RfG – Fast Fault Current Injection

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National Grid – Network Capability

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Acknowledgements

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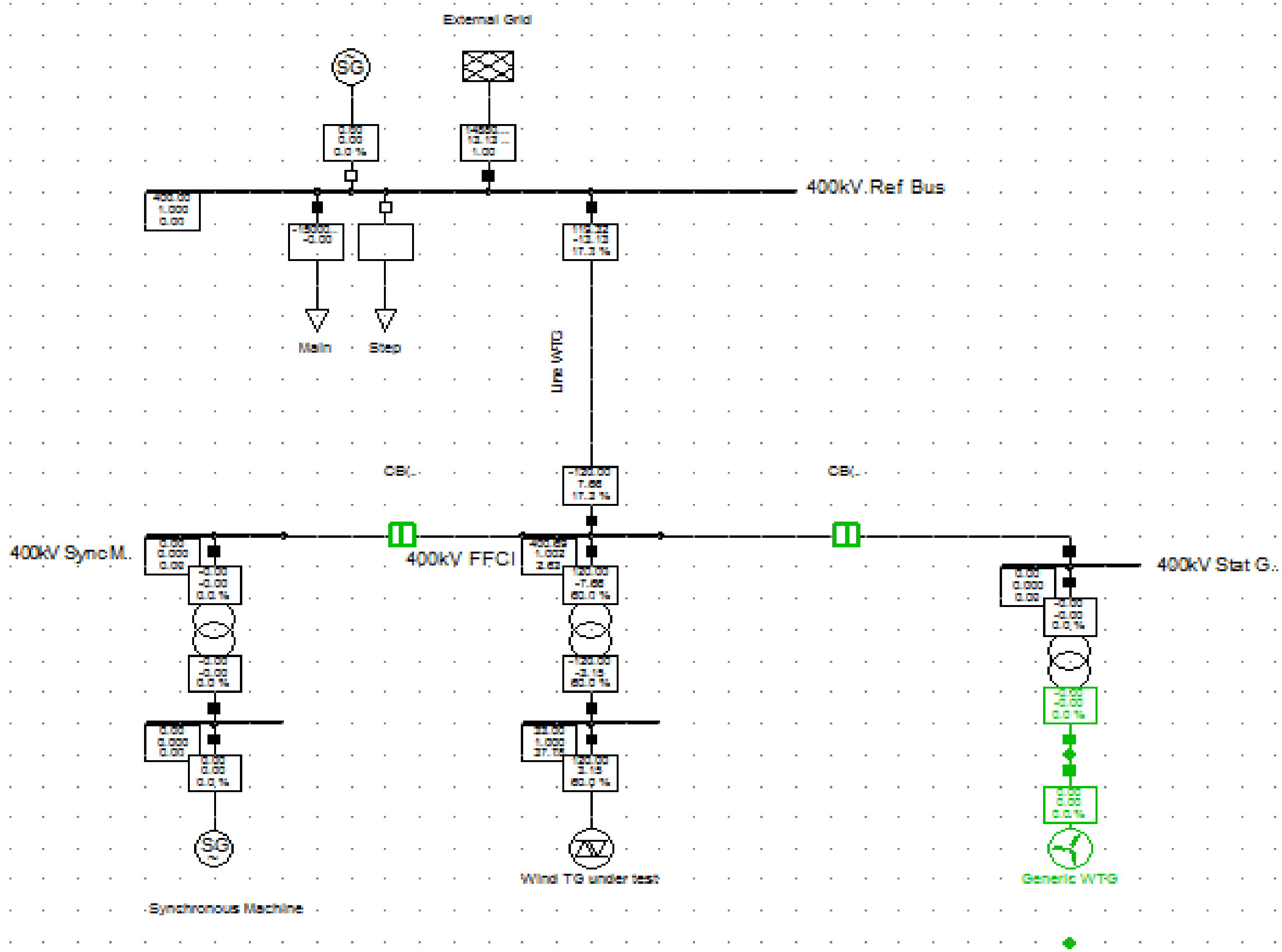
Summary

- Test Network and proof of concepts
- Test Network Performance – Synchronous Machines
- Test Network Performance – Power Park Modules
  - Variations in Converter based reactive current injection
  - Virtual Synchronous Machine
- Multi Machine Study – South West Study Case
- Assumptions
- Case 1 – Synchronous Generation
- Case 2 - Power Park Modules
  - Conventional Converter
  - Virtual Synchronous Machine
- Summary of Results / Conclusions / Review of Fault Ride Through Voltage against time curves

RfG – Fast Fault Current Injection Test Network / Model Validation

Test Network (Fig1)



Test Network :Study Assumptions

- A three phase fault was applied at 400kV Ref Bus
- The retained voltage is measured at the machine terminal [33kV]
- Machine Rating assumed to be 1MVA. The number of machines was increased to achieve a higher current injection.

Test Network - Results

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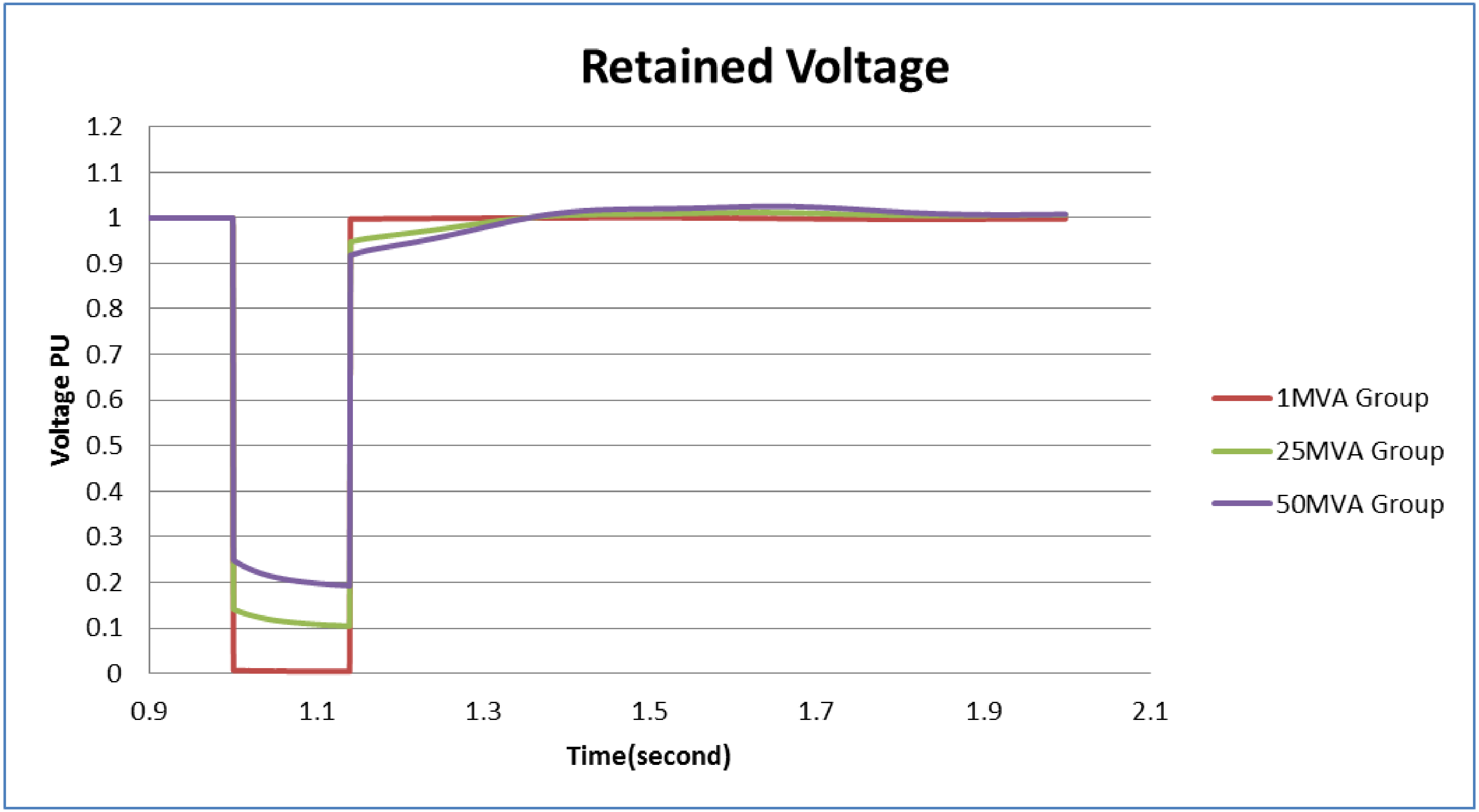
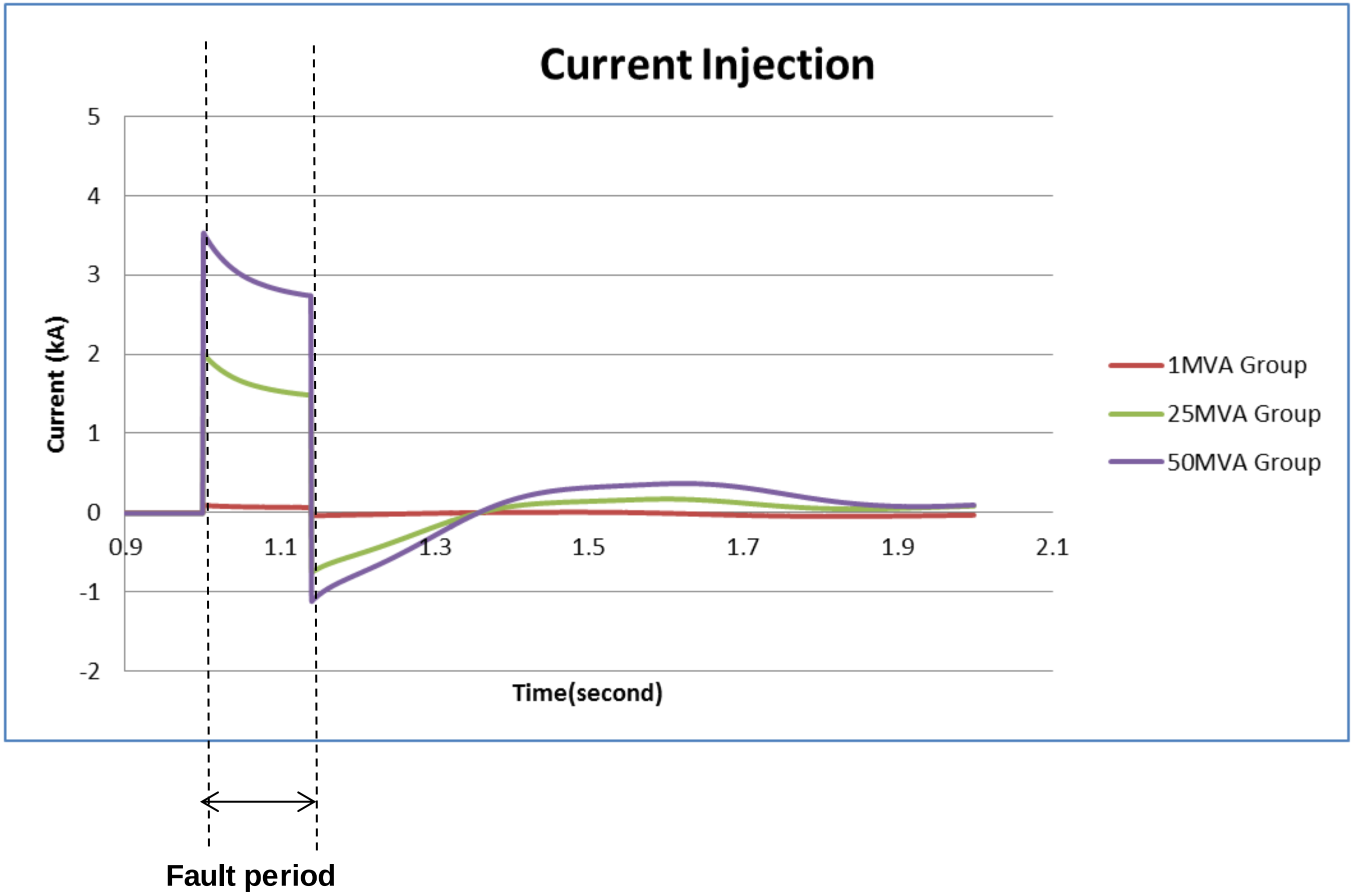
Effect of Synchronous Plant On Retained Voltage at the Machine terminals



Test Network

Current Injection from Synchronous plant - Fault at 400kV Ref Busbar



Test Network – *Synchronous Plant*

Summary of Results

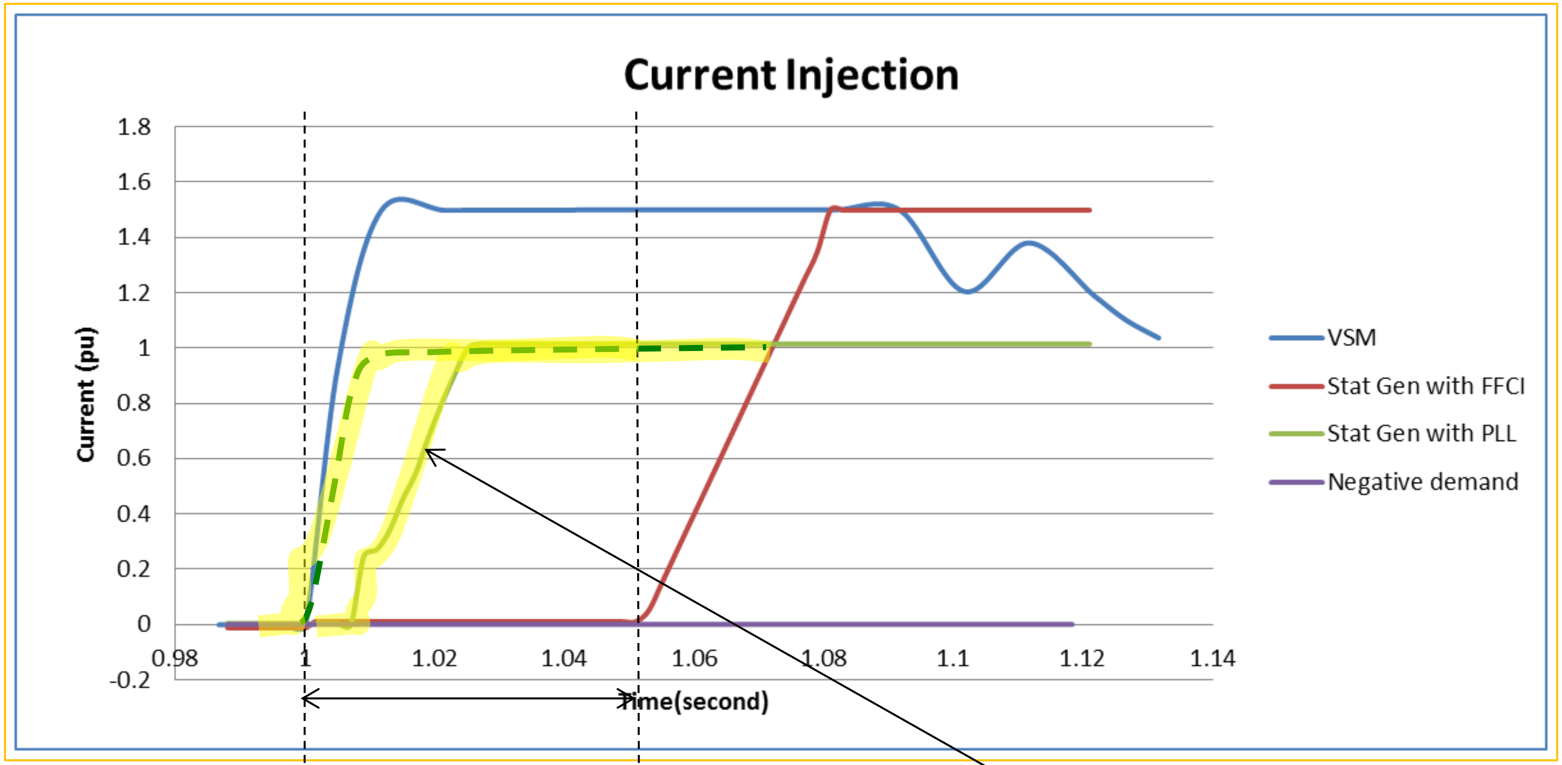
- The current injection from this group of synchronous plant increases from 0.09kA to 3.5kA as the number of machines increase (i.e. 1MVA – 50MVA).
- The retained voltage at 33kV increases from 0 to 0.24pu as the number of machines increase
- A group of 25MVA machines were sufficient to achieve a retained voltage of 0.14pu after the fault has been applied at 400kV Ref Bus

