ENGINEERING CONSULTING SERVICES

# Review of the System Incident Investigation Report for the Tasmanian Region


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# 1 Executive Summary

The Manitoba HVDC Research Centre (hereafter "MHRC"), a division of Manitoba Hydro International Ltd. (hereafter "MHI"), was contracted by the Australian Energy Market Operator Ltd. (hereafter "AEMO") for review of the power system studies related to commutation failures in the Basslink HVDC system.

The study was carried out by AEMO and TasNetworks and is predominantly based on electromagnetic transient simulation studies in PSCAD™/EMTDC™.

The scope consisted of the following tasks:

1. Review the HVDC models used in the study;
2. Perform simulations on selected scenarios and compare with original study results;
3. Review study results and conclusions;
4. Provide expert comments on the original study approach and conclusions.

The PSCAD/EMTDC study models were not available to MHRC for review. However, the report provided the necessary details for MHI to understand the phenomenon leading to the disconnections of the Basslink interconnector following faults on the Tasmanian 220 kV network.

The comments and conclusion included in this report are thus based on the information in the joint AEMO/TasNetworks report, as well as the AEMO comments and clarifications provided in response to MHI's questions.

The report was reviewed by a team of six experts with significant expertise on planning, operation, and design aspects of HVDC links, as well as system-level simulation expertise.

## 1.1 Overall Conclusions

AEMO and TasNetworks have conducted a very thorough investigation of the HVDC (extended) commutation failure events and potential causes. The study approach is clearly stated in the report, and MHI agrees with the approach.

Based on the report, as well as comments and clarification provided by AEMO in response to questions, MHI confirms that the modelling and study methodology applied in the AEMO/TasNetworks report are consistent with good electricity industry practice.

The study model has been verified by comparing simulation results with recorded system event waveforms. The measurements selected for this comparison are key indicators of a HVDC system dynamic performance and hence are good choices for this purpose. The recorded waveforms from the three system events were compared with corresponding simulation results.

The agreement between recordings and simulations is excellent. This validation of the models then makes them credible for analyzing other potential risk scenarios.

MHI experience has shown that even a 10% fall in voltage can set commutation failures. Therefore, the sustained commutation failure in weak conditions, where the voltage is staying above 0.3 pu, is not surprising.

The main conclusions of the report are valid, namely:

1) The fault impedance and fault type are also critical.
2) The identified 15 scenarios identify potential operating conditions that may be problematic from a CF point of view.
3) The point on wave of the fault application is a critical factor on whether CF will occur or not. AEMO clarified that POW analysis was carried out for all scenarios in Table 1 of the report.

## 1.2 Study Model

Since the study model in PSCAD/EMTDC format was not available to MHI, a model review was not possible. However, AEMO confirmed that the AC system model included the whole 220 kV Tasmanian network and a significant portion of the 110 kV Tasmanian network. All generators in Tasmania were included in the model, along with the detailed representation of the excitation system.

Thus, based on information available, including the model validation results enclosed with the study report, MHI concludes that the PSCAD/EMTDC model used for the study is acceptable for the purpose it was used.

AEMO and TasNetworks have proposed to further refine the HVDC converter model by including the Basslink thyristor protection scheme. More specific studies aimed at finding solutions to the commutation failure problem should be performed with this model in place.

## 1.3 Impact of Short Circuit Ratio (SCR)

In general, SCR will not affect the onset of Commutation Failure (CF), as it is the AC voltage depression and phase shift of AC waveforms that is primarily responsible for this. However, a high SCR should enable a more improved recovery and possibly avoid repeated CFs (extended CFs).

The Short Circuit Ratio or the Effective Short Circuit Ratio under different operating scenarios (that were considered in the study) are not explicitly listed in the report. It will be beneficial to readers to have this information in some form.

*AEMO confirmed that the minimum operating fault level for Basslink import of 1500 MVA is maintained at all times via constraint equations.*

## 1.4 System Changes that May Have Had an Impact on Recent CF Event

Basslink has been operational for approximately ten years. The system changes of recent years may have had an impact on the recent CF events.

- Retirement of generators near the converter bus could impact the SCR seen by the HVDC link.
- Addition of new lines, while improving the SCR, may introduce network resonances that can exacerbate the CF vulnerability.

