ENGINEERING CONSULTING SERVICES

Report for Review of the Black System South Australia Report – System Event of 28 September, 2016

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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 final report for 'Black System South Australia – System Event of 28 September 2016'.

The report addresses the South Australian (SA) system event of September 28, 2016 (Black System). Specifically, the report describes the following:

- The series of events that led to the Black System.
- The performance of the system restart process and supply restoration.
- The performance of power system and market operations during market suspension.
- Recommendations for further action.

The report was reviewed by a team of three experts, with Dr. Dharshana Muthumuni as the review team lead. The team members have significant expertise in planning, operation, and design aspects of large interconnected power systems, as well as expert knowledge on wind generation and power system simulation.

1.1 Overall Conclusions

The report under review is very well written and represents a significant amount of investigation and detailed analysis.

The background information required to fully understand the black system event, the identified causes for the event, study findings, assumptions and recommendations is clearly outlined in the reviewed report.

MHI agrees with AEMO's explanation of the events that led to the black system. In addition, MHI agrees that the event was exacerbated due to lack of inertia on the South Australian side once the Haywood interconnector tripped.

AEMO's efforts to understand the system study model response are excellent. A very thorough analysis based on sound engineering guidelines has been carried out to highlight model accuracies and limitations.

MHI has extensive experience with wind turbine modeling and related wind integration studies, which required close interaction with equipment suppliers. As such, MHI confirms that the protection feature resulting in sustained power reduction of wind turbines is not generally implemented in simulation models provided to clients. Even if this feature was present, it is not customary to study multiple faults, as occurred in the actual event.

AEMO has performed a significant amount of system studies to identify the root cause of the black system. In addition, it has performed a significant amount of studies, looking at 'what if' scenarios to better understand the event and identify future system improvements and operational 'restrictions' that may be necessary to improve system security. MHI reviewed the scenarios that AEMO has considered and is in agreement that they are relevant and are selected based on good engineering judgement.

MHI agrees with the main findings and overall conclusions presented in the reviewed report.

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2 Introduction

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 final report for 'Black System South Australia – System Event of 28 September 2016'.

The report describes the following:

- The series of events that led to the Black System.
- The performance of the system restart process and supply restoration.
- The performance of power system and market operations during market suspension.
- Recommendations for further action.

The report was reviewed by a team of three experts (Section 5) with significant expertise in planning, operation, and design aspects of large interconnected power systems, as well as expert knowledge on wind generation and power system simulation.

3 Report Comments

The reviewers commend AEMO on a very well drafted report. The background information required to fully understand the black system event, the identified causes for the event, study findings, assumptions and recommendations is clearly outlined in the reviewed report.

The events that led to the black system are well documented in Chapter 3 of the report provided by AEMO. A thorough analysis of each event (16.18.08.8 hours to 16.18.16 hours) was performed. These events are presented in a simple and clear manner, and MHI agrees with the listed observations.

AEMO's efforts to understand the system study model response are excellent. A very thorough analysis based on sound engineering guidelines has been carried out to highlight model accuracies and limitations. Based on the studies and fact findings, AEMO has identified improvements that may be specified for wind farm simulation models and that will improve the accuracy of study results when analyzing system response under 'extreme' disturbance situations.

In addition to future model improvement requirements, the investigations have identified modifications that shall be implemented on existing, as well as future wind farm installations. One of the key findings in this regard is the protection function that is present in most of the wind turbine generators, where the units are tripped in the event of multiple faults within a short time period. In Section 3.2 of the reviewed report, AEMO mentions that this wind turbine protection setting was not known to it until it came to light during the black system investigations.

MHI has extensive experience with wind turbine modeling and related wind integration studies, which required close interaction with equipment suppliers. As such, MHI confirms that the protection feature resulting in sustained power reduction of wind turbines is not generally implemented in simulation models provided to clients. Even if this feature was present, it is not customary to study multiple faults, as occurred in the actual event.

