



# System Incident Investigation for the Tasmanian Region

Modelling and detailed analysis of transmission line fault events of  
December 2014 and February 2015

A JOINT INVESTIGATION BY AEMO AND TASNETWORKS

NOVEMBER 2015

## TERMS AND ABBREVIATIONS

Term or Abbreviation	Definition
AC	Alternating Current
AEMO	Australian Energy Market Operator
Bridge	Six pulse thyristor group
CCGT	Combined Cycle Gas Turbine
DC	Direct Current
FCAS	Frequency Control Ancillary Services
FCSPS	Frequency Control System Protection Scheme
FRT	Fault Ride Through
GT	George Town
HVDC	High Voltage Direct Current
JWG	Joint Working Group
kA	Kiloamperes (one thousand amperes)
kV	Kilovolts (one thousand volts)
LCC	Line Commutated Converter
LG	Line-to-ground
LL	Line-to-line
ms	Millisecond (one thousandth of a second)
NER	National Electricity Rules
POW	Point On Wave
PSCAD/EMTDC	Simulation program (tool) for analysing power system transients
pu	Per-unit
SCR	Short circuit ratio
μs	Microsecond (one millionth of a second)
Valve	Also referred to as a thyristor valve – for LCC HVDC, typically 50-200 single thyristors connected in series.
VBE	Valve Base Electronics (providing thyristor protection in the context of this report)

## IMPORTANT NOTICES

### Purpose

Further to the initial report issued by the Australian Energy Market Operator Ltd (AEMO) in May 2015 [1], AEMO and Tasmanian Networks Pty Ltd trading as TasNetworks (TasNetworks) have jointly completed modelling and technical studies to understand the root cause of three recent disconnections of the Basslink interconnector following faults on the Tasmanian 220 kV network.

The two key activities discussed in this report, as defined in the initial report, are:

- i. Verify the accuracy of the Tasmanian electromagnetic transient computer models, including the Basslink Interconnector, by replicating the system events of December and February through simulation
- ii. Replicate a scoped set of critical studies using the verified Tasmanian network and Basslink Interconnector electromagnetic transient models to identify potential solutions

The analysis and conclusions presented herein have been developed and reviewed by a Joint Working Group formed in response to the recommendation published as part of AEMO's initial investigations [1].

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## EXECUTIVE SUMMARY

### A. Background

On two occasions in December 2014 and once in February 2015, transmission faults in the Tasmanian 220 kV network resulted in disconnection of the Basslink Interconnector.

Consequently, during power transfer across Basslink from the mainland to Tasmania:

- Loss of the Basslink Interconnector following a remote fault on the Tasmanian 220 kV network has been reclassified as a credible contingency event.
- AEMO is required to source additional Frequency Control Ancillary Services (FCAS) in Tasmania.

The findings of the initial investigation published by AEMO in May 2015 [1] were as follows:

- Each of the three faults on the 220 kV network was cleared in accordance with the System Standard and based upon information provided by TasNetworks, its network control and protection systems performed as the NER provisions require from Network Service Providers.
- Based upon information provided by Basslink Pty Ltd, the Basslink control and protection systems operated as designed.
- The unbalanced nature of each of the faults caused a commutation failure in the Basslink inverter station at George Town which is a normal occurrence on a temporary basis during faults in AC systems.
- The high voltage direct current (HVDC) link tripped because multiple commutation failures were sustained. This has not occurred previously for Basslink [1]. HVDC links are designed to quickly recover from commutation failures so as to avoid loss of the HVDC link. However such a recovery is more difficult when the AC system is weak.

AEMO committed to complete power system modelling work in cooperation with TasNetworks to better understand the reasons for these recent events. The joint power system modelling work has now been completed and this report summarises the results.

### B. Power system modelling and simulation

AEMO and TasNetworks have developed a detailed computer model to study the Tasmanian Power System during credible faults on the 220 kV network, including the interaction between the Basslink HVDC Link and the power system.

The developed model has been benchmarked against the three recent 220 kV faults that caused the disconnection of Basslink and loss of customer load. The results of this benchmarking have given AEMO and TasNetworks confidence in the overall model. While the model does not include all details of the Basslink thyristor protection, AEMO and TasNetworks consider the model sufficiently valid to simulate the sequence of observed events.

The results of the modelling and simulation studies have indicated that:

- Performance of the Basslink Interconnector has not degraded. Recent changes in Tasmanian power system operation have resulted in an increased likelihood of a disconnection following credible contingencies.
- Disconnection of the Basslink Interconnector following credible Tasmanian transmission network faults is sensitive to a number of factors:
  - Level and proximity of online synchronous generation within the Tasmanian region to the Basslink HVDC terminal (increased generation close to George Town reduces the likelihood).
  - Level of import on Basslink into Tasmania at time of transmission fault inception (increased level of import increases the likelihood).
  - Number of phases involved in the transmission network fault and the fault impedance/residual voltage seen by Basslink (phase-to-phase faults and low fault impedance increase likelihood).



- Point on the power frequency (50 Hz) voltage wave form at which the a fault is initiated (this timing has a significant impact on the likelihood of tripping).
- The likelihood of Basslink tripping for a fault at any given location remote from George Town thus varies depending upon how the above factors apply in combination at that time.
- The modelling has shown that a set of circumstances remains possible for locations on the Tasmanian 220 kV system (particularly for faults at connection points of major generating units) where a fault would lead to loss of both a major generating unit and Basslink.
- In particular, commitment of additional generation closer to George Town will reduce the likelihood of Basslink disconnection, though not to a level for which these events can be considered non-credible.

Details of this power system modelling and analysis work are discussed in this joint report.

### **C. Next steps**

Based on the results presented in this report, AEMO is satisfied that the current reclassification of credible Tasmanian contingencies should remain in place.

AEMO and TasNetworks will review the recommendations of the independent expert (Manitoba HVDC Research Centre Inc) and implement appropriate findings.

Further, AEMO proposes to facilitate a Tasmanian power system working group to investigate ways to remove the current reclassification.



## 1. INTRODUCTION

This section highlights the sequence of events for three transmission network fault events which occurred in December 2014 and February 2015. A brief summary of the historical performance of the Tasmanian network and Basslink in response to transmission network faults is also presented.

### 1.1 Sequence of network events

During the period from December 2014 to February 2015, three fault events occurred in the Tasmanian AC 220 kV transmission network which had undesirable consequences for the operation of the Basslink HVDC interconnector.

These three events caused a prolonged commutation failure in the Basslink power inverter. This was manifested by a sudden change in the inverter AC bus voltage caused by the phase shift experienced on the AC network as a result of the 220 kV fault. This resulted in a reduction of the inverter voltage magnitude and phase advance with respect to the control system's internal reference waveform. Additionally, for all three events the Tasmanian end converter was operating in the 'inverter mode' (power transfer from Victoria to Tasmania) for which line-commutated converters (LCC) HVDC links are more susceptible to commutation failure [3].

The three network faults were unbalanced disturbances which are one of the main causes of commutation failure due to the resulting phase angle change in the inverter AC voltage. Two-phase faults generally result in the highest phase angle change.

The combination of sudden voltage dip and phase angle shifts to which the converter was exposed during inverter mode of operation was sufficient to result in the first commutation failure. This is an expected event for any LCC HVDC links as the ability of the HVDC control system to avoid one commutation failure in the presence of an AC network fault is very limited given the speed of response required.