It is recommended to comment on such changes in the report. AEMO clarified the following as a response to a follow-up question.

- *The main differences are disconnection of the large synchronous generator (AETV CCGT) near to Basslink, which contributed an additional 800 MVA of fault level at Basslink terminals, and sustained periods of high import (> 450 MW) into Tasmania due to changed generation patterns. It is however noted that AETV CCGT was commissioned in 2009, and were not therefore operational for several commutation failure events occurred prior to 2009.*

However, it is understood that throughout the lifetime of Basslink, there have only been six commutation failure events due to 220 kV network fault with Basslink import in excess of 400 MW.

Dispatching additional generation would assist in reducing the likelihood of this phenomenon, but may not eliminate such an occurrence under all credible contingency conditions.

## 1.5 Impact of Windfarms

Adjacent windfarms can impact the overall performance of the HVDC converter during faults and other disturbances.

The report states that the Tasmanian wind generation was out of service (disconnected from the system) for the simulation studies carried out. Additionally, it is understood that the three wind farms in Tasmania are connected to a very remote part of the network, and will not therefore have any de-stabilizing impact on the operation of Basslink HVDC converter.

As a potential future work, MHI recommends studying the impact of wind generators (if the percentage wind in the Tasmanian system becomes significant and/or if windfarms are connected in the vicinity of the inverter bus).

## 1.6 Recommended Future Work

The fact that the HVDC link would trip for a voltage level of only 0.7 pu suggests that the ESCR might be low. For example, as shown in Scenario 5, the link would trip for an import level of only 100 MW into Tasmania, when the ESCR should be much higher. It is likely that there are control modifications or setting changes that could improve the fault ride through capability. This would have to be studied in detail.

In HVDC systems that are connected to weak AC systems, AC under-voltage protection has been successfully implemented in the HVDC controls. Two such schemes are described is Section 4 of the report. It is recommended to study the applicability of such schemes to improve the overall behavior.

The addition of Synchronous Condensers is likely a technically viable solution to the extended commutation failure problem. However, it is an expensive solution and should be considered only when other options are investigated.

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# 2 Introduction

## 2.1 Background

Three 220 kV AC system faults (2 faults events in December 2014 and one in February 2015), resulted in the disconnection of the Basslink DC link inverter, while that invertor was transferring power into the AC network. Loss of Basslink DC power resulted in a loss of power delivered to the AC network, which resulted in AC frequency depression and frequency-based load shed protection operation.

As a result of the investigation to date:

- Loss of the Basslink DC link 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 in Tasmania.

## 2.2 Sequence of Events

Phase-to-phase AC unbalanced faults resulted in commutation failure on the Basslink inverters. Commutation fail is expected under such faults, where the AC voltage distortion is inevitable. In the reported cases, the AC distortion led to an “extended commutation fail event”. Extended commutation fail occurs when normal commutation was not restored within 60 ms (3 cycles), and the DC valve group is tripped by the Valve Base Electronic (VBE) thyristor protection, in order to protect the thyristors from damage due to excessive current.

During the system events used to verify the model, the VBE protection of the HVDC system triggered the trip of the HVDC inverter after 60 ms of continuous valve conduction, which occurred about 53 ms after fault inception. This is the interval before the fault is cleared. Thus, a high accuracy of the model is required during the fault period.

However, the normal signalling and relay delays meant that the HVDC circuit breaker did actually open after the fault clearance.

The report states that the Basslink HVDC controls were reviewed and operated as designed.

The two key activities as listed in the report are:

1. Validate the PSCAD/EMTDC model by comparing simulation and field traces;
2. Perform a scoped set of critical studies on verified system models to further investigate potential operating conditions that can lead to extended commutation fails situations;
3. Identify key factors that contribute to extended commutation fail.

Validation of the PSCAD/EMTDC model by comparing simulation results with recordings from the recent system events showed excellent correlation during the fault period, as well as during the post fault period.

The report discusses the details of thyristor valve protection (the extended commutation failure protection in the VBE that operated, resulting in the trip of the Basslink converter). It is stated that the existing thyristor protection model is sufficiently valid to simulate the sequence of events. Based on the simulation comparisons presented, this appears to be true.