Considering the above, it is reasonable that AEMO did not consider that the operating state represented a threat to power system security. AEMO has listed procedures and guidelines that it followed to arrive at this conclusion. The demonstration that had the Group A and B wind farms ridden through all six voltage disturbances, then the system would have survived, is an important finding.

The model validation exercise, as described in Appendix W of the reviewed report, shows that the modified wind turbine generator models are accurate for system studies. Most modified models provide good correlation with field results until the tripping is initiated by the 'multiple fault' check, where a pre-set limit allows only for a specific number of successful fault ride through events. This knowledge is beneficial not only to AEMO but to the global wind industry in general.

MHI agrees with AEMO's explanation of the events that led to the black system. MHI agrees that the event was triggered due to lack of inertia on the South Australian side once the Haywood interconnector tripped. As stated in the report, the cause of the black system was a sustained power reduction of a number of wind farms in SA, leading to angular instability. The dynamic voltage decline observed during the event was a symptom rather than the cause. MHI lists the following comments based on its system operational planning experience and based on discussions in the AEMO report:

- The system inertia on the SA side was not sufficient to maintain the frequency drop (once the Haywood interconnector tripped) and to make the under frequency load shedding (UFLS) effective. This is a key point. This is illustrative from Table 11 of the reviewed report.

- The system inertia requirements must be carefully evaluated to ensure system stability in the event of extreme disturbances, as the one that led to the black system. This is identified in the report. 'Must run' thermal generation may have to be identified. Synchronous condensers may be investigated as a potential solution if the thermal generation dispatch is expected to be low under specific load conditions. Generation mix is identified and mentioned throughout the report as an important consideration from a power system security perspective.

- AEMO has investigated the impact of the SVC and if modified settings or operational characteristics may have impacted the black system event. The conclusion is that the SVC operation (modified response) would not have avoided the black system. MHI agrees with this.

3.1 Under Frequency Load Shedding

In examining the comments on UFLS, MHI agrees that the system would not be effective in mitigating very rapid changes in the frequency, such as the one that occurred on September 28, 2016. The under frequency relays do not start activating until the frequency drops to 49 Hz. The effectiveness of this scheme may have to be revisited if the SA side inertia is increased through thermal generation dispatch. UFLS should be the first line of defense. In MHI's opinion, special protection scheme (SPS) should be considered if UFLS does not provide the required system security. AEMO identifies this in Section 3.6 of the report.

3.2 System Inertia

As systems lose inertia due to the retirement/displacement of thermal plants and the expansion of wind farms, frequency control becomes more important, as frequency control is directly related to inertia. This report was very wise to note the relatively low level of inertia during this disturbance. The whole topic of frequency control and RoCoF should be examined on a system-wide basis, and all devices that protect frequency should be reviewed for their appropriateness. The paper correctly states that the governor's settings did not have an impact on the outcome of this disturbance. However, if it is impossible to consider under-frequency schemes with higher activation frequencies due to frequency regulation, this could be a sign that the governor dead band needs to be reviewed system-wide.

3.3 Special Protection Schemes (SPSs)

SPSs may seem to be the obvious choice in this case but SPSs come with their own risk. The design of the SPS would have to consider a false activation as a potential 'contingency'. If the SPS is trying to protect a highly improbable, one-in-X-year occurrence, then a false activation that may have a similar or worse result should not occur more often. Even in systems where SPSs are common, direct load shed has been considered and rejected, as the cure may be more risky than the extreme disturbance. The beauty of an under frequency load shed scheme is that a single false activation is never significant. In the opinion of MHI, SPSs should only be considered if standard techniques fail to provide the required security.

