NGED point to DigSILENT and PSCAD as being suitable software for carrying out the modelling based on a standard block diagram of the model, where the frequency input is introduced to the model through an AC Voltage Source Controller.
- Dynamic system modelling is not required unless NGED deems the power system at the PCC to be 'very weak' or a risk of power oscillation has been identified.
- An equivalent impedance model of the power system at the PCC is required to be studied under the same worst-case normal operating conditions defined in EREC P28 with fault level data provided by NGED.
- NGED suggest the flicker severity results are inflated by a factor of 140 GVAs/102 GVAs (= 1.373) for assessment to adjust for lower system inertia in the future[8].
- The connectee is required to run a simulation of the BESS output for both a constant 50 Hz input frequency (to check for any oscillation due to the BESS controller representative frequency changes) as well as a fluctuating frequency. The frequency input to the model can be based on raw historic time-series data (published by National grid ESO) or synthesised time-series data that characterises the frequency fluctuations adequately (i.e. similar to the approach taken in the Brunel University Paper [11]).
- Compliance is to be evaluated against EREC P28 Stage 2 planning levels (i.e. P_{st} = 0.5 for flicker).

[8] NGED state that system inertia is reducing due to loss of large synchronous generation and it is expected to drop from the current operational minimum of 140 GVAs to 102 GVAs by 2025 (National Grid ESO, 2022). Lower system inertia results in larger changes in frequency and also a larger rate of change of frequency for the same event, both of which would act to increase flicker. Consequently flicker predictions need to ideally reflect this reduction in system inertia according to NGED.

- NGED believes that frequency data at 1 s intervals will suffice given that the 20 ms data does not vary significantly. This is to be expected given the relatively low rate of change of frequency.

4.6.3 Other DNO Policies & Practices

The following comments arise from Threepwood's critical review of other DNO design policies related to BESS.

UK Power Networks (UKPN) assess single installations based on a pf = 1.0 (import and export) under system intact conditions (contrary to worst-case normal operating conditions in P28) and at the POC.

Scottish Power Energy Networks (SPEN) SPD assess single installations at the POC, whereas SPEN SPM assess single installations based on a pf = 0.95 lead for export and pf = 1.0 for import at the POC.

Electricity North West Limited (ENWL) assess single installations based on a pf = 1.0 at the POC. A step voltage change of 6% is permitted at the POC for co-incident BESS operations. ENW are looking closely at voltage control mode operation to mitigate the magnitude of step voltage change. ENWL also assume BESS operate in the same markets and there is interaction.

No information was forthcoming from SSEN.

The application of shape factors is generally permitted in DNO policies, similar to P28, but no specific examples of how this is applied have been found.

DNOs universally assess compliance with the step voltage change limit of 3 % for a power swing from full export to full import and vice versa as a BESS is technically capable of this mode of operation. This is the case even when the BESS operator states the BESS will not perform this full power swing.

There is limited opportunity for the BESS to exploit the larger voltage change limits in the RVC envelopes in EREC P28 given their normal mode of operation does not create such RVC characteristics.

4.7 Commentary on the Current Flicker Approach[9]

Flicker is defined as "the impression of unsteadiness of visual sensation induced by a light stimulus whose luminance fluctuates with time". It is important to note that the cause of the change in luminance is not stated and flicker is not exclusively the result of changes in supply voltage. This is explained in the commentary below.

[9] Some information in this review was sourced from: https://www.sciencedirect.com/science/article/abs/pii/S0142061516322323.

The flickermeter was first developed in the 1970s and 1980s to replicate the extent to which human beings perceive changes in the luminance of a 230 V 50 Hz 60 W incandescent lamp caused by changes in supply voltage. The incandescent lamp was chosen because this type of lamp was the predominant lamp in use at the time of development. The research was driven by the electricity supply industry to understand what constituted unacceptable changes in voltage fluctuations (magnitude and frequency of changes) that would cause customers to complain of flickering lights.

The design and performance requirements for the flickermeter was first introduced in 1986 in IEC 868 [15], where instantaneous changes in input voltages were processed to produce an output measurement that replicated perceived flicker, known as flicker sensation (P), where a value of P = 1.0 was the threshold of perceptibility. This addressed the issues of combining different elements such as a large change in voltage every 10 seconds followed by a smaller change every second.

In 1991, IEC 868 was updated to define a statistical analysis of the input voltage over a 10-minute period, where the short-term flicker severity P_{st} was introduced. A P_{st} index value of 1.0 represents a ten-minute period where 50 % of observers see flicker as being annoying. Similarly, P_{lt} represents a long-term measure of flicker severity and is the statistical average of P_{st} values over a defined period, typically 2-hours, where the odd annoying value is given appropriate weighting.

Since 1994, the flicker standards were reorganised into IEC 61000-3-3 [16] and IEC 61000-4-15 [17]. IEC 61000-4-15 defines the flickermeter measurement approach which can be applied in the form of an instrument or a simulator incorporated in software that has the same basis in the perceived variability of luminance of a 230 V 60 W incandescent lamp with changes to the magnitude, rate and repetition of changes in supply voltage. This standard was last revised in 2010 and is classed as stable until 2026. However, a recent update from IEC SC 77A[10] states that ongoing research activity is being carried out including the susceptibility of modern lighting to voltage fluctuation.

The IEC Flickermeter measurement approach is the current measurement approach, which is referenced in P28 Issue 2. Applicable IEEE standards (IEEE 141 [18] and IEEE 519 [19]) are being aligned to the IEC Flickermeter. P_{st} has now become a measurement of power supply voltage quality, in particular the acceptability of voltage fluctuation and P_{st} limits apply to a wide range of equipment connected to the electricity system.

Developments in modern lighting technologies, principally Light Emitting Diode lamps (LEDs) and Compact Fluorescent Lamps (CFL), presents a challenge to the application of the current IEC Flickermeter given these modern lamps are known to behave differently than incandescent lamps, where the light fluctuations caused by voltage fluctuations are different. Generally, modern lamps are less sensitive to voltage changes and the resultant light flicker is generally less than for incandescent lamps for the same voltage fluctuation. However,

[10] Source: 77A/1195/RM Unconfirmed minutes of the IEC SC 77A Plenary Meeting held as a virtual meeting, from October 16th, 2023 (starting time: 14:00 UTC+2) to October 16th, 2023 (finishing time: 18:00 UTC+2).

there is an incorrect assumption that modern lighting is immune to voltage fluctuation. Whilst incandescent lighting is acknowledged as being the most sensitive to voltage changes (light intensity being proportional to the power consumed, which is in turn proportional to the square of the voltage), that does not mean other lighting is immune to flicker effects caused by voltage fluctuations. Some modern lighting has a non-linear response to voltage fluctuations, unlike incandescent lamps. At certain frequencies of voltage change, particularly at higher frequencies, the resultant light flicker might be worse than for incandescent lamps[11].

IEC 61547:2020 [20] (identical to BS EN IEC 61547:2023 [21]) was published as a consequence of LED lamp technology to assess light intensity variations emitted from any light source regardless of the power supply voltage. It uses the light variations from a lamp as the direct input in contrast to the IEC Flickermeter, which uses the voltage as the input.

This difference in measurement input is shown in Figure 5 below.

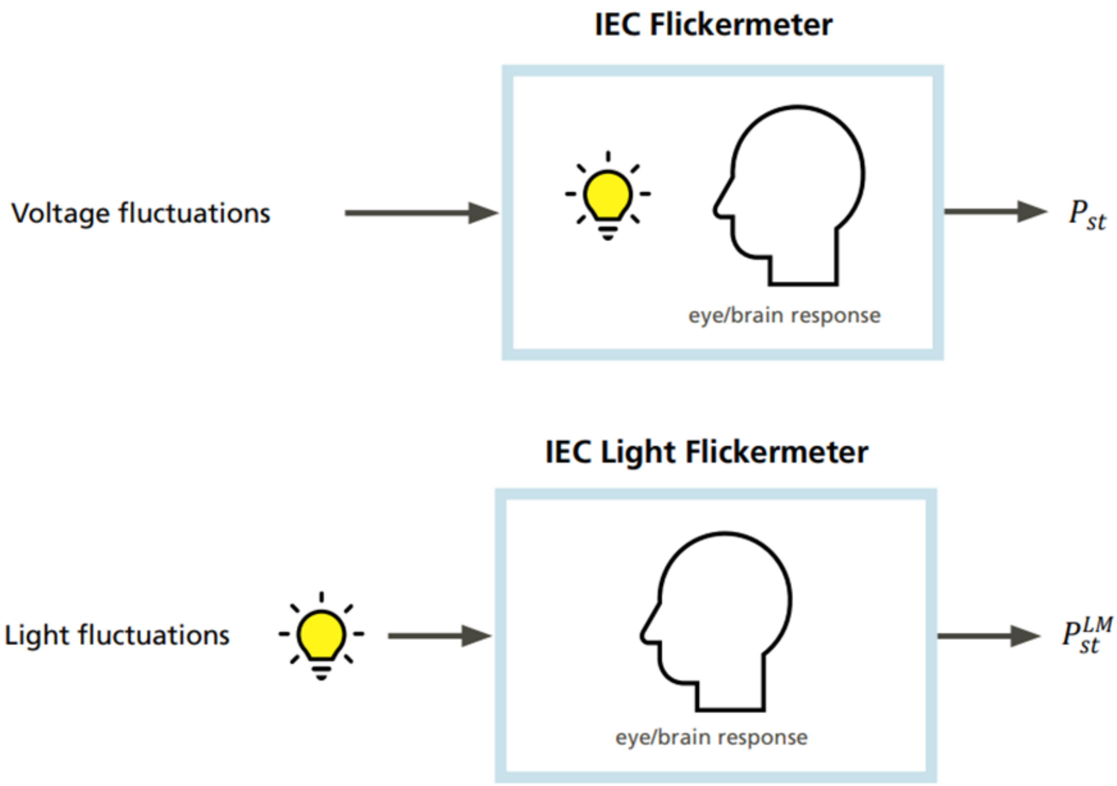


Figure 5 – Comparison of the IEC 61000-4-15 'IEC Flickermeter' and IEC 61547 Light Flickermeter

[11] Source: CIRED, Paper 0409, A protocol to test the sensitivity of lighting equipment to voltage fluctuations, June 2015 [22].

IEC 61547 incorporates requirements and tests to ensure lighting has equivalent or greater immunity to voltage fluctuation than incandescent lamps. The light flickermeter described in IEC 61547 (known as the Light Flickermeter) is a further development of the IEC Flickermeter and has associated limits and recommendations as per IEC 61000-3-3 [16] i.e. limits for voltage changes, voltage fluctuation and flicker for equipment with rated current ≤ 16 A per phase and not subject to conditional connection). This includes lighting and similar equipment. This standard recognises that lighting, other than 230 V 60 W incandescent lighting, can produce different results (different voltage fluctuation rates and % voltage fluctuation for the same value of P_{st}).

Notwithstanding, the IEC Flickermeter flicker curves and compatibility levels are still adopted as a reference to allow consistent evaluations across a wide variety of situations. Studies performed have concluded that, at present, it is not practical to:

- increase the compatibility levels for flicker in respect of modern lighting as not all lighting lamps have lower sensitivity to voltage fluctuations compared with incandescent lamps;
- adjust the flicker measurement procedure to a new reference lamp given the rapid and diverse advancement of lighting technologies.

P_{st} is the current measure of short-term flicker severity, which is the effect of visual irritation to human beings caused by changes in light intensity of a lamp. P_{st} can be measured either as a response to voltage changes (P_{st} using the IEC Flickermeter) or to changes in light intensity (P_{stLM} using the Light Flickermeter). Although the inputs are different (voltage or light intensity), the outputs are the same and can be compared.

5 Workstream A.2 Findings

5.1 Introduction

This section relates to workstream A.2 of the project carried out by Threepwood. It provides a description of how the EREC P28 planning limits (for voltage step change, RVC and flicker) should be applied to an assessment of BESS operating in different operating modes (Frequency Response contracts with National Grid ESO and energy arbitrage) and provides a clear definition of the planning limits and how to calculate them. In addition, it describes the effect of reactive power on voltage fluctuations as well as the feasibility of developing simplified and detailed assessment methodologies.

5.2 RVC Planning Limits & Assessment

For a voltage fluctuation to be classed and assessed as an RVC, it should have the characteristics of an RVC described in clause 4.7 of EREC P28.

RVCs could result from short duration, material power changes caused by BESS operation from one steady state real/reactive power output (or input) to a different real/reactive power steady state output (or input), which gives rise to different steady state voltages.

The following limits within EREC P28 should be applied.

- The limits in Figure 5 of EREC P28 apply to frequent events, where the maximum voltage change of 6% occurs within 100 ms from the start of the event.
- The limits in Figure 6 of EREC P28 apply to infrequent events where the maximum voltage drop of 10% occurs within 100 ms from the start of the event (generally those that occur not more than 4 times per month).
- The limits in Figure 7 apply to very infrequent events where the maximum voltage change of 12% occurs within 100 ms from the start of the event (generally those that occur not more than once every 3 months).

NOTE: In practice for BESS the limit in Figure 6 of EREC P28 is a maximum voltage rise of 6% within a 0.8 s window a voltage drop of 6 % within a 2 s window returning to not more than 3 % after 2 s.

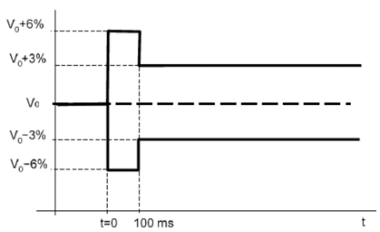


Figure 5

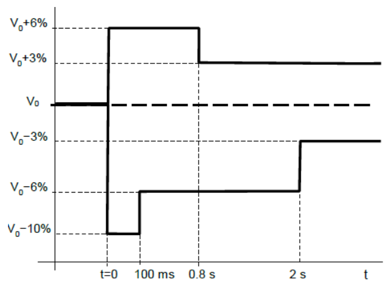


Figure 6

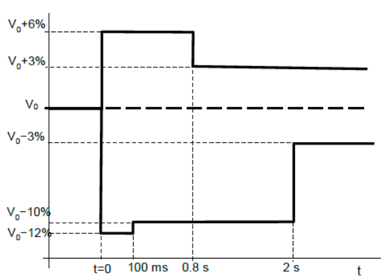


Figure 7

Figure 6 – Replication of Figure 5, 6 and 7 from EREC P28 Issue 2

EREC P28 Issue 1 recognised that the Supply Authority may, at its discretion, allow larger voltage changes than 3 % to occur for continuous process plant where larger motors are only started once in several months. In these cases, EREC P28 Issue 1 required steps to be taken to mitigate the effects by the following.

- Restricting starting to times when system connections were normal.
- Restricting starting to certain hours to minimise the likelihood of disturbance to other customers.
- Liaising with the Supply Authority Control Engineer prior to starting, where reconfiguration of the network to reduce the source impedance could be completed, where necessary.

The limits for RVC in EREC P28 Issue 2 mean that the duration of any fast power change should not be greater than 2 s for a voltage fall or 0.8 s for a voltage rise.

For the effect of a power change event to be considered as being a RVC for at least 1 s before and after the power change event, the voltage change should be ≤ 0.5 % per second, i.e. be at steady-state voltage. Where the BESS is providing frequency response services, and the voltage is constantly changing because of its response, it might be the case that the voltage is never in a steady state condition. If this is the case, the voltage change should be assessed as a step voltage change (see 5.4.1).

A significant RVC could be where the power change would result in a minimum voltage change of say 1.5 % per second. In this case the voltage at the end of the event should be ≤ 3% from the voltage at the start of the event, recognising the voltage change in between can be higher providing it fits within the voltage/time envelope in either Figure 5, Figure 6 or Figure 7 of EREC P28.

BESS operations that are likely to cause an RVC include:

- Energisation of the BESS transformer, where applicable.
- Tripping of the BESS at significant power import or export.
- Fast ramping of BESS power import or export:
  - From zero to full import/export and vice versa (e.g. FR services).
  - Power swing from full import to full export and vice versa (e.g. stacked services or arbitrage service).
- Response to a rapid frequency change ≥ 0.05 Hz/s when providing frequency response services.

NOTE: Fast ramping of BESS power import or export is less likely to produce a voltage change with an RVC characteristic as the X/R ratio of the source impedance reduces.

Ramped power changes over 2 s should not be assessed against the RVC planning limit. These resultant voltage changes should be assessed against the 3 % limit for step voltage change.

For those voltage changes that comply with the definition of a RVC in P28 Issue 2, then the characteristic of the RVC should be compared with the relevant voltage versus time envelopes defined above (see Figures 5-7 of EREC P28). A RVC would be deemed to be compliant with the limits in EREC P28 if its characteristic were to sit within the voltage/time envelope and the frequency of occurrence was to be less than or equal to that relevant to the characteristic in Figures 5-7.

5.3 Flicker Planning Limits & Assessment

5.3.1 Simplified Stage 2 Assessment

Flicker is defined in EREC P28 as the 'impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time'. The note accompanying the definition states that: 'Flicker is the effect on certain types of electric lamps, in particular incandescent lamps, while the electromagnetic phenomenon causing it is referred as voltage fluctuations.'

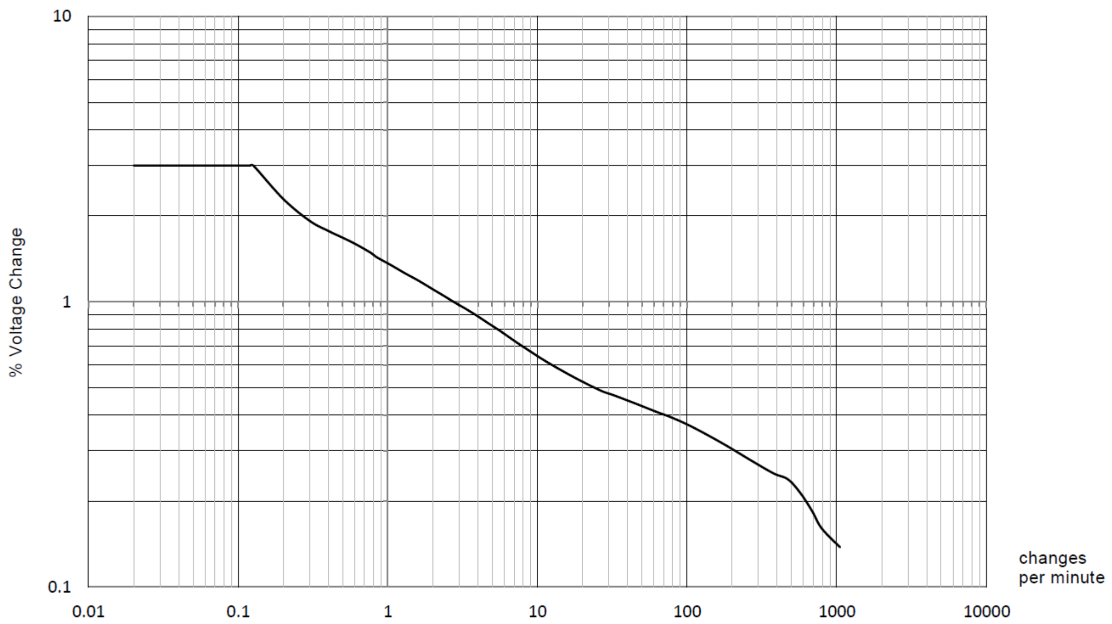
The planning limit for Stage 2 flicker assessment is $P_{st} \leq 0.5$. This applies at the PCC at the minimum fault level for normal operating conditions (the worst case normal operating condition defined in EREC P28). Only the flicker caused by the BESS installation being assessed should be considered. Background flicker or flicker from any other customers' equipment (including any other BESS) does not need to be considered for this Stage 2 assessment.

NOTE: There is no limit for P_{lt} for a Stage 2 assessment, however, this is expected to be less than 0.5 given the limit for P_{st}.

This assessment should be carried out to assess the flicker caused by frequent and repetitive voltage changes. These will be predominantly ramp type voltage changes for BESS.

The following example illustrates a simplified assessment where a BESS operates in the BM and wholesale markets.

The maximum number of voltage changes for a particular magnitude of voltage change occurring in a defined period is defined by the P_{st} = 0.5 curve in Figure B.1.2 of EREC P28 (replicated below).



b) Maximum number of voltage changes per minute

For simplified assessment of flicker, the maximum power change per second for a ramp time of 1 s duration could be determined as follows.

Step 1: From Figure B.1.2 of EREC P28, the maximum step voltage change that can occur every 1 s is ≈ 0.42 %.