Test Network

Effect of Power Park Modules with different control actions (PLL, FFCI and VSM)

- *Assumptions*
- The same number of machines as synchronous machines was used
- The asynchronous machine was modelled as a static generator with different controllers
- Retained Voltage and current injection plots obtained

Test Network - Results
Reactive power Injection Comparison



50ms delay for illustration, shorter delay would be prescribed in practice

Area across which PLL behaviour cannot be guaranteed, injection is potentially out of phase with the retained voltage

Test Network

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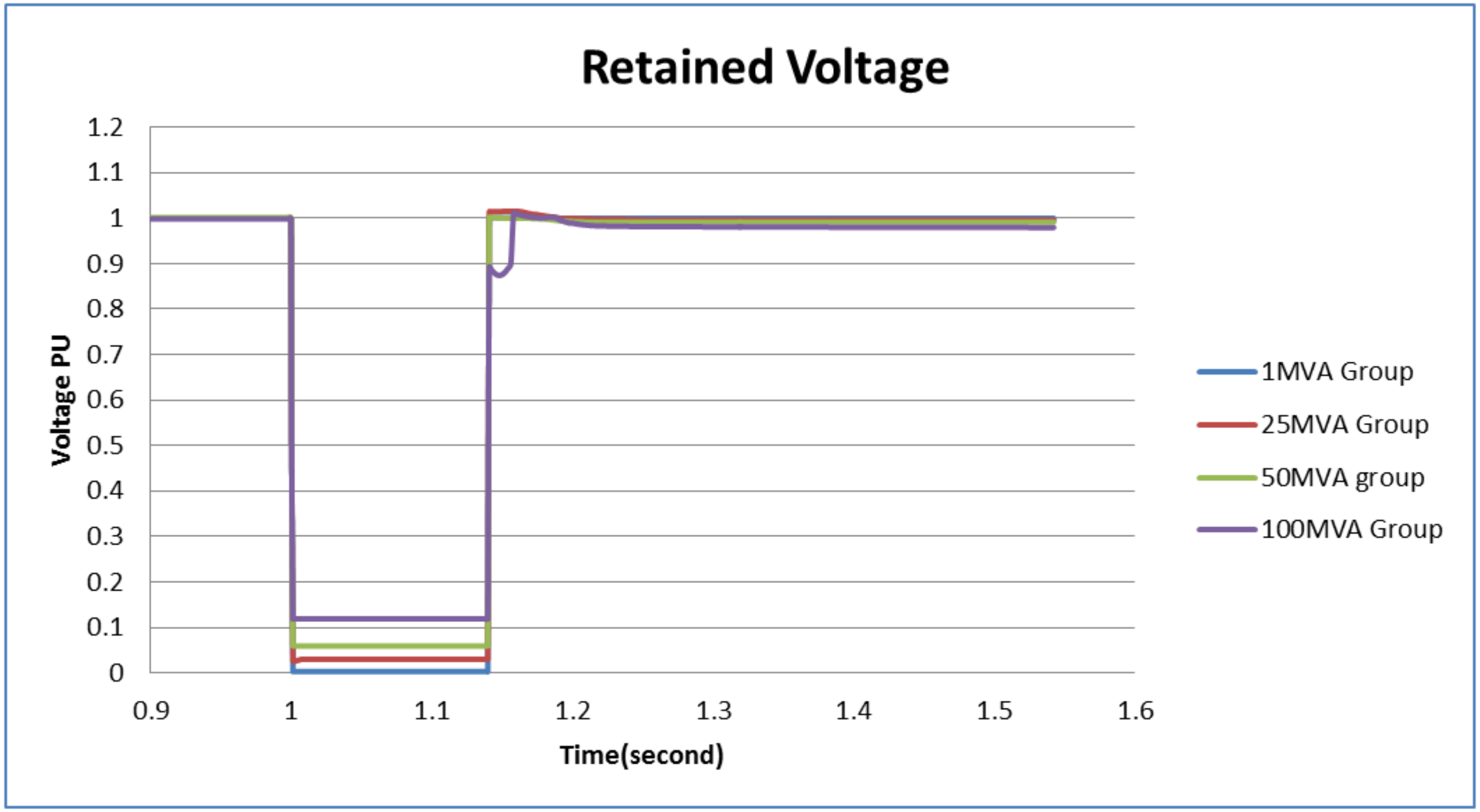
Effect of Power Park Modules with PLL control on Retained Voltage at the Machine terminals

- The same number of machines as synchronous machines was used
- The asynchronous machine was modelled as a static generator with PLL control
- Retained Voltage and current injection plots obtained
- Due to the low voltage involved, the switch off threshold (i.e. blocking) was set to zero to allow the static generator to contribute reactive current at these voltages.
- Normally it is the case that for standard PLL controllers a blocking voltage would apply to this timeframe.

Test Network - Results

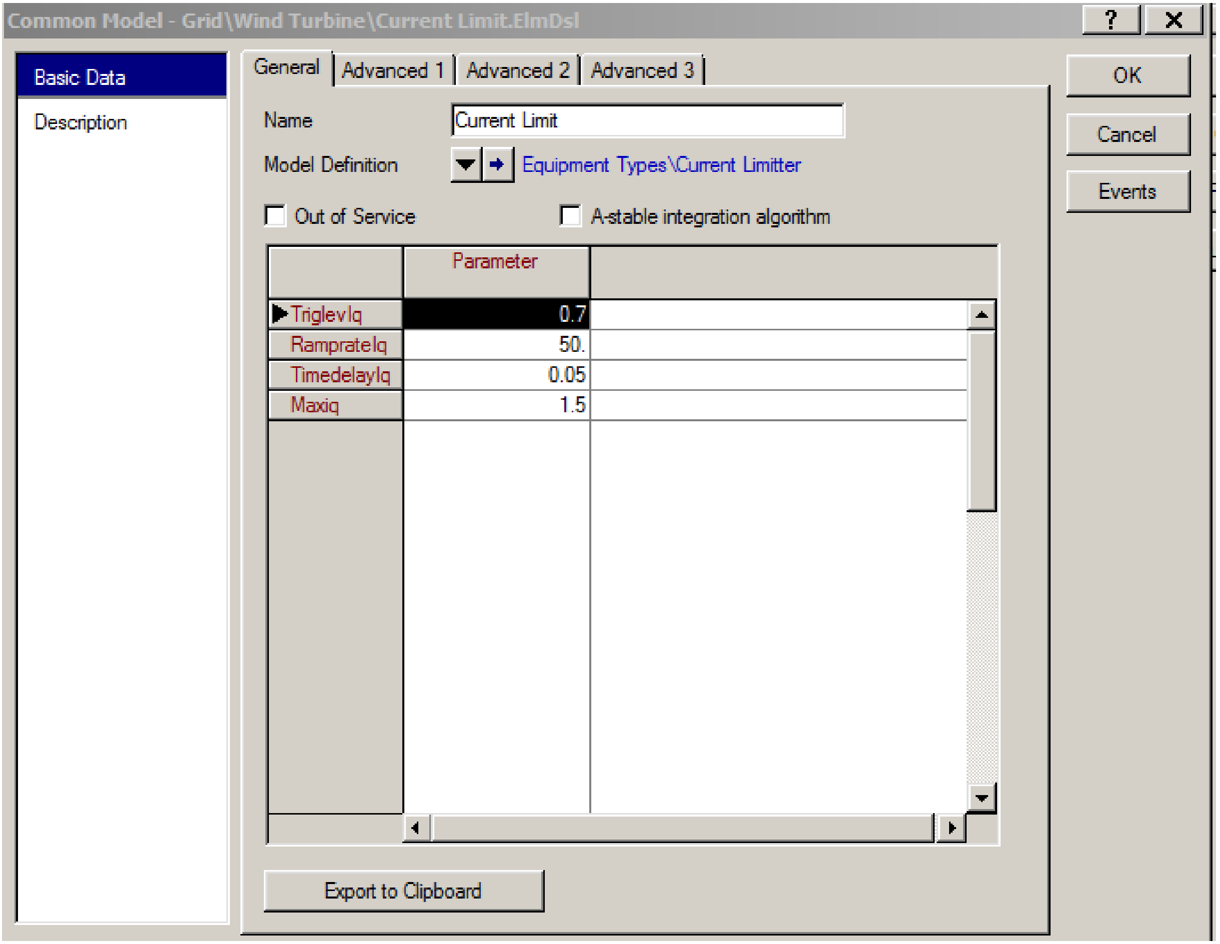
Retained Voltages *of different Capacities of Power Park Module (PLL - No FFCI)**



*** Assumes ideal in phase response of the PLL**

Static Generator

With Fast Fault Current Injection(FFCI) Current limiter Setting



Test Network –

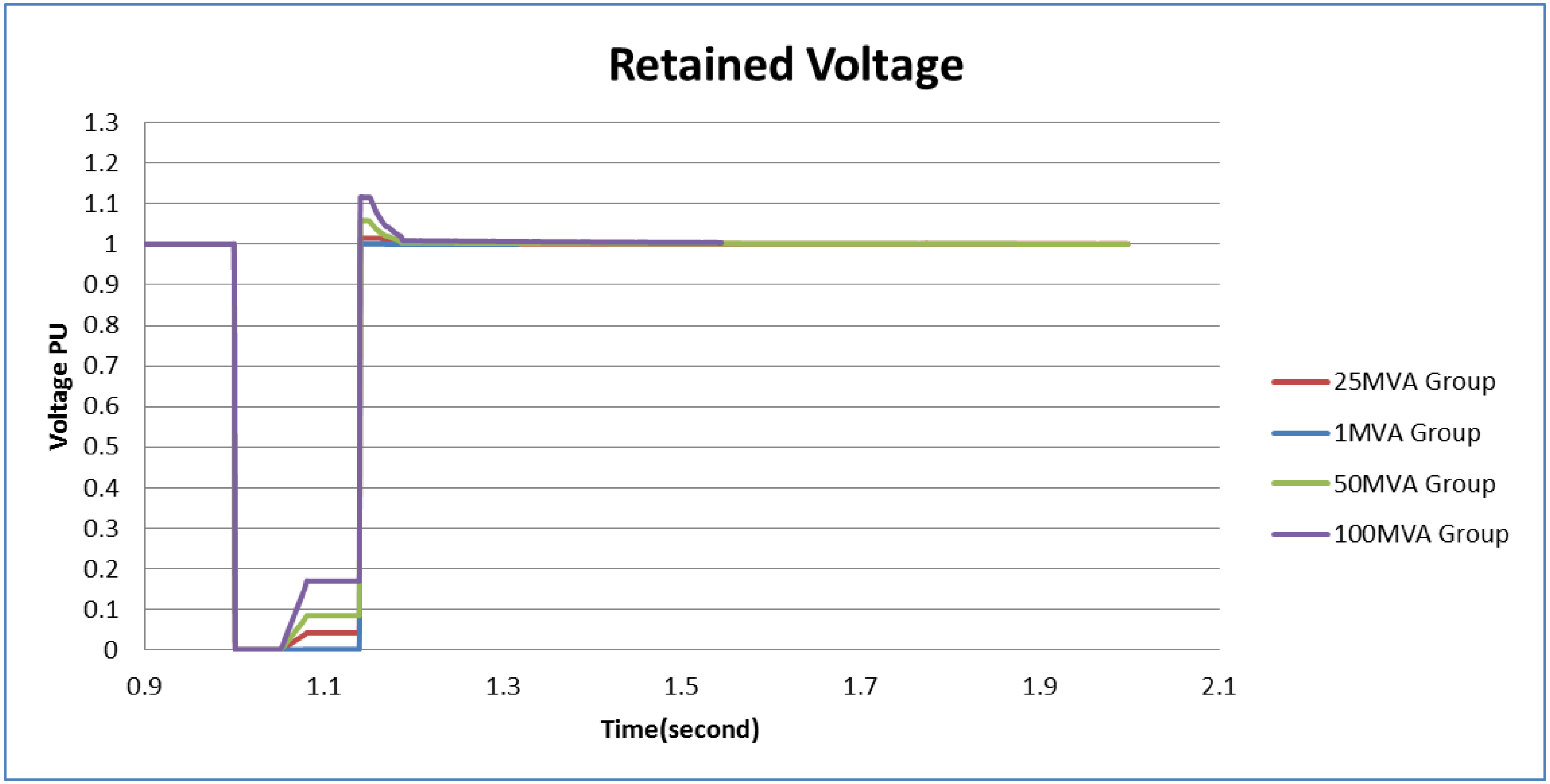
Static Generator with Fast Fault Current Injection (FFCI)

Current Injection (pu)	1.5			
No of Static Generators with FFCI (1MVA each)	**1**	**25**	**50**	**100**
33kV Terminal Voltage[pu]	**0.00**	**0.04**	**0.08**	**0.17**

- The more the machines the better the retained terminal voltage
- As a control function it is desirable to delay the injection to ensure the injection is in phase with retained voltage
- The higher the injection the less the number of machines required to achieve a particular terminal voltage
- Blocking ahead of fault clearance may be required to avoid Transient Over Voltage following the fault, provided reactive and active power is rapidly restored thereafter

Test Network - Results

Retained Voltages *of different Capacities of Power Park Module with FFCI*



Test Network - Results
VSM Model

- The network is the same as that shown in Fig 1
- VSM technology uses the static generator but the controller has been modified to reflect the behaviour and performance of a VSM.
- The Virtual Synchronous Machine control strategy replicates several aspects of Synchronous machine behaviour such that a response to a phase change is immediate and proportionate to the disturbance, as would be the case for a synchronous machine.

