System Studies for Demonstrating the Capability of Inertia Response (IR) from Windfarms
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EXECUTIVE SUMMARY

This report presents the studies conducted for investigating the capability of Inertial Response (IR) from windfarms in providing fast frequency support during loss of generation events. The windfarms providing IR operate in the maximum power tracking mode (i.e. not de-loaded before the IR) and inject extra power by extracting power from the kinetic energy stored in the turbines. The studies use the windfarm IR profile data provided by Siemens Gamesa Renewable Energy (SGRE) and the 36-bus reduced GB transmission system model in DIgSILENT PowerFactory provided by National Grid (NG).

In the studies, the impact of a range of the windfarms' IR characteristics on the effectiveness of supporting frequency control have been investigated. The IR characteristics investigated include: the duration of IR provision and the power ramping down strategies during recovery period (i.e. 10 s duration with a fast power ramping down rate during recovery period and 5 s duration with a slow power ramping down rate); conservative and mean IR profile data; the loading levels and capacities of windfarms; activation time of IR; and the locations of windfarms providing IR in the network. Additionally, combinations of windfarms with different IR characteristics are also investigated, which include a mix of windfarms with 10 s and 5 s profiles and a mix of windfarms with different IR activation times.

From the studies, it was found that the windfarm IR has a great potential to improve the effectiveness of frequency containment following a power imbalance event, thereby enhancing system frequency control. However, as the IR power is from the turbine kinetic energy, there is a recovery period after the IR where the windfarms need to retrieve the extra injected power and thus generate less power than the pre-event level. As a result, the need for power to recover the rotation of the turbine can also introduce a second frequency drop after the IR. With larger windfarm capacities (thus the IR contributions), the first frequency drop can be significantly improved, while the increasing capacity can lead to a more severe second frequency drop. Therefore, the windfarm's capacity need to be carefully chosen to keep both of the first and second frequency nadir above the required 49.5 Hz limit. In this report, the optimal range of windfarm capacities to maintain both of the first and second frequency nadirs above 49.5 Hz for different windfarm loading conditions is provided for the inertia level of 82 GVAs scenario.

The occurring time of the second frequency drop is dependent on windfarm's IR characteristics, which needs to be considered while coordinating with other resources for supporting system frequency response. In general, the performance of windfarm IR with mean data outperforms that with conservative data. Different locations and activation times (in the range of 500 ms to 1000 ms) of windfarm IR do not appear to introduce significant impact on system frequency nadirs.

Comparing 10 s and 5 s duration of windfarm IRs, it was found that the 5 s duration IR with the active power Slow Ramping-down (SR) characteristic showed a significant advantage in limiting the second frequency drop due to slower power drop after the IR.

It has also be shown that voltages across the network are able to recover to above 90% of rated within 500 ms during frequency disturbances following faults. Therefore, it allows the windfarms to provide IR under such circumstances.

Suggestions for future work are also provided, which include the development of a general approach of quantifying the requirements for windfarm IR characteristics (e.g. capacity, duration, power ramp-down rate, etc.) for different inertial levels and operating conditions; and the coordinated control of windfarm IR with other types of generations to enable a smooth power transition from wind IR to power outputs from other sources.

LIST OF ABBREVIATIONS

IR	Inertial Response
SGRE	Siemens Gamesa Renewable Energy
NG	National Grid
SR	Slow Ramping-down
TSO	Transmission System Operator

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1 INTRODUCTION

This report presents studies that have been conducted for investigating the capability of IR from windfarms in providing fast frequency support during loss of generation events using windfarm IR data provided by SGRE and the 36-bus GB transmission system model in DIgSILENT PowerFactory provided by NG.

The following aspects associated with the windfarms' IR characteristics have been simulated and evaluated in order to investigate the capability of windfarm IR in providing frequency support:

- Windfarm IR with different IR durations and power ramp-down rates: 10 s duration with sharp power drop after IR and 5 s duration profiles with SR of power after IR
- Conservative and mean data for IR;
- Different activation times of IR after a frequency event;
- Various loading levels and capacity of the windfarms providing IR;
- Different locations of IR contribution in the network;
- Performance with mix of 10 s and 5 s IR profiles employed at the SGRE windfarms;
- Performance with mix of activation time of windfarm IR;
- Frequency events following faults.

This report is structured as follows:

Section 2 gives an overview of the windfarm IR profiles provided by SGRE, which include both 10 s and 5 s duration park level IR.

Section 3 introduces the configuration of the reduced 36-bus GB transmission model in PowerFactory including the system inertia level, the network demand level, the assumptions for the system studies, and the loss of generation event simulated. The modelling of the windfarm IR response is also introduced and the behaviour from the model is compared with profile data provided by SGRE.