Step 2: From Figure B.2.2 of EREC P28 the shape factor (*F*) for a 1 s ramp is 0.2.

Step 3: Using Equation E.1 from PD IEC/TR 61000-3-7 (see below), determine the maximum voltage change to comply with the Stage 2 flicker limit of P_{st} = 0.5.

$$P_{st} = \left(\frac{d}{d_{P_{st}=1}}\right) \times F$$

Where:

$P_{st} = 0.5$

$d_{P_{st}=1} = 0.85$ taken from Figure B.1.1 of EREC P28 for a voltage change every 1 s (60 voltage changes per minute)

$F = 0.2$

Step 4: Substituting in the equation above gives:

$$d = 2.125\ \%$$

Where: *d* is the maximum ramp voltage change per second to comply with the Stage 2 flicker assessment in EREC P28.

Step 5: Using the source impedance (*Z*) at the PCC, for the worst case normal operating condition (as defined in EREC P28), the maximum power change per second for the BESS should be determined that results in a voltage change of 2.125 %.

Step 6: The BESS will be deemed to have passed the Stage 2 assessment of flicker if the permissible maximum change in BESS power import / export does not exceed the limit value determined in Step 5 (as such a power import / export change would need to occur more frequently than once per second to be non-compliant with P28 - this is unlikely to be the case for a BESS operating in the BM or wholesale market).

NOTE: The maximum change in power will also need to include the associated change in reactive power (Q) as well as real power (P) depending upon the agreed pf for BESS operation.

Hence, as illustrated by this example, a simplified assessment of flicker for BESS is believed to be feasible based on stated maximum rates of change of power and minimum ramp times declared by the BESS operator when trading in the BM and wholesale markets.

5.3.2 Detailed Stage 2 Assessment

5.3.2.1 General

A simplified Stage 2 Assessment, as described above, is not suitable where power changes are complex and unpredictable, such as for BESS providing FR services.

In this case, flicker severity should be characterised in detail using an IEC flickermeter conforming to the requirements of IEC 61000-4-15 [17]. This can be integral to the power system modelling and analysis software or it can be standalone, where voltage fluctuation data from the power system model is the input.

The flicker severity should be measured for the typical operating cycle(s) to be carried out by the BESS. Where there is more than one operating cycle, the most onerous operating cycle should be chosen that will result in the highest P_{st} value of flicker severity. Where the most onerous operating cycle is not known, then flicker severity should be determined for each operating cycle and the worst flicker severity determined. The typical operating cycle(s) need to be reflective of a credible range of operational frequencies which may be different where the BESS provides different services e.g. DR, DM and DC.

A BESS providing stacked services will need to be individually assessed for each service it provides. However, consideration should be given to the effect of transitioning between services, including all the credible transitions between the different services, and whether this could materially increase the flicker severity compared with the individual assessments.

The output from the model should be values of P_{st} and P_{lt} for the operating cycle assessed, nominally a 1-week measurement period. However, shorter measurement periods would be valid if it can be shown they represent the worst case for flicker severity. Similarly longer periods may be required where the full range of credible operational response is not observed in the 1-week period.

The BESS will be deemed to have passed the Stage 2 assessment of flicker if all values of P_{st} are assessed to be less than or equal to 0.5.

5.3.2.2 Additional Considerations for Modelling

The most onerous single operating condition that will result in the highest P_{st} value of flicker is likely to be whilst a BESS is providing DR services.

For assessment of flicker, a static model of the power system should be developed based on the information provided by the DNO. This should satisfy the following requirements.

- Include passive plant (i.e. transformers, cables etc.).
- Include active plant (i.e. BESS, BESS Power Park Controller and other forms of Generation).
- Allow the network to be modelled under intact conditions and the worst case normal operating condition.

The BESS Power Park Controller set up in the model should have the same system, elements, and characteristics as those provided by the manufacturer together with the same configurable settings as those to be applied.

The input to the model should be system frequency time-series data, with a maximum interval of 1 s, which represents system frequency variations, nominally over a typical 1-week measurement period, to a probability not less than 95 % in accordance with clause 6.3.1 of P28. Statistical analysis of historic frequency time-series data published by National Grid ESO could validate the data to be used.

This data can either be:

- obtained from historic system frequency time-series data[12], or
- obtained by synthesising time-series data set(s) from historic system frequency data.
- a standard frequency profile covering a week, which is developed/approved by NPg or preferably by DNOs collectively.

It is acceptable for the connectee to carry out a statistical analysis of 1 s frequency data published by National Grid ESO to determine frequency changes under a range of credible operational conditions (in terms of rate of change of frequency and duration) that can be used to assess flicker severity produced by the BESS.

The output from the model should be values of P_{st} and P_{lt} for the assessment period.

The BESS will be deemed to have passed the Stage 2 flicker assessment if all values of P_{st} over the assessment period are less than or equal to 0.5.

It is proposed that resultant voltage fluctuations from a BESS providing DC services should not be assessed when responding to frequency changes outside the range of 49.8 Hz to 50.2

[12] See National Grid ESO System Frequency Portal https://www.nationalgrideso.com/data-portal/system-frequency-data.

Hz given this is classed as a post-fault service, i.e. similar to the conditions set out in clause 6.1.6 of P28.

5.3.3 Detailed Stage 3 Assessment

The planning limits for Stage 3 flicker assessment are stated in Table 2 of EREC P28 (replicated in Table 1 below). The value of the limit depends upon the supply system nominal voltage at the PCC. For this assessment, the background flicker at the PCC, which should be provided by the DNO, needs to be taken into account.

Table 1 – Replication of Table 2 Planning Levels for Flicker [EREC P28]

Supply system Nominal voltage	Planning level	
	P_{st}	P_{lt}
LV	1.0	0.8
3.3 kV, 6.6 kV, 11 kV, 20 kV, 33 kV	0.9	0.7
66 kV, 110 kV, 132 kV, 150 kV, 200 kV, 220 kV, 275 kV, 400 kV	0.8	0.6
NOTE 1: Planning levels for LV connections are equal to compatibility levels. NOTE 2: The magnitude of P_{st} is linear with respect to the magnitude of the voltage changes giving rise to it. NOTE 3: Extreme caution is advised in allowing any excursions of P_{st} and P_{lt} above the planning level.		

The planning limit applies at the PCC at the minimum fault level for the worst case normal operating conditions).

It is not deemed feasible to carry out a simplified Stage 3 assessment of flicker.

Where the BESS does not pass the Stage 2 assessment of flicker then it should be subject to a Stage 3 assessment in the same manner as Stage 2 but taking into account background flicker at the PCC. The background P_{st} and P_{lt} data for the PCC should be provided by the DNO.

Where the network does not contain another BESS installation then, due to the randomness of the BESS voltage fluctuations interacting with voltage fluctuations from other disturbing equipment connected to the same network, the worst case P_{st} from the BESS should be summated with the worst case background P_{st} using Equation 1 in EREC P28 with a summation exponent of $\alpha = 3$.

NOTE: Table 8 of EREC P28 describes the application of each summation exponent between 1 and 4.

Where one or more BESS providing FR services are connected to the PCC then the worst case P_{st} from each BESS should be summated using Equation 1 in EREC P28. In the absence of any contrary data about the degree of coincidence then it should be assumed, in the first instance, that voltage fluctuations are coincident and a summation exponent of $\alpha = 1$ should be used, i.e. directly added together.

Where one or more BESS providing FR services are connected to the same network then the worst case P_{st} from each BESS should be summated using Equation 1 in EREC P28. In the absence of any contrary data about the degree of coincidence then it should be assumed, in the first instance, that voltage fluctuations are coincident and a summation exponent of α = 1 should be used, i.e. directly added together.

Where the BESS is providing BM or arbitrage services, it is reasonable to assume that the voltage fluctuations are not coincident with the BESS providing FR services hence a summation exponent of α = 3 would be appropriate.

The BESS will be deemed to have passed the Stage 3 assessment of flicker if the summated P_{st} value at the PCC is less than or equal to the appropriate limits from Table 2 in EREC P28.

Where the BESS installation does not pass the Stage 3 assessment then flicker reduction options should be considered, including:

- reducing BESS power ramp rates and/or reducing the number of power changes over each 10-minute measurement period;
- conducting more detailed studies of the coincidence of voltage fluctuations for the BESS installations and, where necessary, verifying whether the summation coefficient of α = 1 is correct;
- reducing the import/export capacity of the BESS.

5.4 Step Voltage Change Planning Limits & Assessment

5.4.1 General

By virtue of the definition in EREC P28 Issue 2, Step Voltage Change is the resultant voltage change after all generating unit AVR and SVC actions have taken place but before any automatic or manual tap-changing actions have commenced within the observation period.

NOTE 1: The definition of step voltage change in EREC P28 does not require the voltage be in steady state at the beginning or end of the observation period. This is important for assessment of BESS providing FR services, where the voltage might not be in a steady state condition for much of the time.

NOTE 2: The term ‘generating unit AVR’ is used for synchronous machines but the term ‘voltage controller’ is used for inverter connected generation such as a BESS, which is something that should be made clear in the guidance in EREP 28. See section 5.5 for discussion on controllers.

The definition of step voltage change from EREC P28 Issue 2 and the relevant reference to step voltage change in DPC4.2.3.3 of the GB DCode has been replicated below for context.

3.32
step voltage change
change from the initial voltage level to the resulting voltage level after all generating unit automatic voltage regulator (AVR) and static VAR compensator (SVC) actions and transient decay (typically 5 seconds after the fault clearance or system switching) have taken place, but before any other automatic or manual tap-changing and switching actions have commenced

NOTE 1: Automatic voltage regulator also applies to other similar fast acting voltage control responses, e.g. associated with power park modules, HVDC voltage control responses.

NOTE 2: For the purposes of this EREC, percentage step voltage change is the value of step voltage change in volts expressed as percentage change of the nominal system voltage (V_n).

NOTE 3: Step voltage change can be equivalent to the steady state voltage change ($\Delta V_{steadystate}$) (see 4.6).

NOTE 4: By virtue of this definition, a ramped voltage change can be a form of step voltage change and subject to the limit in Clause 5.4.

NOTE 5: Step voltage changes can occur as a result of switching on the system, a fault or operation of disturbing equipment that produces an instantaneous change in steady state voltage.

[Similar to definition in DPC4.2.3.3 of the GB Distribution Code [2]].

DPC4.2.3.3 Voltage Step Changes

For voltage step changes caused by the connection and disconnection of **User**'s **Equipment** or **Customer**'s **Demand** to the **DNO's Distribution System**, a general limit of ±3% applies in accordance with Engineering Recommendation P28 Issue 2.

Although not explicitly stated in EREC P28, it has been inferred that the maximum voltage change caused by BESS operation within this observation period, before the tap-changer operates, should not exceed 3 % of the nominal system voltage (V_n). when measured at the PCC. This is the planning limit for step voltage change.

A limit of 3 % needs to be imposed to minimise the risk of unacceptably low or high voltages for other customers connected to the same network until the relevant tap-changer operates at the end of the observation period to bring the network voltage back within limits.

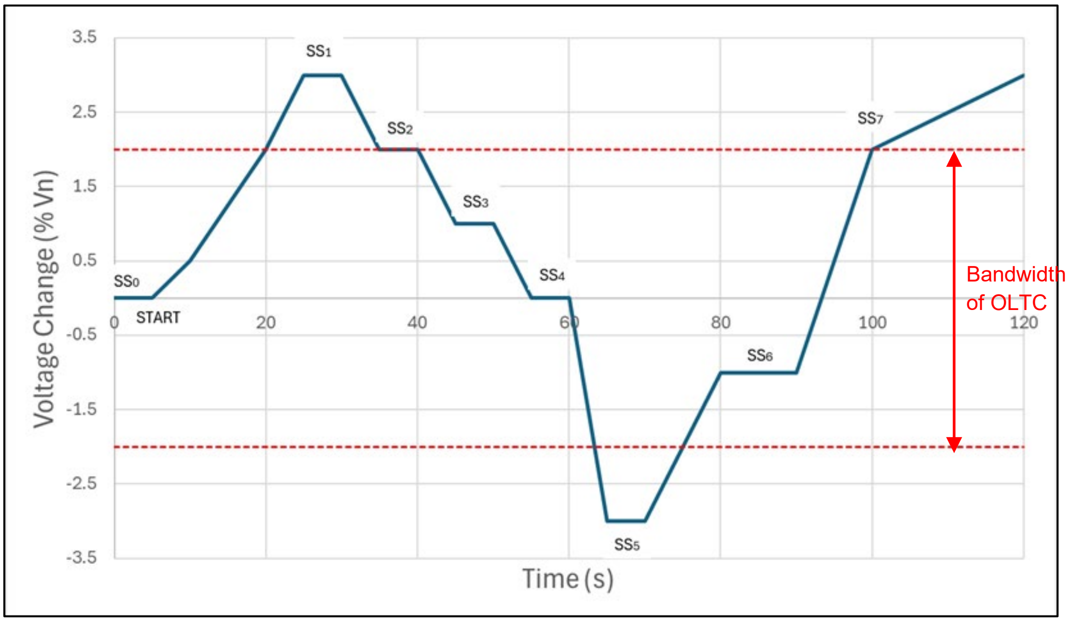


Figure 7 – Example of BESS Voltage Changes

NOTE 1: The observation period in Figure 7 has been chosen to be 120 s to align with the initial tap delay and operation time of the nearest upstream tap-changer.

NOTE 2: The voltage does not necessarily need to be in steady state at the START and END of each observation period.

The observation periods, to align with the AVC and tap-changer time delays, should be determined as follows:

- POC at 132 kV: As advised by the relevant Transmission Owner for 275/400 kV tap-changers.
- POC at 66 kV: 90 s for 132 kV tap-changers.
- POC at 33 kV: 90 s for 132 kV or 66 kV tap-changers.
- POC at 11 kV: 120 s for 33 kV tap-changers.

NOTE: The AVC and tap-changer time delays can differ from those general time delays above for specific substations. These can be found in NPg policy document IMP/001/915 [27].

The observation periods above reflect the typical initial tap delay and operation time of the relevant upstream tap-changer. Alternatively, a default observation period of say 120 s could be used to avoid the need to state specific initial tap delays. This would simplify the assessment slightly.

From the example in Figure 7:

- The observation period is 120 s.
- The change in steady state voltage between the START and END of the observation period is +3.0 %, i.e. within the 3 % limit.

- The maximum step voltage change between steady state voltages (V_{ss}) during the observation period is 3.0 %, i.e. SS_0 – SS_1, i.e. within the 3 % limit.
- The maximum voltage change (ΔV_{max}) during the observation period is 6.0 %, i.e. SS_1 – SS_5, i.e. greater than the 3 % limit.
- The maximum change in steady state voltage (ΔV_{ss}) during the observation period is +6.0 %, i.e. SS_1 – SS_5, i.e. greater than the 3% limit.

In summary, a BESS exhibiting the voltage changes in Figure 7 should be deemed to be non-compliant with the step voltage change limit of 3 %.

The completion of a tap-changer operation should signify the commencement of a new observation period.

When determining the step voltage change caused by a BESS power swing, within a power system model, the taps of any tap-changer should be locked or the AVC should be disabled where the modelled power change takes place in a shorter time period than the automatic tap-changer operation.

NOTE: This is to replicate the actual conditions.

An alternative assessment method based on power ramp rates is stated later in this Report. This considers the maximum rate of change of system frequency determined by the minimum system inertia.

5.4.2 IEC Voltage Limits for Rotating Electrical Machines

IEC 60034-1 [26] includes requirements for the rating and performance of rotating electrical machines, i.e. motors and generators.

An extract of Figure 11 and Figure 12 from IEC 60034-1 is shown below in Figure 8.

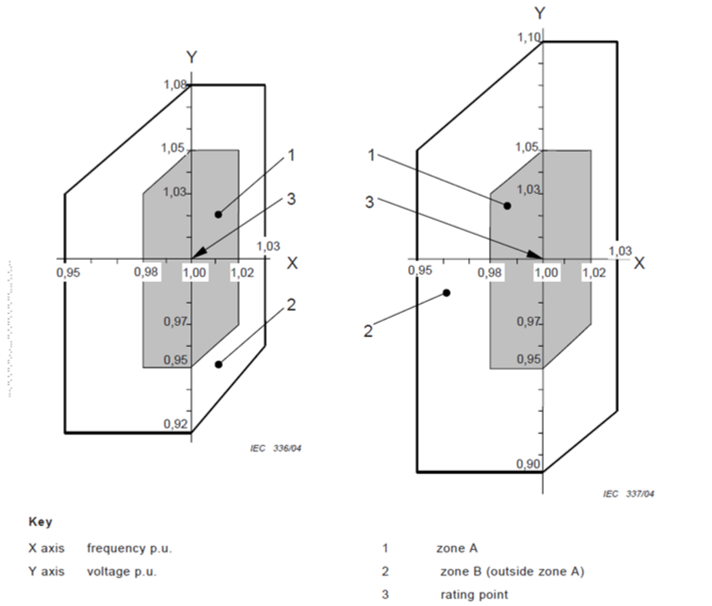


Figure 11 – Voltage and frequency limits for generators

Figure 12 – Voltage and frequency limits for motors

Figure 8 — Voltage and Frequency Limits for Generators and Motors

Figure 8 shows that the normal and extended operating zone of motors/generators are tightly defined - 5 % for normal operation (zone A) and up to 10 % for extended operation (zone B).

In the scenario where the voltage at the terminals of an LV motor was already at or near the statutory limit of -6 %, then a 3 % step voltage change (e.g. reduction) on the distribution network could result in the voltage at the terminals of the motor falling to -9 % for a short period of time. This is close to the -10 % voltage limit of the extended 'zone B' operating range of the motor, where potentially the motor could stall. Similarly, older motor control circuits, operated and protected with contactor closing coils and fuses, could potentially 'chatter' and drop out. These effects would be a major nuisance to any industrial plant.

Impinging on the voltage limits of motors as a result of step voltage changes > 3 % is a concern.

5.5 Effect of Reactive Power on Voltage

5.5.1 General

ENA EREC G99 [10] sets out requirements for automatic control of generating units connected to distribution networks. The relevant sections of G99 are as follows.

- Section 13.4.4: This section sets out the voltage control performance requirements for Type C and Type D Power Park Modules (PPM).
- Section 13.5: This section sets out the reactive power capability of Type C and Type D generating units and PPM.

- Section C.5: This section sets out performance requirements for continuously acting AVC systems for Type C and Type D PPMs.

In GB, a PPM compliant with G99 must have the capability to operate in the following three control modes:

- Constant power factor mode.
- Constant reactive power mode.
- Voltage control mode.

BESS voltage controllers for Type C and Type D PPMs need to comply with G99.

This section of the Report considers the effect of reactive power when a BESS operates in voltage control mode, as this mode is potentially the most effective to reduce voltage fluctuations caused by BESS operation. In particular, whether this affects the assessment of the three categories of voltage fluctuations associated with BESS operation. In this context voltage control means operating on a Q/V slope with a defined target voltage and slope setting.

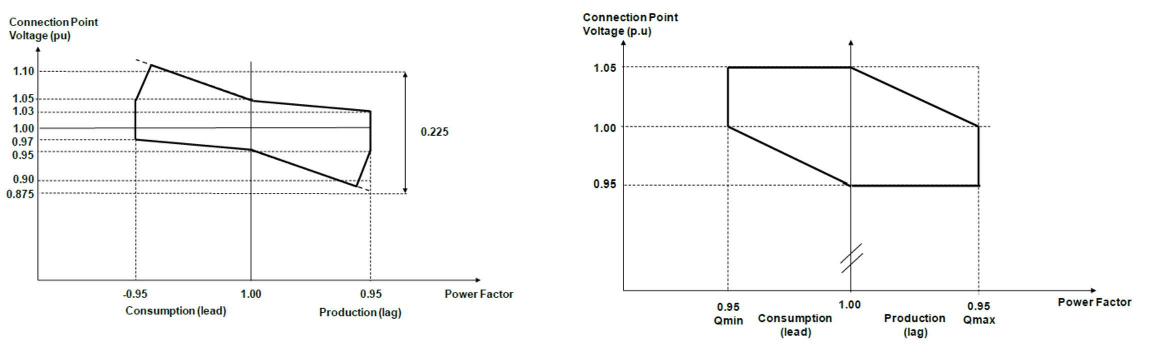
5.5.2 EREC G99 Voltage Control Requirements

This section applies to Type C (>10 MW) and Type D (>50 MW) Power Generating Modules.

EREC G99 [10] (subsequently referred to as 'G99') requires each PPM to be fitted with continuously acting automatic control systems for voltage control at the POC.

G99 provides guidance on the operating range and initial setpoint. Allowance is made for site specific requirements at the DNO's discretion.