Test Network - Results

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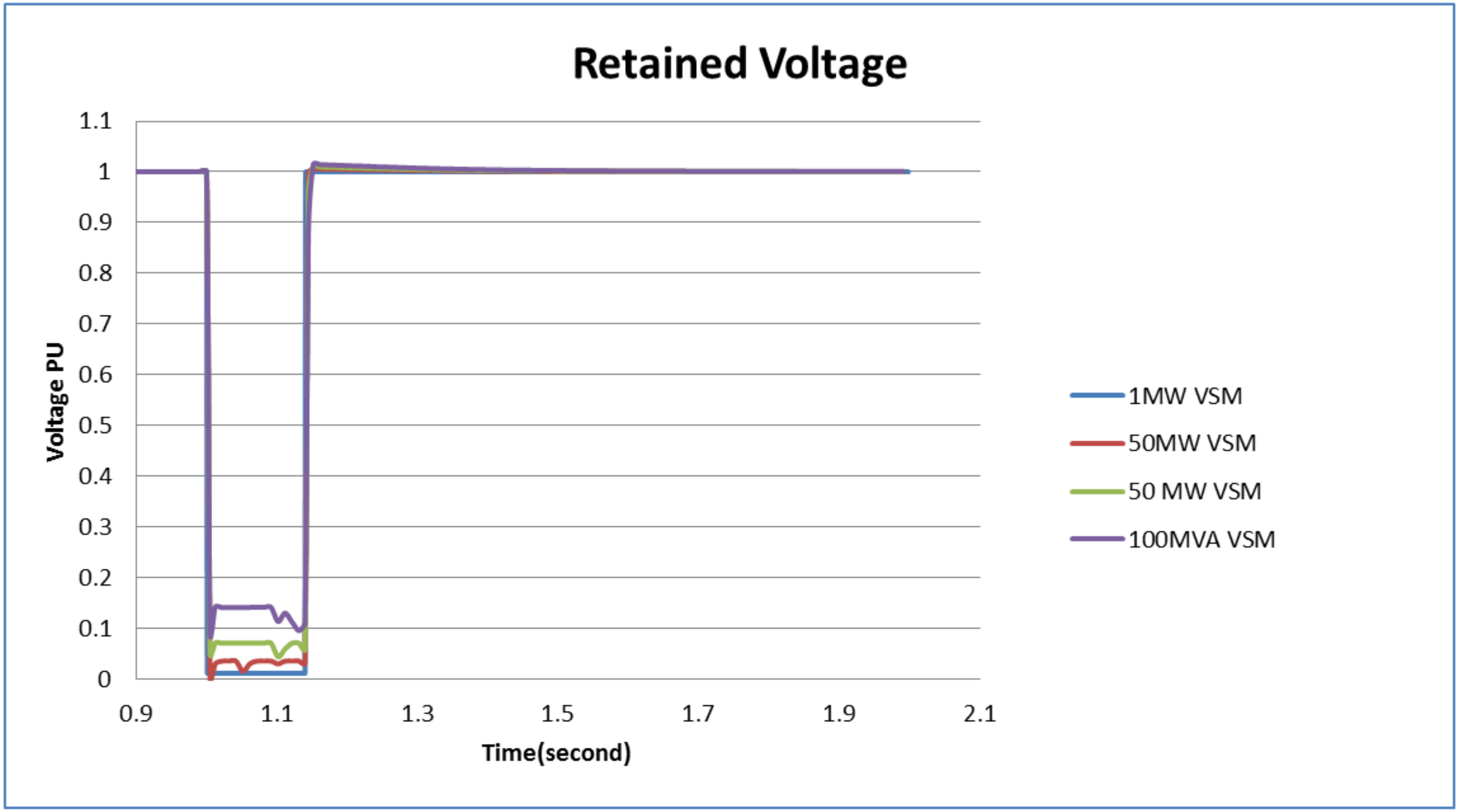
Retained Voltages *of different Capacities of Power Park Module with VSM*



Test Network –
VSM Performance

VSM Size	25	50	100
33kV Terminal Voltage[pu]	0.035	0.071	0.141

- The more the machines the better the terminal voltage
- VSM offers better performance than PLL.

Test Network

Retained Voltage - Comparison for the four cases

Option	1MVA	25 MVA	50 MVA	100MVA
Sync. machine Voltage	0.00	0.13	0.24	0.38
Static Generator Voltage (PLL)	0.00	0.03	0.06	0.12
Stat. Gen With FFCI Voltage (Final)	0.00	0.04	0.08	0.17
Static Generator with VSM Control	0.00	0.035	0.071	0.141

- When the number of machines is very low, the contribution from them is insignificant
- A group of synchronous machines will offer more voltage support compared to the same number of other technologies (in Phase)
- Other than Synchronous machine and VSM approaches there are challenges over immediate quantity and quality of support provided.

RfG – Fast Fault Current Injection Multi Machine Study Results South West Study

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Proposed Study approach and Methodology

- Full GB Transmission Network
- Includes DNO Networks
- Specific area of interest will focus on an area of the network known to have a high volume of Embedded Generation: South West
- Base case study
  - Intact network conditions
  - System conditions – Max / Min Demand
  - All Embedded Generation initially modelled as negative demand
  - Solid Three phase short circuit fault applied adjacent to Indian Queens 400kV substation
  - Voltage profile assessed across the Transmission and Distribution system during and after the above faults

Area Under Study

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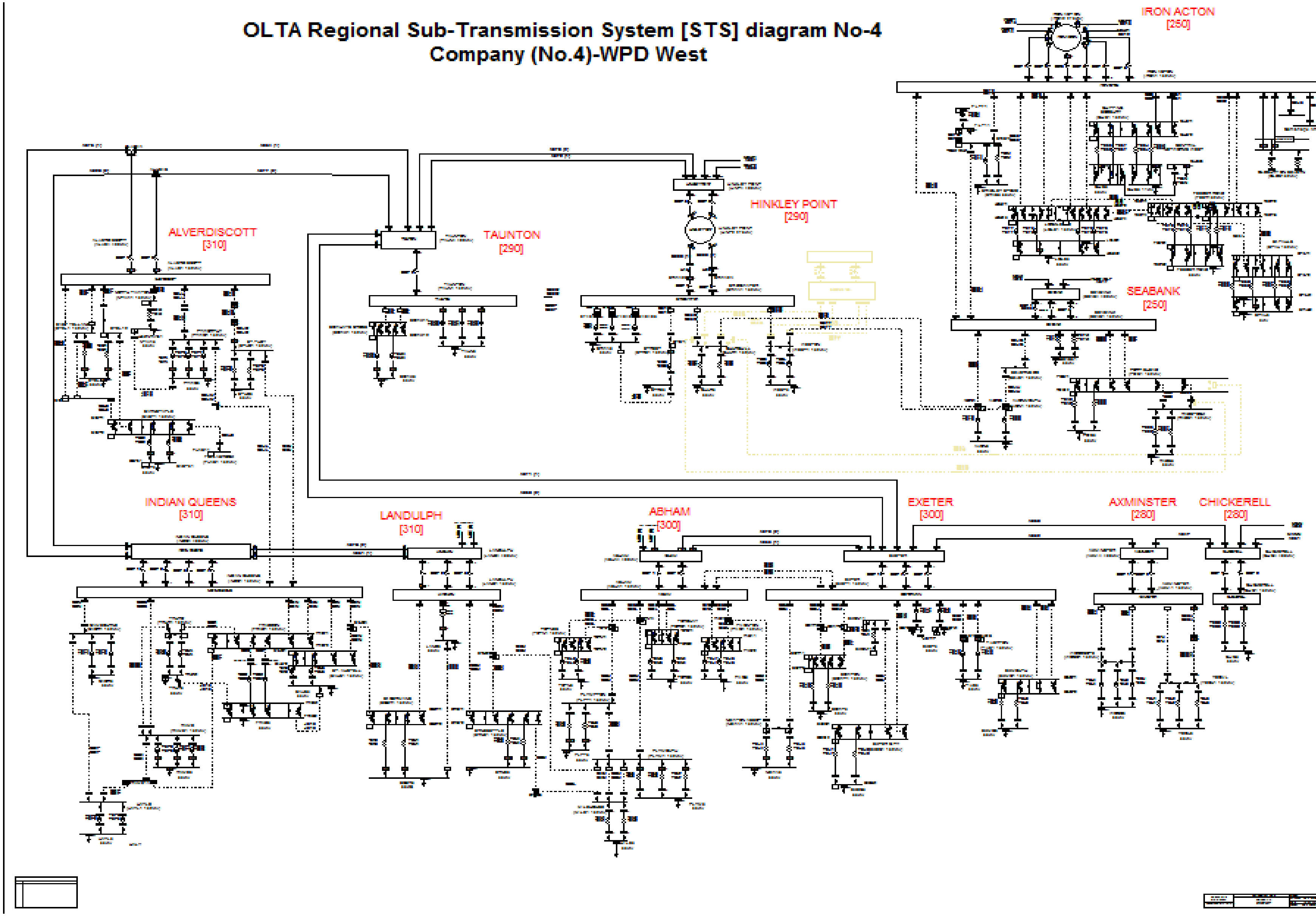
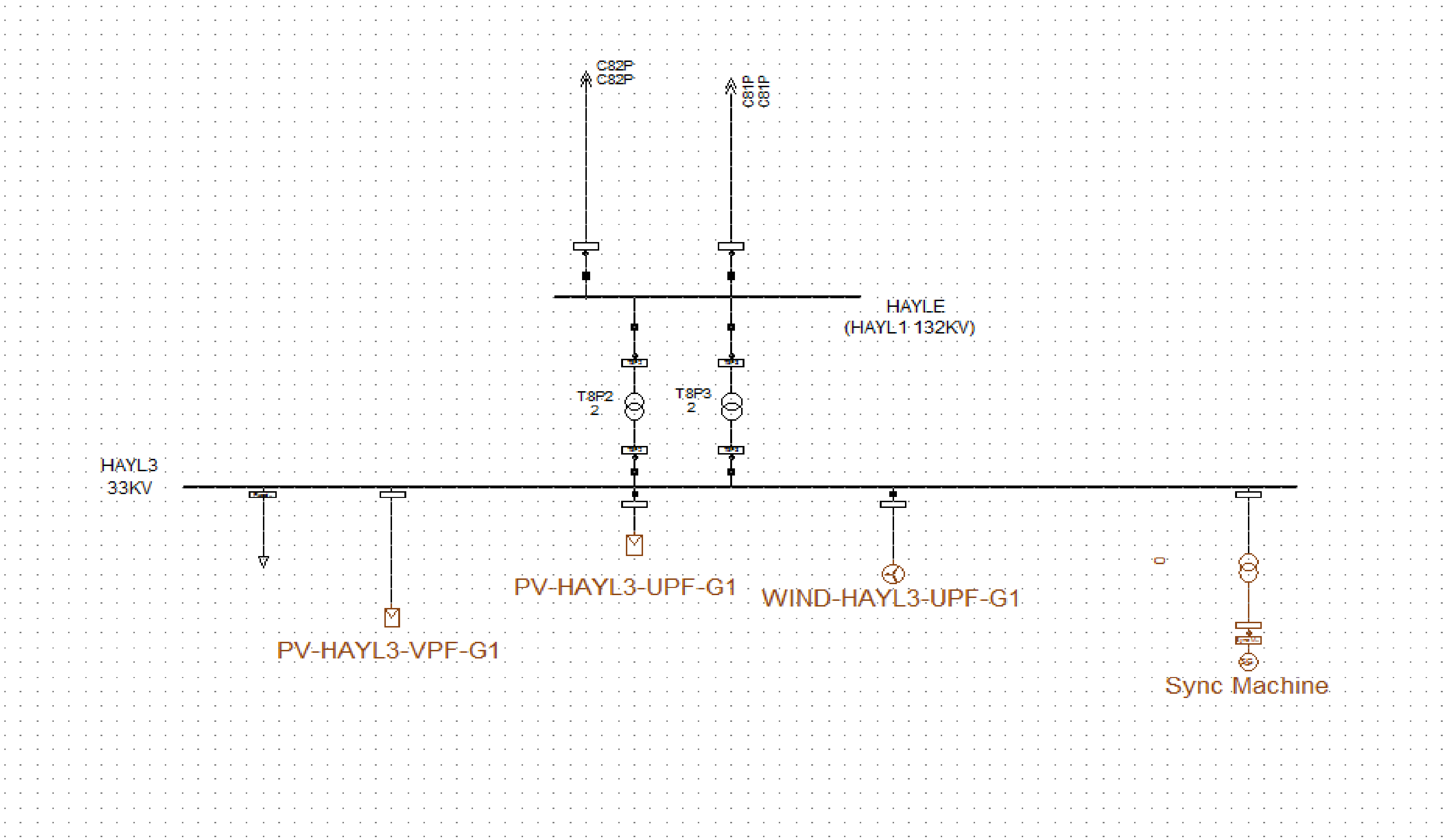


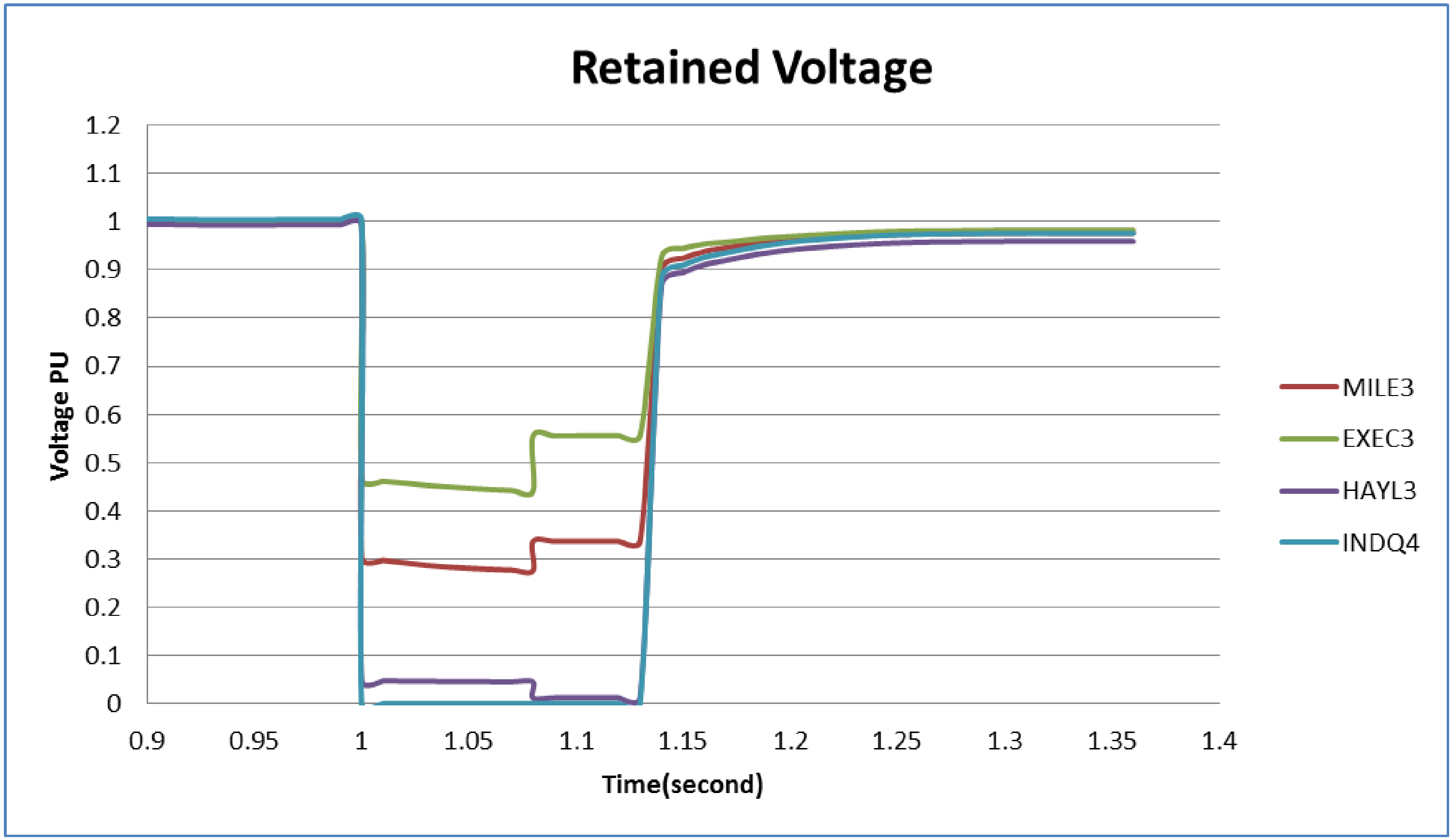
Area Under Study : Hayle

Sync Machine = 13.75MW   Non Synch 37.2MW



Multi Machine System Study *Assumption – Embedded Generation modelled as Negative Demand*

