GC0090: HVDC - Fault Ride Through

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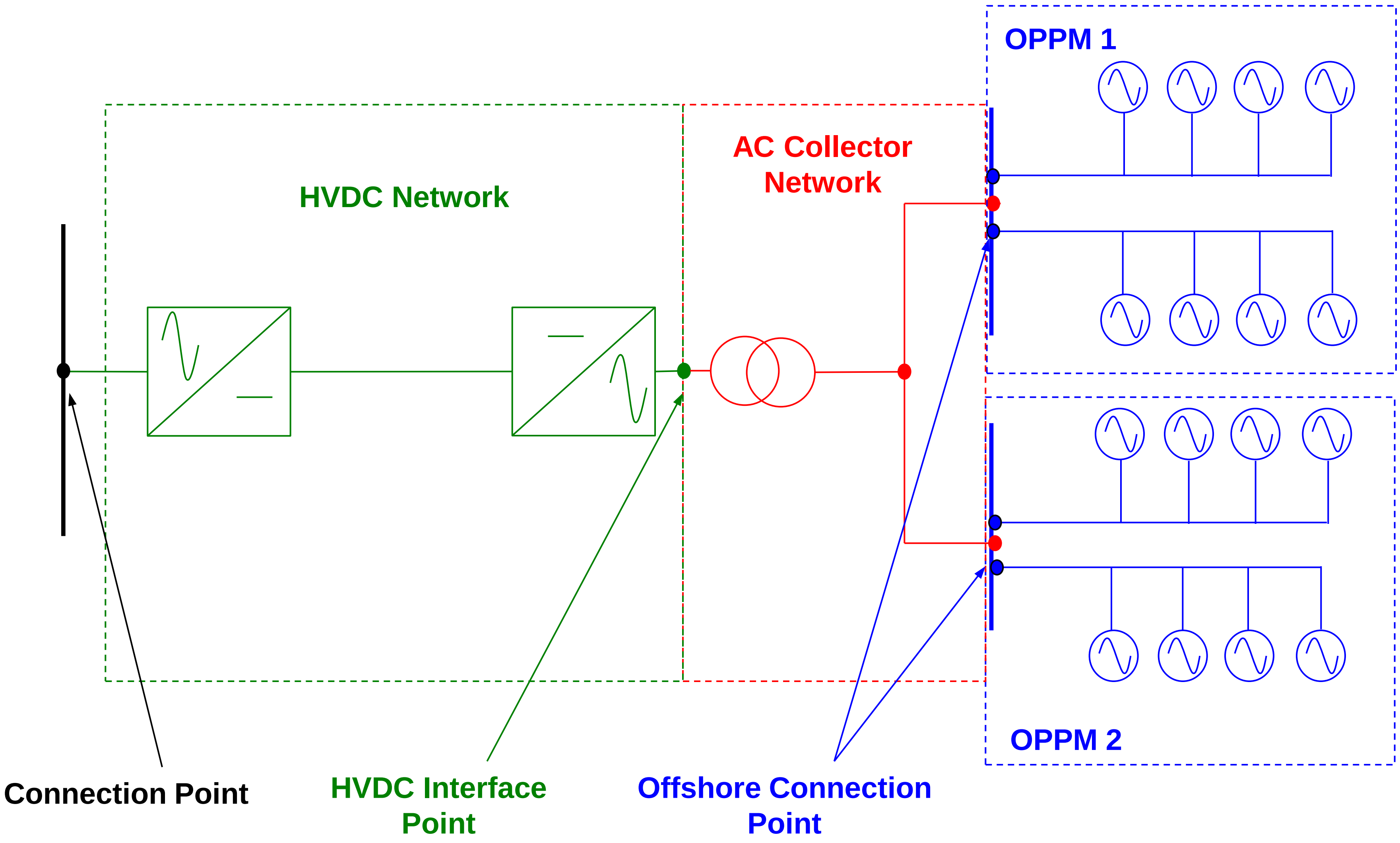
Summary

- Overview
- Definitions
- Fault Ride Through Requirements for HVDC Converters
- Fault Ride Through Requirements for DC Connected Power Park Modules
- Fault Ride Through Requirements for Remote End HVDC Converter Stations
- Fast Fault Current Injection requirements
- Next Steps

Overview

- Title II, Chapter 3 – Article 25, 26, 27, Annex V – Fault Ride Through requirements for HVDC Converters including post fault active power recovery and recovery from DC faults
- Title III, Chapter 1 – Requirements for DC Connected Power Park Modules – As per RfG (Articles 14(3), 16(3), plus fast fault current injection 20(2) and 20(3)) and HVDC Code Article 40(3). All requirements apply at the HVDC Interface Point
- Title III, Chapter 2 – Requirements for Remote End HVDC Converter Stations – As per Title II and applicable at the Remote End Converter Station Network?

Overview of Requirements



Definitions

- Connection Point – means the interface at which the power generating module, demand facility, distribution system or HVDC system is connected to a transmission system, offshore network, distribution system, including closed distribution systems or HVDC system, as identified in the connection agreement [RfG]
- HVDC Interface Point – means a point at which HVDC equipment is connected to an AC network, at which technical specifications affecting the performance of the equipment can be prescribed [HVDC]
- Offshore Connection Point - A Connection Point located offshore [ENTSO-E Metadata]

Fault Ride Through Capability for HVDC Converters

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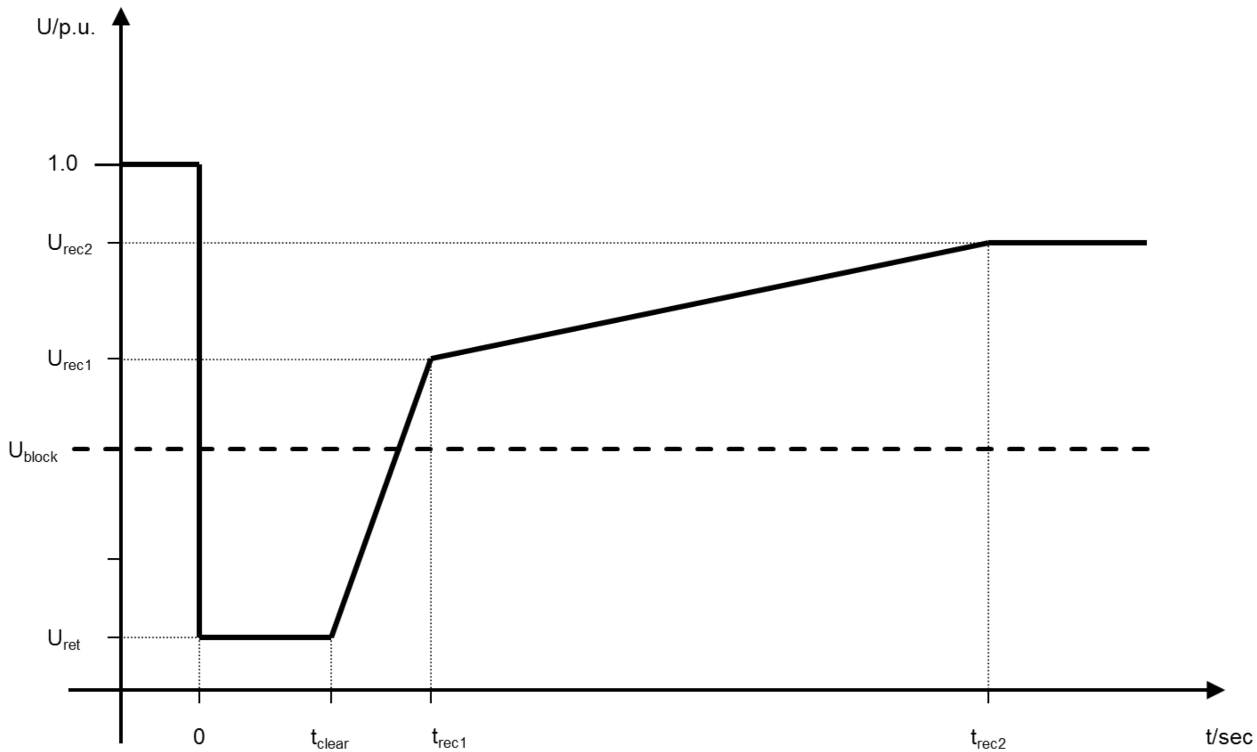
Fault Ride Through Capability for HVDC Converters (Title II - Chapter 3 – Art 25(1))

- The relevant TSO shall specify, while respecting Article 18, a voltage-against time profile as set out in Annex V and having regard to the voltage-against-time-profile specified for power park modules according to [NC RfG]. This profile shall apply at connection points for fault conditions, under which the HVDC converter station shall be capable of staying connected to the network and continuing stable operation after the power system has recovered following fault clearance. The voltage-against-time-profile shall express a lower limit of the actual course of the phase-to-phase voltages on the network voltage level at the connection point during a symmetrical fault, as a function of time before, during and after the fault. Any ride through period beyond t_{rec2} shall be specified by the relevant TSO consistent with Article 18.