Figure 9 displays the required envelope of operation for PPM connected above 33 kV and at/below 33 kV.



Reactive Power capability requirements (PPM operating at Registered Capacity, voltage above 33 kV)

Reactive Power capability requirements (PPM operating at Registered Capacity, voltage at or below 33 kV)

Figure 9 – Q/V Curve from EREC G99

The enclosed area is the required capability range within which the slope and setpoint voltage can be set. Figure 10 illustrates the slope characteristic for a PPM operating at or below 33 kV.

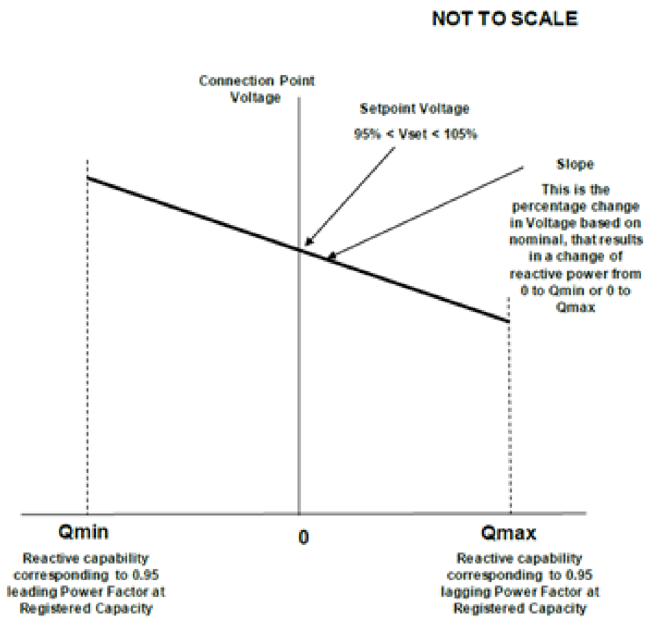


Figure 10 – Setpoint Voltage and Slope Characteristic

The automatic control system should be capable of operating to a setpoint voltage between 95 % and 105 % with a tolerance of 0.25 %, e.g. using a setpoint voltage of 100 %, the achieved value shall be between 99.75 % and 100.25 %.

The slope characteristic should be adjustable over the range 2 % to 7 % with a resolution of 0.5 %, i.e. values of 2 %, 2.5 % etc. are acceptable.

G99 specifies an initial slope setting of 4 % with a 0.5 % tolerance. G99 provides a range of voltage slope settings and allows individual DNOs to set the criteria. The range 2 % - 7 % means that the 4 % described in section 5.5.3 would meet the requirements.

The Q/V curve in G99 is based on POC (voltage) and instantaneous reactive power. It does not differentiate between active power export and active power import.

NOTE: The Q/V curves in G99 are only applicable when the PGM is exporting. The application of these curves for importing would need to be specifically requested by the DNO for BESS operation.

G99 defines the speed of response required whilst operating in voltage control mode.

Most DG in GB operates in constant power factor mode set at a fixed power factor, but can be setup to operate in the other two modes. Operating in voltage control mode can be used to mitigate against voltage fluctuations caused by changes in active power. The definition of 'step voltage change' in P28 includes allowance for a generating unit's AVR to act. With a

BESS this is its voltage controller and it can react instantaneously by modulating reactive power. Using reactive power to control voltage is generally more feasible at 33 kV and above where system X/R ratios are higher.

5.5.3 What is Voltage Control Mode

In voltage control mode the BESS PPM controller regulates the BESS output terminal voltage within close tolerance of a voltage set point. The voltage set point (or desired voltage) can be set in the controller. This is generally set as a per unit value of the nominal system voltage.

The BESS output terminal voltage is influenced by variations in grid voltage as well as the real power (P) and reactive power (Q) being exported or imported by the BESS.

The voltage at the BESS output terminals (or other agreed control point such as the point of connection) is measured against the voltage set point and varied accordingly by the BESS either importing reactive power or exporting reactive power. This is a feedback loop in the controller.

Reactive power is measured in VArs or MVArs.

Exporting reactive power tends to increase the terminal voltage whilst importing reactive power tends to decrease the terminal voltage.

5.5.4 Relationship between Q and V Capability

QV curves are essential tools for analysing the reactive power capability of generating plant, including BESS. These curves provide valuable information about the plant's ability to inject or absorb reactive power, which is crucial for maintaining voltage stability on the grid.

The QV curve, also known as the voltage-reactive power curve, represents the relationship between voltage (V) and reactive power (Q) that the plant can deliver at a given real power output.

Examples of QV curves are shown in Figure 11 and Figure 12.

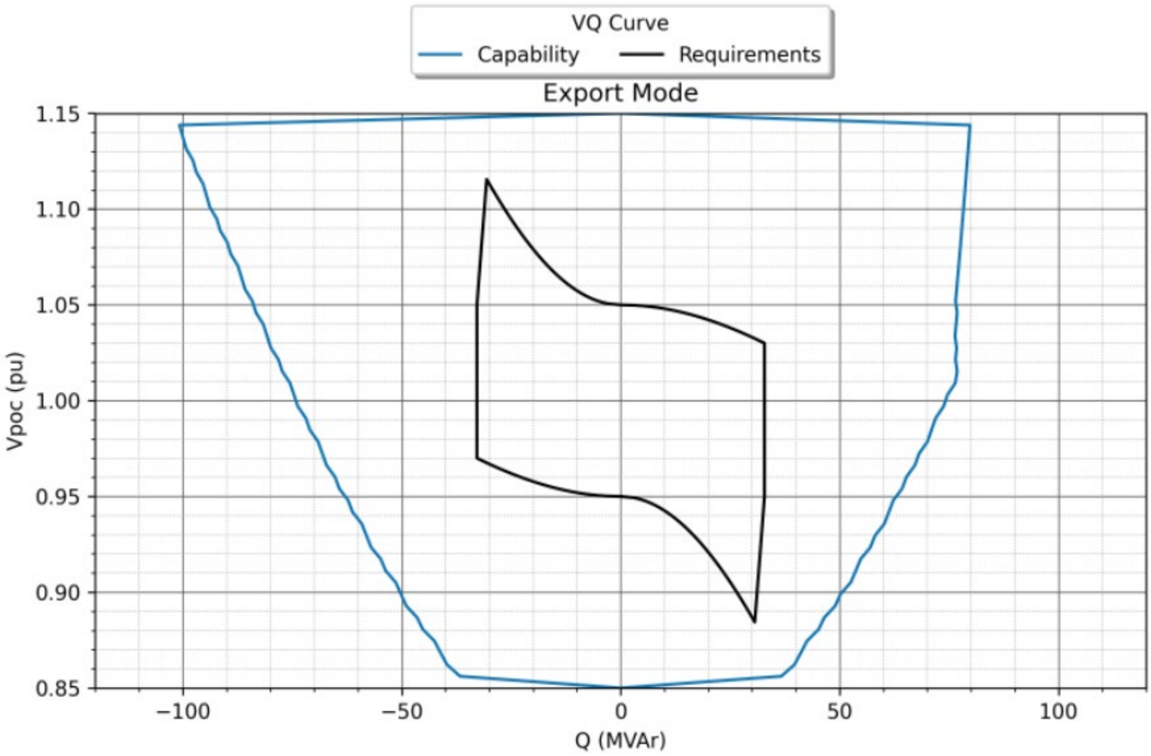


Figure 11 – Example of a QV Curve for a Generator or BESS in Power Export Mode

NOTE: The 'Requirement' curve relates to the performance required by the plant owner/operator in their contract with the manufacturer/supplier, which should be within the capability curve of the equipment specified by the manufacturer/supplier.

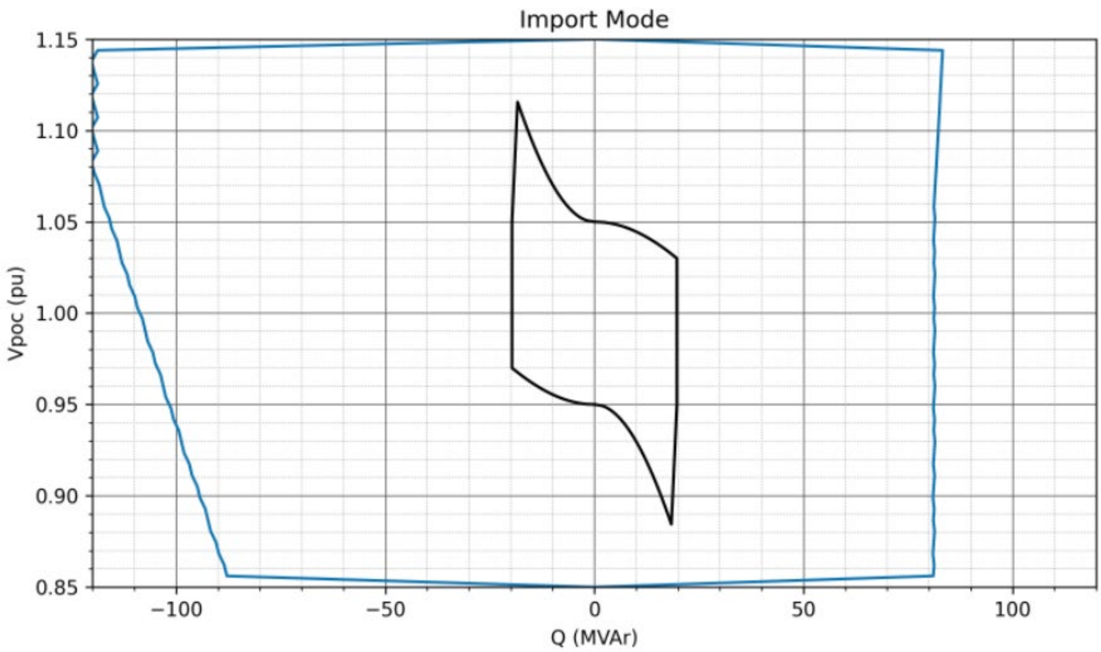


Figure 12 –Example of a QV Curve for a BESS in Power Import Mode

NOTE: EREC G99 does not require BESS to have an Import Mode capability for Q. However, BESS plant will typically have a similar capability to that when in export/generation mode when in import/load mode.

The QV curve provides several important pieces of information about the BESS's ability to regulate voltage.

- The range of voltages over which the BESS can provide reactive power support.
- The amount of reactive power that the BESS can inject or absorb at specific voltage levels.
- The BESS's ability to maintain voltage stability during voltage fluctuations.
- The BESS's ability to provide more reactive power support at lower voltages.

The QV curves are influenced by the size and configuration of the BESS, as well as the inverter control setting.

NOTE: Inverter manufacturers publish QP and QV performance curves, with reference to the inverter's LV terminal voltage: usually 400, 480 or 690 V. This, combined with the collective impedances of the electrical balance of plant: cables and transformers etc., will determine the PQ and QV capability at the connection point which is typically at HV above. The BESS Power Park Controller measures Q and V at the connection point and continuously sends Q setpoints to the individual inverters so as to make the whole PPM behave as it if were a single unit and hence allow it to operate on the linear Q/V slope.

5.5.5 Q/V Slope Setting

Because the capacity of a BESS will typically be small compared with the fault level of the network, it is not generally appropriate to control the POC voltage using a BESS operating in voltage control mode with a target set point voltage. This is because the BESS, as it tries to maintain the voltage at the target value would tend to operate at full reactive power capacity for most of the time. In a worst-case situation, the reactive power could oscillate between full import and full export if the measured voltage oscillates around the target voltage. Such a scenario could be exacerbated where multiple BESS's operating in voltage control mode, connected to electrically adjacent parts of the network, could interact with each other if the controllers were not co-ordinated in some way.

It is typical to control reactive power import/export based on a voltage target set point at the POC and a reactive power slope (referred to as the Q/V slope). This type of control is otherwise known as voltage droop control.

Figure 13 illustrates voltage droop control with a 4 % slope setting, where the Power Generating Module has a maximum/minimum Q capability equivalent to 0.95 power factor lagging (exporting Q) and leading (importing Q). A power factor of 0.95 equates to a Q_{max} and Q_{min} = 32 % of P_{max}). This effectively imposes a limit on the amount of Q that can be imported/exported by the BESS.

The diagram illustrates that if the terminal voltage rises, the Power Generating Module will absorb reactive power and hence tend to lower the terminal voltage.

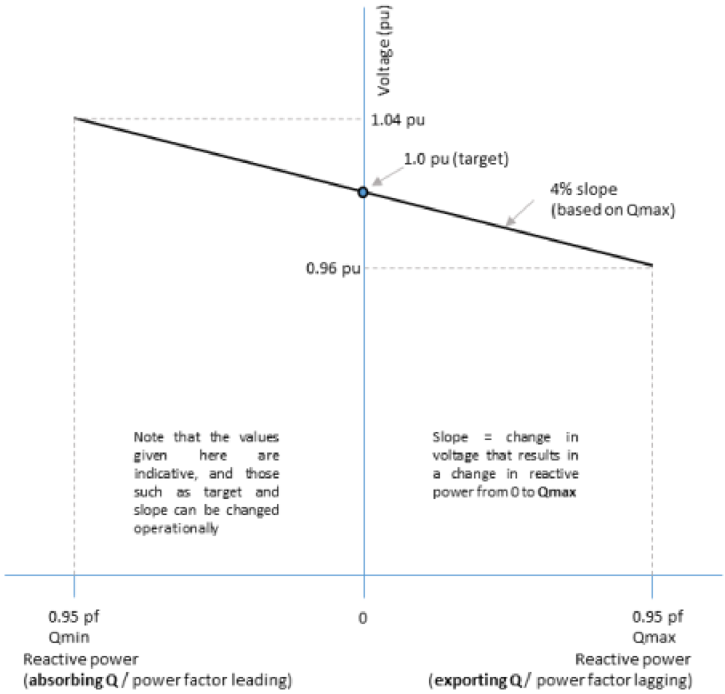


Figure 13 –Example of a Q/V Slope Curve

In relation to a BESS, a 4 % slope setting represents:

- A variation in BESS reactive power from Q = 0 to Q_{min} (import) for a 4 % rise above the target voltage.
- A variation in BESS reactive power from Q = 0 to Q_{max} (export) for a 4 % fall below the target voltage.

5.5.6 Effects

To date, most DNOs in England and Wales have not permitted BESS to operate in voltage control mode due to the complex and unknown interaction of the BESS power park controller with the DNOs' own AVC equipment and other distributed generation controllers. There are concerns that:

- controllers could 'fight' each other in a feedback loop;
- the implementation of BESS voltage control could result in older AVC equipment needing to be replaced. The risk is believed to be higher in lower voltage networks.

It is known that the operation of AVC schemes involving the following would be affected.

- Negative reactance compounding methods
  - These methods are sensitive to power factor, where the controlled voltage rises or falls as the power factor becomes more leading or lagging with respect to that power factor assumed when calculating the AVC relay settings.

- Load Drop Compensation (LDC) - where the BESS exported power could appear to reduce the actual network demand, which would still cause volt drop, but which would become uncompensated.
    - According to ETR 126 [12], most LDC schemes operate by using a single CT, on the LV side of each transformer in the substation, to give an indication of the total demand on the substation. The output from the LDC CT is fed into the LDC scheme. This current is applied to a simple $R+jX$ model of the substation circuits which in turn determines the level of voltage change required at the substation low voltage busbar to cater for the voltage drop down each circuit.
    - When a circuit containing a significant amount of DG exports back to the source substation it effectively cancels out some or all of the demand on the other circuits. This can lead to incorrect operation of the LDC scheme, e.g. the LDC scheme will be calling for a lowering of bus bar voltage during periods of high network demand.
    - Thus, it is necessary to either remove the LDC scheme or apply a 'Cancellation CT' scheme. The principle of the cancellation CT solution is to supply the LDC system with a reversed current contribution from the circuit that contains a significant amount of DG, i.e. the energy contribution from the DG plant to other circuits is considered by the LDC scheme.

In the case of AVC schemes with negative reactance compounding, the import or export of Q from the BESS into the local network could affect the difference in pf between the transformers running in parallel and controlled by the AVC relay. The result could be higher circulating current between the transformers and the required output voltage not being maintained at the required voltage. It is known that this effect can be compensated for in modern AVC relays, such as the Fundamentals Super TAPP relay. However, replacement of older AVC schemes, which do not have this compensation, might be required.

In addition, there might be a small increase in the risk of island operation of BESS. This is because, where a BESS has the capability to control the terminal voltage and hence the voltage on an islanded network, there is a higher risk that under voltage / over voltage G99 protection would not operate and an island may not be detected.

One DNO has stated that it specifies a nominal Q/V slope of 4 % and that this setting might need to be adjusted on site considering actual operation. An underlying issue is the difficulty of modelling a generator/BESS in voltage control mode, hence a trial and error approach in determining the slope setting might be the most pragmatic solution. The slightly 'hit and miss' nature of establishing this setting is undesirable when assessing the acceptability of a connection.

A BESS that is operating in voltage control mode may effectively mitigate voltage changes at the output terminals caused by changes in real power (P) by locally exporting/importing reactive power (Q). Indeed, theoretically, it should be possible, depending on the reactive power import/export capability, to maintain a constant voltage at the terminals / connection point for any change in real power (P) by the BESS. However, voltage control based on Q/V mode operation becomes less effective on systems with lower X/R ratios (see section 5.5.8).

The voltage drop for a particular increase in imported P can be mitigated by exporting more Q. Similarly, the degree of voltage rise for a particular increase in exported P can be mitigated by importing more Q.

For voltage droop control the amount of Q import and export is limited by the capability of the BESS. However, Type C and Type D BESS need to have the capability of providing voltage droop control with a reactive power capability between +/-0.33 of Q/Pmax down to 20% of the plant's Registered Capacity as shown in Figure 13.14 of G99 [10] (equivalent to 0.95 leading to 0.95 lagging power factor at Registered Capacity).

5.5.7 DNO Experience of Voltage Control

National Grid ESO and UKPN are running an innovation project[13] that provides opportunities for DER participants, including BESS operators, to provide new services to support the electricity transmission system in the South-East of England. This includes providing reactive and active power services. The project trials are targeted at DER connected at 33 kV or above with an import / export capacity of ≥1 MW. To participate, a BESS would need to control its active power and/or the reactive power generated or absorbed.

To provide a reactive power service the BESS is required to use voltage droop control.

For the active power service, a BESS is required to ramp active power up or down within the BESS's ramp rate capability. For the reactive power service a BESS is required to move the operating point 90 % of the possible change from full lead (importing reactive power) to full lag (exporting reactive power) within 2 s.

5.5.8 Assessment of Voltage Fluctuation Caused by Q/V Slope Control

Operating a BESS in voltage droop control mode is intended to reduce the magnitude of the voltage change associated with a given real power change. It should not affect the frequency of voltage changes. In this case it will affect the assessment of all three categories of voltage fluctuations within the scope of EREC P28.

For a BESS providing FR services the magnitude of the real power (P) imported/exported by the BESS is determined by the system frequency. The injection or absorption of Q from the BESS does not affect the system frequency or changes in P.

For systems with large X/R ratios and high fault levels, the voltage is almost entirely dependent on Q and is not influenced by changes in P. The relative impact of changes in P on voltage change increases for systems with lower X/R ratios, i.e. 'weaker' systems, where

[13] The Power Potential Project – A technical guide to the services for synchronous and non-synchronous DER participants.

changes in Q have less of an effect. In practice at 132 kV and 33 kV voltage levels, both active power and reactive power affect system voltage.

The relationship between voltage across a system impedance, in terms of X, R, P and Q is governed by the following equations:

$\Delta V = (RP+XQ)/V$ Equation 1

$\delta V = (XP-RQ)/V$ Equation 2

Where the relationship between E, ΔV and δV are shown in Figure 14 below.