- Fault Condition: Solid Three phase double circuit fault between Indian Queens and Taunton substation



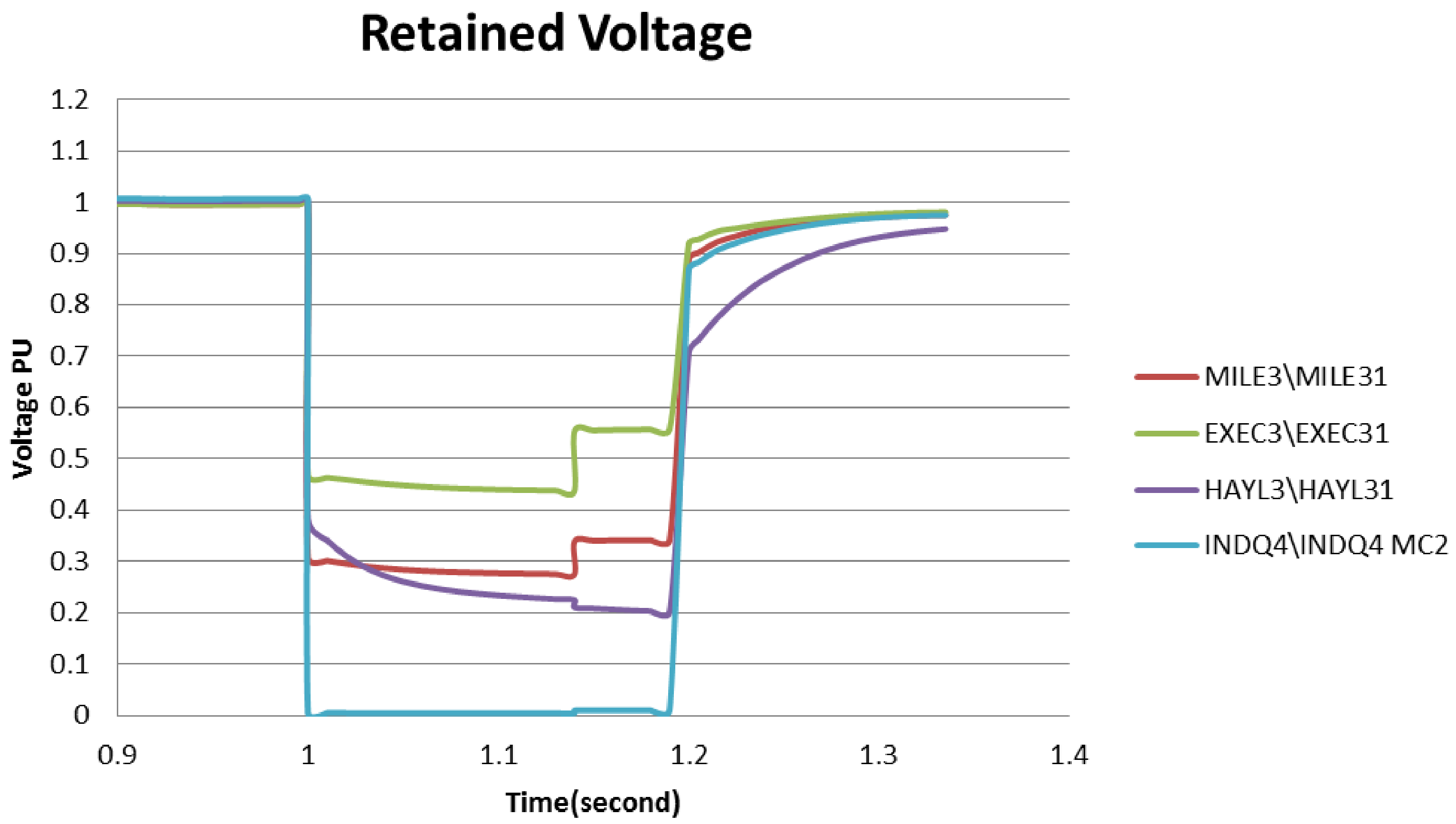
GB System Study Result Summary Negative demand

Node Name	MILE3	EXEC3	HAYL3	INDQ4
Min voltage	0.303	0.467	0.048	0

- The Voltage at the point of fault at 400kV is zero
- A number of busbars have a retained voltage above 10% due to network interconnection
- The minimum voltage at Hayle 33kV busbar during fault is 0.048pu.

GB System Study Result Summary

Embedded Generators - Synchronous Machines



GB System Study Result Summary

Embedded generation synchronous units modelled as synchronous machine

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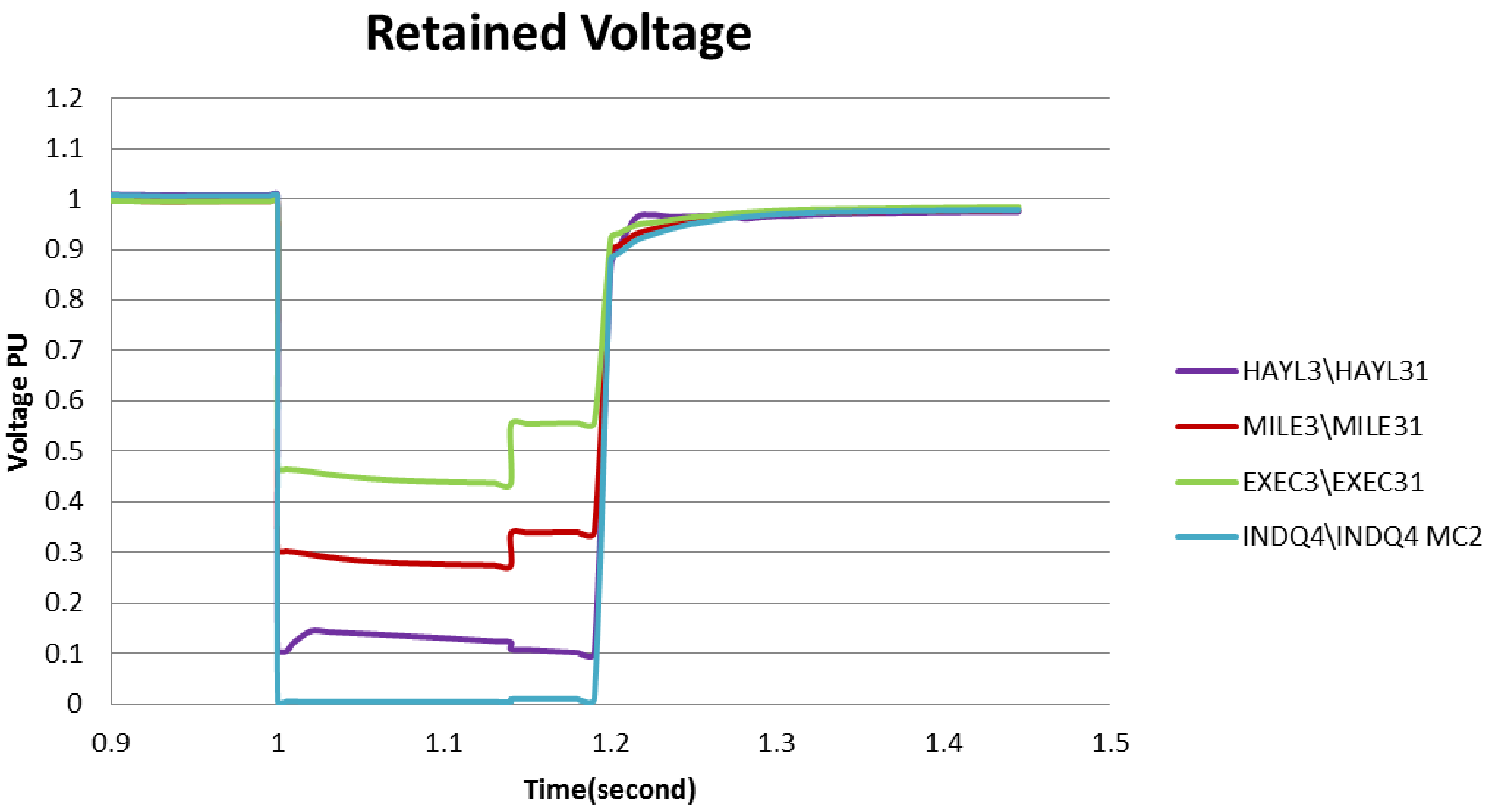
- The Voltage increases with the capacity of synchronous machines
- The Voltage increases with the location of synchronous machines
- The Voltage at Hayle 33 kV substation has increased from 0.048pu to 0.23pu(Minimum)
- This improvement has cascaded to some of the busbars around the network
- Synchronous Plant with a FRT value of Uret of 30% may trip in this case (approx 13.25MW at Hayle), further examples below.

Node Name	MILE3	EXEC3	HAYL3	INDQ4
Min voltage	0.29	0.46	0.23	0.00

GB System Study Result Summary (Embedded non synchronous Generation Modelled as Static Generator only)



GB System Study Result Summary (Embedded non synchronous Generation Modelled as Static Generator only)

Node Name	MILE3	EXEC3	HAYL3	INDQ4
Min voltage	0.31	0.47	0.11	0.00

- The Voltage at the point of fault is zero
- The Voltage at Hayle 33kV Substation has increased from 0.048pu to 0.11pu
- PPM's at Hayle 33kV will trip if there is less than 25MVA plant of plant running for a Transmission System fault (retained voltage recorded at 0.08pu). Based on studies we expect there to be approx 37.04 MW running which holds the voltage above 0.11pu (as per above table).

GB System Study Result Summary
(effect of Embedded non-synchronous Generation Modelled as a Static Gen with FFCI only)

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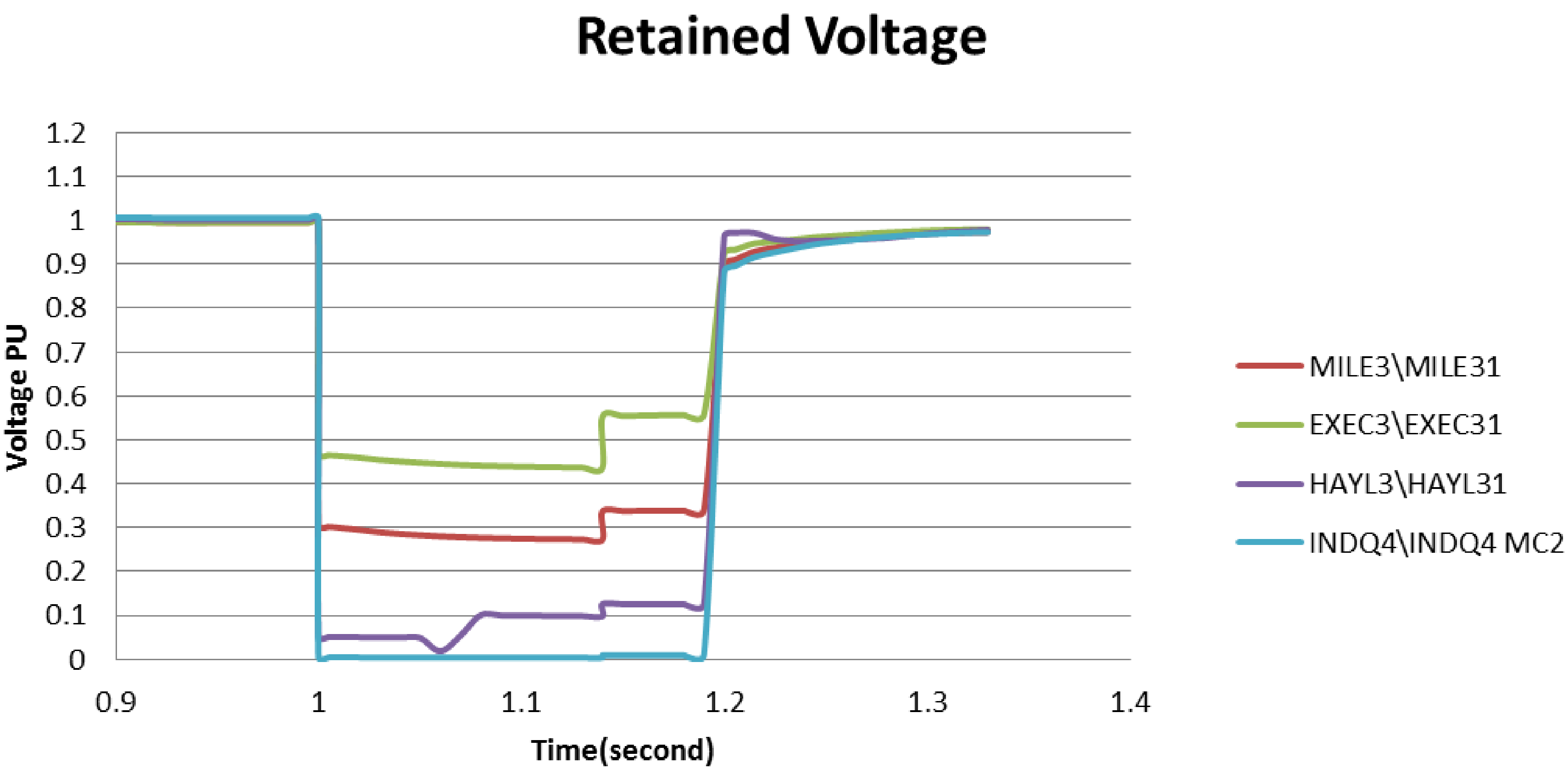
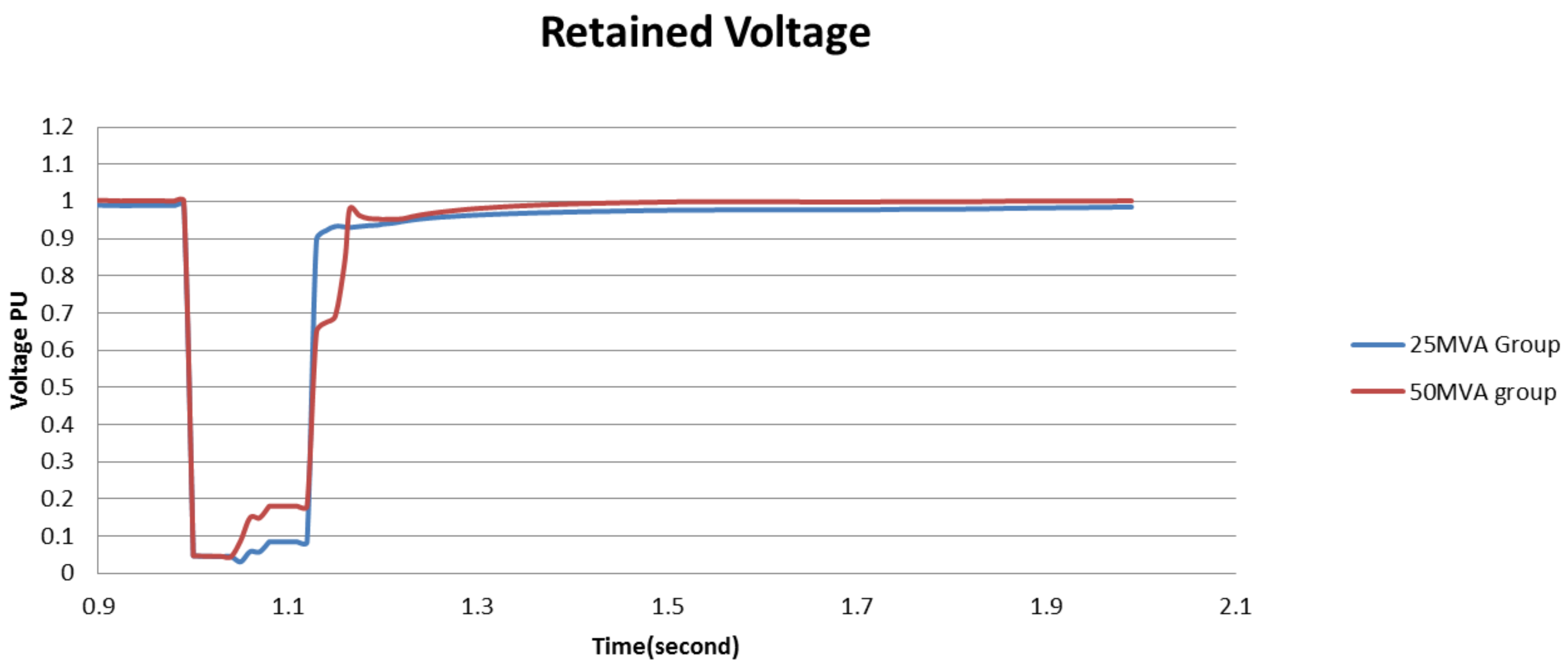