3.4 System Studies

AEMO has performed a significant amount of system studies to identify the root cause of the black system. In addition, it has performed a significant amount of studies, looking at 'what if' scenarios to better understand the event and identify future system improvements and operational 'restrictions' that may be necessary to improve system security. MHI reviewed the scenarios that AEMO has considered and agrees that they are relevant and are selected based on good engineering judgement. As examples:

- AEMO has studied the impact of losing 200 MW of wind generation and four transmission lines. Simulations show that the system would operate stably with 800 MW import from the Haywood interconnector.
- Section X.1: System response due to loss of wind generation following a single credible fault is studied. The analysis considers a number of (high) Haywood Interconnector dispatch levels.

AEMO has highlighted the importance of further modeling and system studies in Section 8.4.1 of the report.

3.5 Other Recommendations

3.5.1 Increased Use of Synchrophasors

Based on the high impact of low frequency, low voltage, and growing phase angle threat due to mixed generations (wind, solar, thermal, etc.) over a wide area of the SA network, it is worth considering the real time WAMS (wide area monitoring systems) using synchrophasors (Phasor Measurement Units - PMUs). Real time wider area early warning systems can be established with the PMUs to cope with the electrical data, such as phase angle stress, voltage stress, and Var phase angle plot.

3.5.2 Line Distance Protection

As per the observations listed in the reviewed report, a small number of line protection operated unexpectedly; however, they did not play a part in the events leading to blackout. With the changing generation mix and different characteristics and fault tolerant levels, line distance protection challenges will increase. It is advisable perform 'critical' protection studies using more detailed relay and system modeling simulation platforms [2]. It is also advisable to consider "Line Differential Protection" as primary protection where possible, with "Line Distance" as a back-up protection to increase reliability.

4 References

[1] "A New Under-Frequency Load Shedding Technique Based on Combination of Fixed and Random Priority of Loads for Smart Grid Applications", J. A. Laghari, Hazlie Mokhlis, Mazaher Karimi, Abdul Halim Abu Bakar, and Hasmaini Mohamad, IEEE Transaction on Power Systems.

[2] "Development of a Virtual Relay Model (VRM) of a Microprocessor Based Sub Harmonic Protection Relay", K. Narendra, N. Perera, M. Poole, L. Akinola, N. Wegner, CIGRE Conference, 2016 Oct, Vancouver

5 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.

Allan Silk, B.Sc., P.Eng., Allan graduated from the University of Manitoba in 1985 with a Bachelor of Science in Computer Engineering. In 1988 he began working with Manitoba Hydro's Information Systems Division where he was responsible for supporting power system applications. In 1990 he moved to the System Performance Department and began work as an AC Network Studies Engineer. Presently he leads a group of 10 Engineers in that department whose responsibility it is to study the AC network , develop operating procedures, and provide real time study support to the Manitoba Hydro Control Centre.
In 2008 Allan moved to the Transmission Services Department as the Section Head for Tariff Administration. In 2011, Allan was seconded to the HVdc Research Centre to work on a project in Saudi Arabia. He returned to Manitoba Hydro in 2014. During 2005 Allan was he president of Engineers Geoscientists Manitoba. EGM is the licensing body for all Professional Engineers in Manitoba.

Krish Narendra, Ph.D., P.Eng., is Chief Technology Officer and Board Member of ERL - Power Automation & Smart Grid. Dr. Narendra has over 25 years of experience in power system protection, monitoring, control and analysis. He is responsible for innovative design, implementation, quality and commercialization of protective relays and disturbance monitoring recorders using advanced digital signal processing technologies on embedded systems, and in Windows development environments.

Dr. Narendra has been an IEEE member for over 15 years. He is actively participating in the IEEE PRSC working groups, and is a member of the PRTT of

NASPI. He is a member of the CIGRE C4-B5 working group and NERC SMS committee. He has published over 35 papers in various IEEE/IEC journals and conferences, and is an innovator of several patents. His areas of interests include power systems disturbance analysis, protection, micro grid protection, sub-harmonics in power systems, SSR (sub synchronous resonance), ferroresonance, HVDC controls, neural networks, artificial intelligence, fuzzy logic, phasor technology (PMUs), and the application of IEC 61850 protocols for protection and control.