Annex V- HVDC Voltage against time curve – Figure 6



Fault-ride-through profile of an HVDC converter station. The diagram represents the lower limit of a voltage-against-time profile at the connection point, expressed by the ratio of its actual value and its reference 1 pu value in per unit before, during and after a fault. U_{ret} is the retained voltage at the connection point during a fault, t_{clear} is the instant when the fault has been cleared, U_{rec1} and t_{rec1} specify a point of lower limits of voltage recovery following fault clearance. U_{block} is the blocking voltage at the connection point. The time values referred to are measured from t_{fault}.

Annex V- HVDC Voltage against time curve Parameters – Table 7

Voltage Parameters [pu]		Time Parameters [seconds]	
U_{ret}	0.00 – 0.30	t_{clear}	0.14 - 0.25
U_{rec1}	0.25 – 0.85	t_{rec1}	1.5 - 2.5
U_{rec2}	0.85 – 0.90	t_{rec2}	T_{rec1} – 10.0

Fault Ride Through Capability for HVDC Converters (Title II - Chapter 3 – Art 25(2))

- On request by the HVDC system owner, the relevant system operator shall provide the pre-fault and post-fault conditions as provided for in Article 32 regarding:
  - pre-fault minimum short circuit capacity at each connection point expressed in MVA;
  - pre-fault operating point of the HVDC converter station expressed as active power output and reactive power output at the connection point and voltage at the connection point; and
  - post-fault minimum short circuit capacity at each connection point expressed in MVA.
- Alternatively, generic values for the above conditions derived from typical cases may be provided by the relevant system operator.

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Fault Ride Through Capability for HVDC Converters (Title II - Chapter 3 – Art 25 (3-4))

- Art 25(3) - The HVDC converter station shall be capable of staying connected to the network and continue stable operation when the actual course of the phase-to-phase voltages on the network voltage level at the connection point during a symmetrical fault, given the pre-fault and post-fault conditions provided for in Article 32, remain above the lower limit set out in the figure in Annex V, unless the protection scheme for internal faults requires the disconnection of the HVDC converter station from the network. The protection schemes and settings for internal faults shall be designed not to jeopardize fault-ride-through performance.
- Art 25(4) - The relevant TSO may specify voltages (U_{block}) at the connection points under specific network conditions whereby the HVDC system is allowed to block. Blocking means remaining connected to the network with no active and reactive power contribution for a time frame that shall be as short as technically feasible and which shall be agreed between the relevant TSOs and the HVDC system owner.

Fault Ride Through Capability for HVDC Converters (Title II - Chapter 3 – Art 25 (5-6))

- Art 25(5) - In accordance Article 34, undervoltage protection shall be set by the HVDC system owner to the widest possible technical capability of the HVDC converter station. The relevant system operator, in coordination with the relevant TSO, may specify narrower settings pursuant to Article 34.
- Art 25(6) – The relevant TSO shall specify fault-ride-through capabilities in case of asymmetrical faults.

Fault Ride Through Capability for HVDC Converters (Title II - Chapter 3 – Art 26 & 27)

- Article 26 – Post Fault Active Power Recovery
  - The relevant TSO shall specify the magnitude and time profile of active power recovery that the HVDC system shall be capable of providing, in accordance with Article 25.
- Article 27 – Fast Recovery from DC Faults
  - HVDC systems, including DC overhead lines, shall be capable of fast recovery from transient faults within the HVDC system. Details of this capability shall be subject to coordination and agreements on protection schemes and settings pursuant to Article 34.

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Article 32 – Network Characteristics

- The relevant system operator shall specify and make publicly available the method and the pre-fault and post-fault conditions for the calculation of at least the minimum and maximum short circuit power at the connection points.
- The HVDC system shall be capable of operating within the range of short circuit power and network characteristics specified by the relevant system operator.
- Each relevant system operator shall provide the HVDC system owner with network equivalents describing the behaviour of the network at the connection point, enabling the HVDC system owners to design their system with regard to at least, but not limited to, harmonics and dynamic stability over the lifetime of the HVDC system.

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Fault Ride Through requirements for DC Connected Power Park Modules

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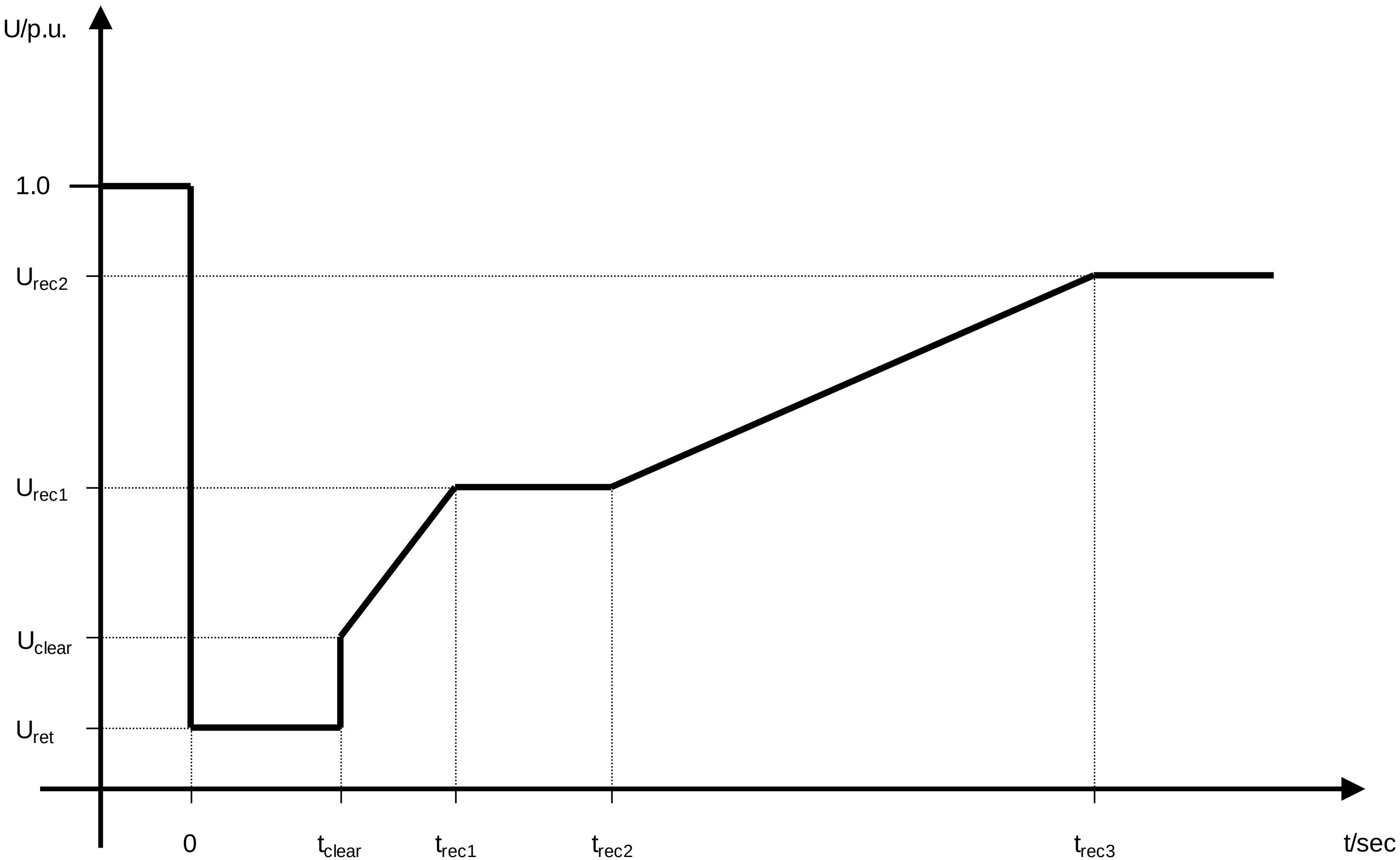
Summary

- The requirements applicable to Offshore Power Park Modules under Articles 13 to 22 of [NC RfG] shall apply to DC-connected Power Park Modules subject to specific requirements provided for in Articles 41 to 45 of the HVDC Code.
- These slides present the latest views of the RfG Fault Ride Through Workgroup (GC0048) in relation to the voltage against time curves for Power Park Modules
- This section of the presentation only covers an abridged version of the RfG fault ride through requirements as applicable to Power Park Modules. For a full summary of the requirements, the reader is encouraged to look at the slides on the GC0048 Website available at:-
  - http://www2.nationalgrid.com/UK/Industry-information/Electricity-codes/Grid-code/Modifications/GC0048/