GB System Study Result Summary

Retained Voltage for different capacities FFCI



GB System Study Result Summary

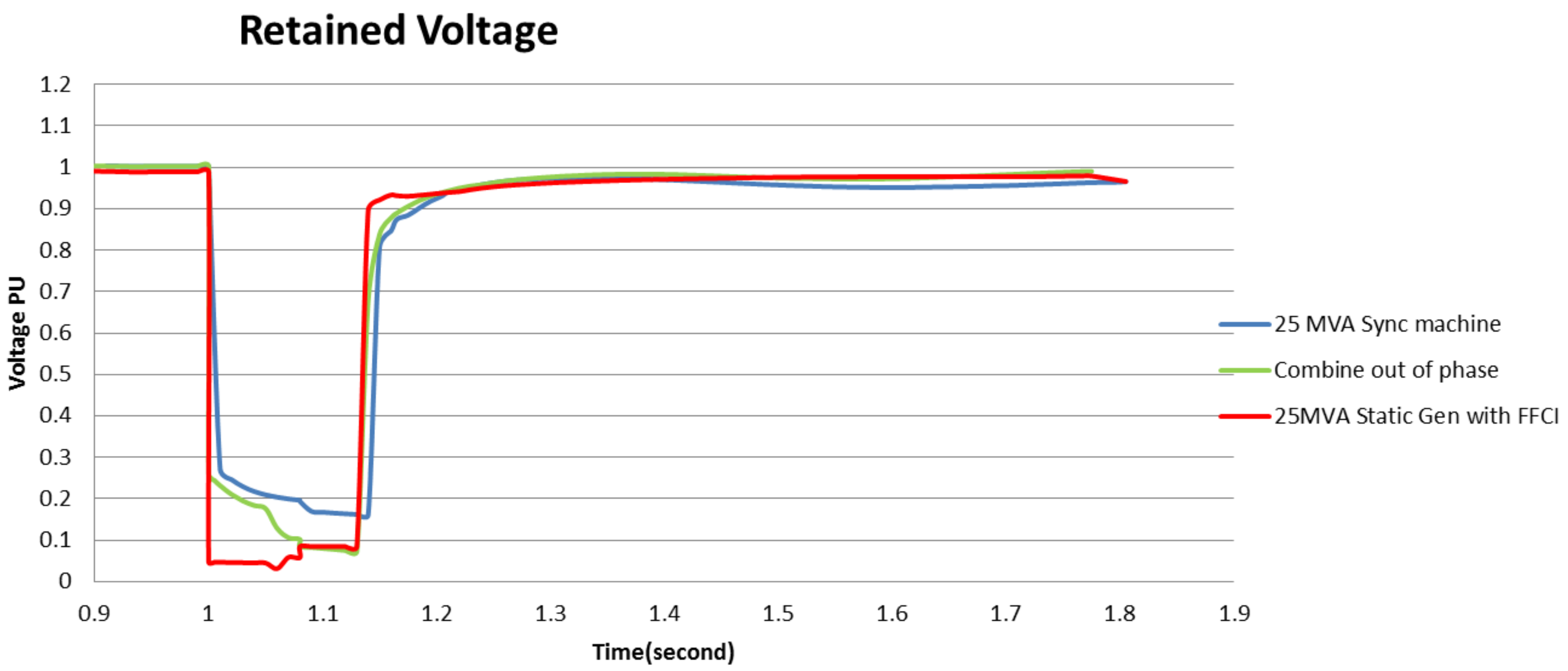
Retained Voltage for different capacities FFCI

Capacity	Initial Voltage	Final Voltage
25MVA Group	0.047	0.058
50MVA Group	0.047	0.149

- With FFCI the delay has a significant effect on the retained voltage nationalgrid

GB System Study Result Summary

Combination of Synchronous machine with static Gen with PLL



GB System Study Result Summary

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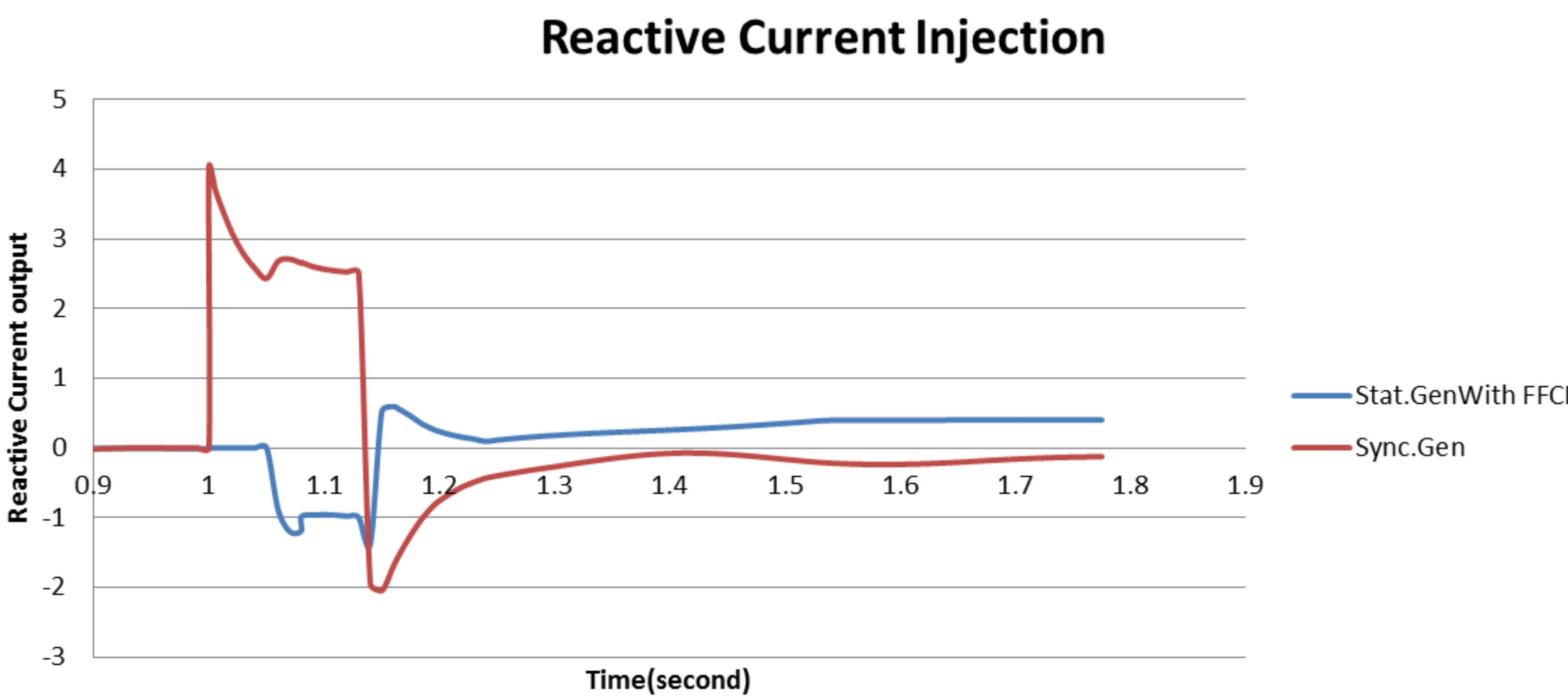
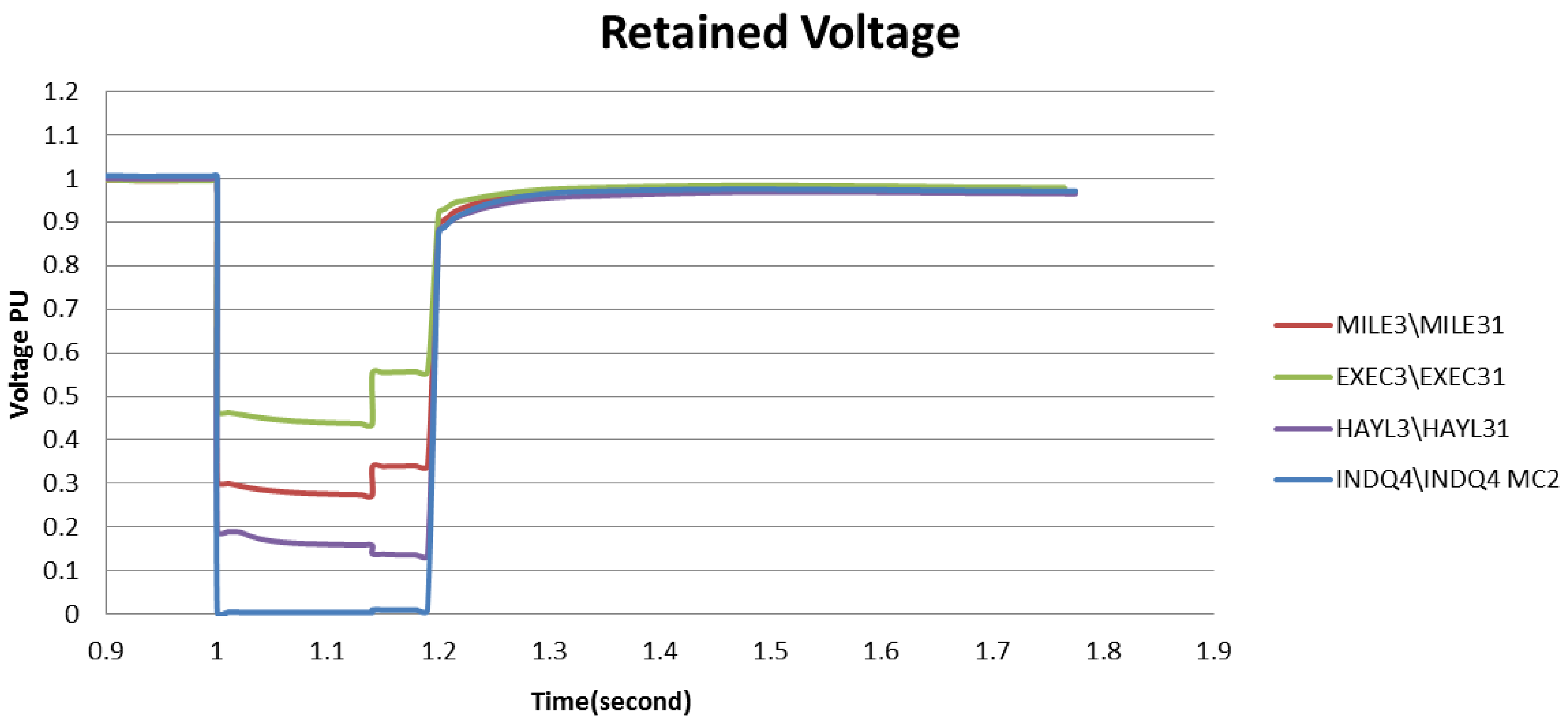
Combination of Synchronous machine with static Gen with PLL



GB System Study Result Summary

non- synchronous embedded Generator modelled as VSM only



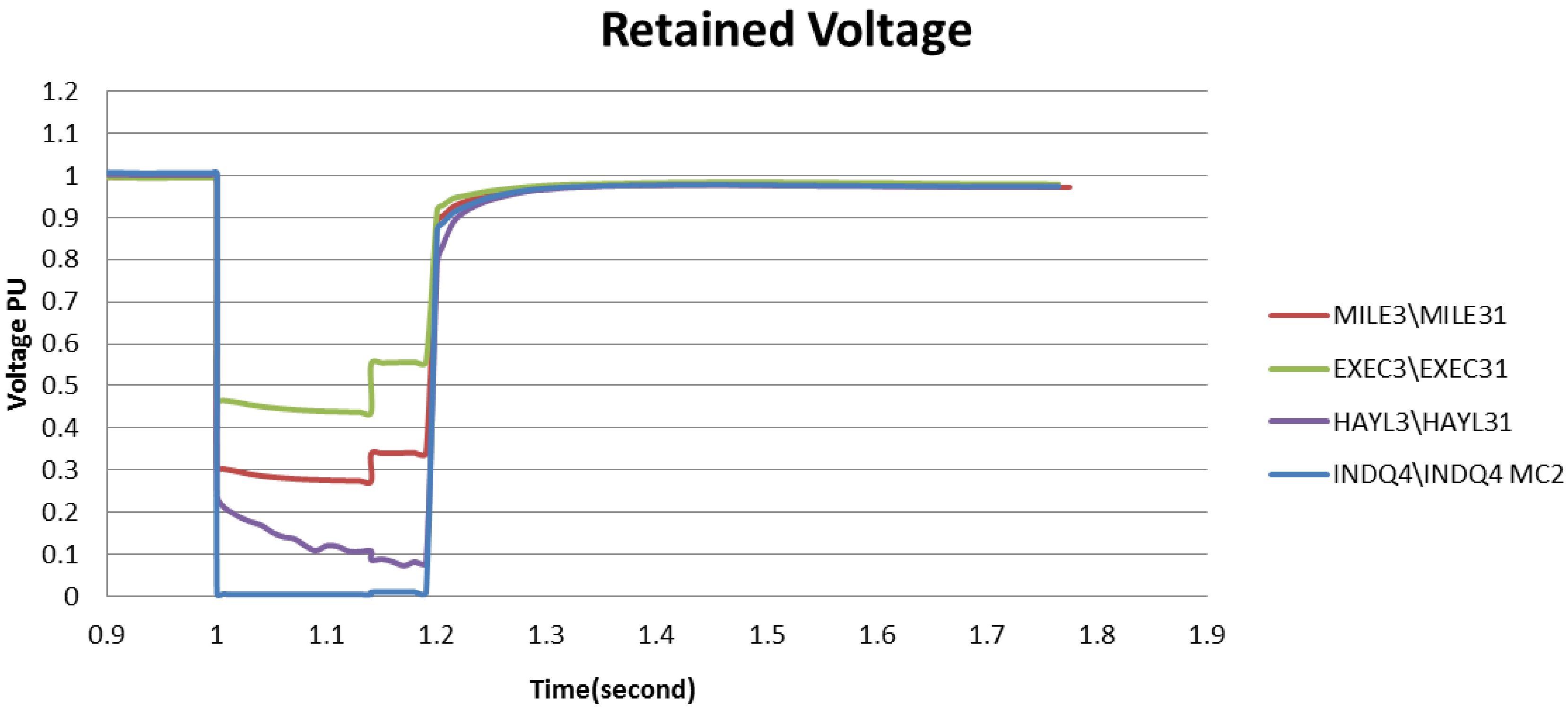
VSM Result Summary

- The retained voltage at HAYLE is greater that 0.1pu

Node Name	MILE3	EXEC3	HAYL3	INDQ4
Min voltage	0.306	0.468	0.191	0.005

GB System Study Result Summary

Combination of Synchronous machine , Static Generator with FFCI and VSM



Result Summary

Combination of Synchronous machine , Static Gen with FFCI and VSM

- The retained voltage at HAYLE if greater than 0.2pu just after the fault for a combination of the three technologies
- Due to higher synchronous fault infeed the phase shift is slower and the PLL is better able to support system voltage
- Early adoption of VSM helps improve areas of the system with already high volumes of PLL technology