Previous commutation failure events experienced in the history of Basslink operation resulted in commutation failures persisting for less than three cycles. By this time, the HVDC control systems had the opportunity to detect the event and regain control of the commutation process.

However, for the three transmission network fault events in December 2014 and February 2015 the commutation did not successfully resume within the desired response time following inception of the AC network fault. Such repetitive commutation failures are also referred to as 'extended commutation failure'. As a result, the Valve Based Electronic (VBE) thyristor protection system issued a trip command to the converter station, removing Basslink from service. Extended commutation failures in response to single network fault events are not common, although they have been reported in technical literature [5]. Such events cause sustained overcurrent in the conducting valves and put at risk the physical integrity of the thyristor valves.

Many LCC HVDC schemes, including Basslink, incorporate an under voltage masking function in the thyristor protection system that is intended to prevent spurious operation during periods of low AC voltage. Activation of the masking function only occurs when AC voltage measurements at a converter station fall below the threshold setting. It is understood that the masking voltage is currently set to 0.3 pu for Basslink. For the three network fault events in December 2014 and February 2015, the resulting residual voltage at all phases was greater than 0.7 pu which did not therefore invoke the masking voltage scheme.

Subsequent investigations by Basslink Pty Ltd confirmed that all thyristor valves were 'healthy' following each of the three recorded trip events. The extension of the commutation failure is understood to have been the cause of the thyristor protection system operating.

The subsequent loss of Basslink triggered operation of the Frequency Control System Protection Scheme (FCSPS). The FCSPS is a Tasmanian specific scheme designed to mitigate frequency deviations that result from instantaneous loss of the interconnector at high power transfers. Operation of FCSPS in the three fault events resulted in disconnection of 383 MW, 402 MW and 485 MW of customer loads, respectively. For all three events the FCSPS operation was expected as it is designed to mitigate the impact on power system frequency caused by the loss of Basslink power transfer.

## 1.2 Historical performance of Tasmanian AC network and Basslink

The available statistical evidence suggests that two-phase and two-phase-to-ground faults are as equally credible as the single-phase faults. This is an important observation in the context of NER clause 4.2.3 (Credible and non-credible contingency events) which defines only three phase faults as being non-credible. Basslink has been exposed to eighty three known fault events in the Tasmanian 220 kV network since 2007 [6]. While the total number of recorded commutation failure events is relatively high, the majority of these were not as a result of contingency events in the 220 kV network, but faults in the distribution system or generator terminal stations. An even smaller subset of transmission events occurred when the interconnector was operating at high power transfers.

It can be observed that while the link has experienced numerous commutation failure events, its historical exposure to *critical credible contingencies*, i.e. contingency events which are likely to have tested the HVDC controls to 'their design limits', has been relatively small. Over the past eight years there have been 13 unbalanced faults on the 220 kV Tasmanian transmission network during which time Basslink was importing in excess of 300 MW from Victoria to Tasmania. Only for the most recent three events did the fault result in disconnection of Basslink and the operation of the Tasmanian FCSPS.



## 2. VALIDATION OF COMPUTER MODELS

### 2.1 Methodology

To ensure veracity of simulation results and the observations / conclusions that have been drawn, the integrated computer model, representing the Tasmanian transmission network, all registered Tasmanian generating units, and the Basslink HVDC interconnector, has been benchmarked against field measurements obtained from TasNetworks and Basslink Pty Ltd (Basslink) for the three system incidents that occurred on 10 and 16 December 2014, and 23 February 2015. The primary objective of the benchmarking studies is to demonstrate that the transmission network faults leading to extended commutation failures experienced by Basslink and the activation of the FCSPS can be accurately recreated by simulation. Accurate representation of the events forms the basis of evaluation of any potential solution.

For the three aforementioned events measured responses indicate that Basslink suffered an extended commutation failure, resulting in the operation of the VBE thyristor protection system, and subsequent tripping of the converter station.

To assess the accuracy of the simulations, the following benchmarking criteria were established using the PSCAD/EMTDC software:

- i. Comparison of inverter three phase AC voltage measurements and simulations
- ii. Comparison of inverter three phase AC currents measurements and simulations
- iii. Comparison of inverter DC current measurements and simulations

### 2.2 Results

The detailed results of the benchmarking studies are presented in Appendix A. Plots are shown of internal and connection point electrical quantities measured during the system events and as recreated by simulation. As illustrated in Figure 5 to Figure 7, phase plots of AC inverter voltage and current correctly predict the magnitude and phase shift of the phase quantities for the recreated transmission fault. This is important to verify the expected response of the Basslink protection systems.

For all three system incidents that were investigated, the integrated PSCAD model will recreate the key phenomena, most critically the extended commutation failure that resulted in disconnection of Basslink for the December and February events. Similarly, the model accuracy was verified for a known system event on 16 December 2014 for which no extended commutation failure occurred. The fault in the latter case was a line to ground fault on the 220 kV Gordon to Chapel transmission line.

Based on the results obtained, AEMO and TasNetworks have concluded that the PSCAD model of the integrated Tasmanian computer model is sufficiently accurate to analyse the issue of extended commutation failure in response to credible transmission fault events in the Tasmanian AC network.

Results shown in Appendix A demonstrate that the difference between measured and simulated waveforms generally lies within a  $\pm 10\%$  error margin, where the largest errors are associated with the peaks and troughs of the waveforms. Similarly, very good correlation is obtained between the timing of the measured and simulated waveforms, where the error margin is less than 1 millisecond. These results give confidence in the adequacy of the integrated computer model for investigating the observed network events and potential solutions.

### 3. FACTORS INFLUENCING RESPONSE TO TRANSMISSION NETWORK FAULTS

The objective of this section is to investigate sensitivities of the Basslink Interconnector to possible disconnection following Tasmanian transmission network faults, which in turn can lead to activation of the FCSPS. Representative simulation results are summarised in Appendix B.

#### 3.1 Scenarios studied

To assess the conditions under which the Basslink disconnection and subsequent loss of customer load could occur, fifteen different network scenarios have been considered for simulation, varying in demand and local generation dispatch, to level of Basslink import and severity of the transmission fault. The scenarios investigated are outlined along with key results in Table 2.

All scenarios considered correspond to zero power being produced by Tasmanian wind generation at the time of fault occurrence. Therefore, the cases considered are conservative, rather than worst case, because wind farms will provide significantly lower contributions to the fault level of the network compared to that delivered by synchronous generation technologies. Hence, wind farms do not assist in strengthening the network. For each scenario multiple simulation case studies were conducted to investigate sensitivity to fault impedance and point-on-wave where the fault occurs.

Furthermore, for scenarios #11-13 the fault impedance and point-on-wave were adjusted so as to replicate the voltage profile seen by the Basslink inverter terminal for the 10 and 16 December and 23 February events, respectively. These simulations are used as the benchmark for model assessment referred to in Section 2.

Similarly, scenarios #14 and 15 were developed so as to recreate the voltage profile seen by the Basslink for 10 December and 23 February events, respectively. However, to assess the sensitivity of the system events under consideration to generation dispatch the Tamar Valley combined cycle gas turbine (CCGT) plant is assumed to be offline.

For the simulations carried out, the HVDC link's longest conducting valve current was used to determine whether or not an extended commutation failure would occur. Model validation results presented in Appendix A, including the DC current, confirm the veracity of using this criterion. Scenarios #1-10 include a full point-on-wave and fault impedance sensitivity analysis, whereas for scenarios #11-15 the longest conducting valve current was determined for a specific point-on-wave and fault impedance.