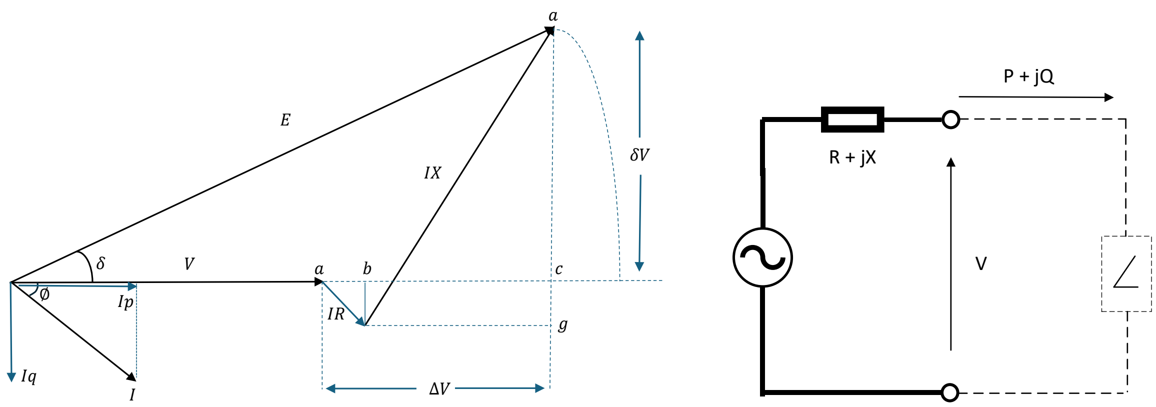


Figure 14 – Phasor Diagram for Power Transfer and Voltage Across a System Impedance[14]

It is apparent from Equation 1 and Equation 2 above that the voltage difference across a system impedance will be increasingly dependent on the value of Q as the X/R ratio increases. Generally, as R is small compared with X, ΔV tends to predominate.

A reasonable starting point for assessment is to assume that there are no other system voltage changes, i.e. the voltage at the PCC only changes due to the import or export of P and Q to / from the BESS. In this case, the BESS controller will react to changes in voltage caused by importing or exporting P and/or Q, where the magnitude of Q is determined from the agreed Q/V slope curve.

For P28 step voltage assessment, it is envisaged that the maximum voltage change could be determined at the PCC, assuming no voltage control and unity power factor for the following scenarios:

- Full export of P to 0 MW (ramping down active power - voltage fall)
- 0 MW to full import of P (ramping up active power - voltage fall)

[14] Reference: Figure 2.22 from Electric Power Systems, B.M. Weedy, Third Edition Revised.

- Full import of P to 0 MW (ramping down active power – voltage rise)
- 0 MW to full export of P (ramping up active power – voltage rise)

Then based on the value of maximum voltage rise or voltage fall determined at the PCC for the above scenarios, select the value of Q that would completely offset the voltage rise / fall from the Q/V slope. This might be more than the maximum value of Q.

Then based on the value of Q selected, determine the resultant voltage change caused by the import/export of Q for the above scenarios.

The assumption that would need to be made is that the response time of the reactive power support is instantaneous so that the maximum voltage change is equal to the voltage change caused by P minus the voltage change caused by Q. The advantage is that this would avoid having to carry out a dynamic study of voltage.

It is expected that voltage droop control, when applied, would impact the assessment of step voltage change and rapid voltage change. It is expected that flicker would not need to be assessed differently than at present, where changes in P at unity power factor are assessed.

A P28 assessment (assuming the BESS operates in power factor control mode with a unity power factor set point) would establish the voltage change at the PCC caused by the change in active power. Because there is no Q being generated or absorbed by the BESS, the change in voltage is directly proportional to the active power change. This voltage change needs to be limited to no more than 3 % for a worst case power swing from full export to full import or vice versa. If the voltage change is greater than 3 % under these circumstances, then the allowable maximum P (import and export) needs to be constrained.

For other than unity power factor set points, the BESS controller adjusts the reactive power in response to changes in active power to maintain the pf at its set point. As the pf is fixed, the ratio of P/Q is a fixed value. Therefore, the change in reactive power is directly proportional to active power. That is not to say the resultant voltage change will be linear. This makes simplified assessment more difficult.

If the BESS exports P then the voltage at the busbar will rise. The rise in voltage can be reduced if the BESS is operated to import Q i.e. leading pf. Power factor conventions are shown in Figure 15.

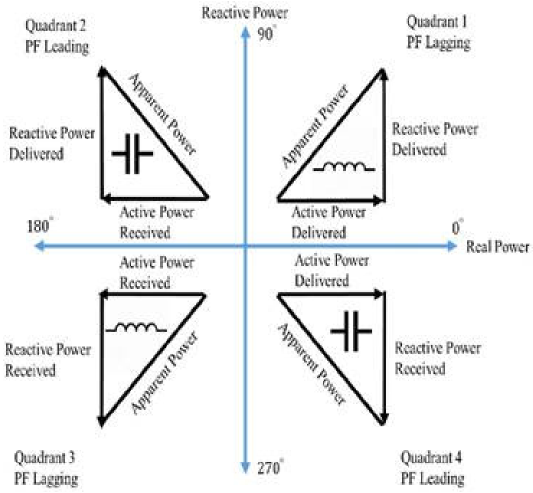


Figure 15 – PF Conventions

In the case of a power change resulting in voltage rise, the reduction in the rise of voltage is dependent upon the X/R ratio of the source impedance - the higher the X/R ratio the greater the effect of Q on reducing the voltage rise.

5.5.8.1 National Grid ESO Frequency Response Service Requirements

For BESS connected at transmission or distribution, the BESS ramp rate will differ depending on the size of the service contracted.

National Grid ESO requires ramp rates not to exceed 5 % of the contracted quantity per minute, when a BESS is acting in the opposite direction to the response contract (i.e. for DC, DM or DR). Slower ramping in this state is intended to keep the grid stable.

When stacking the three different types of frequency services (DR, DM, DC), this maximum ramp rate, for actions in the opposite direction to the response contract, will be 5 % of the sum of the maximum capacity of all the stacked services.

100MW unit	100MW unit
100MW contracted	10MW contracted
5MW/min ramp limit applied to 100MW	0.5MW/min ramp limit applied to 100MW
20m to achieve full recovery/delivery	200mins (3h 20m) to achieve full recovery/delivery

Figure 16 – National Grid Ramp Rates for Dynamic Response Services[15]

[15] Source: National Grid ESO, New Dynamic Response Services Provider Guidance, v.6 January 2024.

5.6 Methodology for Assessing Voltage Fluctuations Associated with BESS

5.6.1 General

This section provides a commentary on the feasibility of developing i) a simplified and ii) a detailed methodology for establishing each of the three types of voltage fluctuations associated with BESS operation where it operates in three distinct modes, National Grid ESO FR services, BM, arbitrage and wholesale markets.

5.6.2 FR Services

System frequency generally changes relatively slowly over time in the form of small ramp changes. Consequently, BESS that provide FR services track the frequency and produce corresponding ramps of power change and hence the associated voltage change.

The maximum rate of change of system frequency is determined by the change in power connected to or disconnected from the system and the system inertia. The FRCR Report [24] produced annually by National Grid ESO determines the worst case change in frequency for a given power change for the stated minimum system inertia. The FRCR Report for 2022 states that, for a minimum system inertia of 140 GVAs, the system frequency change is limited to no more than 0.125 Hz/s for a loss of 700 MW. In summary, the frequency change of 0.125 Hz/s can be seen as the maximum permissible frequency change.

When the system frequency is in the ‘deadband’ for frequency response (i.e. 50 Hz ±0.015 Hz) no frequency response is required.

Historical frequency time-series data shows that for the vast majority of the time the system frequency will be in the band 49.9 Hz to 50.1 Hz[16]. In this band, the maximum response for BESS providing FR services can be determined from Figure 17 below.

[16] Reference: Statistical analysis of monthly 1 s frequency data published by National Grid ESO.

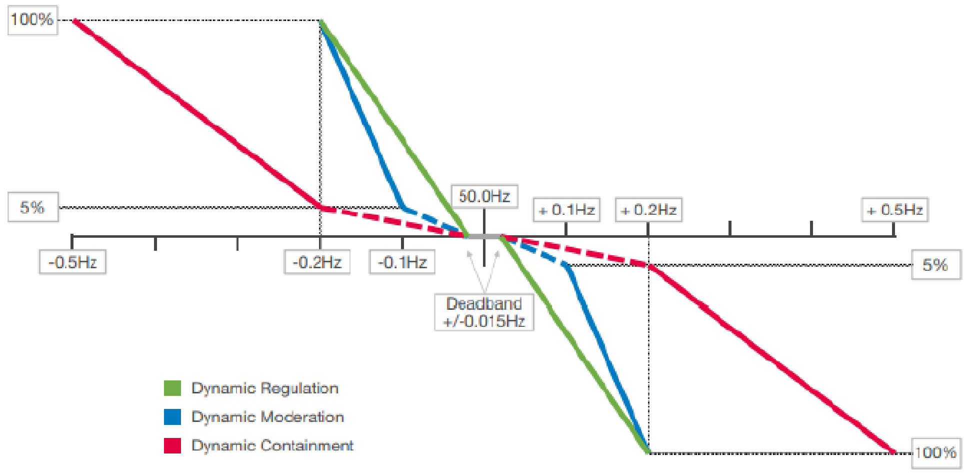


Figure 17 – Frequency Response Delivery Requirement Curves

NOTE: The dashed lines represent a lesser response.

If we take the maximum system frequency change of 0.125 Hz/s and assume a worst case that the BESS ramps power up and down between 49.9 Hz and 50.1 Hz then, at the maximum rate of frequency change, the minimum ramp time would be 1.6 s. With reference to Figure 17, the resultant power changes for this frequency change can be determined.

- For BESS providing DR, this would equate to a maximum change of 91.89% of contracted power.
- For BESS providing DM, this would equate to a maximum change of 10% of contracted power.
- For BESS providing DC, this would equate to a maximum change of 4.59% of contracted power.

It is clear from the above, that the worst case flicker in this frequency band would be caused by BESS providing a DR service. Both DC and DM services provide a lesser response in this frequency band.

A simplified assessment of flicker is described below, where the power change and hence voltage change is limited by the maximum permissible change in system frequency as set out in the FRCR.

For a Stage 2 flicker assessment using the P_{st} = 0.5 curve in Figure B.1.2 of EREC P28 (replicated in Figure 18 below) then the maximum permitted step voltage change for a 1.6 s ramp time (approximately 37.5 voltage changes per minute) would equate to ≈ 0.45 %.

For a Stage 3 flicker assessment using the P_{st} = 1.0 curve in Figure B.1.1 of EREC P28 then the maximum permitted voltage step change for a 1.6 s ramp time (37.5 voltage changes per minute) would equate to ≈ 0.9 %.

The following example illustrates the application of a simplified assessment based on the analysis of the data from Site A BESS, where the highest rate of frequency change observed in each 24 hour period of data was 0.022 Hz/s. This would equate to a minimum ramp time of 9 s.

In this case:

- For a Stage 2 assessment using the P_{st} = 0.5 curve in Figure B.1.2 of EREC P28 then the maximum permitted step voltage change every 9 s (≈ 7 times per minute) would be ≈ 0.75 %.
- For a Stage 3 assessment using the P_{st}=1.0 curve in Figure B.1.1 of EREC P28 then the maximum permitted step voltage change every 9 s (≈ 7 times per minute) would be ≈ 1.5 %.

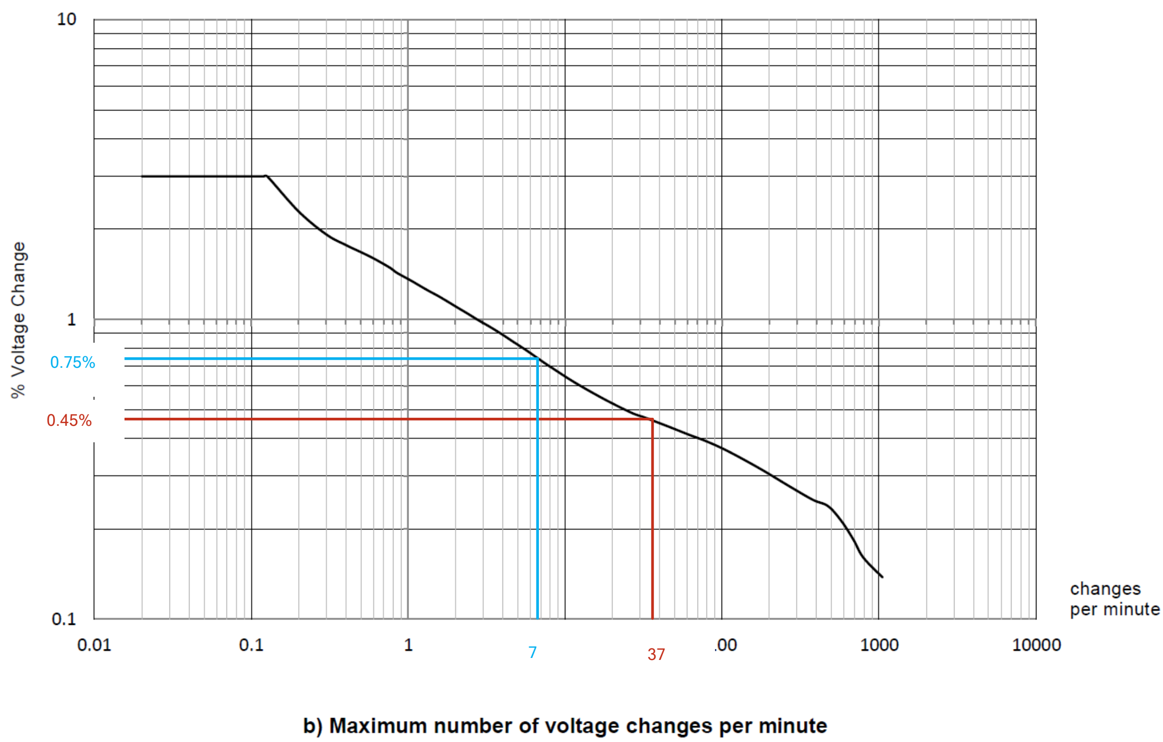


Figure 18 – Replication of Figure B.1.2 from EREC P28 (P_{st} = 0.5 curve)

From the analysis of Figure 17 above, it is increasingly clear that a BESS providing solely FR services, i.e. no stacking of services, will not power swing from full import to full export.

The maximum voltage change for the equated maximum change of % of contracted power change at unity pf can be simply calculated using the X/R ratio and short-circuit current obtained from NPg. This can then be expressed as a percentage of the nominal system voltage (V_n) and compared with the 3 % step voltage change limit.

A simplified assessment of step voltage change could be based on assessing the voltage fluctuation for a power swing from zero to full export or zero to full import, where the ramp time would be determined from the response time required by National Grid ESO. The maximum ramp times should be selected as follows:

- DC – Maximum ramp time of 1 s.
- DM – Maximum ramp time of 1 s.
- DR – Maximum ramp time of 10 s.

NOTE: This approach would provide a more pessimistic result than the power change ramp determined by system inertia.

5.6.3 BM Services

Under this service, a BESS participating in the BM (known as a Balancing Mechanism Unit) submits bids/offers into the BM online auction to reduce generation/increase demand or to increase generation/reduce demand outside its intended operating schedule for the next hour and a half. There is a start power (MW) and a finish power (MW) and any other changes in ramping up or down are set by NGESO.

The Final Physical Notification (FPN) submitted by the BESS sets out its intended starting point into the half-hour period it has bid/offered and its intended finish point. As part of the FPN the BESS can set its own limits on any maximum export limit, power swing, ramp rate etc. However, the rate of ramping must not exceed the run-up and run-down rate parameters for the BESS.

National Grid ESO issues instructions to the BESS during the half-hour period to either increase generation/reduce demand or reduce generation/increase demand taking into account the FPN submitted by the BESS. The BESS then acts on the instruction and changes power accordingly to deliver the requirement.

The BESS gets paid for the volume of energy it was required to increase or reduce within the period.

The BESS is not required to instantly change power under the BM. It is permissible for the BESS to ramp according to the ramp rate in its FPN. For the BM instruction to be fulfilled the BESS must meet its required level of output (MW) for the central five minutes of the relevant Quarter Hour. This generally means the BESS has up to 5 minutes to reach its required output. As such a BESS providing this service does not need to instantaneously change output and can manage power changes within its constraints by appropriate ramp changes. This is illustrated in Figure 19 below.

NOTE: There is no requirement in the service that prevents the BESS from changing power instantaneously other than compliance with the 3% step voltage change limit.

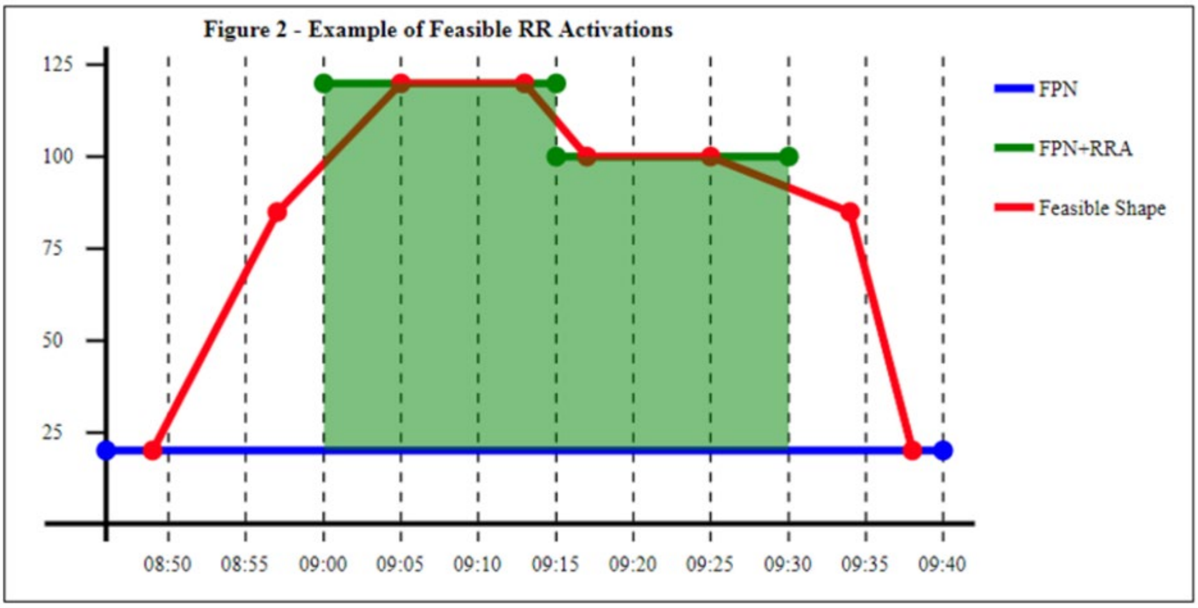


Figure 19 – Example of BESS Response to BM Requirements

NOTE: RRA is the Replacement Reserve Activation.

The blue horizontal line reflects the FPN status of the BESS with its expected start and finish power (MW). The required BM response over the period is shown by the green line. The red line shows a permissible ramping change in power that meets this required response within the operating constraints of the BESS defined in the FPN. One can see this this can be achieved by a series of ramps each over several minutes.

It is very unlikely that the BESS would swing from full import to full export when providing BM services. This is because the BM is about balancing supply and demand in real time - it is not a fault response type service. Also, the proportion of BM dispatch versus the wholesale market is small[17] (< 5%). The increase or reduction in power imported or exported are expected to be a small proportion of the intended start and finish power declared in the FPN.

In short, the BESS response in the BM is defined by the FPN, which is governed by the constraints of the BESS in terms of its maximum permitted ramp rate, state of charge etc. Any P28 limitations e.g. ramp rates should be factored into the FPN submitted to NGESO by the BESS operator. As such, it is expected that BESS operations in the BM will inherently meet step change voltage limits. A power ramp over 5-minutes would be longer than the tap-changer initial delay and operate time. In this case, the voltage change permitted over 5-minutes could be greater than 3 % on the basis that the tap-changer has operated to adjust the voltage.

In summary for BESS providing BM services:

[17] Source: National Grid ESO, Enhancing Energy Storage in the Balancing Mechanism, 16th October 2023.

- Based on Figure 19, it is very unlikely that the relatively slow and infrequent ramp changes in power would result in a flicker compliance issue.
- BESS will not produce rapid voltage changes.
- BESS will not produce step voltage changes greater than those permitted in P28.

5.6.4 Arbitrage Services

Arbitrage services involve changing the amount of energy in the battery according to the market price of energy, the intention being to charge the battery at lower prices and discharge the battery at higher prices. The degree of charging or discharging will depend upon various factors such as the existing and desired State of Charge (SoC) of the battery, the required period for charging or discharging.

BESS operators providing arbitrage services will adjust the power import/export to meet the required energy change over the required period. Generally, these are 30-minute periods to align with energy trading mechanisms.

It is understood that BESS operators can work within the constraints of a maximum power ramp rate to comply with any power change limits imposed in order to comply with the voltage fluctuation requirements in EREC P28 [1]. For example, in the case of a 50 MW BESS that is required to increase charge by 10 MWh over a 30-minute period, this would require an average power import of 20 MW for 30 minutes. Rather than a step change in power from 0-20 MW, the BESS could, for example, be programmed to ramp at 1.5 MW per minute. This would provide 11.25 MWh over the same period.