Section C of the "Executive Summary: Next Steps" states that refinements of this VBE-based thyristor protection are to be undertaken in order to verify by simulation whether or not Basslink would trip under different operating scenarios. The ultimate goal would be to determine if changes would allow the current reclassification to be removed either by power system operation measures or protection/control system setting changes or other further solutions that would emerge.

It would appear from the report that the current model of this VBE thyristor protection monitors the longest conducting valve time, and if this time exceeds 60 ms, a DC trip order is provided. It is noted that this protection is blocked for close-in faults that reduces the AC voltage to less than 0.3 pu. For the remote fault event of December 2014 and February 2015, the AC voltage drop was approximately 0.7 pu and above, hence the thyristor protection was not blocked.

# 3 Report Comments

All reviewers agree that the model is sufficiently validated, and that the correlation between simulation results and with recordings from the recent system events is excellent.

Based on the report, as well as comments and clarification provided by AEMO in response to questions, MHI confirms that the modelling and study methodology applied in the AEMO/TasNetworks report are consistent with good electricity industry practice.

As a general comment, an illustrative diagram of the system showing key buses and a description or placing something similar to Figure 1 earlier in the report will benefit the reader.

## 3.1 Impact of Short Circuit Ratio

The Short Circuit Ratio (SCR) or the Effective Short Circuit Ratio (ESCR) under different operating scenarios (that were considered in the study) is not explicitly listed in the report. It will be beneficial to the readers to have this information in some form. This minor update to the report is recommended.

Additionally, given the comment that only three recent faults have caused sustained commutation failures, it would help to compare the ESCR for the recent times and for previous system conditions, where commutation failure was not sustained.

In general, SCR will not affect the onset of Commutation Failure, as it is the AC voltage depression and phase shift of AC waveforms that is primarily responsible for this. However, a high SCR should enable a more improved recovery and possibly avoid repeated CFs (extended CFs). It would have been informative to check whether scenarios #11-13 (confirming the 3 observed events) actually have a poorer SCR than less vulnerable events. It is recommended to include the following answer (of AEMO) to MHI’s clarification question in the report.

- *Scenarios #11-15 result in lower SCRs than other scenarios where all Tasmanian generation are brought online. The minimum operating fault level for Basslink import of 1500 MVA is maintained at all times via constraint equations. Below this level Basslink import would be reduced (at the next 5 minute dispatch interval). However, Basslink is designed to recover from commutation failure events with fault levels as low as 1200 MVA.*

- *The absolute minimum fault level experienced in the three actual events was approximately 1800 MVA.*

The report mentions that the agreed upon SCR was maintained even at the time when commutation failure events were experienced. ESCR is likely a better parameter that better defines the performance of the HVDC converter. This is due to the fact that the inverter bus behavior depends on the system strength, on the amount of power delivered on the HVDC link, as well as the amount of passive capacitive elements in the vicinity of the inverter bus. The passive elements lose some of their ability to support the voltage during depressed voltage conditions.

- While the ESCR is a quasi-static parameter that can give a good idea of the general inverter behavior, the dynamics of the systems, dominated by such dynamic devices as generators, dynamic reactive power compensation devices and wind farms, are not well captured in the ESCR parameter. Therefore, such details can only be understood through simulation studies.

AEMO clarified that the study model included details of the entire Tasmanian 220 kV, as well as the majority of the 110 kV sections.

## 3.2 Factors that Influence Extended Commutation Failure

In addition to ESCR, other factors that influence the inverter behavior are listed below.

- How much wind terminations are in the vicinity?
    - AEMO confirmed wind generation was zero for all scenarios considered.
- Reactive power compensation in the vicinity of the inverter bus?
    - AEMO confirmed all system details were included in the study model. The validation results are a further indication of adequate system representation in the model.
- Dynamic response of generators in the vicinity of the inverter bus.
    - AEMO confirmed all dynamic devices were included in the model. This is necessary to represent the correct transient fault current contribution and reactive power support during the event.

## 3.3 System Changes That May Have Had an Impact on Recent Extended CF Event

Basslink has been operational for approximately ten years. The system changes of recent years may have had an impact on the recent CF event:

- Retirement of synchronous generators near the converter bus could impact the system SCR;
- Addition of new lines, while improving the SCR, may introduce network resonances that can exacerbate the CF vulnerability (*in this specific study, the recorded waveforms from the system events do not show prominent harmonic resonance characteristics*).