To account for modelling uncertainties, scenarios where the duration of the longest conducting valve current is between 60 and 62 milliseconds are highlighted as uncertain in terms of whether or not they will result in an extended commutation failure.

For all scenarios reported the line-to-line and line-to-ground voltage magnitudes at the Basslink terminals remained above 0.3 pu, hence the HVDC link voltage masking scheme was not invoked (refer to Section 1.1).

#### 3.2 Assessment criteria

The following electrical quantities have been studied for each scenario investigated:

- i. Three phase voltages at the George Town converter station
- ii. Three phase currents at the George Town converter station
- iii. Basslink DC current
- iv. Longest conducting valve current
- v. Line-to-line RMS voltage at the George Town converter station with protection masking threshold shown
- vi. Line-to-ground RMS voltage at the George Town converter station with protection masking threshold shown

The above quantities are instrumental in indicating the behaviour of the system, and the impact on the Tasmanian network following credible contingencies.

In the absence of an accurate thyristor valve protection model, the longest conducting valve current was used as the key criterion to assess whether or not an extended commutation failure had occurred. Where the duration exceeded 60 milliseconds and all line-to-line and line-to-neutral voltages at the George Town converter station were maintained above 0.3 pu, it has been assumed that the VBE thyristor protection system would operate and trip the interconnector.

### 3.3 Sensitivity analysis

#### 3.3.1 Generation dispatch and system strength

A direct indicator of the strength (or weakness) of the power system is the fault current flowing during network fault events, which in turn is directly related to the number of synchronous generating units operating. A higher network fault current indicates a stronger power system, and lower value susceptibility to system disturbances.

Successful steady-state and transient operation of LCC HVDC links requires a minimum number of synchronous machines being online as often characterised by the short circuit ratio (SCR) or available fault level at the converter bus [5]. In all scenarios discussed in this report, including the actual events, the short circuit ratio at the inverter bus exceeds the minimum SCR for correct operation of the HVDC link. As an example Table 1 highlights the fault level, in MVA, and associated SCR seen by the George Town inverter bus. Fault levels shown in the table exceed the minimum required fault level of approximately 1300 MVA, corresponding to the Tasmanian power system load and Basslink import level for the three events, as agreed between TasNetworks and Basslink at the Basslink connection point.

**Table 1 Fault level and associated SCR for the three actual extended commutation failure events**

Event	Fault level (MVA)	SCR
10 December 2014	2210	4.42
16 December 2014	1792	3.58
23 February 2015	2435	4.87

Simulation case studies demonstrate that dispatching additional generation in Tasmania, and in particular generation at George Town, will reduce the risk of extended commutation failure and subsequent Basslink tripping. This can be clearly seen by comparing scenario #4 and #5. Additionally, dispatching all synchronous generation in Tasmania would have avoided an extended commutation failure event and Basslink disconnection for the 16 December and 23 February events.

However, generation dispatch cannot entirely eliminate the risk of an extended commutation failure, and the likelihood of a reoccurrence of the December and February events depends on how various factors discussed in this Chapter apply at any given time.

#### 3.3.2 Basslink import level

Increasing Basslink power import from Victoria to Tasmania increases the risk of an extended commutation failure. In practice, however, constraining Basslink import cannot completely avoid the risk of an extended commutation failure, and, as illustrated by the results of Table 2, Basslink import level cannot independently determine whether or not an extended commutation failure would occur following transmission network fault events.

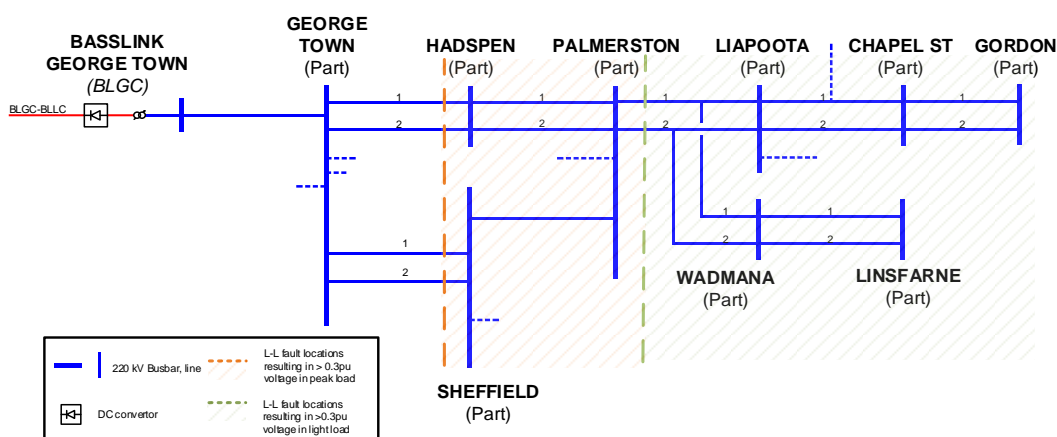
For a historically common synchronous generation pattern which included the CCGT at George Town and no wind generation, a line-to-line fault at Hadsphen was shown to result in a trip of Basslink at an import power level of only 100 MW. (Refer to scenario #5).

### 3.3.3 Fault location

Screening case studies were conducted to determine ‘boundaries’ within the Tasmanian transmission network, within which faults would likely result in an in-fault residual voltage at the Basslink connection point greater than 30% of the normal operating voltage, such that the protection masking would not be invoked (refer to Section 1.1). These boundaries are shown in Figure 1 for high and low demand scenarios, where locations to the right of the boundary represent fault locations for which the link may be exposed to tripping due to extended commutation failure.

Within these boundaries, Gordon and Hadspen 220 kV busbars were chosen as a representative for remote and close-in network faults relative to George Town, where the remote fault is defined as the furthest fault location in the 220 kV transmission network. A close-in fault is one that results in the residual voltage at the inverter bus to remain marginally above the 30% masking threshold. Studies have shown that the occurrence of an extended commutation failure event and subsequent Basslink tripping is most likely to occur for close-in network faults.

**Figure 1: Boundaries beyond which the residual line-to-line converter voltage remains above 30%**



### 3.3.4 Fault type

The majority of PSCAD simulations have been undertaken assuming the application of a line-to-line fault. This is on the basis that such events result in the largest voltage phase angle shifts, with any phase advance reducing the commutation margin available within the converter. Selected line-to-ground faults were also considered for study. Simulation case studies indicate a higher susceptibility of Basslink to extended commutation failure events for a line-to-line fault.

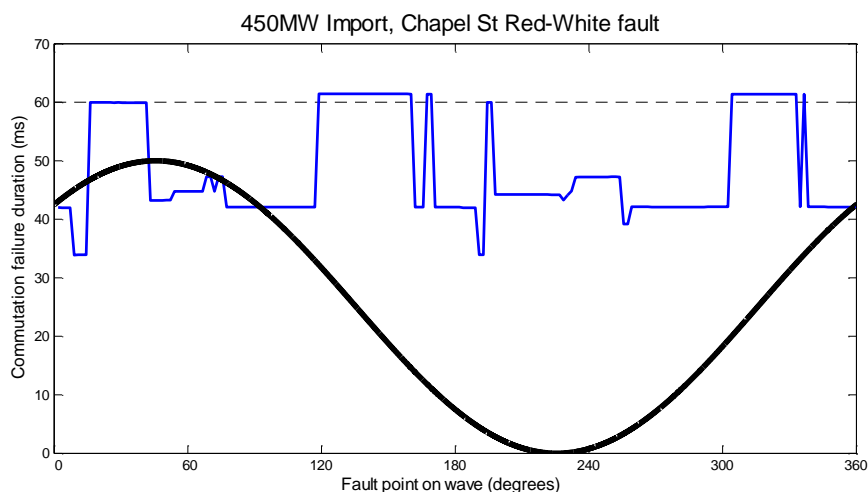
### 3.3.5 Point-on-wave of fault inception

Scenarios #1 to 10 were conducted with varying fault inception times, where the time at which the fault was applied on the voltage sine waves was varied. The findings indicate that the likelihood of an extended commutation failure lasting longer than 60 milliseconds is closely linked with the POW where fault inception occurs. It is noted that this factor cannot be controlled in practice.