Section 4 presents the simulation results from the system studies conducted, which include the comparison of conservative and mean profiles, impact of activation time of IR, impact of loading and capacity of the windfarms, impact of location of windfarms providing IR and frequency events following faults. All the case studies are carried out for both the 10 s and 5 s duration IR profiles. Performance of 10 s and 5 s are compared in this section as well, along with the performance of mix types of profiles including 10 s and 5 s profiles and different activation times of IR.

Section 5 concludes the key findings from the studies and provides recommendations for future work.

2 OVERVIW OF THE WINDFARM IR PROFILES

The windfarms' IR profiles used in these studies were from SGRE D7 windfarm turbines and include the following two data sets.

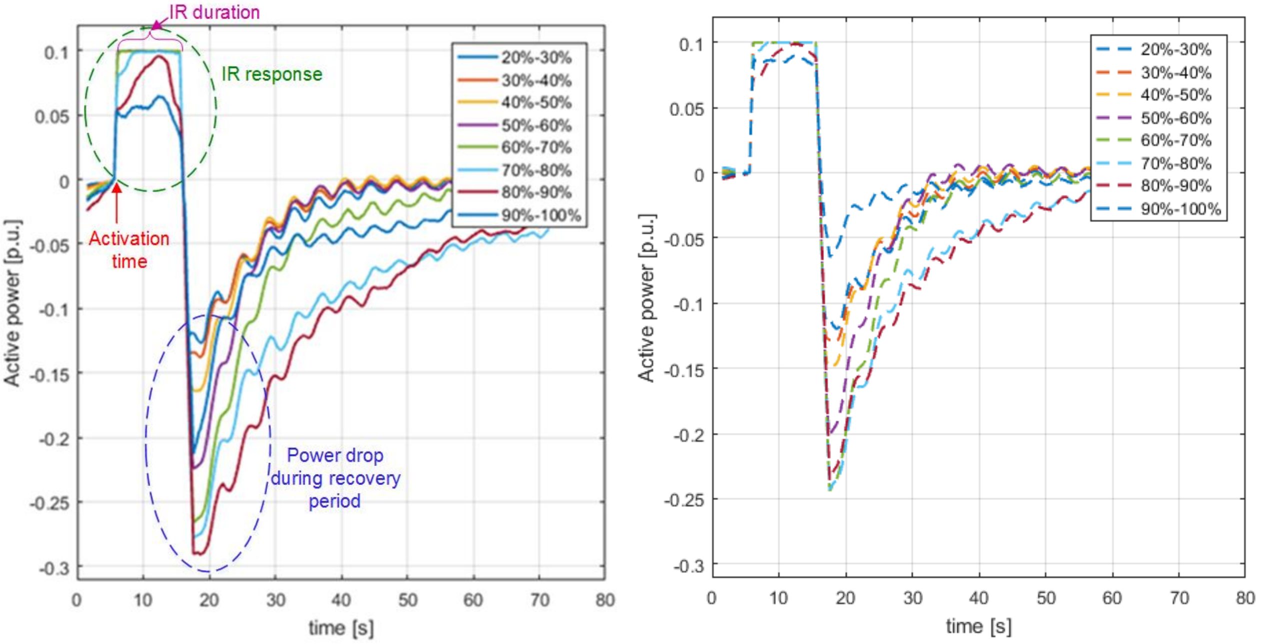
- 10 s duration park level IR with 20%-100% loading of rated power (both conservative and mean data);
- 5 s duration park level IR with power SR during recovery period with 20%-100% loading of rated power (both conservative and mean data).

The above IR profile data sets were plotted in Figure 2-1 and Figure 2-2 respectively. The mean profiles are obtained by averaging all wind IR at park level at certain loading level while the conservative profiles are processed by applying minus 2 times of the standard deviation on to the mean profiles to contain 68.27% of responses assuming the wind IR response following normal distribution.

As illustrated in Figure 2-1(a), the maximum IR output is 10% of rated power for all profiles. The extract triggering time of the wind IR can be adjusted in order to represent different activation times following loss-of-generation events. For example, if a frequency disturbance occurs at 5 s, the data set can be adjusted so that the IR response can start ramping up at 5.5 s to represent a 0.5 s of activation time.