It is believed that a simplified approach to assessing step voltage change is feasible where a maximum power ramp rate can be defined, which would equate to a maximum voltage step voltage change of 3 % when calculated over a defined period of time. The maximum period of time could be determined by the initial tap delay and operation time of the nearest upstream tap-changer. Alternatively, the assessment could split the maximum power change into two ramp changes with a 3 % limit. The first ramp would take place within the 3 % limit followed by a suitable time delay to allow the tap-changer to operate before ramping again within the 3 % limit. This would effectively permit a 6 % step voltage change for full export to full import or vice versa when a suitable time delay is introduced.

As arbitrage does not involve frequent changes in power and hence voltage, compliance with flicker limits is not anticipated to be a problem. A simplified assessment of flicker could involve agreeing a limit on the number of power changes (and hence voltage changes) per minute. Figure B.1.2 and Figure B.1.1 of EREC P28, as appropriate, could then be used to determine the maximum % voltage change permitted. This could then be equated to a maximum change in power and power ramp rate not to be exceeded.

A detailed assessment of step voltage change and flicker could involve assessing the output from a BESS model which calculates the power changes and consequent voltage changes based on arbitrage operating parameters defined by the BESS operator. This would be similar to the detailed assessment for FR services but where the input data to the model is different.

There are no requirements for minimum response times in the Grid Code for arbitrage services.

5.6.5 Wholesale Market

BESS participate in the wholesale market as generators, where there is bilateral trading of electricity between generators and suppliers via the power market exchanges. The objective of the wholesale market is to give suppliers additional liquidity and the ability to 'add shape', over and above the baseload, closer to delivery to better fulfil the specific demand profile of the day (see Figure 20 below).

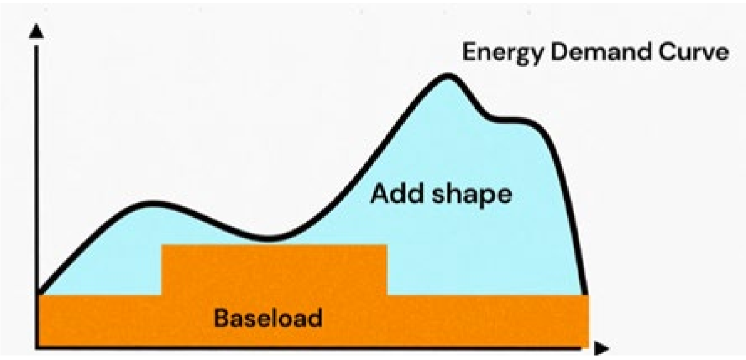


Figure 20 – Example of an Energy Demand Curve

Participants submit bids and offers, i.e. an option to buy or sell power prior to gate closure. At gate closure, the exchange calculates a single market clearing price based on supply and demand. This is only for the Day-Ahead and Intraday auctions. Day-Ahead auctions allow buyers and sellers to trade electricity across hourly or half-hourly blocks for delivery the following day. Intraday auctions provide an opportunity to trade on the day of delivery.

Prices in the Continuous Intraday market can diverge significantly from the auctions. This is because traders can react to events that were not visible within the auctions due to several reasons, i.e. knowledge that a party would have to pay Elexon for being out of balance, correct forecasting of renewables and demand, knowledge of power plant outages and weather etc.

The amount of energy (MWh) that a BESS can bid/offer to trade every half-hour or hour will depend upon its SoC and any other contracted services it might be providing. Whilst there is flexibility for the BESS in terms of the time to ramp up or down, there might be times where the BESS might need to rapidly change power. For example: where the BESS output prior to the wholesale market trading period is significantly different to that required to be supplied. Similarly, at the end of a wholesale market trading period, the BESS might need to change its output quickly in response to changes in the energy price from one trading period to the next.

The analysis of power changes for the Site A BESS are shown in Appendix E Findings from Site A & Site B Data Analysis. In summary, it was difficult to discern any real patterns of power changes associated with the BESS participating in the wholesale market. This was due to the limited data and the interaction with the FR services being provided by the BESS at the same time. However, it did appear that the energy being provided by the BESS when participating in the wholesale market was overlaid on top of the FR response. For example, if the BESS was contracted to provide 10 MWh through the wholesale market over a half-hour then there was an underlying output around 20 MW. There were no obvious large power swings evident at the beginning or end of the wholesale trading periods. However, that is not to say that these do not and cannot happen in practice.

Whilst flicker is not expected to be a problem for BESS operating in the wholesale market, due to relatively infrequent changes in power, there is the possibility of large power swings, particularly at the beginning and towards the end of trading periods, where the BESS might need to quickly change its output to respond to large differences between its current output and its contracted output. This might produce significant step voltage changes.

There are no requirements for minimum response times in the Grid Code for wholesale market operation.

6 Workstream A.3 Findings

6.1 Introduction

This section relates to workstream A.3 of the project carried out by Threepwood. It captures the potential changes to EREC P28 Issue 2 [1] to ensure it is fit-for-purpose and how the existing DCode text relating to EREC P28 and step voltage change might be improved.

It is important to note that the DCRP P28 Working Group are currently developing a guidance document (EREP 28) to accompany EREC P28. This will facilitate the application of EREC P28 until its next scheduled revision (noting that its 5-year nominal review is due in 2024). As such, the potential changes identified in this section apply to EREC P28 and its accompanying guidance document (EREP 28) - no distinction between the two documents is drawn.

6.2 Potential Changes to EREC P28

6.2.1 General

It is suggested that the scope of EREC P28 is changed to:

- explicitly include BESS including associated terminology and definitions (see 'Definitions' below for details);
- exclude the assessment of so-called 'post-fault frequency response services', in particular assessment of DC for system frequencies outside the range of 49.8 Hz and 50.2 Hz.

No changes are suggested to the definition of 'worst case normal operating conditions' or the need to conduct EREC P28 assessments under these conditions.

There is potential to include specific and more detailed guidance on the assessment of BESS in clause 8.9 of EREC P28 titled 'Energy storage' or in a new section on BESS to be added in clause 8. This could include more detailed guidance on the following high-level aspects.

- The basis of the 3 % step voltage limit and its role in minimising the risk of low voltages and its interaction with the operation of tap-changers.
- The different operating characteristics of the BESS and the performance requirements for the main services (i.e., FR, BM, arbitrage, Wholesale Market, STOR) in terms of the nature, magnitude and frequency of power changes and associated voltage changes. This could include clarification of when, or if, a maximum power swing from 100% export to 100% import, and vice versa, should be assessed.
- How the stacking of services provided by BESS should be assessed, in particular, to define the credible maximum power swings and hence voltage changes for various stacked service scenarios.

- How to assess BESS voltage fluctuations if the voltage is continually fluctuating and does not start from or reach a steady state. This includes how the 3 % step voltage change limit should be interpreted.
- How coincident power swings from multiple BESS connected to the same part of the network should be assessed and whether the 3 % limit should only apply to the import/export action of each BESS in isolation.
- How ramping power can assist with compliance against limits for flicker and step voltage change. Also how to interpret and assess ramped voltage changes including simplified assessment using maximum ramp rates for power.
- Cross-reference to ENA EREC G100 [23] and how customer limitation schemes should be applied to manage compliance with step voltage change limits.
- Worked examples of simplified and detailed assessment of BESS compliance.
- Whether there are any rarer than 'very infrequent events' associated with BESS operation where exceedances in the limits in EREC P28 would be acceptable.
- Whether there is a need for dynamic system modelling unless a risk of power oscillation caused by the BESS Controller has been identified.
- Whether National Grid ESO impose maximum ramp rates to BESS that take actions in the opposite direction to the FR services being provided. For example: a BESS contracted to provide Low Frequency Dynamic Services (which will export power at times of low frequency) has a maximum ramp rate applied to importing power whilst the low frequency service is contracted (see 5.5.8.1). For a BESS providing 100% capacity to the service the maximum ramp rate is 5% of capacity per minute. This will effectively reduce the probability that the BESS can go from full export to full import (or vice versa) for BESS providing stacked services. However, it might not eliminate the possibility[18].

These and other specific changes are discussed in more detail in the following sections of this Report.

6.2.2 Definitions

The following terms and definitions could be added to EREC P28 to improve interpretation.

- Shape Factor – in that it only applies to assessment of flicker and not step voltage change or RVC.
- Light Flickermeter.

[18] See Modo Energy video Ramp rates in Dynamic frequency response services: be aware | Modo Energy.

- BESS[19].
- Agreed Export/Import Capacity.
- Power Rating (kW or MW).
- Energy Rating (kWh or MWh).
- Charge Rate.
- Export Limiting Scheme.
- Ramp Rate.

The followings terms and definitions in EREC P28 could be improved.

- Normal operating condition – to clarify the application of this term to the distribution system, the transmission system, user plant and control system.
- Step voltage change – to clarify that the 3 % limit refers to the difference between the highest r.m.s. voltage and lowest r.m.s. voltage caused by the BESS operation in the time before the tap-changer operates. This includes a limit on aggregated voltage rise or aggregated voltage fall over the same period.
- Steady state voltage – to clarify whether the definition of a 0.2 % voltage change within 1 s (according to IEC 61000-3-3 [16]) or 0.5 % voltage change within 1 s. (according to IEC 61000-3-7 [5]) should be used.
- Figures 5 requires a note to be added to clarify that the envelope between +3 % and - 3 % only applies to a specific RVC event with a start and finish. It does not apply to continuous voltages changes caused by BESS operation, in particular when providing FR services. This is to make clear that BESS voltage cannot ramp from +3 % to – 3 % in the time before the tap-changer and vice versa, as this would exceed the 3 % step voltage change limit.

6.2.3 Light Flicker

The recent introduction of IEC Standards for the Light Flickermeter and how this measurement method differs from the IEC Flickermeter could be explained.

Opportunity could be taken to confirm that, whilst the origins of the IEC Flickermeter are in the perceptibility of changes to the luminance of a 230 V 60 W incandescent lamp, testing and compliance against IEC 61547 [20] ensures that modern lighting, such as LED lighting, will not result in flicker that is worse than that of an incandescent lamp under similar conditions. Also, this proposed change could make clear that modern lighting is not immune from flicker effects largely due to the variety of lamp types and their differing responses to voltage fluctuations, in particular at greater frequencies of voltage fluctuation.

[19] Electricity storage is the term used in the DCode and EREC G99.

6.2.4 System Inertia

Given National Grid ESO has indicated that minimum system inertia might reduce in the short-term, there could be provision for adjusting the step voltage change and flicker assessment results undertaken at the current minimum 140 GVAs to the proposed lower operational minimum value of 102 GVAs. This would provide an element of future proofing to minimise the risk of voltage complaints caused by BESS operation.

6.2.5 Modes of Operation

There is potential to provide greater clarity on the role that operating at constant power factor (pf) plays in the assessment of voltage changes in EREC P28. This would include the following.

- The need to model the change in voltage caused by Q as well as P when operating with a pf < 1 and recognition that the voltage change for power changes is unlikely to be linear under this mode of operation.
- Explain and clarify the pf conventions for leading/lagging and importing/exporting for BESS when importing and exporting.
- Explain for pf < 1 (leading and lagging) how Q could change when the BESS swings from import to export and vice versa to minimise the associated voltage changes.
- Explain the difference in simplified assessment of a BESS operating at unity pf compared with a pf = 0.95 (leading and lagging).

However, given the current difference in approaches by DNOs, it is not considered possible to agree a common assessment approach for assessment of BESS at constant power factor. This recognises the subtlety between assessing step voltage changes at 0.95 leading and lagging power factors, where assessment by NPg at a 0.95 lagging power factor for import and export[20] creates a worst-case and differs from the policies of other DNOs.

Similarly, there is an opportunity for EREC P28 to include guidance for BESS operating in voltage control mode with a defined Q/V slope (voltage droop control). This could include how this control mode can reduce the magnitude of voltage fluctuation by locally injecting/absorbing Q. Notwithstanding, there is believed to be greater discussion amongst the DNOs on the risks and challenges of allowing BESS to operate in voltage control.

6.2.6 Specific Changes for FR Services

There is potential to include the following specific guidance in EREC P28 regarding the assessment of BESS that provide FR services.

For detailed assessment of flicker severity:

[20] This policy is currently being reviewed.

- The DR FR service is likely to produce the worst flicker severity for the most common system frequency variations, i.e. 50 Hz ±0.1 Hz.
- There is a requirement to develop a representative power system model that can be used to determine the expected flicker severity produced by the BESS. This recognises that flicker caused by BESS providing FR services is unpredictable and can only accurately be assessed by a detailed model.
- The BESS controller model should have the same system, elements, and characteristics as those provided by the manufacturer together with the same configuration settings as those to be applied.
- The input to the model should be system frequency time-series data, with a maximum interval of 1 second, which represents system frequency variations over a typical 1-week measurement period to a probability not less than 95 % in accordance with clause 6.3.1 of P28. . This data can either be:
  - obtained from system frequency time-series data[21], or
  - obtained by synthesising time-series data set(s) from historic system frequency data.
- The operation of the BESS controller should be studied to determine the flicker severity:
  - at a constant 50 Hz input frequency and approaching the knee point frequencies of the FR services being provided to ensure that the BESS controller action does not cause an oscillatory frequency response resulting in high flicker severity values;
  - in response to the system frequency time-series data set.
- The requirement to conduct additional dynamic system studies should be confirmed where a risk of an oscillatory response has been identified.

For simplified assessment of flicker severity:

- Consider adopting 0.125 Hz/s as the maximum rate of frequency change for determining maximum power ramp rate for BESS providing FR services.

  NOTE: This is based on the current information provided by National Grid ESO in the FRCR Report [24] - including minimum system inertia of 140 GVAs.
- Consider introducing a simplified assessment of step voltage change, where the maximum voltage change for the equated maximum change of % of contracted power change at unity pf can be simply calculated using the X/R ratio and short-

[21] See National Grid ESO System Frequency Portal https://www.nationalgrideso.com/data-portal/system-frequency-data.

circuit current obtained from the DNO. This can then be expressed as a percentage of the nominal system voltage (V_n) and assessed against the 3 % limit.

- For BESS not providing stacked services:
  - But providing DR-L and DR-H:- to assess the step voltage change for a worst-case maximum change in power 100 % full export to 100 % full import and vice versa. A minimum ramp time of 1 s should be used in accordance with National Grid ESO FR service requirements for maximum time to full delivery of the service.
  - But not providing DR-L and DR-H:- to assess the step voltage change for a worst case maximum change in power of 100 % of contracted power. A minimum ramp time of 1 s should be used in accordance with National Grid ESO FR service requirements for maximum time to full delivery of the service.
- For BESS providing stacked services including FR:
  - Assess the step voltage change for a worst case maximum change in power from 100 % full export to 100 % full import and vice versa. A ramp time of 1 s should be used in accordance with National Grid ESO FR service requirements for maximum time to full delivery of the service (based on DM and DC).

6.2.7 Step Voltage Change Limit

At present, there is insufficient information to justify a change to the 3 % general limit for step voltage change in EREC P28. The consequence of increasing this limit would require more detailed investigation and evaluation at an industry level, i.e., via ENA. There are concerns regarding immunity of customer equipment to greater step voltage changes and the increased risk that the voltage at the terminals of some customers could fall outside statutory voltage limits (until correction of the voltage by the tap-changer).

The scope of EREC P28 states: *"The final decision as to whether or not disturbing equipment exceeding the limits in this EREC may be connected to the public electricity supply system is at the discretion of the relevant system/network operator."*

NPg might wish to consider circumstances where it and possibly other DNOs would consider discretion in exceeding the 3 % limit taking into account any guidance from the DCRP P28 Working Group. This might apply to the connection of BESS providing similar frequency response services at the Point of Common Coupling (PCC).

6.2.8 Definition of Step Voltage Change

The definition of step voltage change in EREC P28, in relation to assessment of BESS, could be clarified in EREC P28.

Although the term 'step voltage change' is not defined in the IEC 61000 series of Standards, the term 'step change' or 'voltage step change' is used. This relates to a voltage change with a rectangular or square wave form, i.e., an instantaneous change in voltage from one value to another. The definition of 'step voltage change' in EREC P28 is not aligned with the step changes referred to in the IEC 61000 series – by definition, step voltage changes according to EREC P28 can include other forms of voltage change, such as ramps, that are not instantaneous and can last in the window until the tap-changer operates.

The current definition fits events that have a clear start and finish. Ramp voltage changes caused by BESS can be unpredictable and long, often lasting longer than the time for automatic tap-changers to operate.

Potential clarifications to the definition of step voltage change in EREC P28 for assessing BESS could be as follows.

- The 3 % limit applies to any form of voltage change meeting the definition in EREC P28 not just rectangular or square wave instantaneous voltages changes.
- The 3 % limit mitigates the risk of excessively low system voltages that might breach the lower statutory voltage limit.
- The 3 % limit represents the "maximum permitted change in r.m.s. voltage when expressed as a percentage of the nominal system voltage (V_n), when measured between any two points, in the time period after all generating unit automatic voltage regulator (AVR) and static VAR compensator (SVC) actions and transient decay (typically 5 seconds after the fault clearance or system switching) have taken place, but before any other automatic or manual tap-changing and switching actions have commenced."
- Automatic or manual tap-changing refers to the operation of those tap-changers that will reduce the magnitude of the voltage change.
- The voltage in the time/observation period does not need to reach steady state.
- Alignment with IEC 61000-3-3 [16], where a voltage that does not exceed 0.2 % in one second is deemed to be in 'steady state'.

6.2.9 Assessment of Step Voltage Change

The following potential changes to assessing BESS operation, in terms of step voltage change, should be considered.

- Recognition that compliance with the 3 % step voltage limit produced as a consequence of large power swings over several seconds will generally be the limiting factor compared to the limit for flicker.
- Add a figure/illustration which clarifies the permissible voltage changes (i.e., to comply with the 3 % limit) over time in relation to the point that the tap-changer operates.
- Allow the operation of the tap-changer within the assessment for slow ramp voltage changes, where the voltage change event resets at the point the tap-changer operation is completed.
- Ramp voltage changes should be assessed as step voltage changes in terms of compliance against the 3 % general limit.

- Shape factors should not be applied to ramp voltage changes when assessing compliance against the 3 % general limit.
- Make clear the initial tap delay and operation time of the relevant automatic tap-changer determines the time/observation period for the assessment of the step voltage change. This time is expected to be specific to each voltage level and each DNO and might need to be assessed on a site-by-site basis. Alternatively, a default time/observation period, say 120 s, could be considered for simple assessment. This is believed to be the worst-case operating time for 33 kV and 132 kV tap-changers.
- The completion of the tap-changer operation should signify the commencement of a new observation period.
- For BESS providing stacked services, propose a simplified assessment of step voltage change based on a worst-case power swing from 100 % full export to 100 % full import and vice versa.

  NOTE: Different criteria apply to BESS providing FR services only.
- For BESS providing BM and/or arbitrage/Wholesale Market services only, propose a simplified assessment of step voltage change based on the maximum stated power change per second (i.e., ramp rate in MW/s) and the maximum ramp time declared by the BESS operator, where the BESS operator agrees to this constraint in the Connection Agreement. Otherwise, the BESS should be assessed based on a worst-case power swing from 100 % full export to 100 % full import and vice versa.

6.2.10 Flicker Limit

No potential changes in the flicker emission limits in EREC P28 for BESS operation are foreseen.

6.2.11 Assessment of Flicker

The following potential changes to assessment of flicker in EREC P28 have been identified:

- Clarification on the application of shape factors to simplified assessment of ramp voltage changes (see section 5 of this report). In particular, clarification that a shape factor of 0.2 can be applied to voltage ramps > 1 s.
- Propose a simplified assessment of flicker compliance using the maximum stated power change per second (i.e., ramp rate in MW/s) declared by the BESS operator (see section 5 of this report).
- For BESS propose a maximum permitted voltage change of 2.25 % for a ramp time ≤ 1.6 s to comply with the EREC P28 Stage 2 limit of $P_{st} = 0.5$.
- Flicker caused by BESS providing FR services, or services where the power can change frequently and unpredictably, should normally be subject to detailed assessment using the IEC flickermeter conforming to the requirements of IEC 61000-4-15 [17], which is either integral to the power system modelling and analysis software or standalone.

- For BESS providing different services then flicker should be assessed for each service/operating cycle provided and the worst flicker severity determined. Clarify that the worst-case flicker would be caused by BESS providing a DR service and that BESS providing only DM or DC services are not likely to produce significant flicker for the majority of the time.
- Where more than one BESS is causing coincident voltage changes at the PCC or similar substation, e.g., two BESS providing the same FR services, then there is an argument for flicker to be summated using a summation exponent of $\alpha = 1$, i.e. directly added together. This is unless the BESS operator can otherwise demonstrate that the summation exponent of $\alpha = 1$ is too onerous.