As an example,

Figure 2 demonstrates the impact of point-on-wave in the case of Chapel Street 220 kV fault. This plot illustrates the duration of commutation failure predicted by the computer simulation for a remote transmission fault occurring at various points of a single cycle of one phase of the AC inverter voltage. The computer model suggests that approximately one quarter of the sinewave presents the risk of commutation failure extending beyond 60 milliseconds when Basslink is operating at 450 MW import.

**Figure 2: Commutation duration vs. point on wave for a higher fault impedance case**



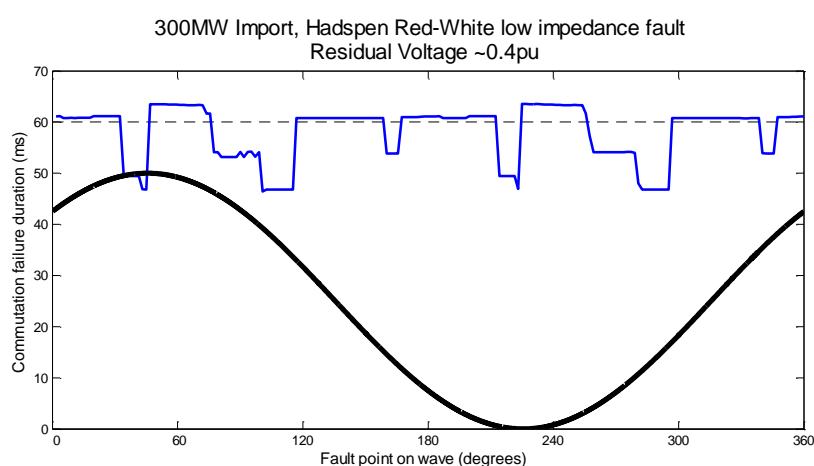
### 3.3.6 Fault impedance

Fault impedance can be considered as a proxy for residual voltage at the converter terminals, as well as the likely phase angle shift that is experienced. Simulation case studies indicate that a high fault impedance results in a reduced commutation failure duration.

To assess sensitivity to fault impedance simulation studies were conducted using two different fault impedances; one that would result in a voltage dip just above 0.3 pu (lower fault impedance case) and another that would result in a voltage dip that was well above 0.3 pu (higher fault impedance case). For this sensitivity analysis, a line-to-line fault was applied at Hadspen 220 kV substation under a medium import level of 300 MW.

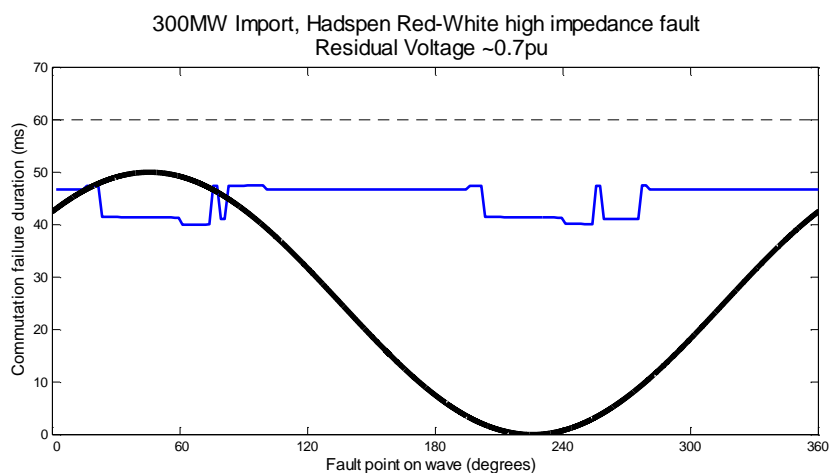
Figure 3 shows duration of commutation failure predicted by the model for a low impedance fault, relative to the point on the voltage cycle that the fault occurs. The plot illustrates that commutation occurring during more than half of the sinewave presents a risk of commutation failure extending beyond VBE protection setting of 60 ms when Basslink is importing 300 MW from Victoria to Tasmania.

**Figure 3: Commutation duration vs. point on wave for a lower fault impedance case**



**Figure 3** Figure 4 presents the same analysis with a high fault impedance. In this case, the residual voltage at the George Town converter station is maintained at approximately 0.7 pu. Under these conditions, a line to line fault at Hadspen does not produce a commutation failure with long enough duration to cause Basslink to trip, irrespective of the POW of fault inception.

**Figure 4: Commutation duration vs. point on wave for a higher fault impedance case**



By increasing the simulated impedance of the fault (which depends on factors such as electric arc, grounding impedance, etc.), the duration of the commutation failure was reduced by approximately 10 milliseconds. The intention of the simulation is to demonstrate the sensitivity of the HVDC commutation process to the fault impedance which cannot be controlled in practice.

Based on observed responses of the Basslink Interconnector to variations in fault type, fault impedance, and point-on-wave where the fault occurs AEMO and TasNetworks are able to note that increasing residual AC connection point voltage decreases the chance of disconnection of the HVDC Interconnector. However, the actual probability of successfully riding through a credible contingency event is determined by many variables, some of which are not directly controllable. Additionally while the probability of successful ride through increases with in-fault Basslink AC connection voltage; some residual risk appears to remain, potentially due to voltage phase shift.

Based on advice from Basslink for a residual voltage of less than 0.3 pu, the protection masking is activated thereby eliminating the risk of Basslink Interconnector being tripped (at least by the mechanism being investigated within this report). Fault locations that will result in low residual voltages are to the left of the boundaries marked in Figure 1.

For scenarios where the longest conducting valve current is less than 60 milliseconds, AEMO and TasNetworks are not in a position at the present time to categorically state that Basslink *would not* trip. Given the lack of detailed design information presently available, a level of certainty only exists around when Basslink *will* trip, with this certainty being based on the three 'actual' system incidents previously discussed.

### 3.4 Results summary

Table 2 highlights a summary of simulation case studies conducted and key results obtained. It also provides an indication of operating conditions which result in an extended commutation failure and subsequent Basslink tripping. As shown in the table a number of controllable and non-controllable factors will play a part in determining whether or not an extended commutation failure would occur. Consequently, different outcomes can be achieved depending on how these factors apply collectively at any given time.