RfG - Fault Ride Through Requirements – Voltage Against Time Profile – Figure 3



Type D Power Park Modules connected at or above 110kV

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RfG - Voltage Against Time Parameters – Table 7.2 – Type D Power Park Modules connected at or above 110kV

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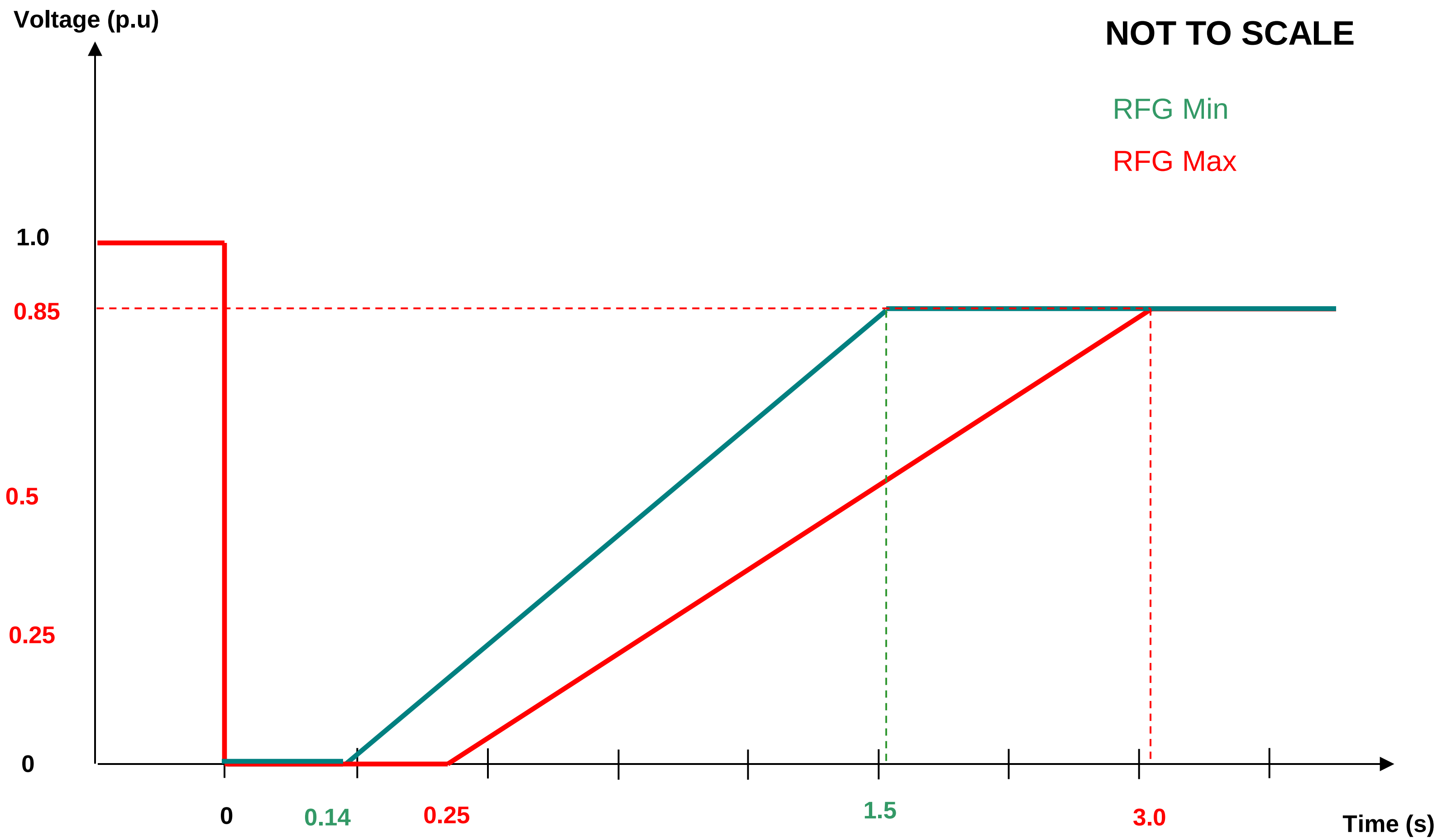
Voltage parameters [pu]		Time parameters [seconds]	
U_{ret}:	**0**	t_{clear}:	**0.14 – 0.15** (or 0.14 – 0.25 if system protection and secure operation so require)
U_{clear}:	U_{ret}	t_{rec1}:	t_{clear}
U_{rec1}:	U_{clear}	t_{rec2}:	t_{rec1}
U_{rec2}:	**0.85**	t_{rec3}:	**1.5 – 3.0**

Table 7.2 – Fault Ride Through Capability of Power Park Modules

RfG - Voltage Against Time Profile

Type D Power Park Modules Table 7.2 connected at or above 110kV



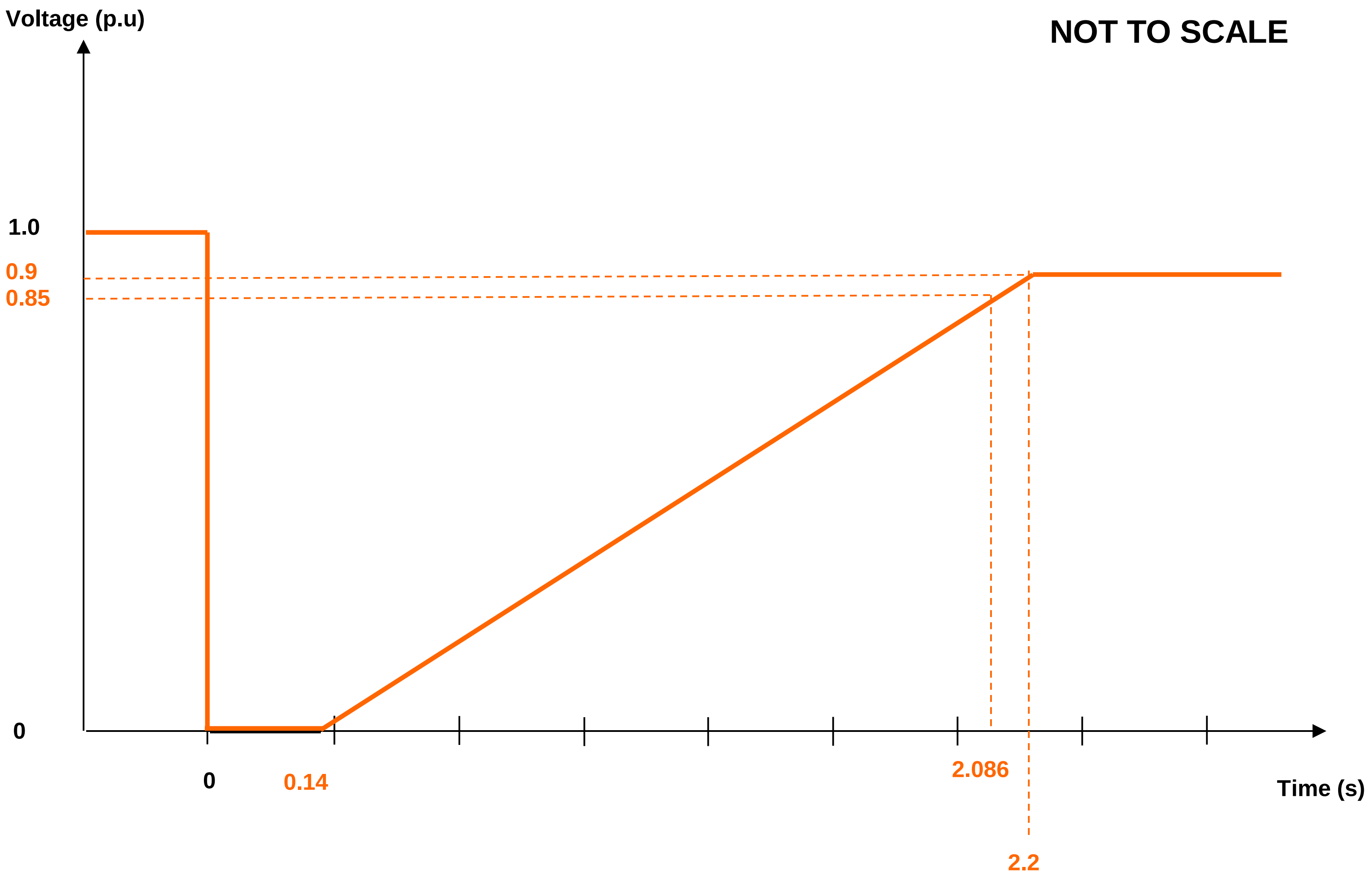
Derivation of Voltage Against Time Profile