It is recommended to comment on such changes in the report. AEMO clarified the following as a response to a follow-up question:

- *The main differences are disconnection of the large synchronous generator (AETV CCGT) near to Basslink, which contributed an additional 800 MVA of fault level at Basslink terminals, and sustained periods of high import (> 450 MW) into Tasmania due to changed generation patterns.*

- *The Tamar Valley CCGT was commissioned in 2009, and was not therefore operational for the first 3-4 years of Basslink service. There were some commutation failure events prior to 2009 where Basslink successfully resumed commutation before 60 ms time for thyristor protection tripping.*

The above points indicate that the retirement of a large generator (AETV CCGT) seems to have some impact on the fault recovery capability of the HVDC link.

Section 3.3.1 demonstrates the impact of generator dispatch on commutation failure. The results are consistent with MHI experience and general industry knowledge.

> *"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".*

## 3.4 Study Model

Since the study model in PSCAD/EMTDC format was not available to MHI, a model review was not possible. However, AEMO confirmed that the AC system model included the whole Tasmanian 220 kV network and a significant portion of the 110 kV network. Thus, the AC system model is likely representing the following important features and characteristics that can impact CF:

- Network resonance characteristics;
- Fault level;
- System inertia;
- Dynamic response (dynamic representation of generators and any other dynamic devices in the system are included in the model).

AEMO confirmed that all generators in Tasmania were included in the model, along with the detailed representation of the excitation system.

In a very specific investigation of this nature, it is important to represent the HVDC converter with a 'vendor level' model. As per AEMO's information: "*The model was that initially provided by the vendor (Siemens) and it was the same model that was* *used by Siemens for Basslink design. The model includes detailed representation of converter control and protection".*

Thus, based on information available, including the model validation results included in the study report, MHI concludes that the PSCAD/EMTDC model used for the study is acceptable for the purpose it was used.

## 3.5 Impact of Windfarms

The windfarms can impact the overall performance of the HVDC converter during faults and other disturbances.

- Some of the synchronous generators may not be dispatched during high wind periods, thus potentially affecting the SCR at the converter bus.
- Depending on the type of wind generator technology and the Fault Ride Through strategy of the wind farm, the reactive power support from the wind farms maybe limited or in some cases detrimental to the overall system performance.

Additionally, it is understood that the three wind farms in Tasmania are connected to a very remote part of the network, and will not therefore have any de-stabling impact on the operation of Basslink HVDC converter. AEMO also clarified that all scenarios that are studied and presented in the report considered zero wind generation.

*"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".*

As a potential future work, MHI recommends studying the impact of wind generators (if the percentage wind in the Tasmanian system becomes significant and/or if windfarms are connected in the vicinity of the inverter bus).

## 3.6 Point on Wave Impact (POW)

AEMO has studied the impact of POW of the fault inception. This is a factor that would influence the overall dynamic response following the fault.

If point on wave sensitivity study suggests extended commutation failure even for faults occurring (inception) only at some parts of the voltage waveform, such faults should be considered 'critical faults'. This is due to the fact that the POW of fault inception is a random occurrence. There is an equal probability that the fault can occur at any point on the waveform.

Therefore, a proposed mitigation measure should eliminate commutation failure for faults inception at any point on the waveform.

## 3.7 Clarifications

### 3.7.1 Impact of Remote Faults

The following line in the report was later clarified by AEMO *"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".*

> *The point being conveyed here is that historically there have been more than 70 faults in Tasmanian network for which Basslink has rode through the faults. However, the vast majority of those faults were distribution faults or faults within the generating systems. Therefore, the resulting voltage dip for these faults as seen by the George Town bus and Basslink has been very small. Events of relevance are only those faults occurring at the 220 kV Network which results in more than a 10% voltage dip, and hence leading to commutation failure".*

MHI agrees with the above clarification. It is recommended to include the above clarification in the report.