**Table 2: Simulation case study summary**

Scenario no.	Tasmanian Load (MW)	On-line Tasmanian generation	Basslink import (MW)	Fault location	Fault type	Basslink trip?
1	1800	All	450	Hadspen	LL	Yes
2	1800	All	300	Hadspen	LL	Yes
3	1800	All	200	Hadspen	LL	Yes
4	1800	All	100	Hadspen	LL	No
5	1300	All	100	Hadspen	LL	Yes
6	1800	All	300	Hadspen	LG	Uncertain
7	1800	All	450	Chapel St	LL	Uncertain
8	1800	All	300	Chapel St	LL	No
9	1800	All	200	Chapel St	LL	No
10	1800	All	100	Chapel St	LL	No
11	1090	All	443	Lindisfarne-Waddamana	LG	Uncertain
12	1175	All	469	Gordon- Chapel St	LG	No
13	1000	All	464	Gordon- Chapel St	LL	No
14	1090	All except CCGT	443	Lindisfarne-Waddamana	LG	Uncertain
15	1000	All except CCGT	464	Gordon- Chapel St	LL	No



## 4. REFERENCES

- [1] AEMO; *"Trip of transmission lines in Tasmania followed by the loss of Basslink on 10 and 16 Dec 2014, and 23 Feb 2015 (May 2015)"*, Version 1, 12 May 2015.
- [2] Basslink Pty Ltd, TasNetworks; *"Inverter Operation of Line Commutated Converters for HVDC"*, 2 March 2015.
- [3] CIGRE Working Group (WG) 14.05; *"Commutation failures causes and consequences"*, 1995
- [4] CIGRE Working Group (WG) 14.02, *"A summary of the report on survey of controls and control performance in HVDC schemes"*, 1994.
- [5] CIGRE Working Group (WG) 14.07, *"Guide for planning DC links terminating at AC system locations having low short-circuit capacities"*, 1997.
- [6] Basslink Pty Ltd; *"Basslink Fault Response History.xls"*, As published on the AEMO website in conjunction with References [1] and [2].

Please note that References [1], [2] and [6] can be obtained from the AEMO website at:

[http://www.aemo.com.au/Electricity/Resources/Reports-and Documents/~/\\_link.aspx?\\_id=10F603F478C04BC7899FB1D41E08A217&\\_z=z](http://www.aemo.com.au/Electricity/Resources/Reports-and Documents/~/_link.aspx?_id=10F603F478C04BC7899FB1D41E08A217&_z=z)

## APPENDIX A – PSCAD MODEL VERIFICATION

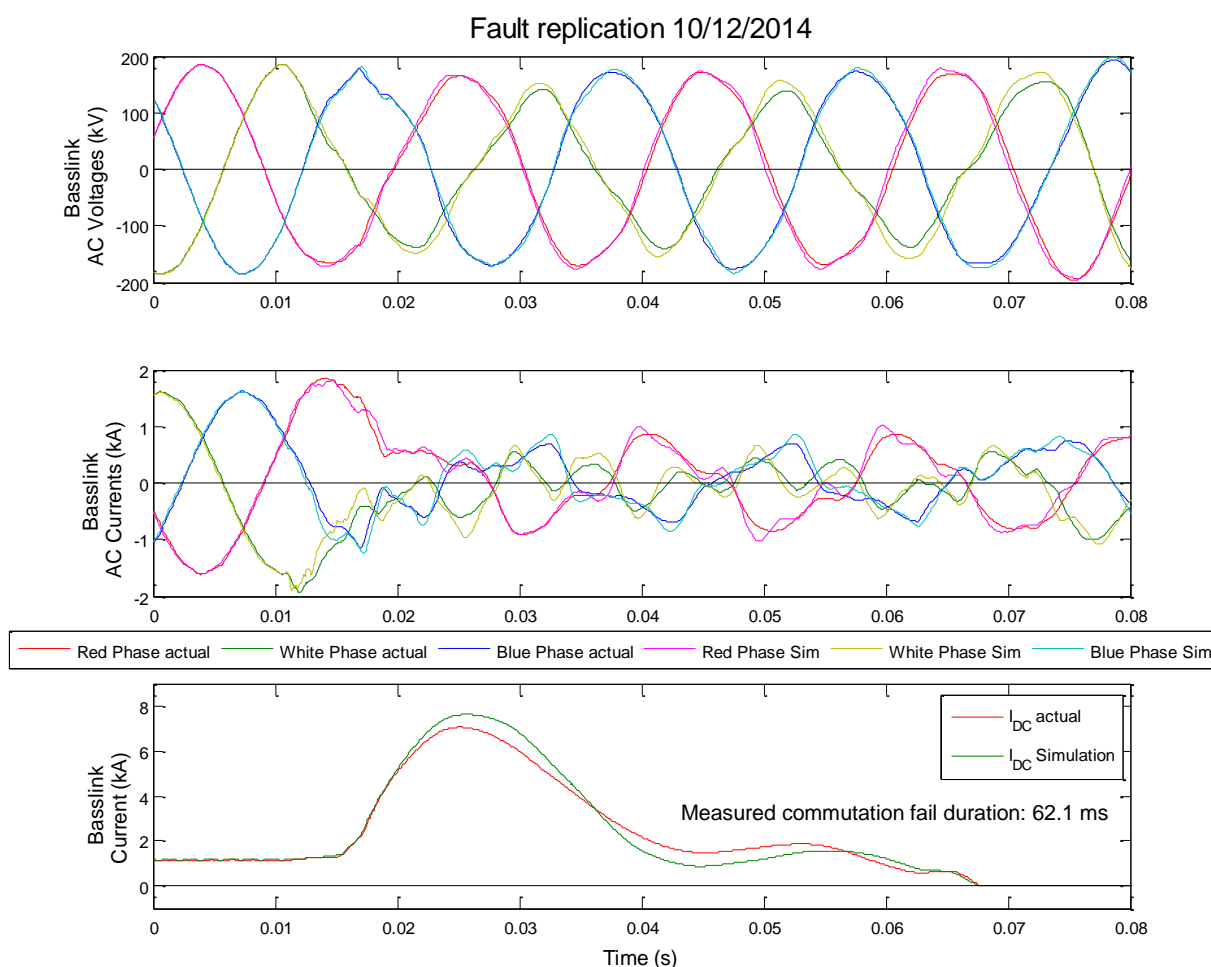
### A.1 Event #1 – 10 December 2014

The line-to-ground fault on 10 December 2014 did not result in AC fault current greater than the pre-fault current present and the AC voltage remains relatively undistorted, apart from white phase which is faulted and has a lower magnitude during the fault period (see Figure 5).

In this case the DC current is the most useful measure for comparison since it indicates the duration of the commutation failure. Simulating this duration is critical to assessing the performance of the PSCAD model. As Figure 5 shows, the DC current duration and oscillation period indicates a high level of model accuracy. The extended commutation failure is evident in both the measurement and simulation results. However, there is a difference between the current peak and first trough. However, the peak and trough of the simulated response are within  $\pm 10\%$  of the respective measured responses.

The AC voltage waveforms also show a high level of accuracy, with similar harmonics being displayed in the faulted white phase. Since it is the AC voltage distortion that initiates the commutation failure, the simulation must be able to reproduce accurate network voltages during the fault period.