Node Name	MILE3	EXEC3	HAYL3	INDQ4
Min voltage	0.28	0.44	0.21 -0.09	0.00

2025 Study case Solar Peak Scenario

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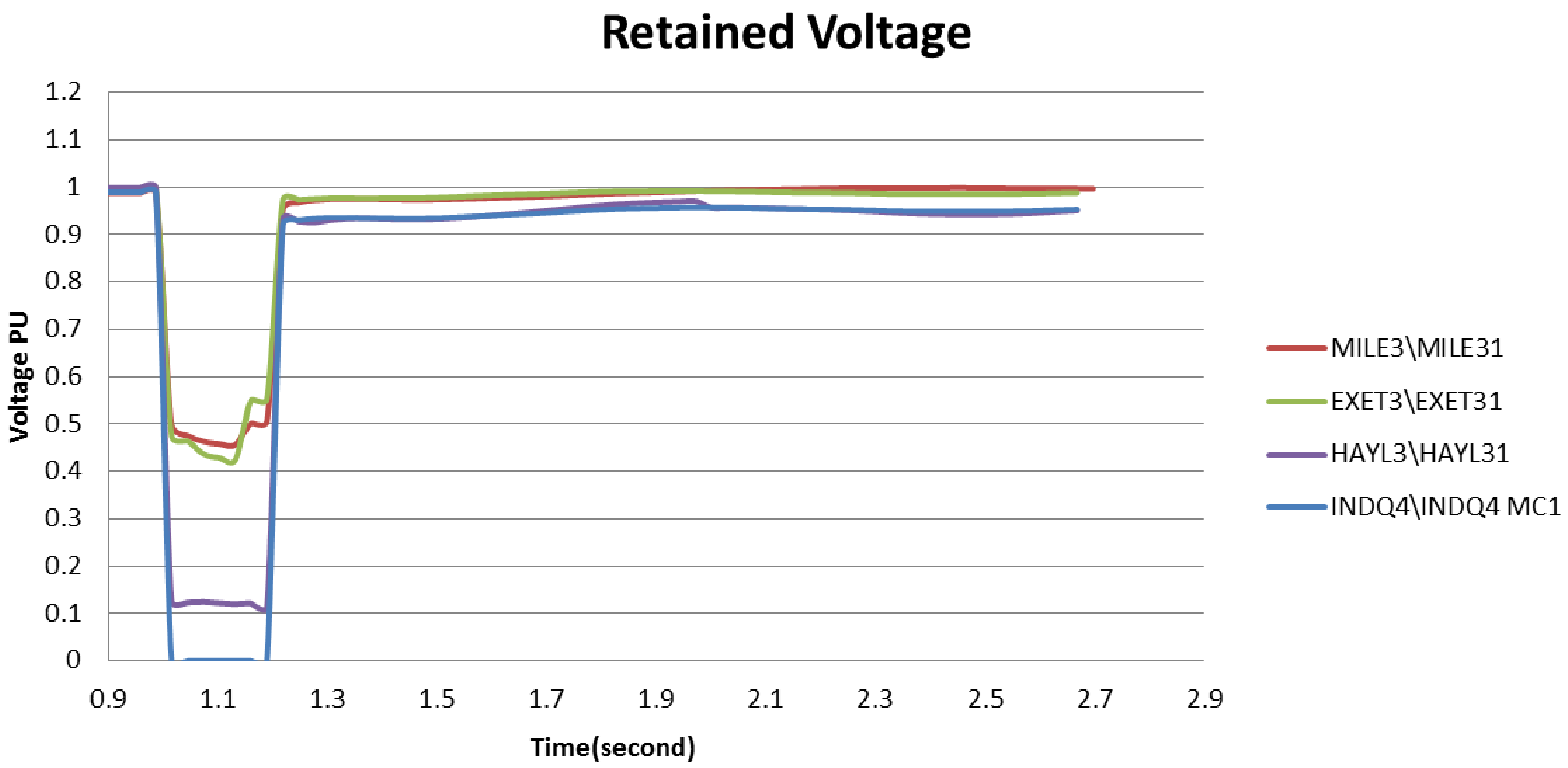
Transmission System - Minimum Demand

- The model Contains small synchronous machines at various busbars with the rest of the embedded generators are modelled as static generators. The total embedded generator output(South West region) is 141MW and 2270MW for synchronous and non synchronous plant respectively.
- The retained Voltage is above 0.1 pu
- Below is the embedded generation output matrix on the three busbars.

	Synchronous[MW]	Non Synchronous[MW]
Milehouse	**21**	**10**
Exeter City	**4**	**86**
Hayle	**13**	**46**

2025 Study case Solar Peak Scenario
Transmission System - Minimum Demand – PLL with FFCI



2025 Study Case Solar Peak Scenario

Transmission System - Minimum Demand (Without VSM)

Node Name	MILE3	EXEC3	HAYL3	INDQ4
Min voltage	0.50	0.47	0.13	0.00

- For the 2025 solar peak model the retained voltage is 0.13pu for a combination of synchronous machines and static generators with Fast Fault current injection (FFCI)

2025 Study case Solar Peak Scenario

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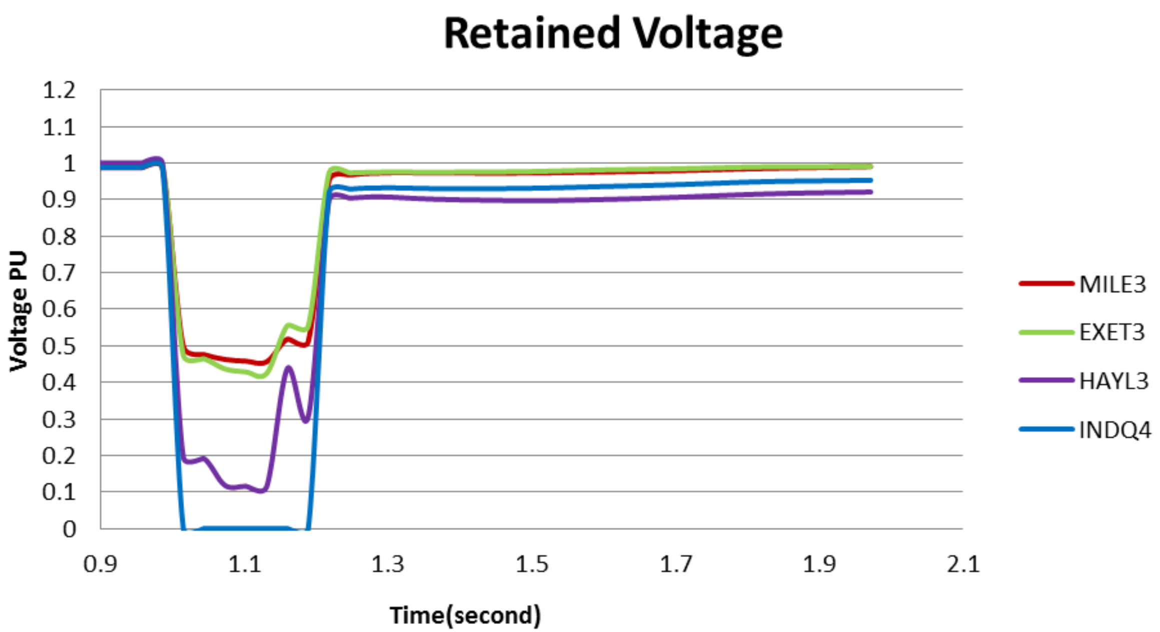
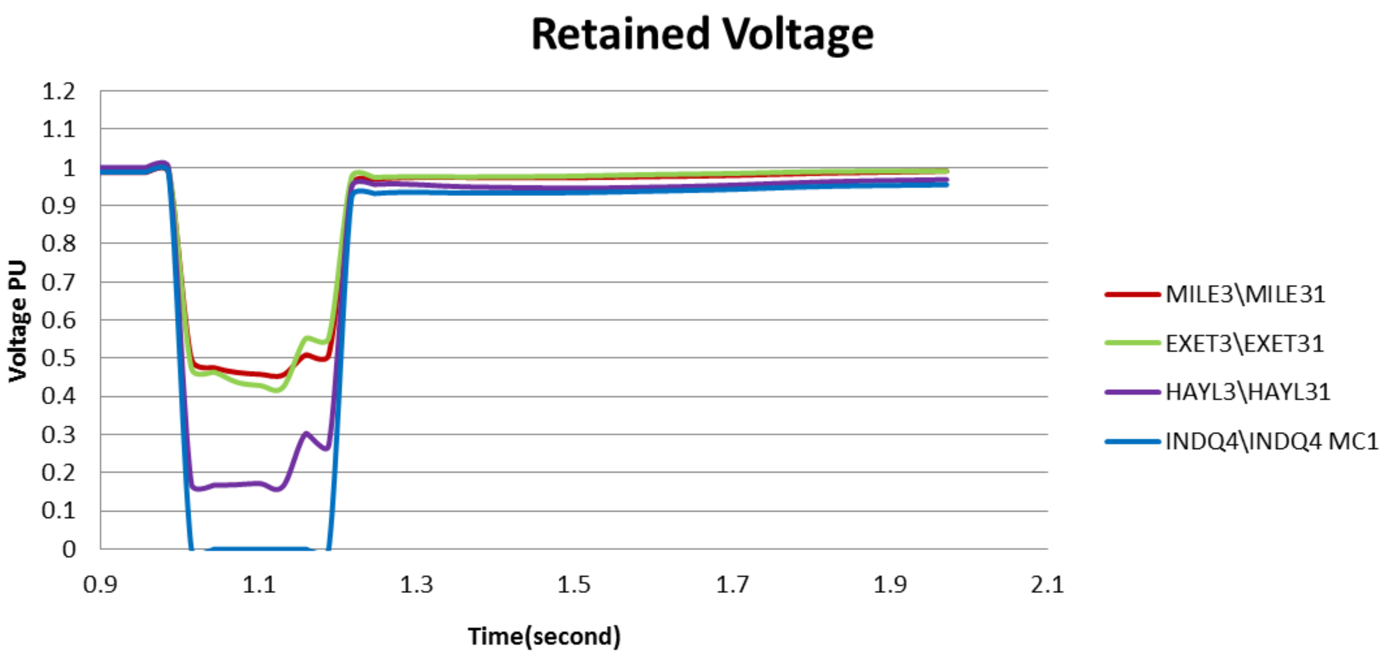
Results With VSM + PLL + Synchronous plant included - Transmission System - Minimum Demand



Node Name	MILE3	EXEC3	HAYL3	INDQ4
Voltage	0.50	0.47	0.19- 0.12	0.00

2025 Study case Solar Peak Scenario

Results With VSM + Synchronous plant included - Transmission System - Minimum Demand



Node Name	MILE3	EXEC3	HAYL3	INDQ4
Voltage	0.50	0.47	0.19	0.00

RfG – Fast Fault Current Injection Update – Results / Conclusions

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High Level Observations (1)

- The amount of fault current injected is a function of the volume of Generation at a specific location
- The retained voltage during the period of the fault is a function of the amount of reactive current injected
  - The lower the fault infeed, the lower the retained voltage
- The fault infeed from Synchronous Generation is superior compared to Converter based plant
- The performance from Converter based plant can be modified depending upon the control strategy employed
  - The best performance can be obtained from VSM technology
  - The poorest when modelled as a Negative Demand
  - The performance of PLL based converters will be a function of the delay, response speed and maximum ceiling current (in these studies this was set to 1.5pu)
  - The performance of the PLL is fundamental to getting the phase relationship correct which can result in incorrect current injection and delays in performance

High Level Observations (2)

- If high levels of fast fault current injection are achieved, this helps maintain the voltage profile across the network. VSM can be seen to stabilise local retained voltage against a future greater level of nonsynchronous generation
- Volume of Generation is a primary issue in defining the levels of fast fault current injection required and the retained voltage (Uret)
- Any requirement that is proposed needs to be robust over the range of Transmission System operating conditions (ie max demand to min demand).
- The more generation running (in particular DG - with the wrong control philosophy) the greater the risk of incorrect behaviour hence the need for these requirements which creates self supporting situation.
- The reactive current injected by Synchronous plant is fixed and is a function of the machine parameters.

Constraints / Issues (1)

- The Transmission System is currently secured to a maximum infrequent infeed loss of 1800MW. If Embedded Generation is lost above this level, the frequency will not be secured without holding of additional reserves or operation of the demand disconnection scheme (initiated at 48.8Hz). Much of the embedded generation connected at lower voltages does not have operational metering to inform the scale of the potential maximum loss.
- Synchronous Generators driven by reciprocating Diesel / Gas engines are unable to ride through voltage dips where the retained voltage is below 30%. There is no known cost effective solution to overcome this issue at the present time. Time frame for tripping to be discussed.
- The best results (highest retained System voltage) for multi machine studies with high converter penetration were obtained with VSM technology included (see slide – 45)
- Based on studies, a Transmission System fault may result in voltage dips at certain busbars as low as 10% retained voltage even with the VSM from converter based plant modelled. This will result in tripping of some Embedded Generation; FRT settings need to balance operational costs with the potential cost of compliance.