### 3.7.2 Signals that Are Being Used to Determine the Converter Behavior

AEMO clarified a comment from MHI regarding signals that are being used to determine the converter behavior:

***MHI Comment***: *Rather than use long current duration in a single valve as the indication for repeated CF, it would have been instructive to plot the extinction angles. Repeated CF does not necessarily mean that the valve that suffered CF suffers it again; it could be another valve or valves.*

***MHI agrees with AEMO clarification:*** *For each event the thyristor valve that caused the converter to be tripped remained in continuous conduction from the time of first commutation failure to the moment of protection tripping - by the Valve Based Electronics (VBE). As such the extinction angle for this valve remained zero – since the valve did not recover (at least not in the 60 ms time window allowed by the VBE protection).*

## 3.8 Comments

### 3.8.1 Fault Duration

Fault duration is not specifically stated in the report. AEMO confirmed that the fault durations applied are consistent with the typical fault clearance time in the Tasmanian power system which is in the range of 90 ms. As fault duration is a key parameter impacting the dynamic response of the system, it is recommended that a note be included in the report.

### 3.8.2 Voltage Angle at Inverter Bus

Page 9, Section 2.1 (i): The accuracy of the voltage angle at the inverter AC bus is important – this can be observed in the waveforms presented in Appendix A.

# 4 General Expert Comments

This section presents comments from the reviewers based on their past experience. Some of the points may not directly apply to the specific report that was reviewed. MHI is available to discuss and clarify these points with AEMO as required.

1. Figure 1 shows network nodes, for which voltage stays above 0.3pu. This would only help in the conclusion that the Basslink will not activate its under-voltage blocking, during those faults. Experience has shown that even a 10% fall in voltage can set commutation failures. Therefore, the sustained commutation failure for weak conditions, where the voltage is staying above 0.3 pu, is not surprising.

2. The fact that the HVDC link would trip for a voltage level of only 0.7 pu suggests possibly the ESCR might be too low. It is even more surprising that it would trip for an import level of only 100 MW into Tasmania, as the ESCR should be much higher under this transfer level. It is likely that there are control modifications or setting changes that could improve the fault ride through capability. This would have to be studied in detail. An example might be to change the masking setting from 0.3 to 0.75 pu, or increasing the gamma kick on detection of a commutation failure or providing for temporary blocks with automatic restarts for the converters.

3. One additional point recommended to be investigated is the behavior of the general load profile and wind during fault ride through (at least those connected close to inverter may be up to Chapel St).

    a. Has Basslink reactive consumption increased dramatically, which means their impedance changed dynamically?

    Since the sustained commutation failures do not appear to be due to overly depressed voltage magnitude, but due to varying system impedance, MHI would pay more attention to modelling the dynamic behavior of the system loads and the sources on the buses up to at least the Chapel St. bus.

4. It is not clear how the high impedance of the fault is simulated. High impedance faults usually tend to have varying impedance as the fault progresses, and that would be a primary cause of the change in voltage angle during the fault. However, this is not likely to be a major contributing factor considering the close correlation between simulations and recordings presented in the report.

5. The reviewer has no knowledge of any implemented AC under-voltage protection for the Basslink HVDC system. Disturbed AC voltages due to AC system faults will produce commutation failure events; this is inevitable.

In HVDC systems connected to weak AC systems, AC under-voltage protection has been successfully implemented in the HVDC controls. Two such schemes are described.

I. For AC events with AC voltage <0.85, it is possible that DC Current reference is increased as a result. DC current reference is calculated as Power order/DC voltage measured. If AC voltage goes down, VDC goes down and the DC current reference increases. Increased DC current reduces the thyristor recovery window and makes it more susceptible to com fail. By holding the DC voltage to a calculated valve instead of a measured value, the DC current reference would remain constant. The power delivered would drop but the HVDC may not fail commutation and improve overall system response.

II. Another possible item to investigate is the addition of a system under-voltage controller. If an AC UV is detected, then the DC power order is automatically reduced. This causes power drop but releases MVAr into the AC system, which may help the AC system recover faster and may prevent the thyristor protection from operating [3].

6. Addition of Synchronous Condensers is likely a technically viable solution to the commutation failure problem. However, it is an expensive solution and should be considered only when other options are investigated.

Having a trustable VBE protection model would help assess if any changes/solutions to AC/DC system operation would help prevent further DC pole (and eventually, if poles are added) or bipole blocks and subsequent impact to the AC system.