Type D Power Park Modules connected at or above 110kV

- Limited flexibility due to defined parameters
- t_{clear} set to 140ms for protection operating times (as per synchronous power generating modules)
- All other parameters are defined other than t_{rec3}. Based on System Studies, the slow voltage recovery that can be observed due to high MVAr demands under minimum demand conditions and low fault infeeds results in the requirement for this value in the order of 2 seconds. Under the SQSS an important value is a voltage of 0.9p.u voltage at 2.2 seconds. It therefore seems appropriate to set t_{rec3} to 0.85p.u at 2.086 seconds which is the interpolated value from 2.2 seconds at 0.9p.u voltage

RfG - Voltage Against Time Profile

Type D (connected at ≥110kV) Power Park Modules



RfG - Voltage Against Time Parameters – Table 7.2 – Type D Power Park Modules connected at or above 110kV

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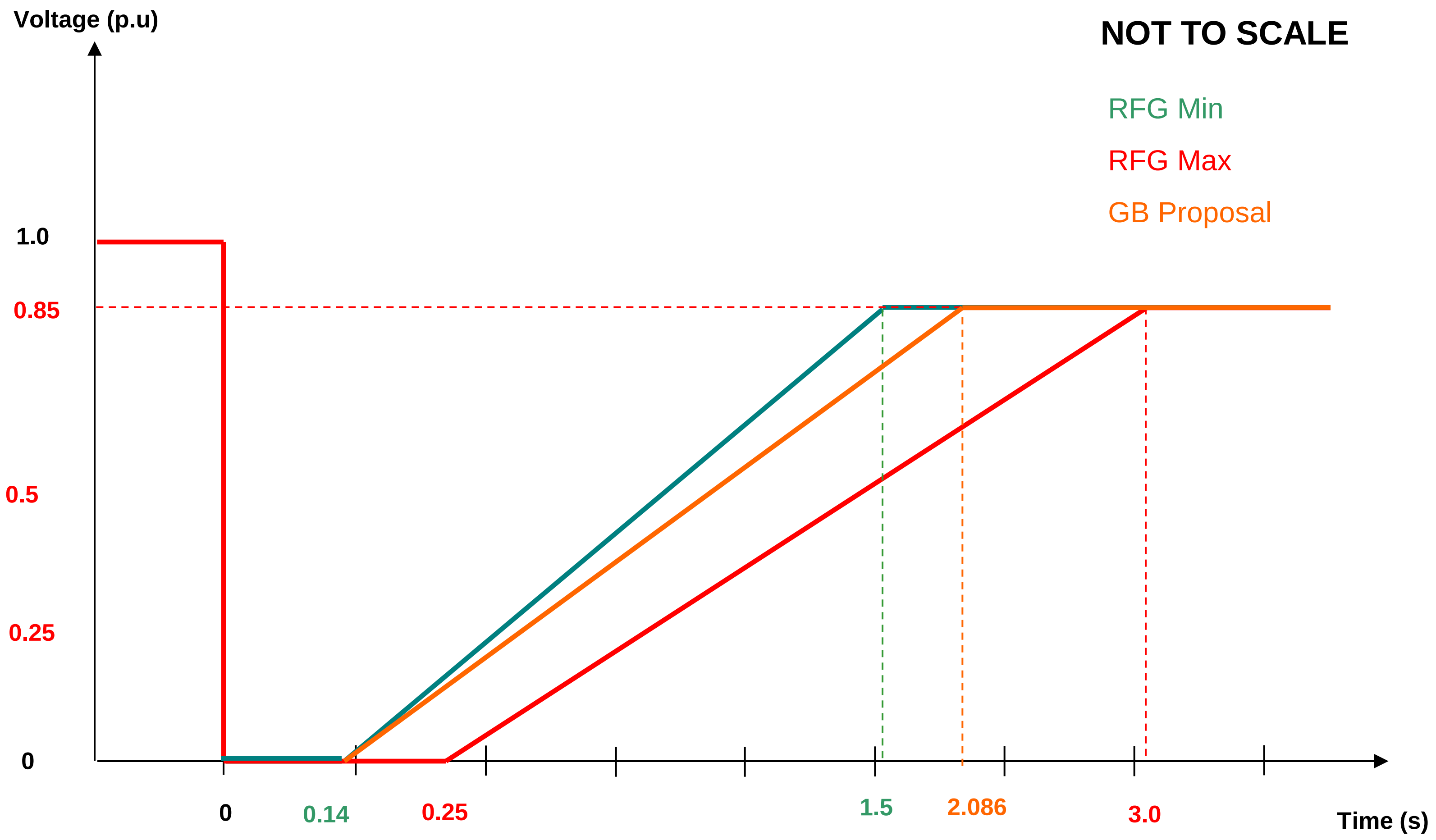
Voltage parameters [pu]		Time parameters [seconds]	
U_{ret}:	0	t_{clear}:	0.14
U_{clear}:	0	t_{rec1}:	0.14
U_{rec1}:	0	t_{rec2}:	0.14
U_{rec2}:	0.85	t_{rec3}:	2.086

Table 7.2 – Fault Ride Through Capability of Power Park Modules

RfG - Voltage Against Time Profile

Type D Power Park Modules Table 7.2 connected at or above 110kV



Issues

- None envisaged for Power Park Modules connected at 400/275kV as broadly similar to current Grid Code requirements
- Under the current GB Grid Code, Generating Units, Power Park Modules and HVDC Converters are required to remain connected and stable for any fault at 200kV or above
- For a 132kV connected Power Park Modules currently connected at 132kV, they need to remain connected and stable for 400/275kV faults but not 132kV faults
- There are not expected to be major issues for Power Park Modules connected at 132kV
- Input required from stakeholders

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Type B, C and D Power Park Modules connected below 110kV

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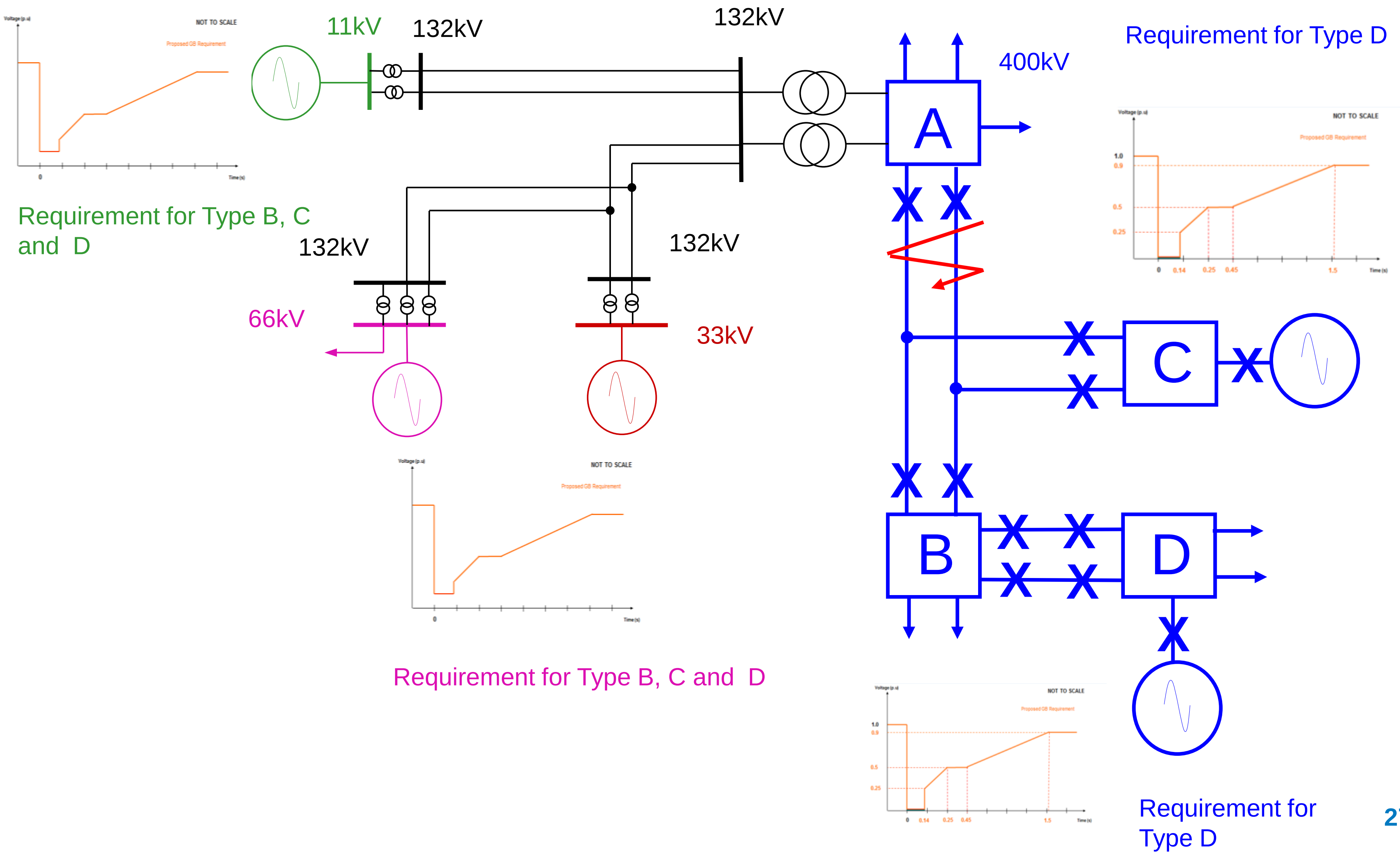
Fault Ride Through Interpretation