  NOTE: Further research might be required to support this proposed change.
- Clarify that Table 8 [EREC P28] relates to summation of flicker only.

6.2.12 Rapid Voltage Change (RVC)

No potential changes to the limits, assessment methodology or definition of RVC in EREC P28 are foreseen for assessment of BESS. This is because BESS operations do not generally produce voltage changes with an RVC characteristic. Notwithstanding, the specific guidance for BESS in EREC P28 could make the following clear.

- Energisation of any transformer connecting the BESS to the distribution network should be assessed as an RVC.
- Voltage changes produced by ramp changes in BESS power, over several seconds, are not to be assessed as RVC and that BESS voltage cannot ramp from +3 % to - 3 % in the time before the tap-changer and vice versa, as this would exceed the 3 % step voltage change limit.
- Sudden fast ramping of BESS power import or export from one steady state voltage to another providing it is within a 2 s window can be assessed as an RVC.
- Sudden fast ramping of BESS power is less likely to produce a voltage change with an RVC characteristic unless the X/R ratio of the source impedance is high, e.g. ≥ 25.

6.2.13 Voltage Droop Control Mode

For large BESS connected at 132 kV, and possibly 33 kV, there is potential to allow operation of BESS in voltage droop control mode. Whilst EREC P28 does not specifically preclude this, the guidance could be clearer on the benefits of operating the BESS in this control mode, particularly in networks with high X/R ratios, where power swings might need to be constrained to comply with the 3 % step change limit.

The accompanying guidance on EREC P28 could include the simplified method for assessing the voltage drop caused by a mixture of real power (P) changes and reactive power (Q) changes. This includes the application of the following equations to calculate voltage change:

$\Delta V = (RP+XQ)/V$ Equation 1

δV = (XP-RQ)/V Equation 2

6.3 Suggested Distribution Code Text Related to EREC P28

NPg has requested suggestions for how the existing DCode [3] text relating to EREC P28 and voltage step change might be improved. A commentary on the existing text and suggestions for improvement are documented below.

The existing text in the DCODE is replicated below from DPC4.2.3.3.

"For voltage step changes caused by the connection and disconnection of ***User****'s* ***Equipment*** *or* ***Customer****'s* ***Demand*** *to the* ***DNO's Distribution System****, a general limit of ±3% applies in accordance with Engineering Recommendation P28 Issue 2.*

For very infrequent events that result in rapid voltage change type characteristics, such as when complete sites including a significant presence of transformers are energised as a result of post fault switching, post maintenance switching, or carrying out commissioning tests on the ***DNO's Distribution System*** *or on* ***Users****' Systems, it will generally be acceptable to design to an expected depression of around ±10%, recognizing that a worst case energization might cause a larger depression, on the basis that such events are considered to be rare and it is difficult to predict the exact depression because of the point on wave switching uncertainty."*

This text was last updated in Issue No. 39 of the DCode on 23/05/19. This coincided with the Implementation of EREC P28 Issue 2 and was intended to align the text in the previous issue of the DCode with the changes in EREC P28 Issue 2.

The initial paragraph regarding step voltage changes, as worded, raises the following potential issues.

- The term 'voltage step change' in the text is not aligned with the defined term 'step voltage change' in EREC P28.

  Commentary:
  This is a relatively minor point but could cause doubt whether voltage step change in the DCode has the same meaning as step voltage change in EREC P28. The author believes the term 'voltage step change' was used in previous versions of the DCode long before EREC P28 was revised, hence why it was not changed. If this DPC clause is retained the DCode term could be changed to be 'step voltage change'.

- The application of the general limit of ±3 % only applies to connection and disconnection of User's Equipment or Customer Demand.

  Commentary:
  In EREC P28, the 3 % general limit applies to any step voltage change caused by the user's equipment and not just during its connection or disconnection. Notwithstanding, EREC P28 is listed in Annex 1 of the DCode as a 'Qualifying Standard' and, therefore, the technical requirements in EREC P28 form part of the

DCode. It would seem this text is specifically clarifying the 3 % general limit applies to the energisation and de-energisation of equipment and customer load causing an instantaneous voltage change, which is distinct from the very infrequent RVC type multiple transformer energisations discussed in the following paragraph of the text.

NOTE: Although the terms 'connection' and 'disconnection' are not defined in the DCode they are interpreted as meaning when energised or when de-energised from the DNO's distribution system by switching.

- The term 'very infrequent events' is not defined in the DCode or in EREC P28. However, Table 4 in EREC P28 does state the maximum number of occurrences for very infrequent events and might be worthy of reference.

- The second paragraph refers to a voltage depression and the associated limit is stated as 'around ±10%'.

  Commentary:
  EREC P28 has specific envelopes and limits for RVCs, including those type of RVCs referred to in the text of the DCODE. The statement "…of around ±10%." is somewhat vague compared with the clear envelopes in clause 5 of EREC P28. It would seem better to refer to the RVC envelopes in EREC P28. In addition, the use of the +/- symbol is not believed to be correct given this text refers to voltage depressions.

It would seem that the purpose of the 2nd paragraph is to make clear the maximum value of RVC that the user should design to but that there is some scope for greater voltage changes than 10% in practice due to the unpredictable nature at which switching takes place on the voltage wave. Whilst the 10 % figure is not strictly correct in relation to the RVC limits in Table 4 of EREC P28 the allowance to exceed the limits on rare occasions under worst case conditions, due to the unpredictability of switching on the voltage waveform, might still be valid.

The preferred approach and simplest solution would be to remove the text in DPC4.2.3.3 in its entirety. It is believed that these requirements in the DCode are adequately covered by EREC P28 Issue 2, if interpreted correctly. One could argue that removing these requirements from the DCode and simply relying on the interpretation of EREC P28 will avoid any perceived conflict between the two documents.

Alternatively, if removal of the text is deemed too drastic then the following amendments to the existing text in the DCode are suggested to improve alignment with EREC P28 Issue 2.

- Reword paragraph 1 as follows:
  In accordance with Engineering Recommendation P28 , a general limit of 3% applies to instantaneous step changes in steady state voltage caused by the connection and disconnection from ***DNO's Distribution System*** *of* ***User****'s* ***Equipment*** *or* ***Customer****'s* ***Demand*** *.*

This proposed text change avoids the misalignment of the terms 'voltage step change' and 'step voltage change' and clarifies this distinction between instantaneous rectangular type voltage changes caused by the connection and disconnection of user equipment and customer demand as opposed to the RVC characteristic transformer energisations covered in the paragraph below.

- Reword paragraph 2 as follows:
*For events that result in rapid voltage change type characteristics, including energisation of complete sites with multiple transformers, as a result of post fault switching, post maintenance switching, or carrying out commissioning tests on the **DNO's Distribution System** or on **User**s' Systems, the design should ensure that voltage changes comply with the relevant limits in Table 4 of EREC P28 Issue 2. However, it is recognised that on rare occasions, under worst case energisation conditions, the resultant voltage depression might be greater than designed due to the point on wave switching uncertainty.*

7 Recommendations

R1. The recommended improvements to EREC P28, identified in section 6 of this Report, should be fed into the development of EREP 28 by the DCRP P28 Working Group.

R2. Workstream B should provide a statistical analysis of historic 1 s frequency data published by National Grid ESO to determine how frequently large variations occur from the nominal 50 Hz and whether these can be considered 'infrequent' or 'very infrequent' events according to EREC P28.

R3. Workstream B should carry out further analysis on the likely magnitude and frequency of power swings associated with different BESS services, including likely scenarios of stacked services for rare system events where the frequency falls outside the range of 50 Hz ± 0.2 Hz.

R4. Consider whether fast tap settings in modern AVC relays should be implemented to mitigate step voltage changes caused by BESS, particularly when responding to abnormal system frequency events.

R5. Workstream B should consider whether the characteristics of the voltage fluctuations produced by BESS operation can fit within the envelopes in Figure 6 of P28 for infrequent events and Figure 7 for very infrequent events, which would enable the greater limits for RVC to be exploited by BESS under certain circumstances.

R6. Workstream B should evaluate the impact that modelling BESS at different power factors (for export and import) and for different control modes (e.g. constant power factor control, constant reactive power control, voltage control etc.) can have on the magnitude of the step voltage change.

R7. NPg should consider whether maximum stated power swings by the BESS Operator, if less than 100 % of full import to 100 % full export, and vice versa, are acceptable and whether such limitations can be written into Connection Agreements and monitored on an ongoing basis.

R8. The text in DPC4.2.3.3 of the DCode is removed in its entirety or modified as proposed in section 6.3. Reliance should be placed on the fact that EREC P28 is listed in Annex 1 of the DCode as a 'Qualifying Standard' and, therefore, the technical requirements in EREC P28 form part of the DCode.

8 Abbreviations & Conventions

The following abbreviation and conventions used throughout this Report are summarised in Table 2.

Table 2 – Abbreviations and Terms

Abbreviation	Description
AC	Alternating Current
AVC	Automatic Voltage Control
AVR	Automatic Voltage Regulator
BESS	Battery Energy Storage System
BM	Balancing Mechanism
BS	British Standard
BSI	British Standards Institution
CFL	Compact Fluorescent Lamp
CIRED	Congrès International des Réseaux Electriques de Distribution (International Conference on Electricity Distribution)
CLS	Customer Limitation Scheme
DC	Direct Current
DC	Dynamic Containment
DCODE	Distribution Code
DER	Distributed Energy Resource
DG	Distributed Generation
DM	Dynamic Moderation
DNO	Distribution Network Operator
DPC	Distribution Planning Code
DR	Dynamic Regulation
EHV	Extra High Voltage
ELS	Export Limitation Scheme
EN	Euro Norm (European Standard)
ENA	Energy Networks Association
ENWL	Electricity North West Limited
EREC	ENA Engineering Recommendation
EREP	ENA Engineering Report
ESO	Electricity System Operator
ETR	ENA Engineering Technical Report
EV	Electric Vehicle
FFR	Fast Frequency Response
FPN	Final Physical Notification

Abbreviation	Description
FR	Frequency Response
GEL	General Electrical Committee of BSI
GSP	Grid Supply Point
HV	High Voltage
IEC	International Electrotechnical Committee
IEEE	Institute of Electrical and Electronic Engineers
LDC	Line Drop Compensation
LED	Light Emitting Diode
LV	Low Voltage
MV	Medium Voltage
NGED	National Grid Electricity Distribution
NIA	Network Innovation Allowance
NPg	Northern Powergrid
PCC	Point of Common Coupling
pf	Power Factor
POC	Point of Connection
POS	Point of Supply
PPM	Power Park Module
RVC	Rapid Voltage Change
SoC	State of Charge
SPEN	Scottish Power Energy Networks
SPM	Scottish Power Manweb
SSEN	Scottish and Southern Electricity Networks
STOR	Short Term Operating Reserve
SVC	Static Voltage/VAR Compensator
UKPN	UK Power Networks

9 References

[1] ENA Engineering Recommendation P28, Issue 2, 2019, Voltage fluctuations and the connection of disturbing equipment to transmission systems and distribution networks in the United Kingdom.

[2] NIA Project. BESS P28. Project reference number: NPG_NIA_046.

[3] Distribution Code. The Distribution Code of Licensed Distribution Network Operators of Great Britain. Issue 55 - 15 December 2023.

[4] Source: LinkedIn article by Charlotte Johnson, Chief of Staff & Global Head of Markets at Kraken, 9 June 2021.

[5] IEC/TR 61000-3-7 Ed 2: Electromagnetic compatibility (EMC) - Part 3-7: Assessment of emission limits for the connection of fluctuating load installations to MV, HV and EHV power systems.

[6] ENA Engineering Technical Report (ETR), Issue 2, 2024, Guide to the application of Engineering Recommendation G5/5.

[7] ENA Engineering Recommendation G5, Issue 5, 2020, Harmonic voltage distortion and the connection of harmonic sources and/or resonant plant to transmission systems and distribution networks in the United Kingdom.

[8] ENA Engineering Recommendation P28, Issue 1, 1989, Planning Limits for Voltage Fluctuation Caused by Industrial, Commercial and Domestic Equipment in the United Kingdom.

[9] NGED Guidance Note. Flicker Assessment of Battery Energy Storage Systems (BESS) Providing Frequency Response Services. 21/08/2023.

[10] ENA Engineering Recommendation G99, Issue 1 - Amendment 9, 3 October 2022, Requirements for the connection of generation equipment in parallel with public distribution networks on or after 27 April 2019.

[11] Electronics MDPI, Article, 'Assessment of Voltage Fluctuations for Battery Storage Systems Providing Frequency Response Services' by Stephen Sommerville, Gareth Taylor and Maysam Abbod, 22 February 2023.

[12] ENA Engineering Report 126, Issue 2, 2012, Guidelines for actively managing voltage levels associated with the connection of a single Distributed Generation plant.

[13] Northern Powergrid, IMP/001/007, Code of Practice for the Economic Development of Distribution Systems with Distributed Generation, Version 7.0.

[14] Northern Powergrid, IMP/001/007/001, Battery Energy Storage System Guidance Document, Version 1 (April 2018).

[15] IEC 868, Flickermeter, First Edition, Functional & Design Specifications.

[16] IEC 61000-3-3: Ed.3.2, Electromagnetic compatibility (EMC) - Limits. Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤ 16 A per phase and not subject to conditional connection.

[17] IEC 61000-4-15 Ed.2: Electromagnetic compatibility (EMC) - Part 4-15: Testing and measurement techniques - Flickermeter - Functional and design specifications.

[18] IEEE 141 – 1993, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants.

[19] IEEE 519 – 2022, IEEE Standard for Harmonic Control in Electric Power Systems.

[20] IEC 61547:2020: Equipment for general lighting purposes - EMC immunity requirements.

[21] BS EN IEC 61547:2023, Equipment for general lighting purposes. EMC immunity requirements.

[22] CIRED, Paper 0409, A protocol to test the sensitivity of lighting equipment to voltage fluctuations, June 2015.

[23] ENA, Engineering Recommendation G100, Issue 2 Amendment 2, 2023, Technical Requirements for Customers' Export and Import Limitation Schemes.

[24] National Grid, Frequency Risk and Control Report (FRCR), Security and Quality of Supply Standards, Methodology and Assessment, Reducing minimum inertia requirement under FRCR policy, March 2023.

[25] IEC 61000-3-11 Ed. 2: Electromagnetic compatibility (EMC) - Part 3-11: Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems - Equipment with rated current ≤ 75 A and subject to conditional connection.

[26] IEC 60034-1 Ed. 14: Rotating electrical machines - Part 1: Rating and performance.

[27] Northern Powergrid, IMP/001/915, Code of Practice for Managing Voltages on the Distribution System, Version 1.0, February 2017.

[28] BSI, BS EN 50160:2022, Voltage characteristics of electricity supplied by public electricity networks.

[29] ENA, Engineering Technical Report (ETR) 122, 2002, 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 U.K.

10 Appendix A Detailed Scope of Work for Each Task

SCHEDULE A

SCOPE OF WORK AND PAYMENT SCHEDULE

Scope of Work

Task A.1 - Desktop Review

Threepwood shall:

- Carry out a desktop review of the latest version of IEC 61000-3-7, other DNOs' policies and practices (as informed by the DER Technical Forum BESS Group and/or the DCRP EREC P28 working group).
- Carry out a comparison of these policies and practices with the assessment methodologies in EREC P28 e.g. in the application of shape factors and in the assessment of ramp changes;
- Form an interpretation of the relevant limits, definitions and terms from EREC P28 as they relate to operation of a BESS when it provides a NGESO frequency response service, provides arbitrage services, or operates in the balancing mechanism and how the interpretations, definitions and terms might need to be improved;
- Comment on the appropriateness of the 3% voltage step change limit to BESS operation and its relationship with ramped voltage change;
- Clarify the application of shape factors in EREC P28 to the assessment of voltage fluctuations;
- Provide a brief commentary on the current flicker meter approach to assessing flicker and its legacy relationship to incandescent light bulbs including reviewing the Brunel University paper published in 2023 "Assessment of Voltage Fluctuations for Battery Storage Systems Providing Frequency Response Services", which describes a method for calculating and assessing voltage fluctuations from BESS operating in frequency response mode.

The deliverable for this task shall be a memo from Threepwood to Northern Powergrid.

Task A.2 - Interpretation

Threepwood shall:

- Provide a description of how the EREC P28 planning limits (for voltage step change, RVC and flicker) should be applied to an assessment of BESS operation and provide a clear definition of the planning limits;
- Identify how NPg should be assessing the three categories of voltage fluctuations associated with BESS operation;

- Consider the effect of reactive power on voltage when BESS operates in voltage control mode (with a Q/V slope setting) and whether this affects the assessment of the three categories of voltage fluctuations associated with BESS operation;
- Comment on the feasibility of developing i) a simplified and ii) a detailed methodology for assessing voltage fluctuations associated with BESS operation where it provides NGESO frequency response services e.g. Dynamic Containment, Dynamic Modulation and Dynamic Regulation, provides arbitrage services in the wholesale market or operates in the balancing mechanism and considering what limits on MW swing rates would need to be imposed. The simplified methodology would be something DNO's could use at the connection design stage. The detailed methodology would be at a similar level of detail to that provided in EREC P28 section 6.4.2 Transformer energisation.

The deliverable for this task shall be a memo from Threepwood to Northern Powergrid.

Task A.3 - Improvements

Threepwood shall:

- Identify potential changes to EREC P28 (including limits, assessment methodology and definitions) to ensure it is fit-for-purpose in terms of assessing operation of a BESS when providing a NGESO frequency response service, providing arbitrage services and /or when operating in the balancing mechanism;
- Suggest how the existing Distribution Code text relating to EREC P28 and voltage step change might be improved.

The deliverable for this task shall be a memo from Threepwood to Northern Powergrid.

Task A.4 – Findings and recommendations

Threepwood shall produce a report from the previous tasks, seeking formal review comments from Northern Powergrid. Threepwood shall prepare and deliver a presentation, via MS Teams, of the findings and recommendations from the review to the Northern Powergrid project team and invited stakeholders. The presentation would include time to address any comments received from Northern Powergrid on the documented review.

The deliverable from this task shall be the report and the presentation.

11 Appendix B Summary of Differences Between EREC P28 & IEC Standards

	Summary of Differences
General	EREC P28 Issue 2 [1] was revised in line with the UK implementation of IEC Standards (particularly the IEC 61000 series), where appropriate. Some key differences are described in the rows below.
Voltage Fluctuation	The definitions in PD IEC/TR 61000-3-7:2008 [5] and EREC P28 Issue 2 are different but similar in intent and have no material difference for assessment purposes.
Step Voltage Change	Step voltage change is defined in EREC P28 Issue 2 but not in IEC Standards. The term 'step change' is used in the IEC 61000 series of Standards in relation to instantaneous rectangular voltage changes. The definition in EREC P28 Issue 2 is wider and includes these type of voltage changes plus ramp type changes and other non-RVC voltage changes. The operation of the tap-changer is mentioned in the EREC P28 Issue 2 definition but not in PD IEC/TR 61000-3-7:2008. A 3 % limit is mentioned in IEC 61000 series of Standards in relation to limiting voltage change in normal circumstances in MV systems. A higher value of 3.3 % is referenced in IEC 61000-3-3 as being the limit of steady state voltage change at the equipment terminals.
Flicker	The limits for voltage fluctuation in EREC P28 Issue 2 are compatible with the existing flicker curve in IEC 61000 series of Standards. The definition of flicker in EREC P28 Issue 2 is equivalent to definition in Clause 3.6 of PD IEC/TR 61000-3-7:2008]. The planning limits are different, where PD IEC/TR 61000-3-7:2008 only provides generic indicative values. EREC P28 Issue 2 provides specific values appropriate to GB.
RVC	The definition of RVC in EREC P28 Issue 2 is similar to definition in PD IEC/TR 61000-3-7:2008. Step voltage changes are considered RVCs in the IEC Standard. The limits differ between the two standards. This is largely because the limits in the IEC Standard are indicative and cover a wider range of voltages at MV.
Steady State	The term 'steady state' is not defined in IEC 61000 Standards or EREC P28 Issue 2. The threshold value used in EREC P28 Issue 2 is ≤ 0.5 % of V_n for at least 1 s, which is the same as for RVCs in PD IEC/TR 61000-3-7:2008. The threshold in IEC 61000-3-3 is ≤ 0.2 % of V_n for 1 s.
Normal Operating Condition	PD IEC/TR 61000-3-7:2008 has a definition for 'normal operating conditions', which includes planned outages (of the system, generation and loads), non-ideal operating conditions and normal contingencies for which the system/installation had been designed. This excludes faults. EREC P28 Issue has a similar but not identical definition for 'normal operating conditions' but has an addition term 'worst case normal operating condition', which is the normal condition that produces the max. short-circuit impedance when measured at the PCC.