# 5 References


[1] Rahimi, E.; Gole, A.M.; Davies, J.B.; Fernando, I.T.; Kent, K.L., "Commutation failure in single- and multi-infeed HVDC systems," in AC and DC Power Transmission, 2006. ACDC 2006. The 8th IEE International Conference on , vol., no., pp.182-186, 28-31 March 2006

[2] Rahimi, E.; Gole, A.M.; Davies, J.B.; Fernando, I.T.; Kent, K.L., "Commutation Failure Analysis in Multi-Infeed HVDC Systems," in Power Delivery, IEEE Transactions on , vol.26, no.1, pp.378-384, Jan. 2011

[3] CIGRE Guide On Multi-Infeed HVDC Systems; REF 364 2008 SC B4 WG B4.41 (although this publication is on multi-infeed DC, its conclusions on CF apply to both single and multi-infeed systems)

[4] CIGRE Use of an Integrated AC/DC Special Protection Scheme at Manitoba Hydro (B5-206, CIGRE 2006) (available for public download from http://www.ceb5.cepel.br/arquivos/artigos_e_documentos/artigos_bienal_2006/b5_206.pdf).

# 6 Review Team Members

**Dharshana Muthumuni,** **Ph.D., P.Eng.,** is the Managing Director of the Manitoba HVDC Research Centre, a division of Manitoba Hydro International. He has over 20 years of experience in engineering studies using a variety of simulation products, including PSCAD™ and PSS/E. His expertise is regularly sought out by clients around the world for his strong and wide ranging technical knowledge on power system behavior, model development, and simulation studies. He has lead the technical team to solve challenging problems, including HVDC and generation interconnections, wind integration into weak grids, FACTS based solutions, SSR screening techniques, and power quality and harmonics.

Dharshana has worked extensively and closely with equipment vendors to develop simulation models and techniques to address difficult interconnection problems. He has developed many customer custom models and simulations techniques for specific studies, including working closely with equipment vendors to address their simulation study requirements.

In addition to his engineering study experience, Dharshana has been a key developer of the PSCAD™ simulation tool and has conducted training workshops on a variety of power system topics for our global clients. He has led our engineering teams on a number of engineering study projects, including the Saudi Electric Company system operation and interconnection project.

**Ani Gole** **, Ph.D., P.Eng.,** is a distinguished professor at the University of Manitoba and a world authority on HVDC Transmission, FACTS and Simulation Technology. His have contributed significantly to the power system industry through his research publications, international lecturing and working group involvements. He is the recipient of the IEEE PES Nari Hingorani FACTS Award (a major award of the IEEE Power and Energy Soc.), for "Outstanding Contributions and Leadership in Advancing Flexible Ac Transmission Technology" June 2007
Dr. Gole holds a B. Tech. (EE) degree from the Indian Institute of Technology, Bombay, India, and a Ph.D. from the University of Manitoba Canada. He is a professional engineer in the province of Manitoba, an IEEE Fellow and a Fellow of the Canadian Academy of Engineering. Dr. Gole holds the NSERC/ Manitoba Hydro Industrial Research Chair in Power Systems Simulation at the University of Manitoba, Canada. He has over 30 years of experience in HVDC Transmission and FACTS technologies and in addition to his University employment, he has worked at Manitoba Hydro, Quebec Hydro (IERQ), and the Manitoba HVDC Research Centre. He has a long term involvement with the development of off-line and real time tools for Power System simulation, and was a member of the original design team that developed the PSCAD/EMTDC program.

**Farid Mosallat,** **Ph.D., P.Eng.,** completed the Ph.D. degree at the University of Manitoba in 2012. He received the B.Sc. degree from Tabriz University (Tabriz, Iran) and the M.Sc. degree from Sharif University of Technology (Tehran, Iran) in 1996 and 1998, respectively. Farid joined the Manitoba HVDC Research Centre in 2005, where he is currently the Engineering Research & Development Manager. His areas of expertise include ETM-type studies on the integration of HVDC VSC systems into AC networks; application of SVCs and STATCOMs in voltage flicker mitigation and power quality improvement; design and implementation of inverter-based distributed generation sources, such as hydrokinetic and hybrid diesel-generator (supplemented by battery storage) systems. He also has experience in AC system performance studies, including contingency analysis, transient stability simulations, etc.

Prior to joining the Centre, Farid worked as an Automation and Drives Engineer in the manufacturing sector, and was involved in the design, installation and commissioning of electrical distribution and control systems for material handling equipment such as shipyard cranes, and stacker/reclaimer systems.