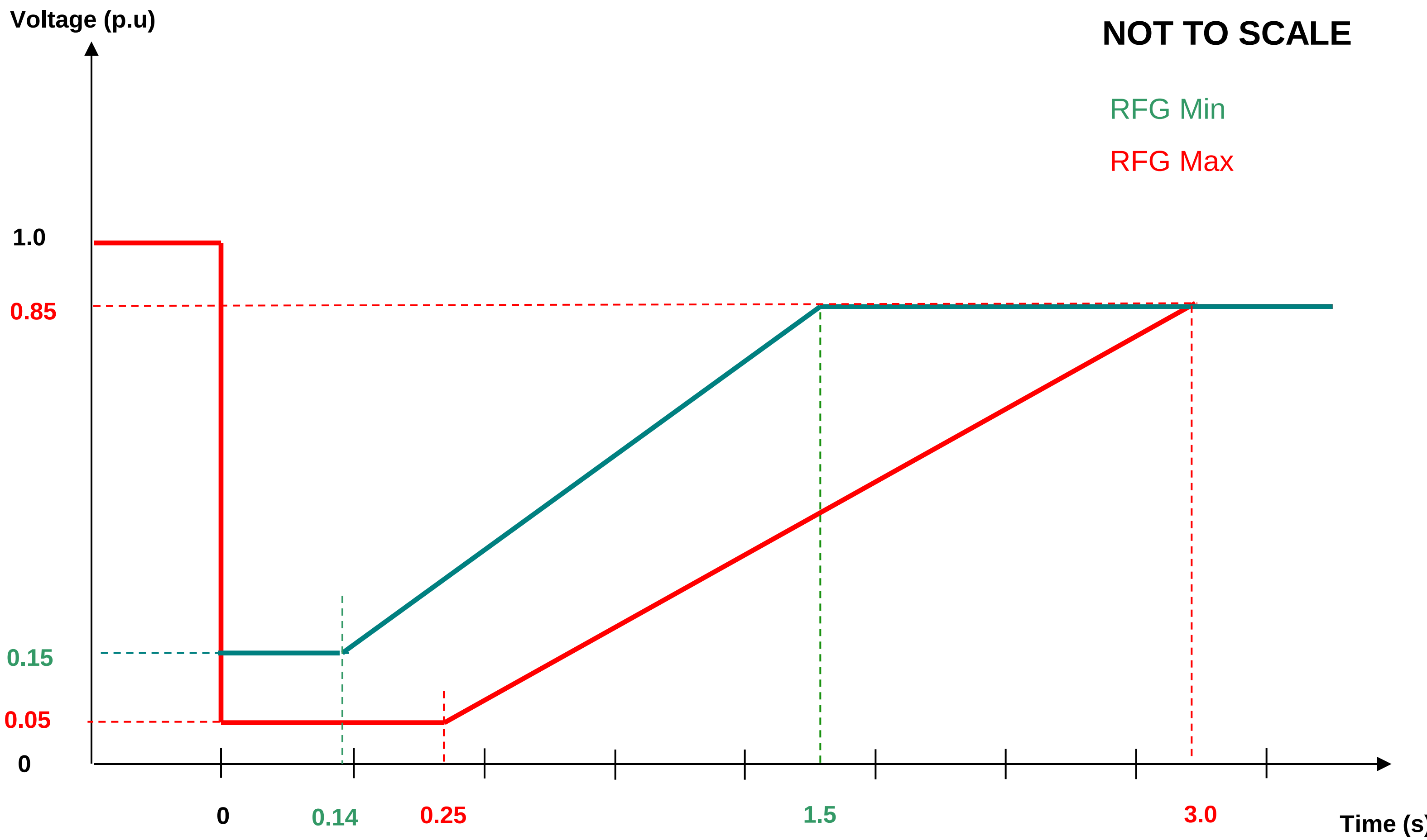
RfG - Voltage Against Time Parameters – Table 3.2 – Type B & C and D Connected below 110kV Power Park Modules

Voltage parameters [pu]		Time parameters [seconds]	
U_{ret}:	**0.05 – 0.15**	t_{clear}:	**0.14 – 0.15** (or 0.14 – 0.25 if system protection and secure operation so require)
U_{clear}:	U_{ret} **– 0.15**	t_{rec1}:	t_{clear}
U_{rec1}:	U_{clear}	t_{rec2}:	t_{rec1}
U_{rec2}:	**0.85**	t_{rec3}:	**1.5 – 3.0**

Table 3.1 – Fault Ride Through Capability of Power Park Modules

ENTSO-E RfG - Voltage Against Time Profile

Type B / C and Type D Connected below 110kV Power Park Modules - Table 3.2



Fault Ride Through Type B, C and D
Power Park Modules connected below 110kV

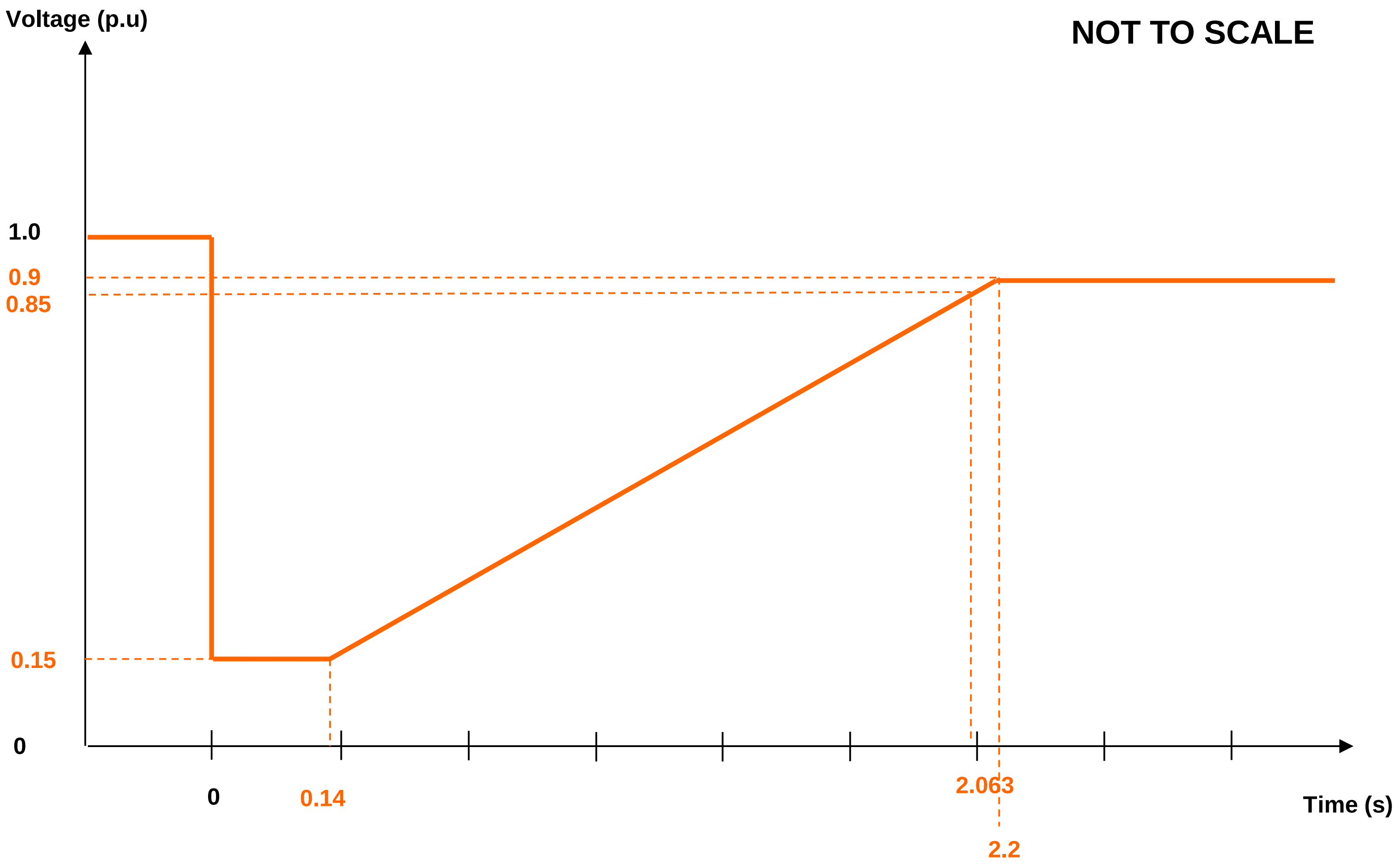
- Requirements for Type B / C and D Power Park Modules connected at or below 110kV
- Adopt same principles as that for Synchronous Power Generating Modules.
- The Voltage against time curve seen at the connection point should reflect the equivalent voltage at that point for a Transmission System fault