12 Appendix C Example of the Application of Shape Factors

An example of motor starting taken from Figure 10 of EREC P28 is shown in Figure 21.

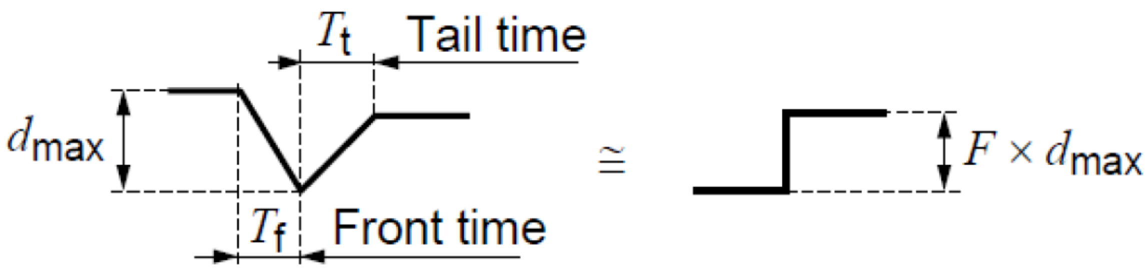


Figure 21 – Application of shape factor (*F*) for motor starting

In this case:

dmax = 4 %

T_f = 100 ms

T_t = 1,000 ms

Then from Figure B.2.4 [EREC P28 Issue 2]:

The value of *F* = 0.6.

The equivalent step voltage change = d_{max} x *F*

= 4 % x 0.6

= 2.4 %

From the P_{st} curve in Figure B.1.1 [EREC P28 Issue 2], one can see a maximum of 1.8 voltage changes per minute at this magnitude are permitted to meet the P_{st} = 1 criteria.

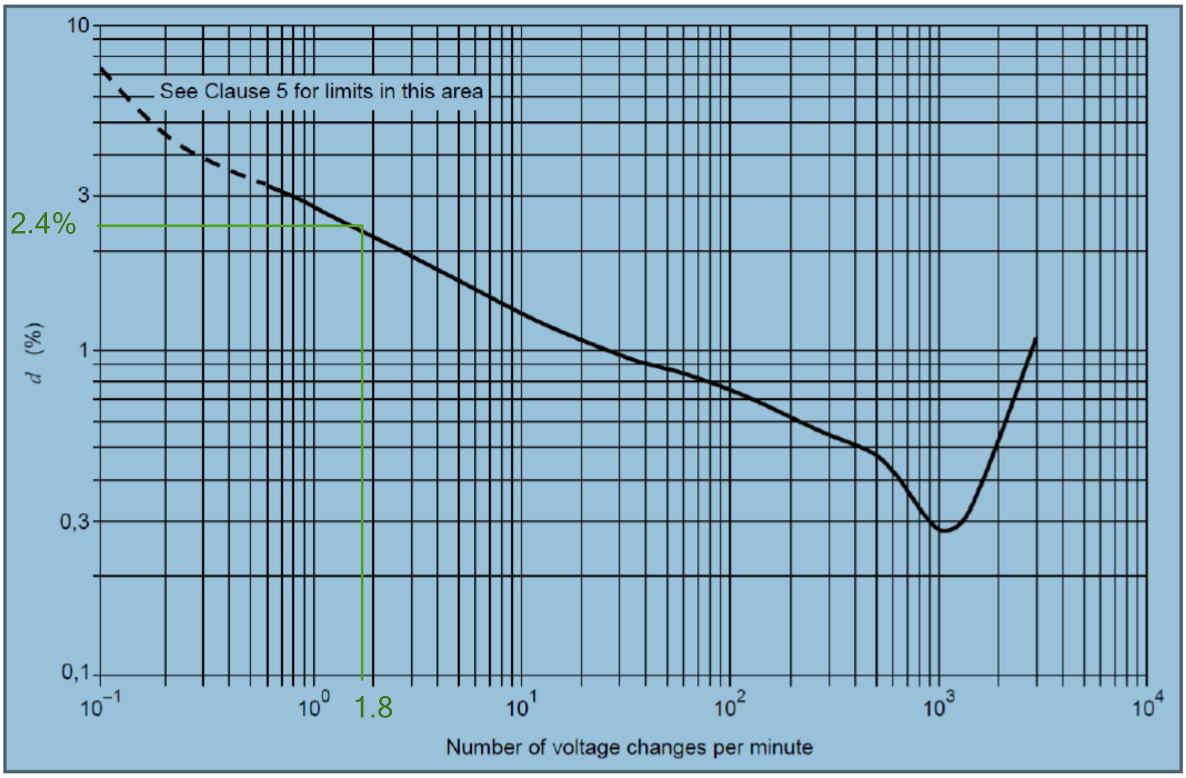


Figure 22 – P_{st} = 1 Curve from Figure B.1.1 in EREC P28 Issue 2

13 Appendix D Commentary on Technical Paper (Brunel University)

A review of the Article 'Assessment of Voltage Fluctuations for Battery Storage Systems Providing Frequency Response Services' [11] was undertaken. This paper is an extended version of the paper published by the IEEE. Commentary and findings from that review are summarised below.

The paper discusses the standard frequency disturbance generator that was used in the modelling which is representative of network frequency disturbances. The extent to which this considers worst case conditions is not known. Also how the disturbance generator relates to a system frequency distribution curve – is it representative of conditions for 95 % of time in a year? Notwithstanding, generating representative frequency disturbances for use in modelling BESS providing FR has validity.

The paper discusses FR being a balancing service pre-fault and FFR and DC as post-fault services. It is believed that such post-fault services might be classed outside the scope of P28 as they are necessary to prevent system instability and occur very infrequently.

The paper suggests that system frequency changes are gradual events over several minutes and that step changes in frequency, and consequently in voltage, are rare. This is distinct from the more conservative approach currently being taken by NPg for P28 assessments, which assumes a power swing from maximum export to maximum import in less than 1 s.

The paper recognises that DR is a pre-fault dynamic response that results in more frequent ramping up and down of power over several seconds and might cause voltage disturbances more akin to flicker than step voltage change.

The power ramp depends upon the controller. The set points of the controller are clearly important. For frequency response services the ramp should be linear to meet the requirements of National Grid ESO frequency response services. For a constant impedance this will produce a ramped voltage change.

The voltage changes are complex and are best analysed by the flickermeter built into the model.

For correct modelling both P and Q need to be taken into account.

The paper picks on scenarios based on selected frequency data rather than assessing the whole of the frequency data set.

The paper characterises nicely the amount of time frequency excursions occur in section 4.1.

The paper concludes that BESS can interact together therefore summation techniques might need to use a summation exponent of $\alpha = 1$.

Further work is recommended around oscillation/interaction of small frequency changes to see whether this can generate any significant P_{st}.

If the BESS is at different points but uses the same controller, then the response and hence the voltage fluctuation will be coincident.

The following questions and clarifications arise from reviewing the paper.

- Can BESS near each other all move together and provide co-incident voltage fluctuations? What should we consider for modelling?
- A generic controller was developed and used to model the BESS response. Is this correct?
- Is the BESS controller ramping?
- Should we consider how the BESS is measuring frequency. For example: rolling average or instantaneous frequency?
- What is the max ramp start?
- What about switching services? Does it matter?
- Do we need to consider transient studies for fast acting power swings – What power change over what time?
- What about Q? Even with constant power factor does Q change?
- Statistically frequency changes are slow – what does this mean for BESS output? It will mean step changes in frequency are not likely. How does frequency changes vary from second to second?
- Having a frequency generator would be good? Is the frequency disturbance representative? Would this be the same for all studies?
- What about system inertia reducing in the future? Should we allow for it now? What effect will it have?
- Is the DM response the most onerous condition?
    - Yes, in that for a small change in frequency the change in power will be the greatest. However, we have seen some significant power changes for DR.
- Is there is a problem defining an event if it does not reach steady state (i.e. ≤ 0.5 % per second)?

The paper considers the 3 % limit and its interaction with tap-changers. Tap-changers can operate to raise or reduce the voltage by the % tap value (typically 1.25 % at 33 kV and 1.67 % at 132 kV). Fast tap threshold settings are usually set at ±2 % outside the deadband, where deadband is usually equal to target voltage ±1.25 %. Time delay settings can be as low as 3 seconds. In the technical paper this has been set for 5 s at 132 kV, 10 s for 33 kV and 15 s for 11 kV. Because the voltage change does not reach steady state then we must assume that the voltage fluctuation does not exceed 3 % within the fast tap time.

14 Appendix E Findings from Site A & Site B Data Analysis[22]

14.1 General

Threepwood carried out an initial assessment of the data provided by NPg from the BESS connected at Site A and Site B. The key findings are outlined below in sections 14.2 and 14.3.

14.2 Site A Data Analysis

The BESS, with a MIC and MEC of 50MW, provides a mixture of frequency response services (i.e. DR-H, DR-L, DM-L, DC-H and DC-L) over the 24-hour period.

The largest power responses contracted for the period of the data are '48MW DM-L' and '47MW DC-L and DC-H'.

On the 25th October 2023, the BESS was participating in the wholesale market at various volumes across a half-hour period as below.

- -5.75 MWh Intraday Buy Volume across half-hour (1.30am to 2am).
- 2.5 MWh Intraday Sell/Export Volume across half-hour (4pm to 4.30pm).
- 10.5MWh Intraday Sell/Export Volume across half-hour (4.30pm to 5pm).
- 11.5 MWh Intraday Sell/Export Volume across half-hour (5pm to 5.30pm).
- 13 MWh Intraday Sell/Export Volume across half-hour (5.30pm to 6pm).

This trading is provided as a stacked service on top of the frequency response service (always during DR-L or DR-H) - there are no periods in the data where the BESS solely operates in the wholesale market. Consequently, it is difficult to determine the power response solely attributable to wholesale trading. The data does not show any particularly large step changes in power and the power changes generally follow the shape of the frequency changes. However, there was one anomaly when the BESS was providing -5.75 MWh on the Intraday market (i.e. import in a half-hour period), where there was a step change in power of approximately 10 MW (in less than 5 s) which was within 5 s of the wholesale trading period ending (see Figure 23). However, as the imported power associated with this wholesale trade was a fraction (approx. 20 % of the BESS import capacity) it is not likely to cause an issue with step voltage change compliance.

[22] The terms 'Site A' and 'Site B' have been used for anonymity of two BESS sites connected to the NPg distribution network.

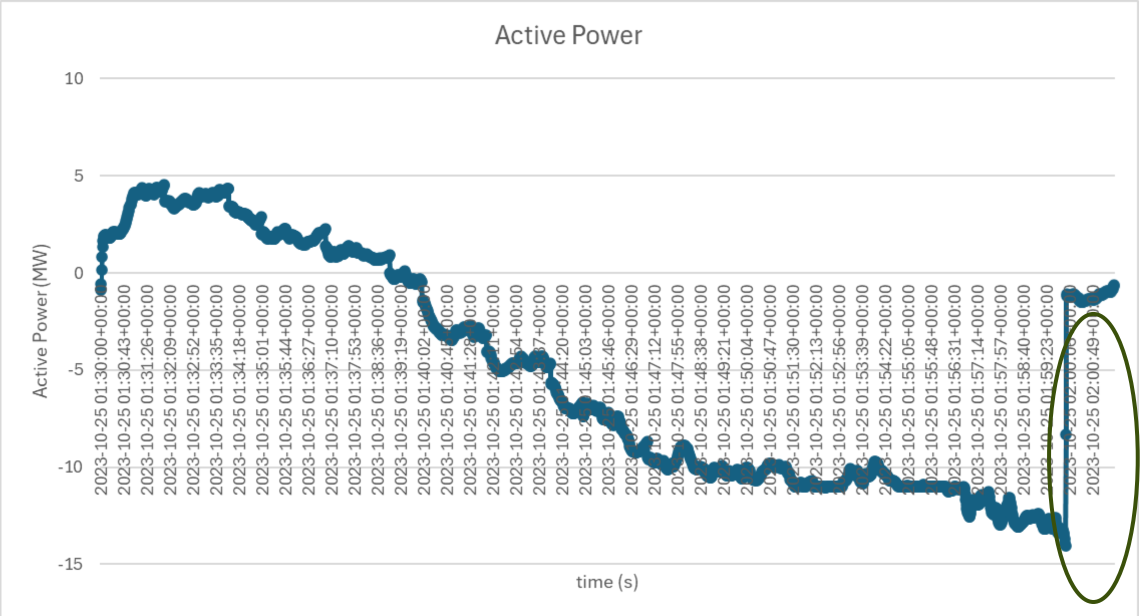


Figure 23 – Change in BESS Power at End of Wholesale Market Trade Period

Wholesale Market Trade	Time Start	Time End	DFR Service
-5.75MWh Intraday Buy Volume across half hour	01.30.00	02.01.30	10MW of DRH and 16MW of DRL

The highest import is approx. 39 MW. The highest export is approx. 32 MW compared with a capacity of 50 MW export and 50 MW import.

The highest SoC is 61 % and the lowest SoC is 15 %. The mean SoC was 32 %.

The frequency largely keeps within the range of 49.8 and 50.2 Hz over the 24-hour period. There is an event for 5 s where the frequency drops to 49.79 Hz. Most of the time frequency changes are relatively slow over several seconds.

The highest instantaneous power change was 7.1 MW/s at import. This corresponded to the highest voltage change of 0.83 % in a 1 second period.

Eight out of the top 10 ranked rate of power changes were import events and related to the frequency response services.

Two of the three highest ranked rates of change of power were attributed to the 10 MW of DR-H and 16 MW of DR-L response service - both were responses in the 50 Hz ± 0.1 Hz band. This highlights the magnitude of response required to be provided by DR in the ±0.1 Hz band.

The top two rates of frequency change of 0.02 Hz/s were import events and occurred whilst providing 10 MW of DRH and 16 MW of DRL where:

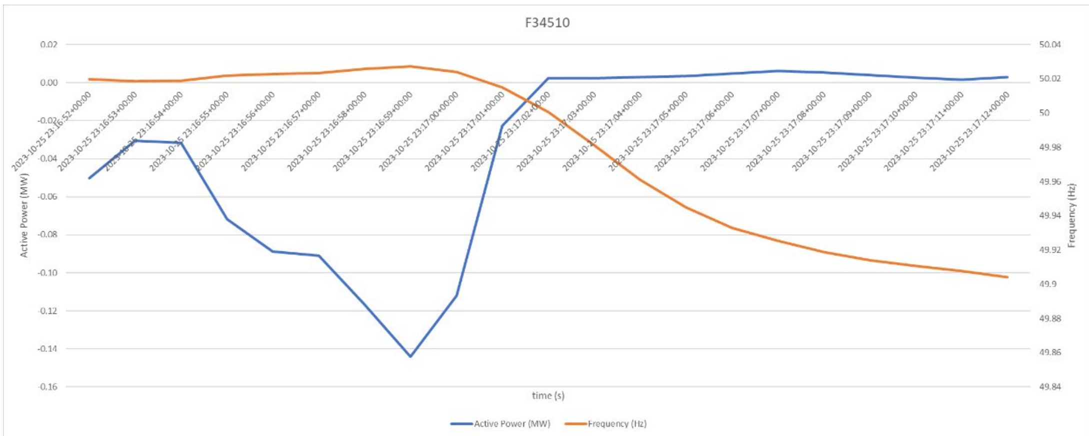
- The BESS was also importing 5.75 MWh trade across a half-hour.
- The associated rate of change of power was not large (< 0.38 MW/s).

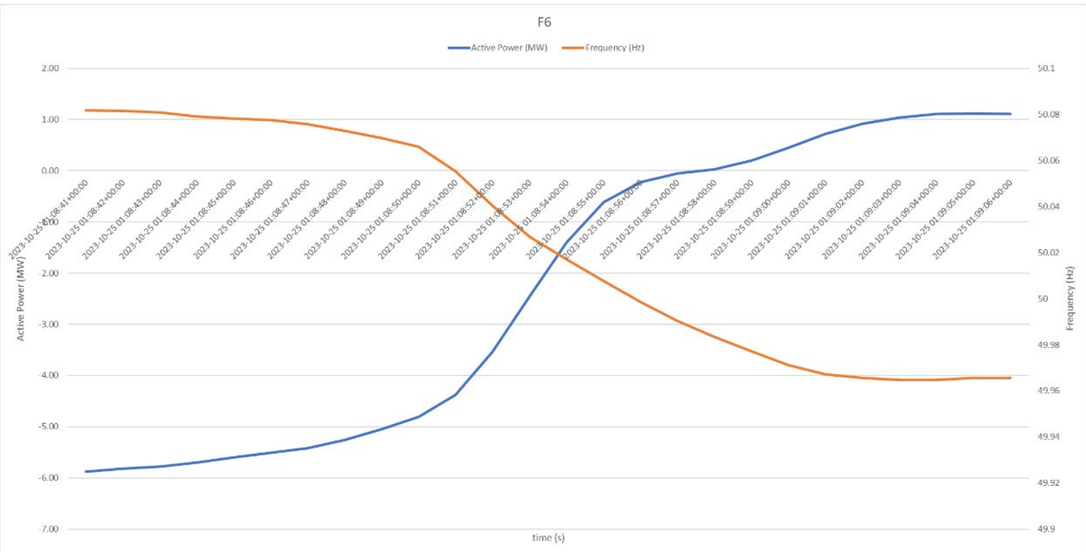
The longest period of response was 4 s (see the Figure 24 below for events F3,4,5,10, titled F34510) whilst providing 47 MW of DC-H and DC-L. However, the frequency was only marginally outside deadband at 50.02 Hz.

The highest rate of active power changes (see Figure 24 for events AP1 and AP3 titled 'AP1 3') occurred during 10 MW or DR-H and 16 MW of DR-L but this only lasted 2 s. This did not correspond to a particularly large frequency change (approx. 0.003 Hz/s. This odd response could be attributed to the -5.75 MWh of intraday trading that initiated at the time.

There were a number of classical frequency responses:

- See Figure 24 event F6 where the frequency fell in the 50 Hz + 0.1Hz band over approx. 25 s and the BESS corresponding reduced the amount of import (this was a DR response).
- See Figure 24 event F27 where the frequency starts to fall outside of deadband and the BESS switches from import to export by 2.5 MW (approx. 5 % of rated output) over 6-7s. This is consistent with the change in expected power response for the DRL response it was contracted to provide.
- See Figure 24 for events AP7 & 10 (titled 'AP7 10') where the frequency is above the 50 Hz + 0.1 Hz band and the BESS reduces import by 10 MW over 10 s until the frequency comes back within the 50 +0.1 Hz band. This is consistent with the change in expected power response for DM-L.