**Figure 5: Simulation and measurement comparisons for 10 December 2014 line-to-ground fault**



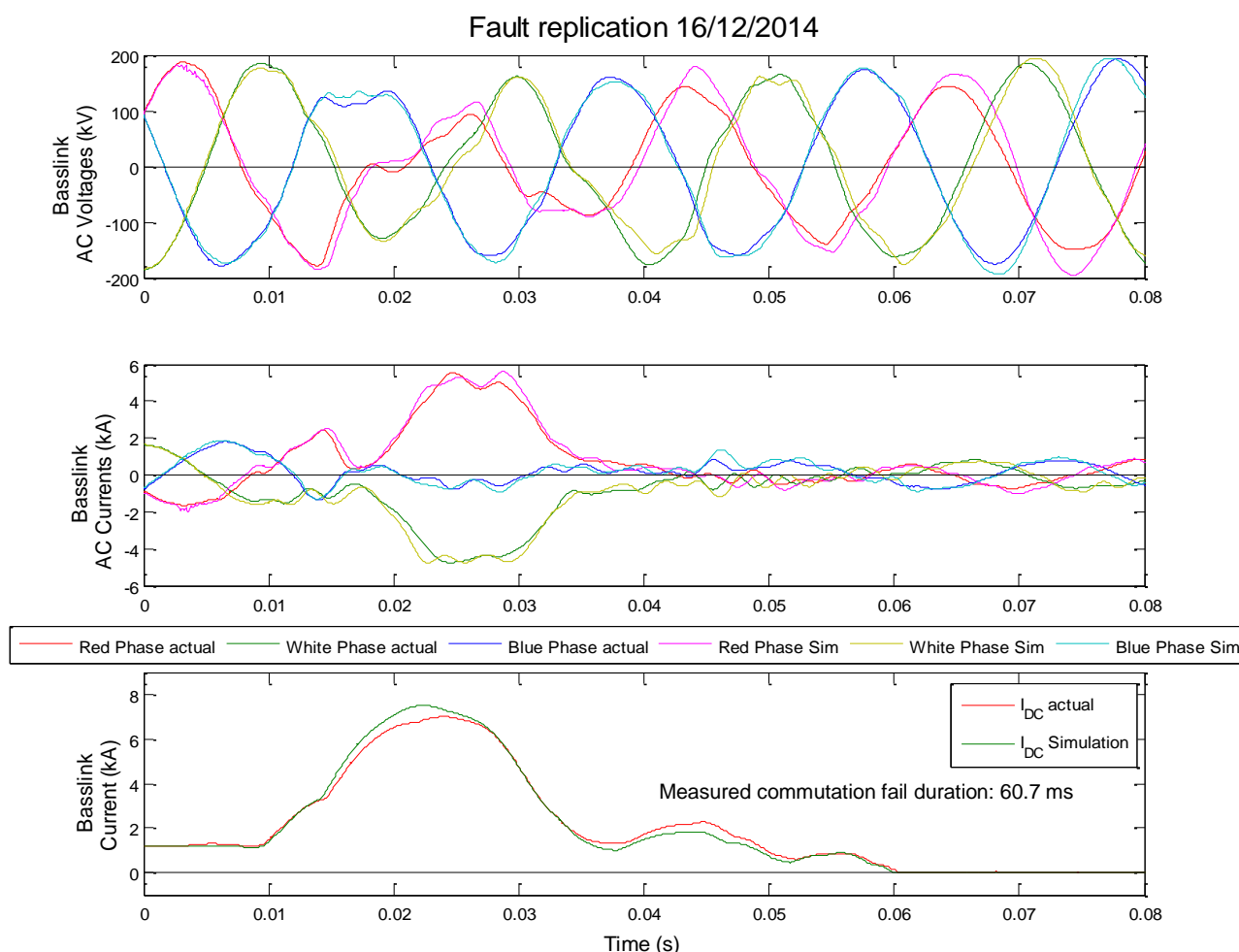
## A.2 Event #2 – 16 December 2014

The two simultaneous line-to-ground faults on 16 December 2014 resulted in large current pulse seen within the AC system as shown in Figure 6. Comparing the shape and magnitude of the graphs shows a high degree of alignment between measurement and simulation results for both the AC current and voltage waveforms.

The magnitude of the AC fault current in the red and white phases is directly comparable to the measurement data. As expected, this causes a large distortion of the AC voltage on the corresponding phases. As for the 10 December event, the DC current shows a high degree of correlation for both commutation failure duration and oscillation frequency. The DC current simulation exhibits the same increased oscillation that was seen in the 10 December event, believed due to the DC cable modelling assumptions.

By observing the commutation failure duration, and correctly simulating magnitude and phase of the AC fault current, it is concluded that the PSCAD model accurately represents this network event.

**Figure 6: Simulation and measurement comparisons for 16 December 2014 line-to-ground faults**



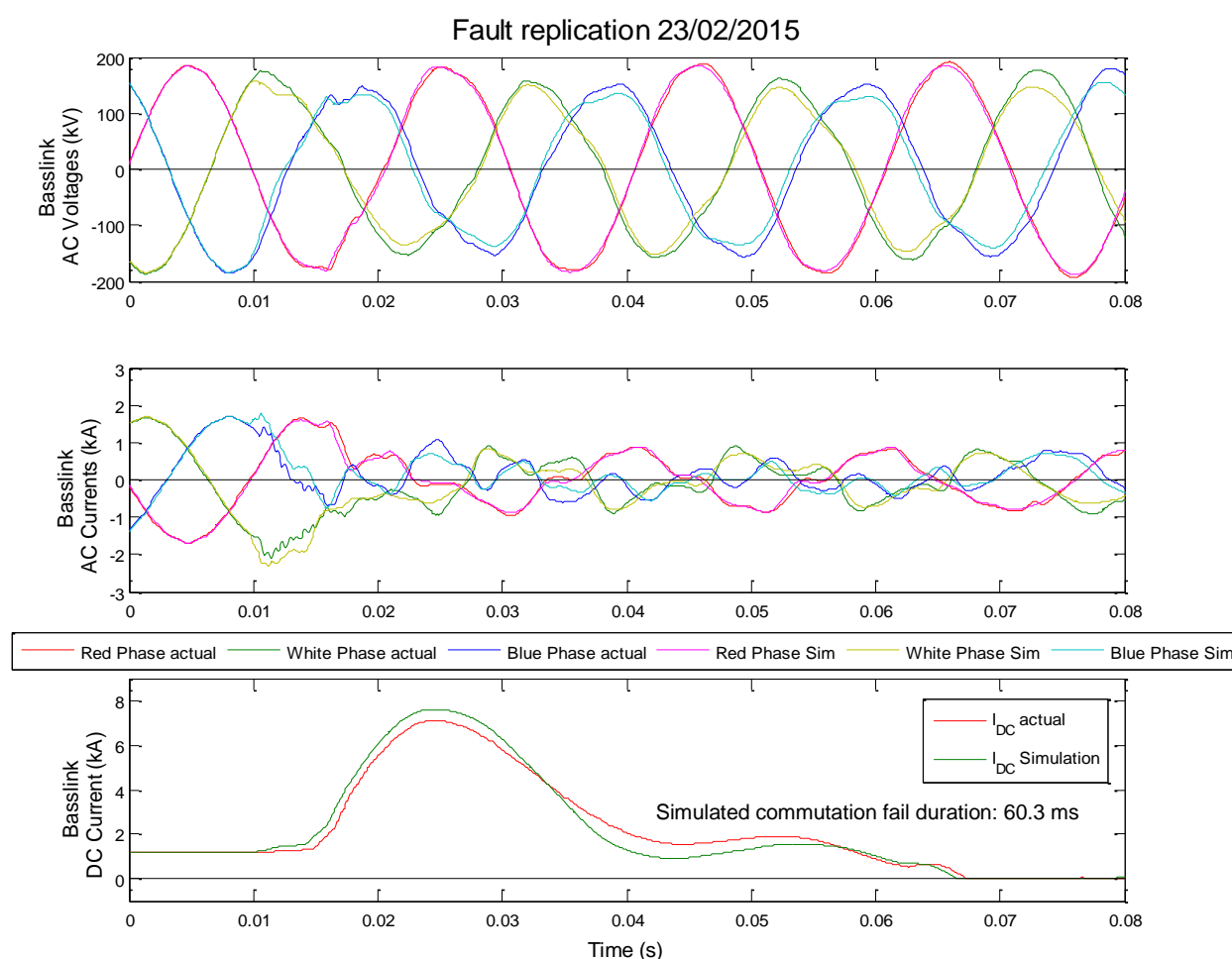
### A.3 Event #3 – 23 February 2015

The 23 February 2015 event was different to the two previous disturbances as it was a line-to-line fault that triggered the commutation failure. Figure 7 shows that there was no large AC fault current evident at the converter connection point.