Derivation of Voltage Against Time Profile
Type B, C and D Power Park Modules connected below 110kV

- t_{clear} set at 0.14s – consistent with Transmission Protection Operating times
- U_{ret} set at 0.15 (see studies – concern is due to low fault infeed depressing system voltage, especially with low levels of synchronous generation running but also manufacturer capability)
- t_{rec3} - set at 2.063 seconds which is interpolated from a value of 2.2 seconds at 0.9p.u voltage

RfG - Voltage Against Time Profile

Type B, C and D Power Park Modules connected below 110kV



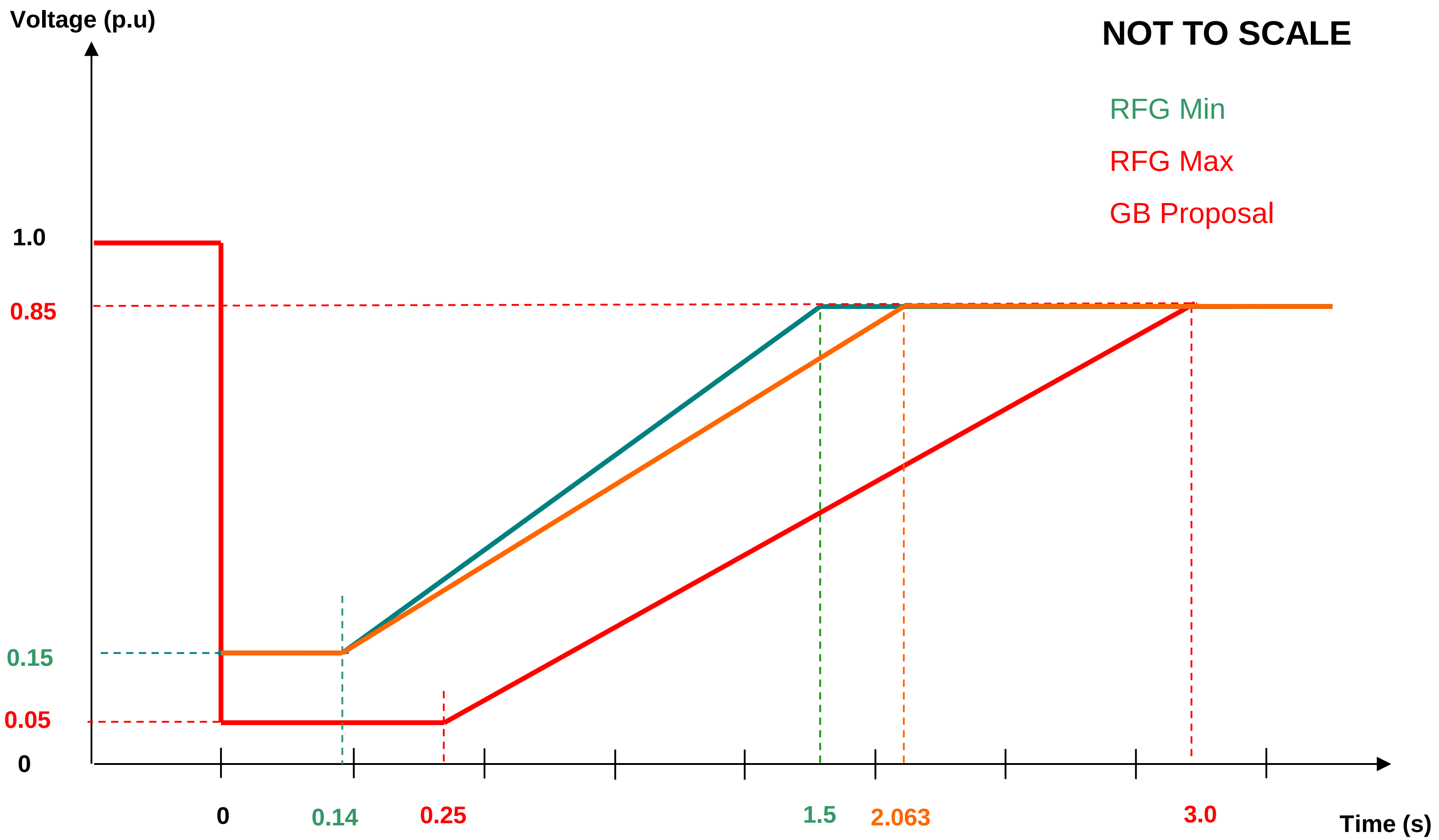
RfG - Voltage Against Time Parameters – Table 3.2 – Type B & C and D Connected below 110kV Power Park Modules

Voltage parameters [pu]		Time parameters [seconds]	
U_{ret}:	0.15	t_{clear}:	0.14
U_{clear}:	0.15	t_{rec1}:	0.14
U_{rec1}:	0.15	t_{rec2}:	0.14
U_{rec2}:	0.85	t_{rec3}:	2.063

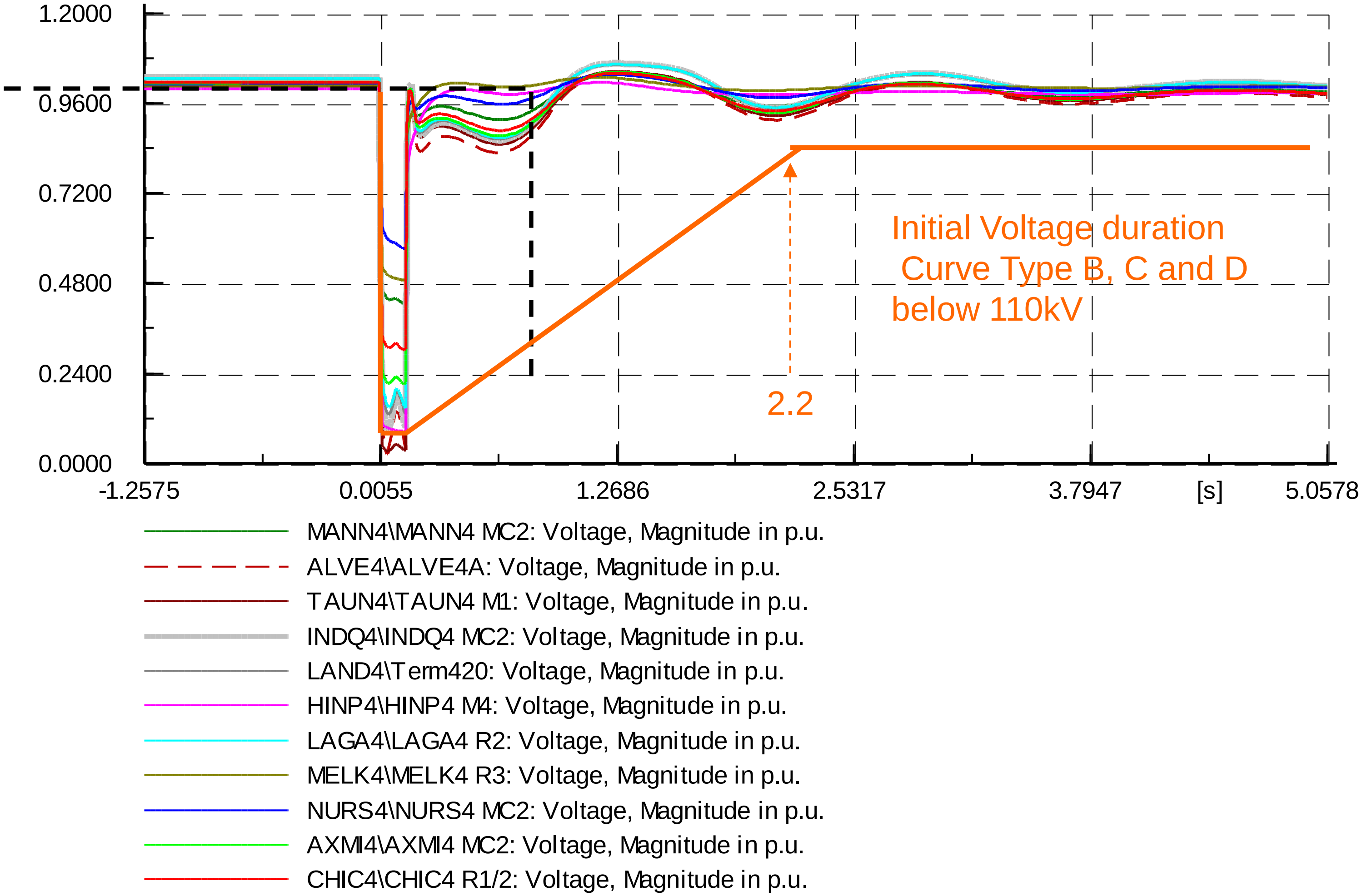
Table 3.1 – Fault Ride Through Capability of Power Park Modules