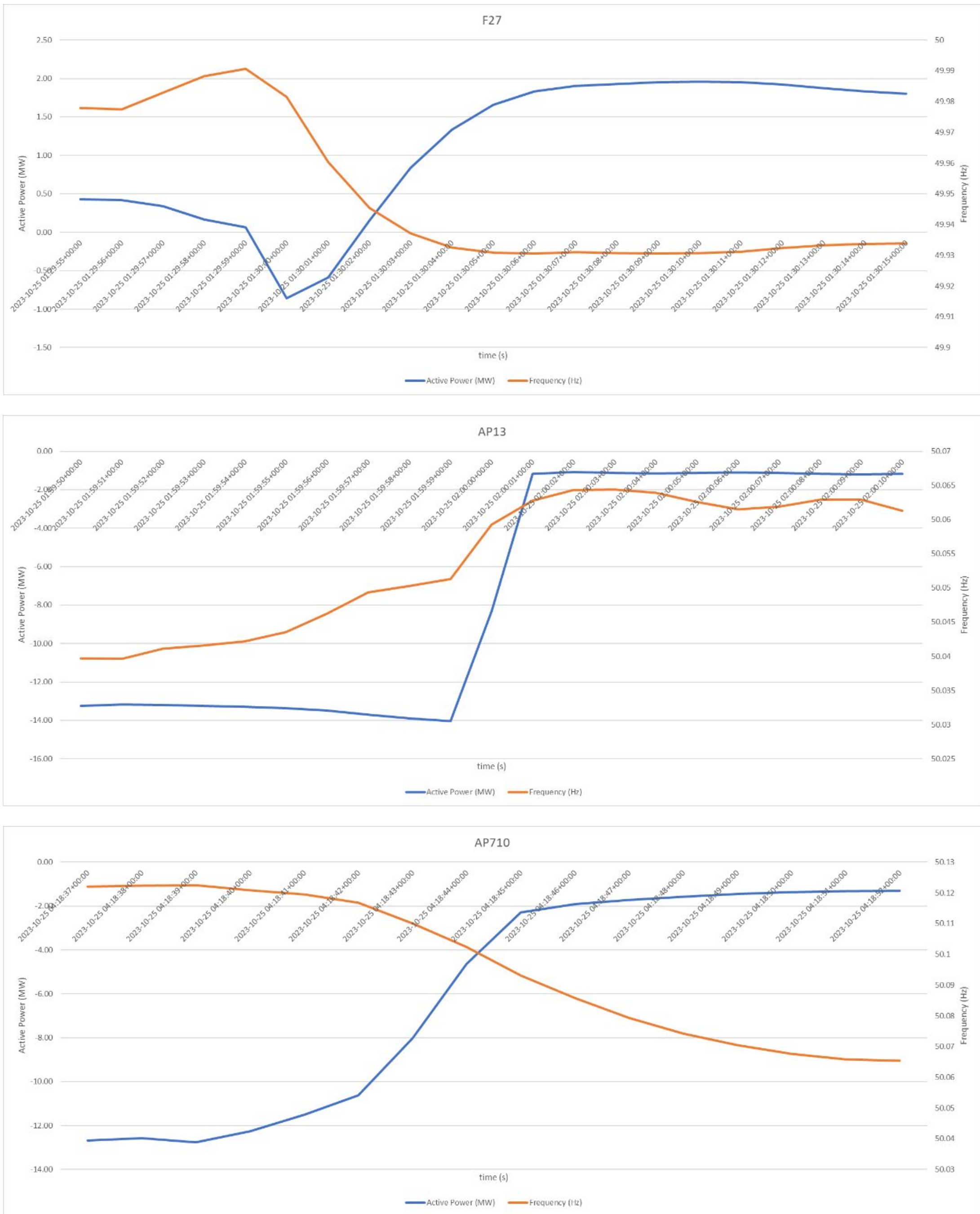


Figure 24 – Plots of Active Power Change Against Frequency Change for Site A BESS

14.3 Site B Data Analysis

Both 1 Hz and 20 Hz (i.e. every 50 ms) data over a 1 hour period was provided. However the sets of data did not match.

For the 20 Hz data there are insignificant power changes in the order of 100’s of kilowatts. These provide no real voltage changes.

The maximum voltage change recorded was 0.45 % from nominal voltage within the 1 hour period.

The biggest 1 s voltage change was approx. 31 V (0.1 % of nominal voltage). This suggests the BESS is operating well within its maximum potential capacity.

15 Appendix F NPg Approach to P28 Assessment

During the application process for the connection of a BESS to the EHV network (or connected at the HV busbars of EHV/HV substations), the EHV Connection Design Engineer carries out a simplified assessment of the maximum voltage step that could be caused by the proposed BESS (see Figure 25).

This assessment is carried out by performing a load flow analysis with the BESS operating at maximum active power export and at 0.95 power factor lag (exporting VArs). All transformer tap-changers in the network model are then locked. A subsequent load flow analysis is then carried out with the BESS operating at maximum active power import and at 0.95 power factor lag (importing VArs). In both cases the load flow analysis calculates the voltage at the Point of Common Coupling (PCC). The difference in the two voltages determined by the load flow analysis is the voltage step. This is assessed against the EREC P28 voltage step limit of 3 %.

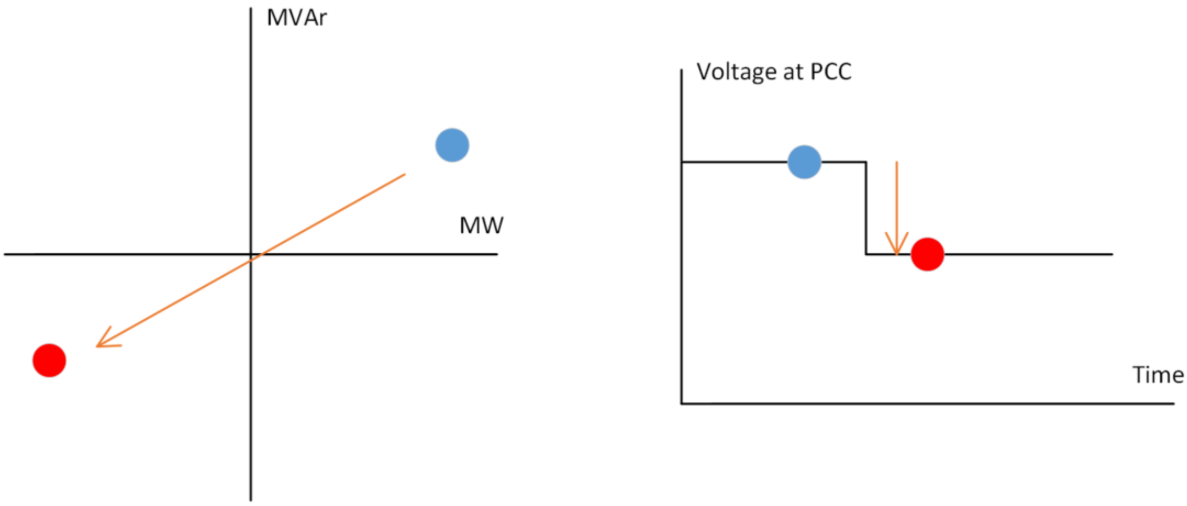


Figure 25 – NPg Simple Assessment of Voltage Step Change (Blue Initial Condition, Red Final Condition)

This voltage step change assessment is carried out under network intact conditions and also under other contingency conditions where the fault level at the PCC would be lower and the BESS can remain connected. If we take as an example a 20 MW BESS, the Design Engineer, may determine that the voltage step change is less than 3% under network intact conditions but that under a N-1 condition the voltage step change is more than 3%. They may then recommend that a constraint scheme is put in place to limit the maximum active power import and/or export of the BESS under N-1 conditions such that the 3% voltage step change limit is not exceeded. This import / export constraint is then included in the connection offer.

During the construction phase of the BESS project, the developer will commission a full EREC P28 study. EREC P28 categorises voltage fluctuations into three: (1) voltage step, (2) Rapid Voltage Change (RVC), and (3) flicker. The EREC P28 study is usually carried out as follows:

1. A voltage step change assessment based on the BESS tripping off the network whilst operating at maximum active power export and maximum active power import. This may be done at a particular power factor, or under a range of power factors between 0.95 lag and 0.95 lead.
2. A voltage step change assessment may be made based on the BESS swinging from full export to full import active power, at particular power factors, but there is not a consistent approach to this.
3. A Rapid Voltage Change (RVC) study for transformer energisation.
4. A voltage flicker study based on the flicker caused by the high frequency power electronic switching within the BESS inverters. System fault level and the flicker emissions published by the inverter manufacturer are the inputs to this study.

On some projects the developer has challenged the active power swing limit that may be present in the connection offer based on how the developer believes that the plant will be operated after it is commissioned. For example the developer may explain that:

1. The BESS will never instantaneously swing between maximum active power export to import and vice versa. It will always ramp over a period of time, and this must be properly considered in a voltage fluctuation assessment.
2. Although the BESS is required to have the capability to operate between 0.95 power factor lead / lag (as per the reactive capability requirements of EREC G99), in reality, post-energisation it will operate at a fixed power factor, or fixed reactive power output. The simplified assessment carried out by NPg considers swings between worst case power factors.

In the case of (1), it can be difficult for the developer to exactly assess how fast this ramping will be. In the case of a BESS operating in a frequency response mode, it will depend on how quickly the system frequency changes and how quickly the BESS must react to that frequency change in accordance with the performance specification of the frequency response contract with NGESO. In the case of (2), NPg may require the BESS to operate at a fixed reactive power when exporting (due to National Grid ESO requirements) or may allow the BESS to operate within a particular power factor range depending upon local network conditions.

The NPg assessment, whilst simple and fast to carry out, is a worst case and the most conservative assessment. However, EREC P28 does not offer detailed guidance for assessing BESS, and it is left open for interpretation by the DNO, developer and their consultants.

16 Appendix G Explanation of Voltage Fluctuations

16.1 General

P28 defines three types of voltage fluctuation:

- Flicker.
- Step voltage change.
- Rapid voltage change.

These types of voltage fluctuation are summarised in this Appendix for ease of reference,

16.2 Flicker

Flicker is defined in P28 as:

"impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time".

P28 requires the severity of flicker to be assessed against limits. The short term flicker severity caused by voltage changes is measured using an index known as P_{st}.

Generally the more frequent the voltage changes the higher the value of P_{st} will be. Alternatively, voltage changes that are larger but less frequent can also result in a higher value of P_{st}.

For a given rectangular (instantaneous) voltage change it is possible to determine the maximum frequency of repetition to comply with a given flicker severity limit, e.g. P_{st} = 1 by referencing the 'flicker curves' in P28.

A rectangular voltage change is defined as an instantaneous change in voltage, where d_{max} is the maximum voltage change. Rectangular voltage changes produce the highest flicker severity for a given d_{max} compared with ramp voltage (see below).

Where the voltage change characteristic (or shape) of the voltage change is known (but it is not a rectangular (instantaneous) voltage change) then shape factors can be used to determine the equivalent rectangular (instantaneous) voltage change that can be used with the flicker curves in P28.

Shape factors can be derived from the curves presented in P28 for the following types of voltage change characteristics.

- Ramp type voltage characteristics (known as ramp voltage changes).
- Motor start type voltage characteristics.
- Sinusoidal type voltage characteristics.
- Triangular type voltage characteristics.
- Pulse type voltage characteristics.

BESS operation tends to produce ramp type voltage changes. The ramp voltage changes discussed here should not be confused with the term rapid voltage change (RVC) described below. A ramp voltage change is defined as a linear change in voltage over a time period (see Figure 26 below), where d_{max} is the maximum voltage change over a time period *T*.

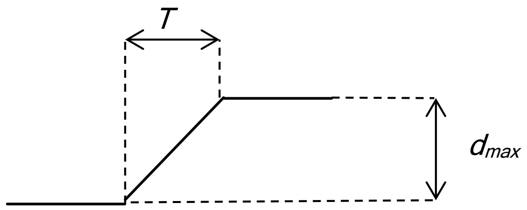


Figure 26 – Ramp Voltage Type Characteristic

The duration of ramp voltage changes, at a given ramp rate, produced by BESS are generally in the order of several seconds. The voltage change created by a BESS can last several minutes and can comprise of consecutive ramp voltage changes.

For BESS operation, the ramp rate relates to the voltage change over a given time period, which is dependent on a given BESS power change (import or export), e.g. MW/s, over the same time period.

The shape factor curves for ramp voltage changes in P28 show that, for the same magnitude of voltage change, a voltage that ramps over a longer time period will result in a lower flicker severity.

It is important to note that shape factor curves are only applicable to the assessment of flicker. They are not applicable to the assessment of step voltage change or RVCs.

16.3 Step Voltage Change

Step voltage change is defined in P28 as:

"change from the initial voltage level to the resulting voltage level after all generating unit automatic voltage regulator (AVR) and static VAR compensator (SVC) actions and transient decay (typically 5 seconds after the fault clearance or system switching) have taken place, but before any other automatic or manual tap-changing and switching actions have commenced"

A variety of different voltage change characteristics, such as rectangular (instantaneous) type voltage changes and ramp voltage changes can be classed as step voltage changes and assessed as such according to P28.

Step voltage changes can be changes in steady state voltages or changes from one non steady state voltage to another. There is no defined time period that a voltage change must occur within to be a step voltage change unlike RVCs. A step voltage change that can be classed as an RVC if it is a steady state voltage and lasts no longer than 2 s.

16.4 Rapid Voltage Change

A rapid voltage change is defined in P28 as:

"change in root mean square (r.m.s.) voltage over several cycles"

P28 clarifies for a voltage to be assessed as a RVC it must be a change in steady state voltage lasting no more than 2 s.

The purpose of RVC assessments in P28 is to assess voltage changes arising from transformer energisation or motor starting where there is a transient change in voltage that decays over time to a steady state value.

It is not believed that normal BESS operation can produce this type of voltage characteristic. As such ramp type voltage characteristics produced by BESS are assessed against the step voltage change limit of 3 %.

17 Appendix H Worked Examples

17.1 Simplified Assessment for Constant Power Factor

The following example assumes a fixed X/R ratio and short circuit power with a unity pf.

Example

Let pf = 1.0 (i.e. unity pf) with no *Q*.

$$\Delta V = \frac{(RP + XQ)}{V}$$

Therefore, as *Q* = 0 then: $\Delta V = \frac{RP}{V}$

For a 3% voltage change which is equivalent to ΔV = 0.03pu where *V* = 1pu.

Hence, $P_{max} = \frac{V\Delta V}{R} = \frac{0.03}{R_{pu}}$

$$\delta V = \frac{(XP - RQ)}{V}$$

Therefore, as *Q* = 0 then: $\delta V = \frac{XP}{V}$

For a 3% voltage change which is equivalent to δV = 0.03pu where *V* = 1pu.

Hence, $P_{max} = \frac{V\delta V}{X} = \frac{0.03}{X_{pu}}$

For an example of 100MVA base where *X* = 0.3pu. Then, $P_{max} = \frac{0.03}{0.3} = 0.1$pu which is equivalent to 10MW.

Assuming a tap-changer operation at 120s.

Therefore, the max. ramp rate (power/s) = $\frac{10MW}{120s} = \frac{1}{12}\ MWs^{-1}$

Applying an example *X/R* ratio = 20 to the above equations and *V* = 1pu.

$$\Delta V = \frac{RP}{V} = \frac{XP}{20}\ and\ \delta V = \frac{XP}{V} = XP$$

Change in Voltage = $\sqrt{(\Delta V)^2 + (\delta V)^2} = \sqrt{\left(\frac{XP}{20}\right)^2 + (XP)^2} = \sqrt{\left(\frac{X^2P^2}{400}\right) + X^2P^2} = \sqrt{1.0025X^2P^2}$

For a 100MVA base and *X* = 0.3pu and a 3% voltage change:

$$P = \sqrt{\frac{(Change\ in\ Voltage)^2}{1.0025X^2}} = \sqrt{\frac{(0.03)^2}{1.0025 \times 0.3^2}} = 0.099875pu = 9.9875MW$$

Therefore the maximum power change permitted before the tapchanger operates to comply with the 3% step voltage change limit is 9.9875MW.

17.2 Simplified Assessment Using Maximum Ramp Rate

In this example the maximum ramp rate for a power change P is calculated which gives a step voltage change = 3% at 0.95 pf.

Example

$$\Delta V = \frac{X}{R}P + X\text{Ptan}\emptyset \; and \; \delta V = XP - \frac{X}{R}\text{Ptan}\emptyset$$

Change in Voltage = $\sqrt{\left(\frac{X}{R}P + X\text{Ptan}\emptyset\right)^2 + \left(XP - \frac{X}{R}\text{Ptan}\emptyset\right)^2}$

Assuming an X/R ratio of 20 and X = 0.3pu:

For a real fault level, S and with a given pf. The X pu can be determined.

E.g. If S = 8MVA and pf = 0.95:

Change in Voltage = $\sqrt{\left(\frac{X}{20}P + X\text{Ptan}\emptyset\right)^2 + \left(XP - \frac{X}{20}\text{Ptan}\emptyset\right)^2}$

As cosØ = 0.95, then tanØ = 0.329 and 3% voltage change and a 100MVA base:

Change in Voltage = $\sqrt{(0.379XP)^2 + (0.98355XP)^2} = \sqrt{1.111011X^2P^2}$

$$P = \sqrt{\frac{(Change\ in\ Voltage)^2}{1.111011X^2}} = \sqrt{\frac{(0.03)^2}{1.111011 \times 0.3^2}} = 0.094873pu = 9.4873MW$$

For the above example with a maximum power change of 9.4873MW and for a given maximum ramp rate of $4MWs^{-1}$. The maximum time for the ramp can be given as:

$$Ramp\ time\ (s) = \frac{Maximum\ Power\ Change\ (MW)}{Maximum\ Ramp\ Rate\ (MWs^{-1})} = \frac{9.4873MW}{4MWs^{-1}} = 2.37s$$

Thus if the maximum power change in MW for a 3% step voltage change is known then an acceptable ramp rate (MW/s) and ramp time (s) can be determined using the operating envelope (see Figure 27).

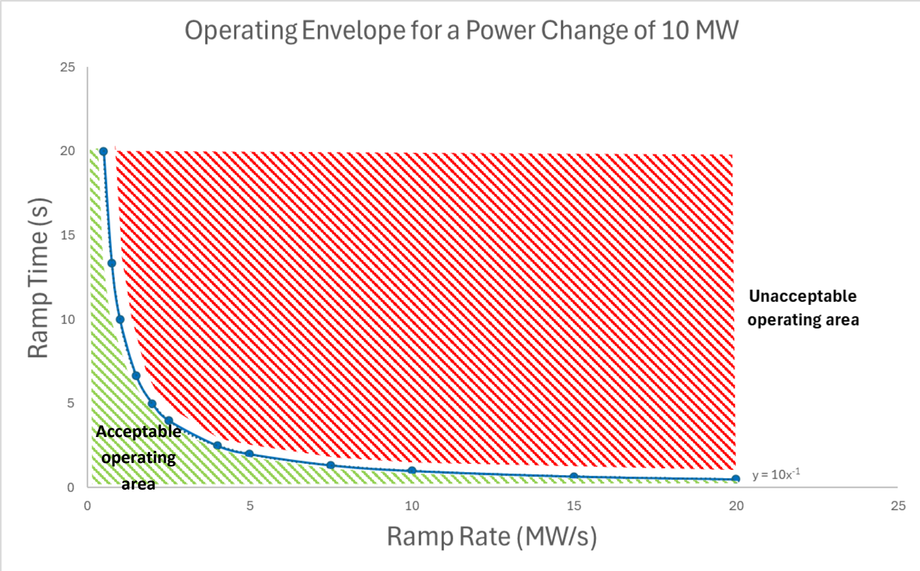


Figure 27 – Operating Envelope For A Given Power Change

Similarly, if we know the maximum ramp rate in MW/s then for a 3% step voltage change, an acceptable power change (MW) and ramp time (s) can be determined from the operating envelope (see Figure 28).

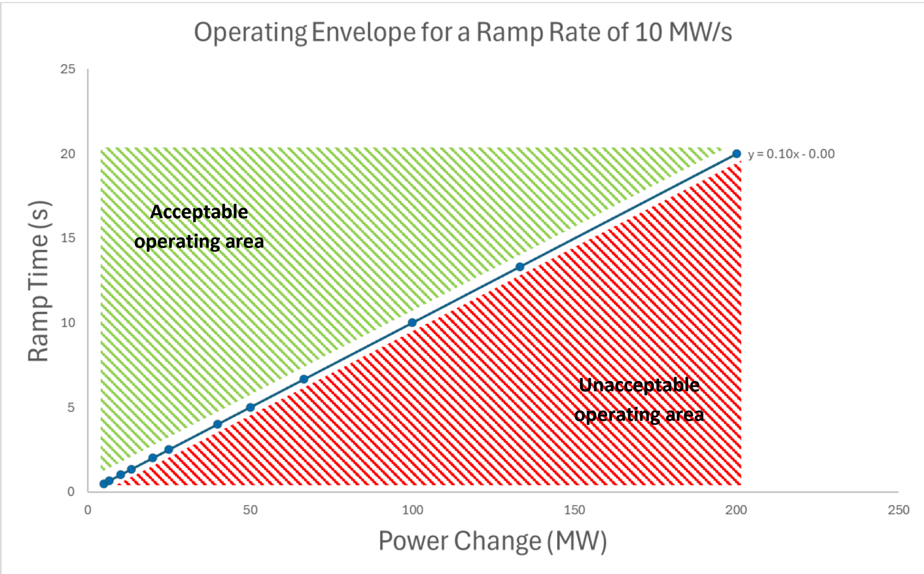


Figure 28 – Operating Envelope For A Given Ramp Rate

The BESS operator shall ensure that their stated maximum power change/ramp rate is less than the maximum power change at 3% step voltage change using the calculations above.

An example for a BESS with a capacity of 100MW. It has a calculated maximum power change for a 3% limit = 250MW. For this BESS, the maximum power swing, i.e. full export to full import, is 200MW. Hence, the BESS can apply full capacity. If the BESS is found to not be able to meet this requirement, then its capacity must be constrained.

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