The comparisons of AC voltage waveforms show good consistency between simulation results and measurement data, and demonstrate that the PSCAD model is capable of simulating the physical network quite accurately. The AC current also shows a high degree of correlation, however the large AC current pulse is absent. As shown in both the 10 and 16 December events, the DC current for this event shows a high degree of correlation for both the duration and oscillation frequency. A similar increased oscillation that was seen in the simulations of the December events was also observed, believed to be due to the DC cable modelling assumptions.

As for the other two examples, the simulation results confirm the outcomes of the actual event, i.e. the extended commutation failure was sufficiently long for the VBE thyristor protection to have operated, resulting in a trip of the HVDC link.

**Figure 7: Simulation and measurement comparisons for 23 February 2015 line-to-line fault**



## APPENDIX B – EXAMPLES OF PSCAD SIMULATION RESULTS

The plots shown represent the following electrical quantities:

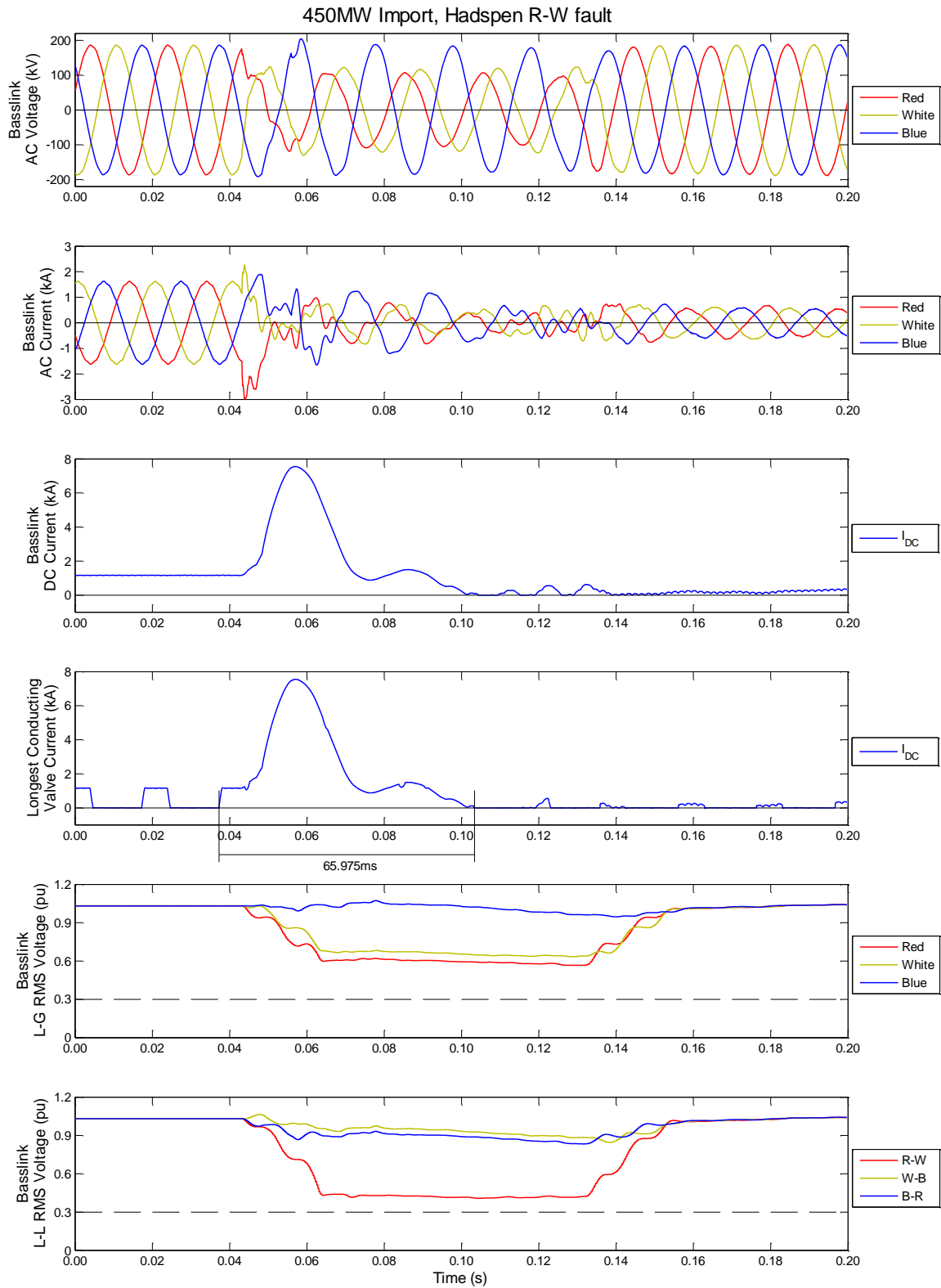
- i. Three phase voltages at the George Town converter station
- ii. Three phase currents at the George Town converter station
- iii. Basslink DC current
- iv. Longest conducting valve current
- v. Line-to-line RMS voltage at the George Town converter station with protection masking threshold shown
- vi. Line-to-ground RMS voltage at the George Town converter station with protection masking threshold shown

All electrical quantities are shown for consistency with presentation of the model validation results. However, most critical for the purpose of evaluating the likelihood of a network resulting in disconnection of Basslink are the line to line, and line to ground voltages, and the longest conducting valve current.

The commutation failure duration time referred to as critical for establishing the severity of the event, is indicated on the figure showing the longest conducting valve current, while line-to-neutral and line-to-line voltages at the converter AC terminals are shown overlaid with the 0.3 pu protection mask setting.