ENTSO-E RfG - Voltage Against Time Profile

Type B / C and Type D Connected below 110kV Power Park Modules - Table 3.2



SW Area Voltage against Time (2015 NSG capacities)



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Issues

- No major issues expected for new Generation Power Park Modules but input required from Stakeholders and Manufacturers
- G59 protection issues remain and some change is likely to be required to settings?
- Voltage profile well within tolerance based on system studies.
- Article 40(3) defines requirements for priority of Active or Reactive Power with regard to DC Connected Power Park Modules. These requirements are slightly different to the requirements defined in RfG Art 21(3)(e). It is assumed HVDC Art 40(3) takes priority

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Fault Ride Through requirements for Remote-End HVDC Converter Stations

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Title III – Chapter 2 – Article 46

- The requirements of Articles 11 to 39 apply to remote-end HVDC converter stations, subject to specific requirements provided for in Articles 47 to 50.
- There are no specific clauses within Articles 47 – 50 that relate to fault ride through.
- For the fault ride through requirements for HVDC Connections see slides 6 -15.

Fast Fault Current Injection

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Overview

- Title II – Chapter 2 – Article 19 – Short Circuit contribution during faults – Requirements for HVDC Connections - Priority for active or reactive power contribution – Article 23
- Title III – Chapter 1 – Requirements defined in RfG – Fast Fault Current covered in Articles 20(2) and 20(3)
- Title III – Chapter 2 – Requirements for Remote-End HVDC Converter Stations – Requirements same as those for HVDC Connections

Fast Fault Current Injection for HVDC Connections

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Fast Fault Current Injection for HVDC Connections – Title II Chapter 2 - Art 19 (1) – (3)

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- Article 19 - If specified by the relevant system operator, in coordination with the relevant TSO, an HVDC system shall have the capability to provide fast fault current at a connection point in case of symmetrical (3-phase) faults.
- Where an HVDC system is required to have the capability referred to in paragraph 1, the relevant system operator, in coordination with the relevant TSO, shall specify the following:
    - how and when a voltage deviation is to be determined as well as the end of the voltage deviation;
    - the characteristics of the fast fault current;
    - the timing and accuracy of the fast fault current, which may include several stages.
- The relevant system operator, in coordination the relevant TSO, may specify a requirement for asymmetrical current injection in the case of asymmetrical (1-phase or 2-phase) faults.

Fast Fault Current Injection for DC Connected Power Park Modules

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RfG Requirements for Fast Fault Current Injection

- Applies for Type B and above Power Park Modules
- Defined in RfG Article 20(2)(b) and Article 20(3)

RfG Requirements for Fast Fault Current Injection (1) – Article 20(2)(b)

- Article 20(2)(b) – The relevant System Operator in coordination with the relevant TSO *shall have the right to specify* that a power park module be capable of providing fast fault current injection at the connection point in the case of symmetrical (3-phase) faults under the following conditions:
  - (i) the power park module shall be capable of activating the supply of fast fault current either by:
    - Ensuring the supply of the fast fault current at the connection point: or
    - Measuring voltage deviations at the terminals of the individual units of the power park module and providing a fast fault current at the terminals of these units.

RfG Requirements for Fast Fault Current Injection (2) – Article 20(2)(b)

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- (ii) the relevant system operator in co-ordination with the relevant TSO shall specify
  - How and when a voltage deviation is to be determined as well as the end of the voltage deviation
  - The characteristics of the fast fault current, including the time domain for measuring the voltage deviation and fast fault current, for which current and voltage may be measured differently from the method specified in Article 2;
  - The timing and accuracy of the fast fault current, which may include several stages during a fault and after its clearance;

(c) With regard to the supply of fast fault current in case of asymmetrical (1-phase or 2-phase faults, the relevant system operator in co-ordination with the relevant TSO shall have the right to specify a requirement for asymmetrical current injection

Fast Fault Current Injection Definition – RfG Article 2

- ‘fast fault current’ means a current injected by a power park module or HVDC system during and after a voltage deviation caused by an electrical fault with the aim of identifying a fault by network protection systems at the initial stage of the fault, supporting system voltage retention at a later stage of the fault and system voltage restoration after fault clearance;

RfG Requirements for Fast Fault Current Injection (3) – Article 20(3)

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- Type B power park modules shall fulfil the following additional requirements in relation to robustness.:
- (a) the relevant TSO shall specify the post fault active power recovery that the power park module is capable of providing and shall specify:
  - (i) when the post fault active power begins, based on a voltage criterion
  - (ii) a maximum allowed time for active power recovery; and
  - (iii) a magnitude and accuracy for active power recovery;
- (b) the specifications shall be in accordance with the following principles
  - (i) interdependency between fast fault current requirements according to points (b) and (c) and paragraph (2) and active power recovery;
  - (ii) dependence between active power recovery times and duration of voltage deviations
  - (iii) a specified limit of the maximum allowed time for active power recovery
  - Adequacy between the level of voltage recovery and the minimum magnitude for active power recovery and
  - Adequate damping of active power oscillations

RfG Requirements
Article 21(3)(e) – Type C PPM’s

- With regard to prioritising active or reactive power contribution, the relevant TSO shall specify whether active power contribution or reactive power contribution has priority during faults for which fault ride through capability is required. If priority is given to active power contribution, this provision has to be established no later than 150ms from the fault inception.

GB Grid Code Requirements

- Within the GB Grid Code requirements for reactive current injection are loosely covered in CC.6.3.15.
  - Requirement to inject maximum reactive current during the period of the fault without exceeding the transient rating of the Power Park Module
  - Active Power to be restored within 0.5 seconds of restoration of the voltage at the Grid Entry Point to the minimum levels specified in CC.6.1.4
  - Active Power oscillations will be acceptable provided that
    - The total active energy delivered during the period of the oscillations is at least that which would be delivered if the Active Power was constant
    - The Oscillations are adequately damped

Proposals for Reactive Current injection under balanced fault conditions

- Applies at the Connection Point
- Voltage deviation is any event where the connection point voltage falls below 0.9p.u
- For a solid three phase short circuit fault a PPM should inject maximum reactive current without exceeding any transient rating
- The reactive current injection should be fully available within XXms?
- *For high impedance faults (retained voltage > zero); reactive current injection should be in proportion to the retained voltage? Consideration being given to a dynamic voltage control characteristic.*
- Upon restoration of the voltage to nominal levels (> 90%), active power should be restored to 90% of the pre-fault value.
- Reactive current injection is only required during the period of the fault and not following fault clearance.
- The Power Generating Facility owner should submit a time trace of reactive current injection before during and after the fault.
- Further analysis and investigation required
- Input from HVDC Workgroup members useful due to high input of Converter representatives

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Published Research

- University Of Strathclyde “Protection Challenges in future convertor dominated power systems” PACWORLD conference at Glasgow,UK, 2015.
- https://pure.strath.ac.uk/portal/files/43497504/Li_etal_PACWorld_2015_Protection_challenges_in_future_converter_dominated_power.pdf
- University Of Strathclyde- “investigation of high convertor penetration on power system stability and potential solutions”
- DMV KEMA ENTSO-e report:- https://ec.europa.eu/energy/sites/ener/files/documents/KEMA_Final%20Report_RfG%20NC.pdf
- Danish standard on fast fault current injection
- http://www.energinet.dk/EN/El/Forskrifter/Technical-regulations/Sider/Forskrifter-for-nettilslutning.aspx
- German approach to assymettric fault injection
- https://www.uni-due.de/ean/downloads/papers/neumann2012.pdf