Options

Option	Advantages	Disadvantages
Negative Demand	Do Nothing	Not sustainable- higher maximum loss occurs which cannot easily be tracked or managed. No fault current supplied – System Operability issues / Protection issues
Static Generator with PLL	Potentially gives relatively fast response but delays still exist	Real Converter unlikely to behave in this way Delayed response Anti phase PLL – requires tuning Power System Operational issues High post fault TOV issues Do not contribute to System Services
Static Generator with FFCI	Higher fault current than options 1 and 2	Do not contribute to System Services (e.g no inertia) Delayed response will risk voltage dips below defined voltage against time curve in areas of low synchronous generation Little System benefit unless high volumes connect Still requires manufacturer development of control strategies – but some experience in GB of doing this Still has dependencies upon PLL function
VSM	Offers many system benefits –over and above other options (see next slide) EU may introduce similar requirements in the longer term Offers better long term system performance than other current options No delay in response VSM Technology - current driven by Power System not converter	Unproven technology Requires manufacturer development Solution needs storage technology or primary energy source may need to be curtailed Development timescales unknown Potential Power System Stabilser issues

VSM Summary

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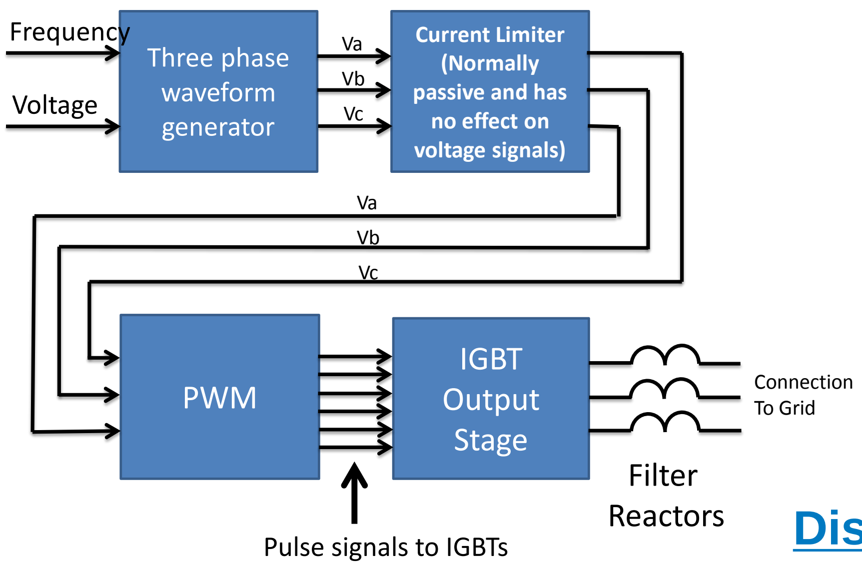
- VSM has been subject to a whole range of simulation work and a number of papers have been published on this subject (see references published in earlier GC0048 meetings / actions)
- VSM covers a wider range of system events in different scenarios unlike many other solutions, with a better performance
- VSM can be combined with the other solutions, it is not intrusive with the other technologies, these can work together with VSM
- VSM has similar response to Synchronous Machines under generation loss events, the operator can use the same expertise.
- Application, analysis, operation and commercialisation of the services of VSM are similar to those of Synchronous Machines

Virtual Synchronous Machine (VSM)

3 Phase VSM Output Stage



Changes for VSM

1. Simulate inertia
2. Reduce the bandwidth of F and V to 5Hz

Advantages (main)

1. Contributes to RoCoF
2. Compatible with SG
3. Reduced interaction and HF instability risks
4. Can be modelled in RMS system studies

Disadvantages

1. Requires additional energy (eg storage)
2. Possibility of traditional power system instability

Summary

- From a Transmission System perspective, the VSM functionality or immediate fault current injection is the preferred option based on the study results in addition to the wider system benefits – see previous slide. It also helps lift the retained voltage (Uret) across the system
- The EU are already looking at these concepts - a one year study is being initiated for Type 1 Grid Forming Converters.
- There could be additional costs to developers. For battery storage and solar projects these are considered to be modest, for wind based plant they could be higher
- The dilemma – From a Network Operators perspective VSM functionality is the preferred solution but it is acknowledged that development time needs to be factored into this and to meet RfG timescales, a solution must be available by May 2019.
- If these timescales cannot be met, then there would still be a requirement for converter based plant to contribute to reactive current injection. The risk is that it could result in manufacturers to develop one solution on an interim basis and then adopt the immediate current injection approach in the longer term which could result in doubling development costs.

High Level Proposals

- For fast fault current injection an immediate reactive current injection (VSM type functionality or otherwise) would be proposed in the longer term - in the shorter term conventional converters with delays would only be available until 1 Jan 2021?)
- Fault Ride Through Voltage against Time Curves
  - For Type D Power Generating Modules connected at or above 110kV the proposed requirements (circulated in October) would remain unchanged
  - For Type D, C and B Power Park Modules connected below 110kV the requirements would remain as they are
  - For Type C and D Synchronous Power Generating Modules below 110kV the requirements would remain unchanged
  - For Type B Synchronous Power Generating Modules the value of Uret would have to remain at 0.3 pu as no known technical solution is believed to exist
- Synchronous Generators driven by reciprocating engines are limited in size to about 5 MW. Synchronous Generating Units above this size are generally driven by non reciprocating prime movers and not believed to present a problem. A Band B / C threshold of 10MW is therefore proposed.
- Even with these values and based on the studies run, it is possible that small volumes of embedded generation could be lost though these are small (based on the fault at Indian Queens this is limited to about 13MW) even this has low risk due to the higher volumes of embedded generation running

Fast Fault Current Proposals

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FFCI Requirement

Immediate fault current injection

Conventional Converter with delays (Time limited until 1 January 2021?) then VSM type performance would be required

Eg VSM Type Functionality

The delay in response here does however cause concern as it would mean that the retained voltage drops during the initial part of the fault which could have implications for the Voltage against time curves

High level proposals for Immediate Reactive Current Injection (VSM Type Performance or Equivalent)

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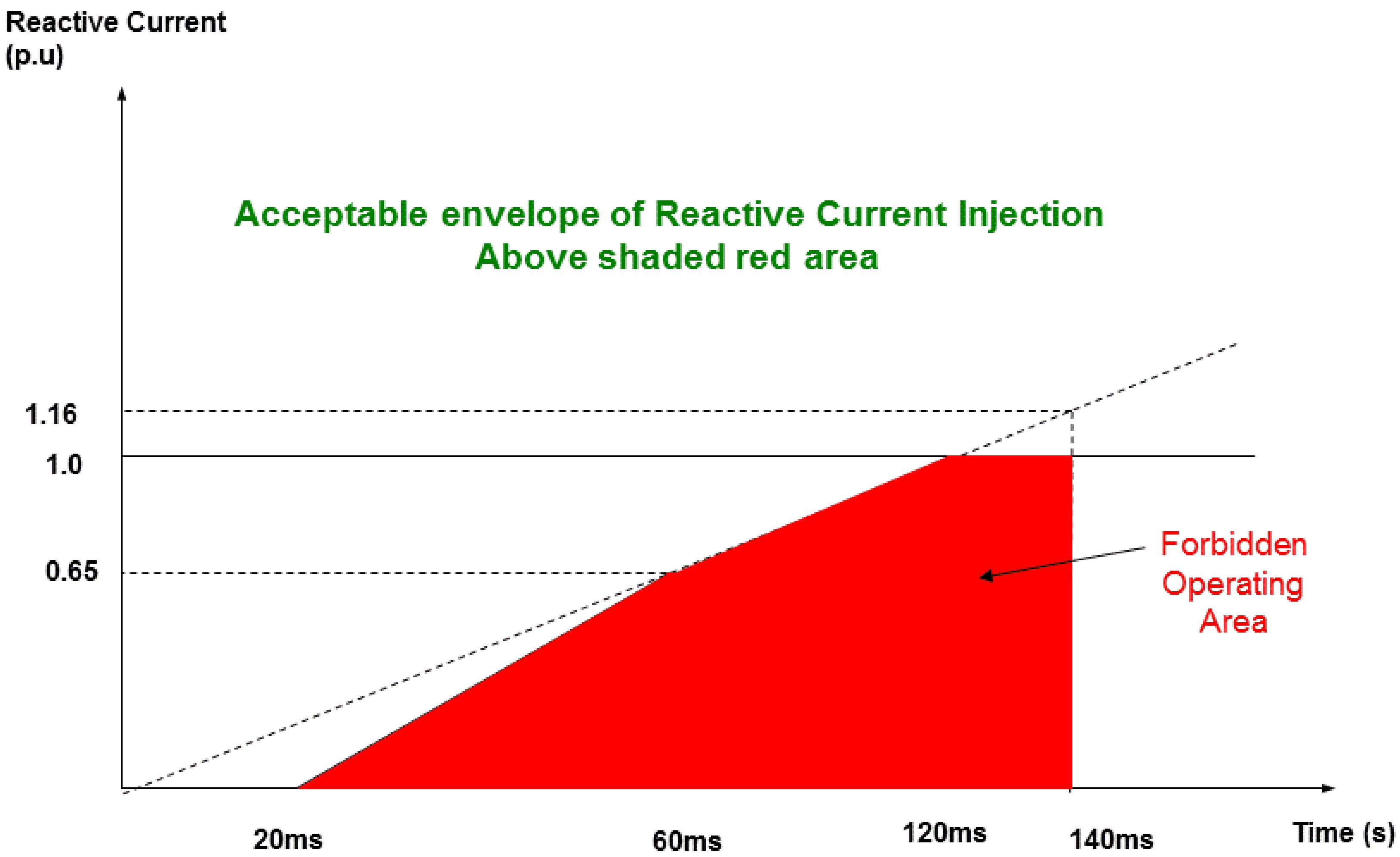
Requirement	Specification
Point of Fast Fault current injection	Connection Point of Power Park Module
How and when voltage is to be determined as well as the end of the voltage deviation	Current supplied as required by the System
The characteristics of the fast fault current, including the time domain 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	Current supplied as required by the System (Voltage Source Converter). This type of technology will limit the current within the capability of the rating of the converter. This would be proposed to be set to 1.5pu (assuming the converter is rated to circa 1.3p.u real power).
The timing and accuracy of the fast fault current, which may include several stages during a fault and after its clearance	Current limit needs to be fast to prevent converter damage
When post fault active power recovery begins based on a voltage criterion	Active Power to be delivered immediately the fault has been cleared providing the current limit has been switched off and system voltage has recovered to nominal levels.
Maximum allowed time for active power recovery	Active Power to be delivered immediately the fault has been cleared providing the current limit has been switched off and system voltage has recovered to nominal levels.
Magnitude and accuracy for active power recovery	Active Power to be restored to 90% of its pre-fault value. Active Power oscillations shall be acceptable provided that the total active energy delivered during the period of the oscillations is at least that which would have been delivered if the Active Energy was constant and the oscillations are adequately damped.

High Level proposals for Conventional Converters



High level proposals for Conventional Converters

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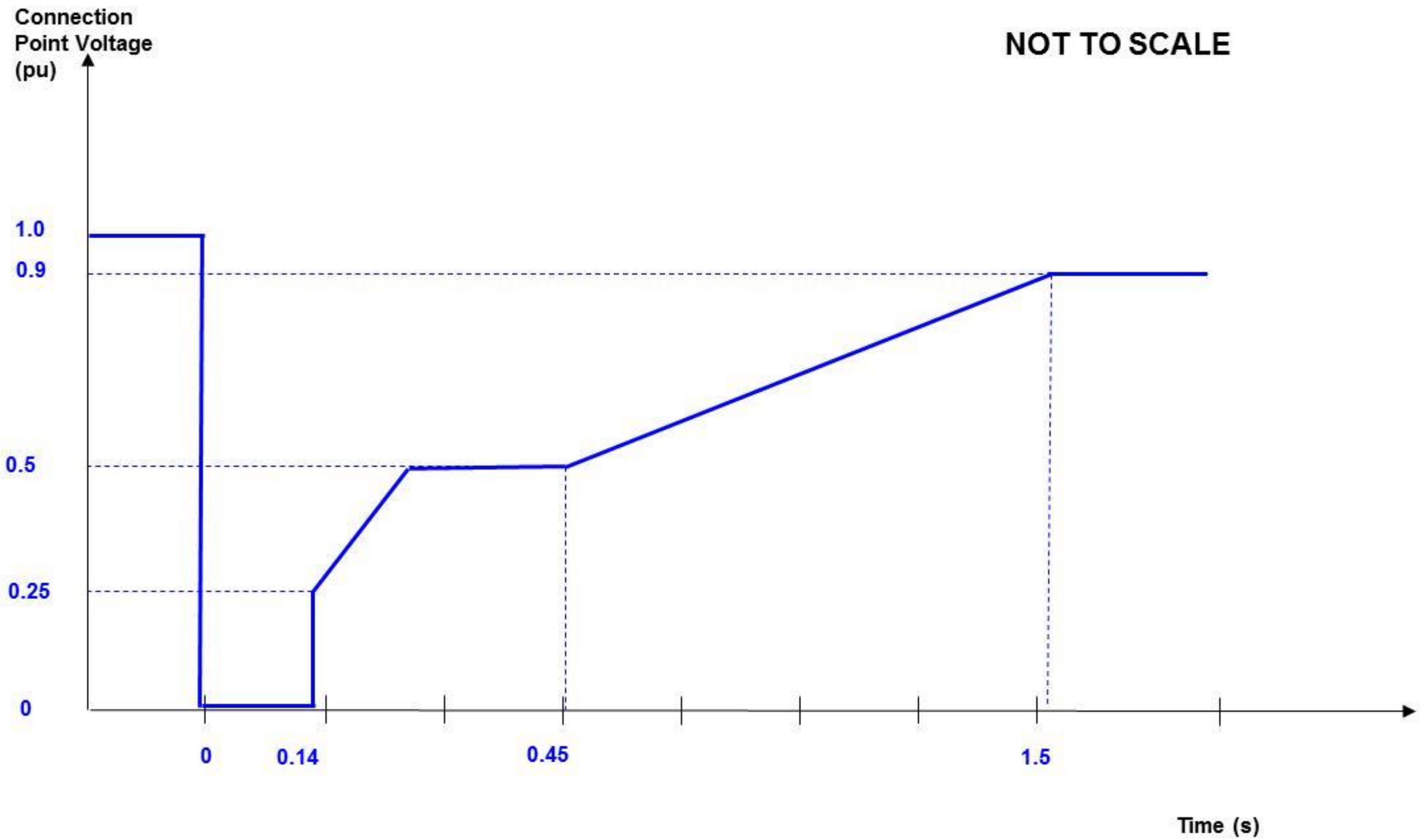
Requirement	Specification
Point of Fast Fault current injection	Connection Point of Power Park Module
How and when voltage is to be determined as well as the end of the voltage deviation	Each time the voltage at the Connection Point drops below 0.9p.u Blocking Voltage expected to be set at 0.09 pu
The 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	Each Power Park Module shall be capable of generating maximum Reactive current during the period of the fault without exceeding the transient rating of the Power Park Module. The PLL needs to be disabled in order to maintain the same phase reference
The timing and accuracy of the fast fault current, which may include several stages during a fault and after its clearance	Power Park Module Facility Owner to provide a continuous time trace of reactive current injection before during and after the fault, which demonstrates an acceptable degree of injection within the time period 20-60ms – See previous slide
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, but less than 1.05p,u)
Maximum allowed time for active power recovery	Active Power to be restored within 0.5 seconds of fault clearance (ie voltage above 0.9p.u)
Magnitude and accuracy for active power recovery	Active Power to be restored to 90% of its pre-fault value. Active Power oscillations shall be acceptable provided that the total active energy delivered during the period of the oscillations is at least that which would have been delivered if the Active Energy was constant and the oscillations are adequately damped.