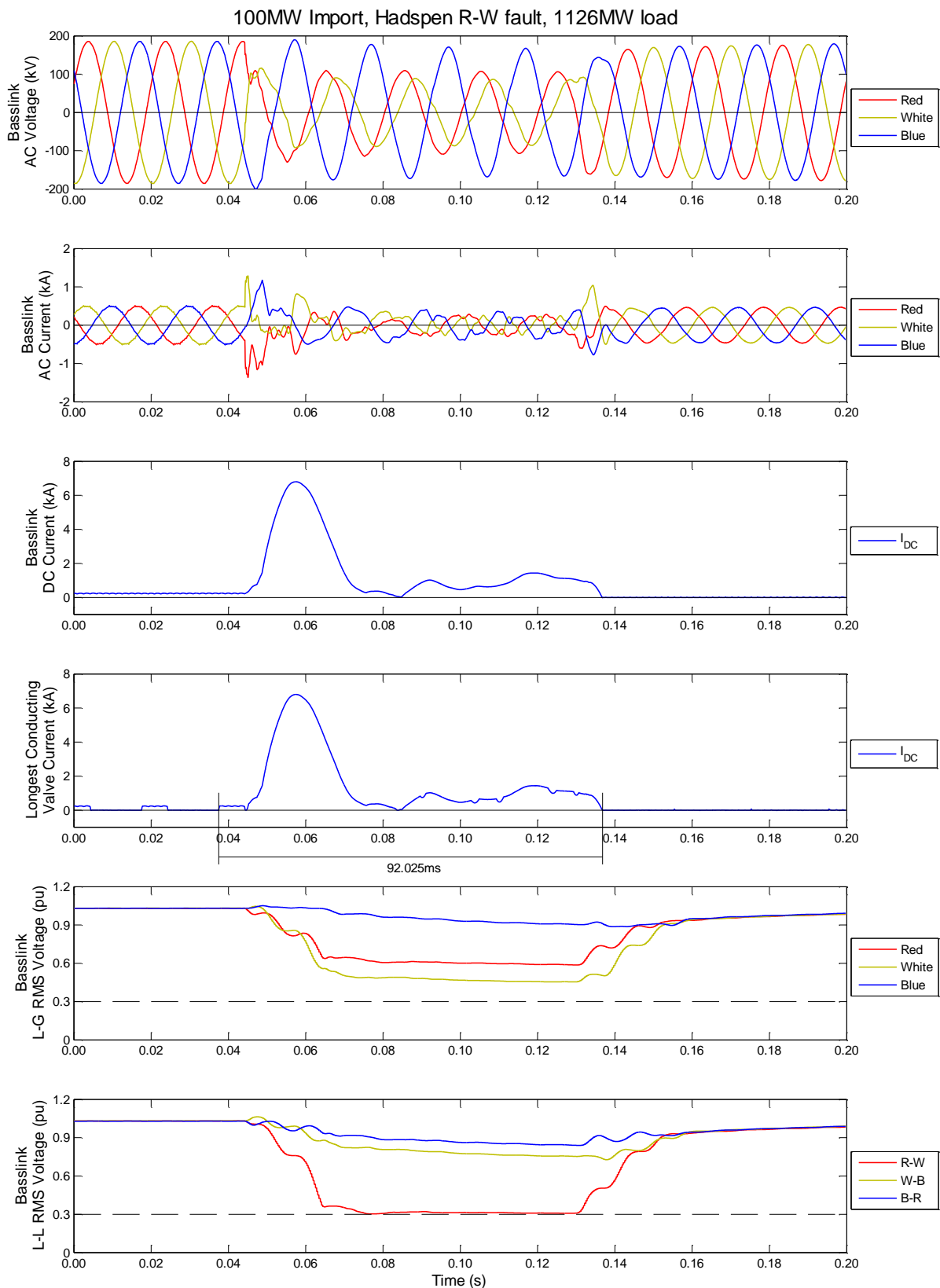
## B.1 Simulation results for scenario #1

Figure 8: Basslink import at 450 MW, commutation failure duration: 65 ms



## B.2 Simulation results for scenario #5

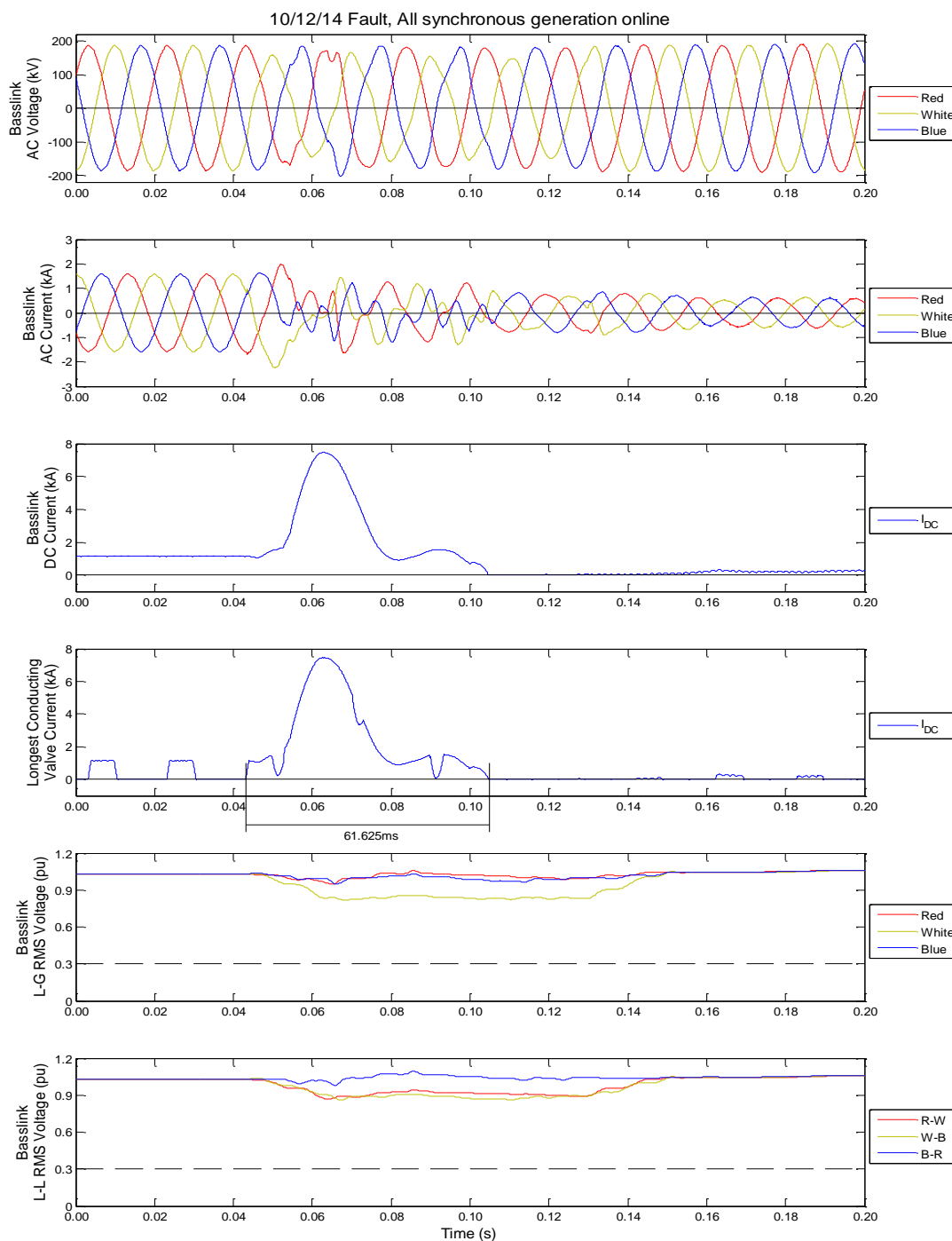
Figure 9: Realistic scenario and Basslink importing 100 MW, commutation failure duration: 92 ms





### B.3 Simulation results for scenario #11

**Figure 10: Results for 10 December 2014 line-to-ground fault event with all synchronous generators in service, commutation failure duration: 61 ms**



## B.4 Simulation results for scenario #13

Figure 11: Results for 23 February 2015 line-to-line fault event with all synchronous generators in service, commutation failure duration: 36 ms