**Les Recksiedler, P.Eng., CIM.,** Senior Manager, Engineering and Business Development, has over 40 years of experience and expertise in the electrical utility industry, including the station apparatus design, specifications, bid reviews, contract negotiations, design reviews , factory acceptance testing (FAT), drawing approval for construction, installation supervision, pre-commissioning, commissioning , performance testing, as-built drawings, warranty, operations and maintenance (O&M), and life assessment. In addition, he has over 34 years of HVDC experience in the design, modification, O&M of the Nelson River +/- 500 kV, 3 854 MW HVDC system. At the Manitoba HVDC Research Centre, Les is specializing in HVDC Systems, Power Apparatus, and Business Development. He is actively involved with IEEE Standards development and is currently vice chair of the Converter Transformer and Smoothing Reactor Subcommittee and co-chair of a joint IEEE/IEC Standard on DC Bushings (recently published). In addition, Les actively participates in CIGRE HVDC working groups and is a convener of B4.54 working group – Life Assessment and Extension of HVDC Converter Stations.

**Randy Wachal, P. Eng.,** graduated from the University of Manitoba with B.Sc. in Electrical Engineering in 1981. Following his graduation, Randy joined Manitoba Hydro, where he worked for 13 years on the Nelson River HVDC System as a Control Design and Commissioning Engineer. In 1995, Randy joined the Manitoba HVDC Research Centre, with his most recent role being Engineering Project Manager, responsible for Research and Engineering Services Departments. Randy has been involved in commissioning and lifetime investigation studies on a number of HVDC and SVC systems, including Manitoba Hydro Ponton SVC project. He is a senior member of IEEE, a CIGRE member, CIGRE Working Group Conveyor of B4-57 on DC Grid VSC Modeling, and a registered Canadian Professional Engineer in the Province of Manitoba and Saskatchewan.

**Ioni Fernando, Ph.D., P.Eng.,** is a professional engineer with over 20 years of experience in high voltage AC/DC system planning and interconnection studies. Currently in her role as AC/DC System Studies Engineer in the System Planning Department at Manitoba Hydro, Dr. Fernando provides planning studies of HVDC systems and AC interconnection of multi infeed HVDC systems that involves power voltage stability, harmonics, controls and all other technical aspects of power systems. She has also been involved in R&D activities for multi infeed HVDC systems, voltage sourced converters, small signal stability of power systems and their mitigation, and wide area protection algorithms using phasor measurement units.

Dr. Fernando has provided very important technical expertise by conducting and guiding the planning studies which determine the technical aspects of Manitoba Hydro's Bipole III Project. Notably, that is the ratings/technical specifications of all elements associated with the Bipole III Project, synchronous condensers, and the AC system requirements for Manitoba Hydro's major transmission system stability and performance. She has also studied and provided reports pertaining to the Manitoba Hydro system's electromagnetic field effects and related information. Planning and design of the functional requirements of HVDC system's special protection and control is an integral part of this work.

Dr. Fernando has contributed directly to the Bipole III specification writing team as a subject matter expert by providing technical information to the specification writing process. In addition review and comment on technical specification documents.

**Lalin Kothalawala,** **M. Sc., P.Eng.,** received his B.Sc. in Electrical Engineering from the University of Moratuwa, Sri Lanka, in 2002 and his M.Sc. in Electrical Engineering from the University of Manitoba, Canada, in 2010. Upon joining the Manitoba HVDC Research Centre in 2010, Lalin worked as a consulting engineer to provide engineering services to a variety of clients and projects, including power system simulation studies, engineering design analysis, and commissioning support. In his current role as Manager, Simulation and Design Analysis, Lalin is supervising a team of engineers and is involved in various PSCAD simulation studies, including insulation coordination, GIS VFT studies, ferro-resonance, and lightning studies.

Prior to joining the Manitoba HVDC Research Centre, Lalin worked as a commissioning engineer for thermal power stations and high voltage substations in Sri Lanka. He has been in the commissioning team of thermal power stations (100 MW diesel and 300 MW combined cycle) and 132 kV substations. He has also been the warranty engineer for 100 MW thermal power plant and worked as the Chief Operations Engineer in one of the thermal power stations he commissioned.