German Requirement for rapid current Injection

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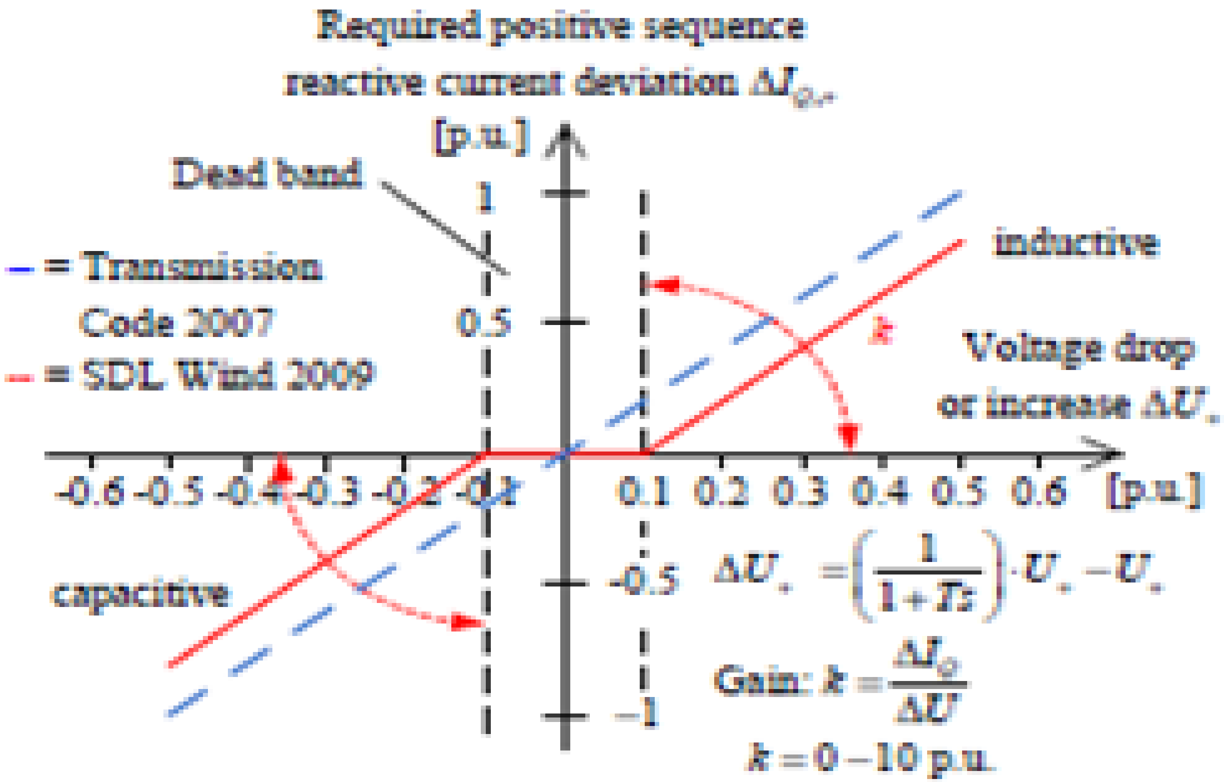

Fig. 2. Dynamic voltage control characteristic

High level proposals for Reactive Current injection under three phase fault conditions – Summary

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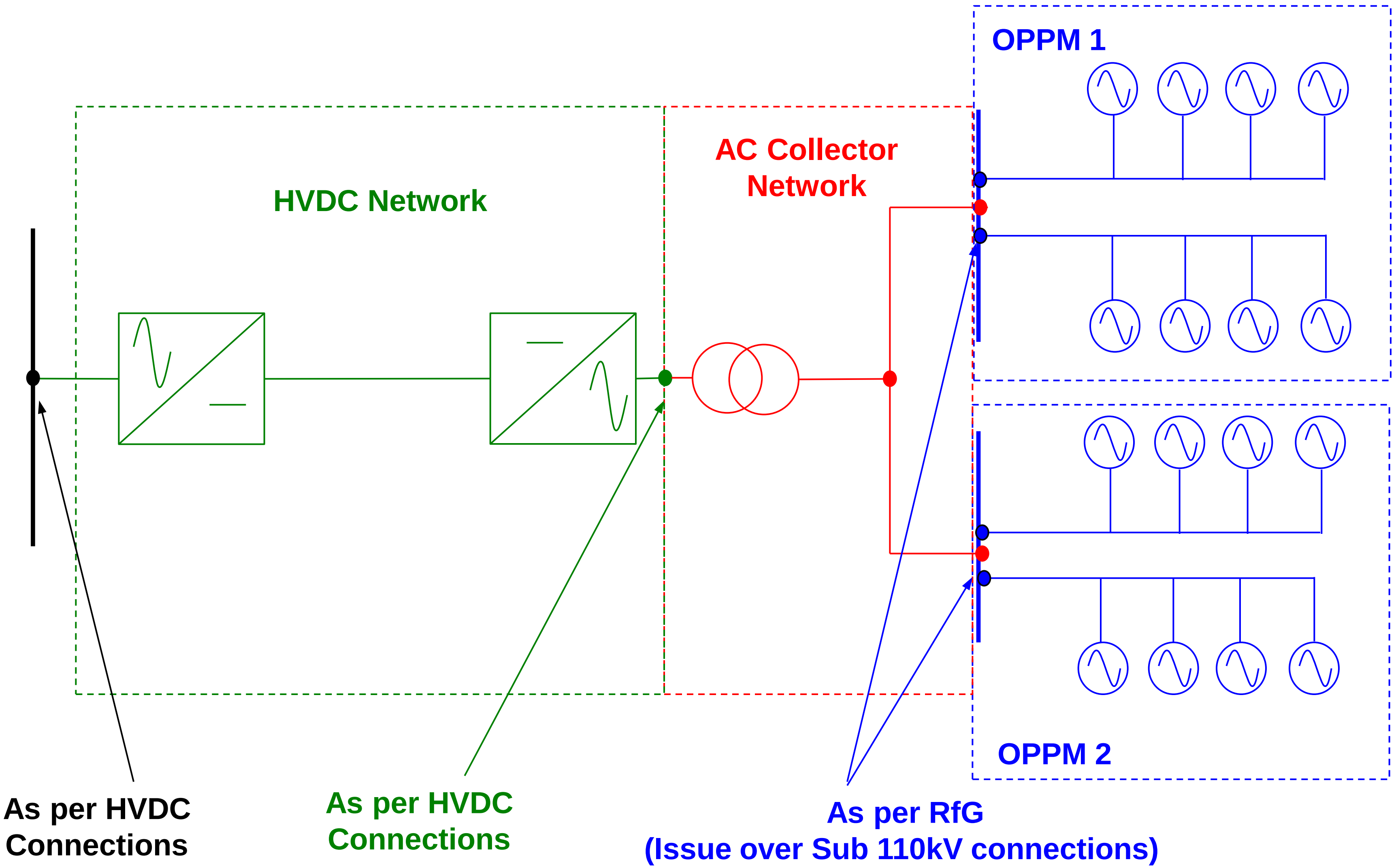
Requirement	Specification
Point of Fast Fault current injection	Connection Point of Power Park Module
How and when voltage is to be determined as well as the end of the voltage deviation	Each time the voltage at the Connection Point drops below 0.9p.u
The characteristics of the fast fault current, including the time domain for measuring the voltage deviation and fast fault current from which current and voltage may be measured differently form the method specified in Article 2	100% Reactive current injection to be supplied for a Balanced three phase solid short circuit fault Maximum reactive current to be provided within XXms without exceeding the transient rating of the Power Park Module. For a balanced high impedance fault, reactive current to be supplied in proportion to retained voltage (eg 30% retained voltage requires 70% reactive current)? Power Generating Module facility owner to provide a continuous time trace of reactive current injection at the connection point during before and after the fault.
The timing and accuracy of the fast fault current, which may include several stages during a fault and after its clearance	See above – maximum reactive current to be injected within XXms.
When post fault active power recovery begins based on a voltage criterion	Active Power Recovery to commence on fault clearance (ie voltage above 0.9p.u)
Maximum allowed time for active power recovery	Active Power to be restored to 90% of its pre-fault value within 0.5 seconds of fault clearance (ie voltage above 0.9p.u)
Magnitude and accuracy for active power recovery	Allowance made for post fault power oscillations provided the damping requirements in the SQSS and in CC.A.6 of the Grid Code can be satisfied

Unbalanced Faults

- RfG is silent on this issue as it is left to the System Operator
- At this stage the requirements for unbalanced faults would be similar to that for balanced faults but on a phase basis.
- Additional work is however required on this section
- Input required from HVDC Representatives

Summary
Fault Ride Through Requirements



Next Steps

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Next Steps

- Develop voltage against time parameters for HVDC Connections (Annex V)
- Refine the voltage against time curves for AC and DC Connected Power Park Modules.
- Consider the implications for fast fault current injection in particular the time at which the maximum fault current should be injected.
- Concern over the fault ride through requirements for DC Connected Power Park Modules connected below 110kV

Discussion