Note

- Whilst the concepts of immediate reactive current injection are being proposed in the longer term, the requirements for fast fault current injection will ultimately be specified in the Grid Code as a functional performance requirement.
- There is no restriction on the equipment used to satisfy these requirements so long as they can meet the functional performance proposed Grid Code.
- This presentation has suggested the approach going forward. The consultation will cover the functional performance requirements in more detail.
- Stakeholder discussions are required on these proposals

RfG Fault Ride Through Voltage against Time curves

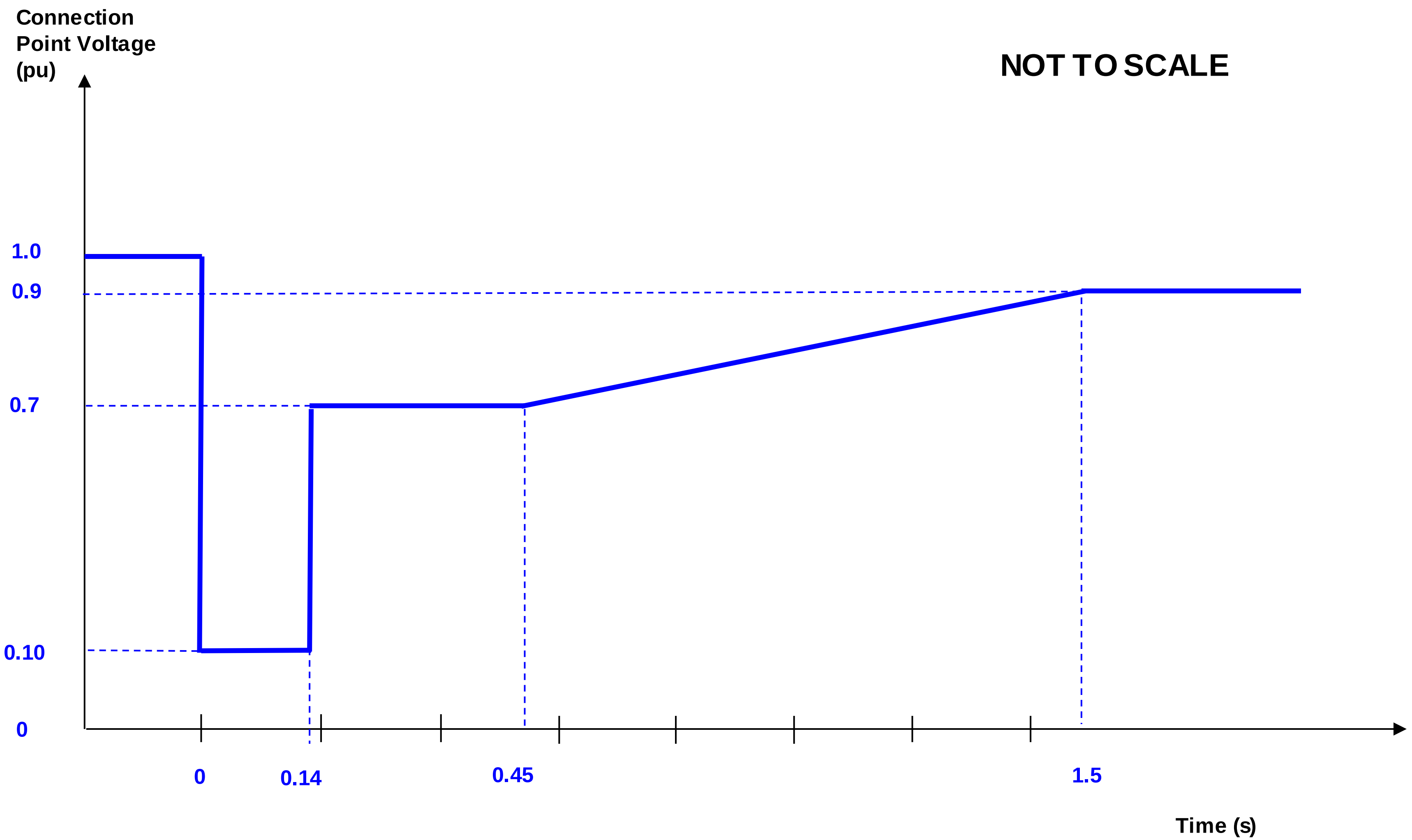
GB Type D Voltage Against Time Curve



Type C and D Synchronous Power Generating Modules Connected <110kV

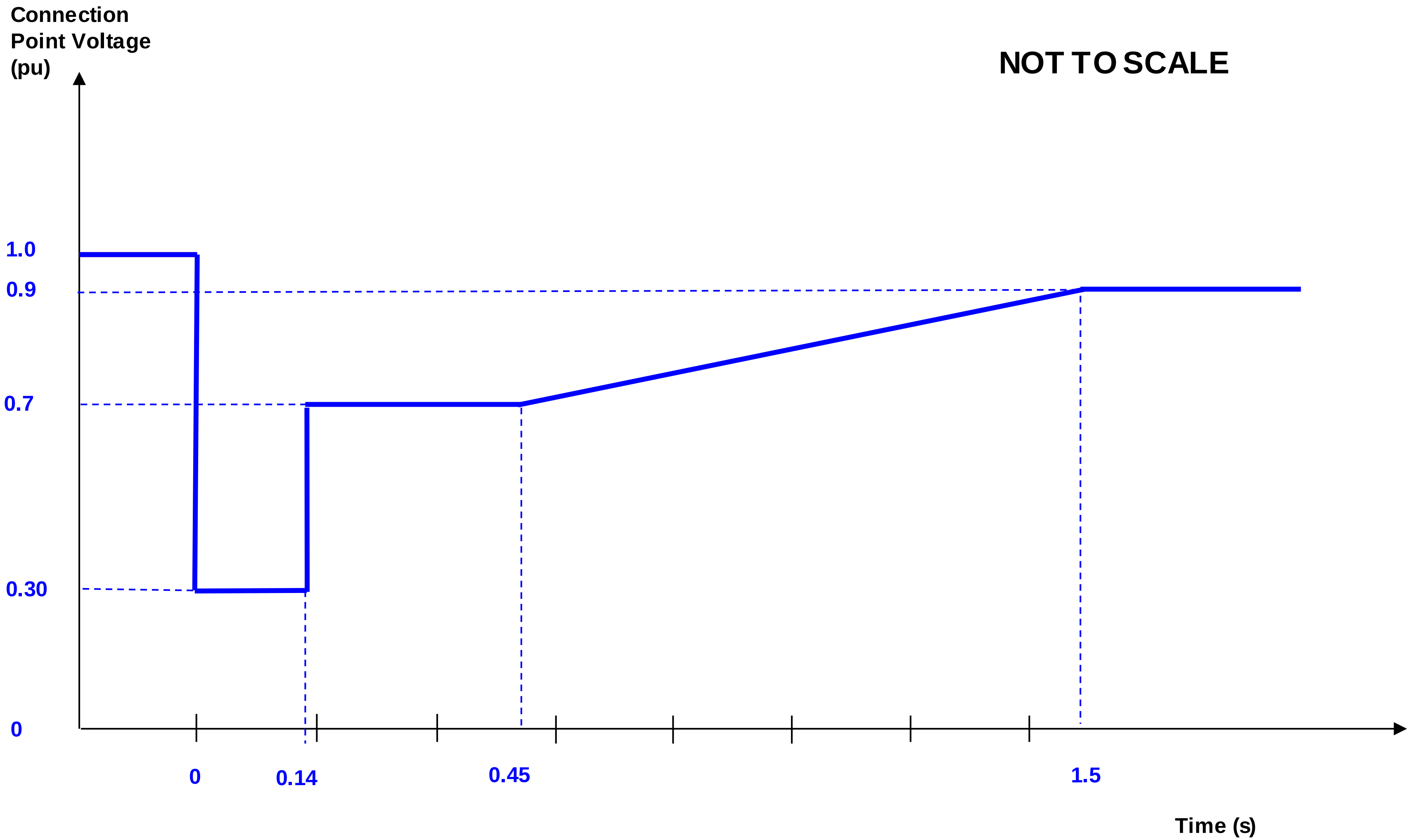
nationalgrid

Suggested Voltage Against Time Profile – Type C and D



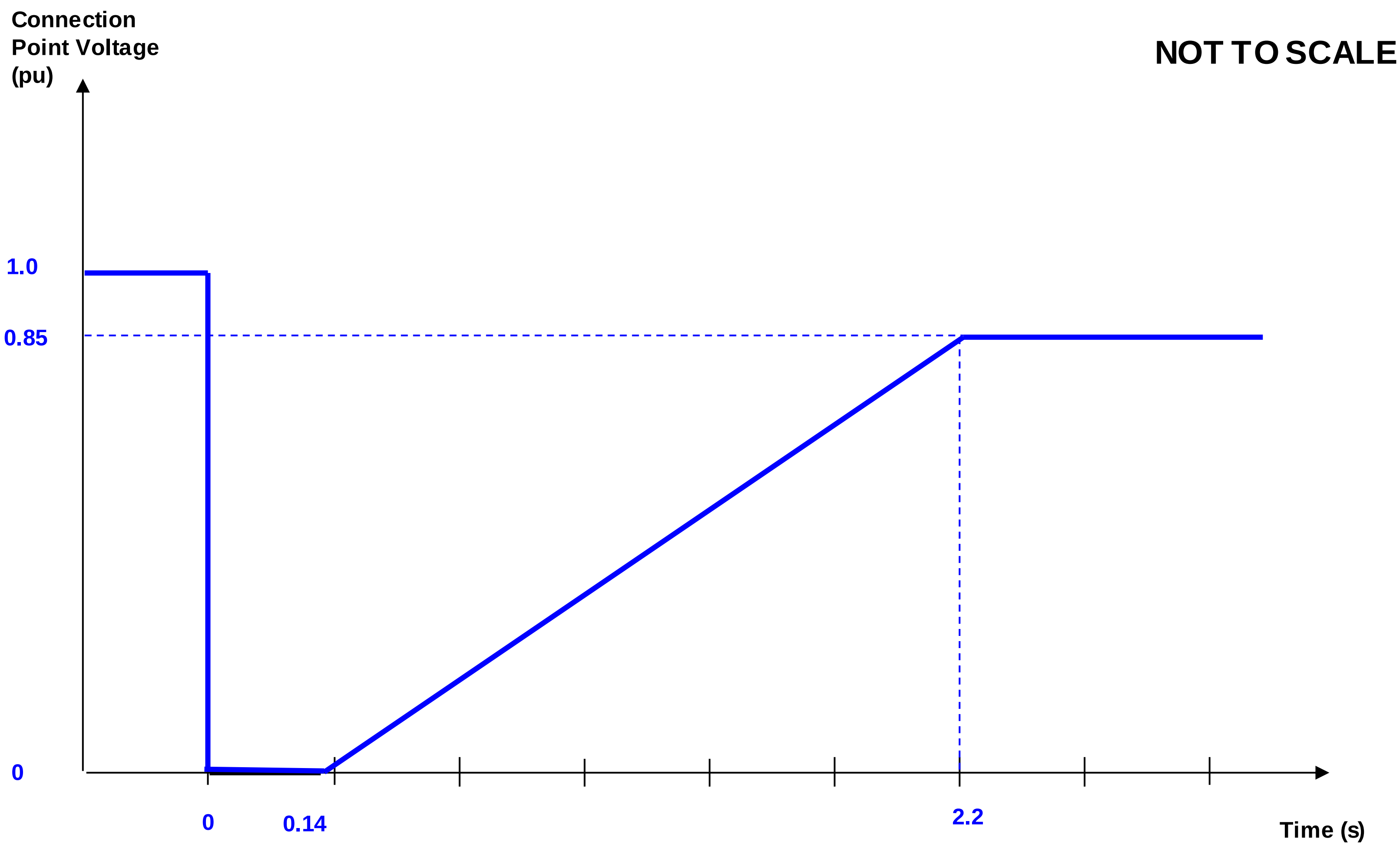
Type B Synchronous Power Generating Modules Connected <110kV

GB Voltage Against Time Profile – Type B



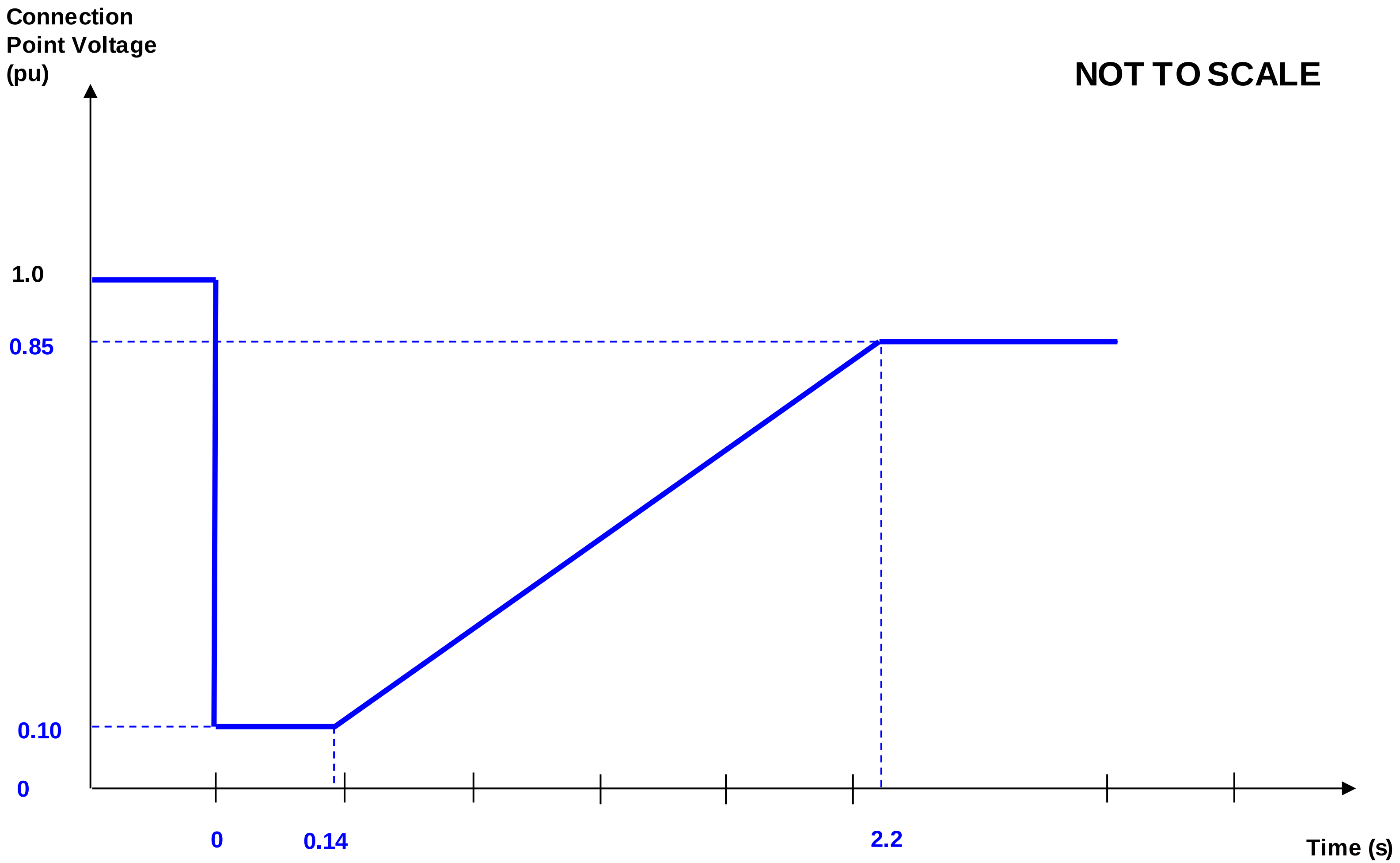
Type D Power Park Modules connected ≥110kV

GB Voltage Against Time Profile – Type D



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

GB Voltage Against Time Profile - Type B, C and D



Summary

- Immediate current injection may be considered an unproven option but its overall cost is considered to be the lowest and offers many other system benefits. The VSM is an example of such technology – it is not the only option
- Time allowed for manufacturers to develop solutions. Conventional Converters with delays can be used as a short term solution until 1 January 2021? Immediate current injection performance can be employed at any time but conventional converter performance would only be available until 1 January 2021 due to concerns over delays and the effect on system performance.
- Based on current studies, a Transmission System fault will result in voltage dips at certain busbars which could be as low as 10% even with the VSM from converter based plant modelled.
- The proposed voltage against time curves require a value of Uret = 10% for all Type B, C and D Plant connected below 110kV (excluding Type B Synchronous).
- Embedded Generation losses need to be mitigated for major Transmission System faults. Based on the study results, the Band B/C threshold in RfG is recommended to be 10MW; It is believed the potential loss of Embedded Generation including smaller Synchronous machines (up to 10MW) driven by reciprocating engines (with a value of Uret set at 30%) is manageable at these levels.
- Costs are not believed to be excessive for any plant in meeting these Uret values (eg FRT already applies in SHET Transmission area and Offshore for all plant of 10MW and above)
- The EU are looking at these concepts – Type 1 Grid Forming Converter performance