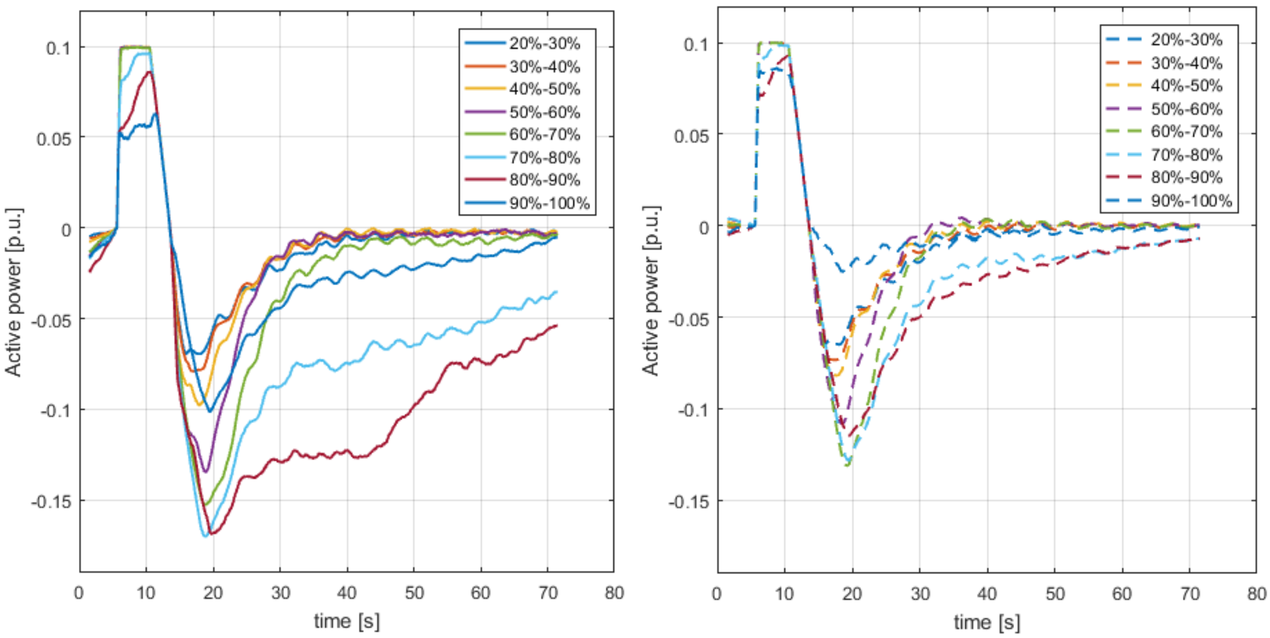
Comparing the 10 s duration data presented in Figure 2-1 and the 5 s duration data presented in Figure 2-2, 10 s duration profiles provides IR for 10 s and has a sharp drop in power, while 5 s duration profile provides 5 s of IR and has a slower power ramp-down rate after the IR.

From Figure 2-1 and Figure 2-2, it can also been seen that the power drops after IR for both 10 s and 5 s profiles are generally larger with higher loading levels, except for the cases with 90-100% loading for 10 s profiles and 80-100% for 5 s profiles. From the discussion with SGRE, it was suggested that this is associated with the specific operating point pointing in the power curve of the windfarms, which is outside of the scope of this work.



(a) Conservative (b) Mean

Figure 2-1. 10 s duration park level IR for D7 windfarm turbine with 20%-100% of rated power



(a) Conservative (b) Mean

Figure 2-2. 5 s Duration park level IR with slow ramping down afterwards for D7 windfarm turbine with 20%-100% of rated power

3 MODELING OF WINDFARM IR AND CONFIGURATION OF NETWORK MODEL

The reduced 36-bus GB transmission network model in PowerFactory was dispatched to represent the minimum system inertia level at 2021/22, i.e. 82 GVAs, as defined in the future energy scenarios [1]. Details of model configuration are summarised below:

- **Network demand level: 25 GW**
- **System inertia: 82 GVAs**
  To achieve the 82 GVAs system inertia level, the active power output for Transmission System Operator (TSO) synchronous generation in the network is configured based on the assumptions of 5 s inertia constant in the synchronous generators (based on MVA rating) and 0.8 power factor.
- **Loss of generation event: the Ireland DC link in Zone 01**
  The Ireland DC link is to be tripped at 5 s of the simulation (total simulation time is 80 s) to simulate the loss of infeed event. After the initial model dispatch using the spreadsheet, the active power output of the Ireland DC link is 1500 MW. This value was adjusted to 1320 MW, and the 180 MW difference is shifted to the windfarm generator connected in the same zone.
- **Assumption of available primary and secondary response**
  The plant margin in the dispatch spreadsheet is set to 7%, which considers the event size and an additional 30% reserve on the synchronous generation.
- **Modelling of the windfarm IR response**
  A static generator is installed in each of the 36 zones to represent the SGRE windfarm whose active power output is configured to closely follow the IR profile provided. Figure 3-1 shows the installation of SGRE windfarm static generator in Zone 01 as an example. Figure 3-2 shows that the actual output from the SGRE static generator model tracks the raw data provided by SGRE satisfactorily. Active power output (based on a rating of 2 GVA windfarm) with 10 s and 5 s profiles are shown in Figure 3-3 and Figure 3-4.

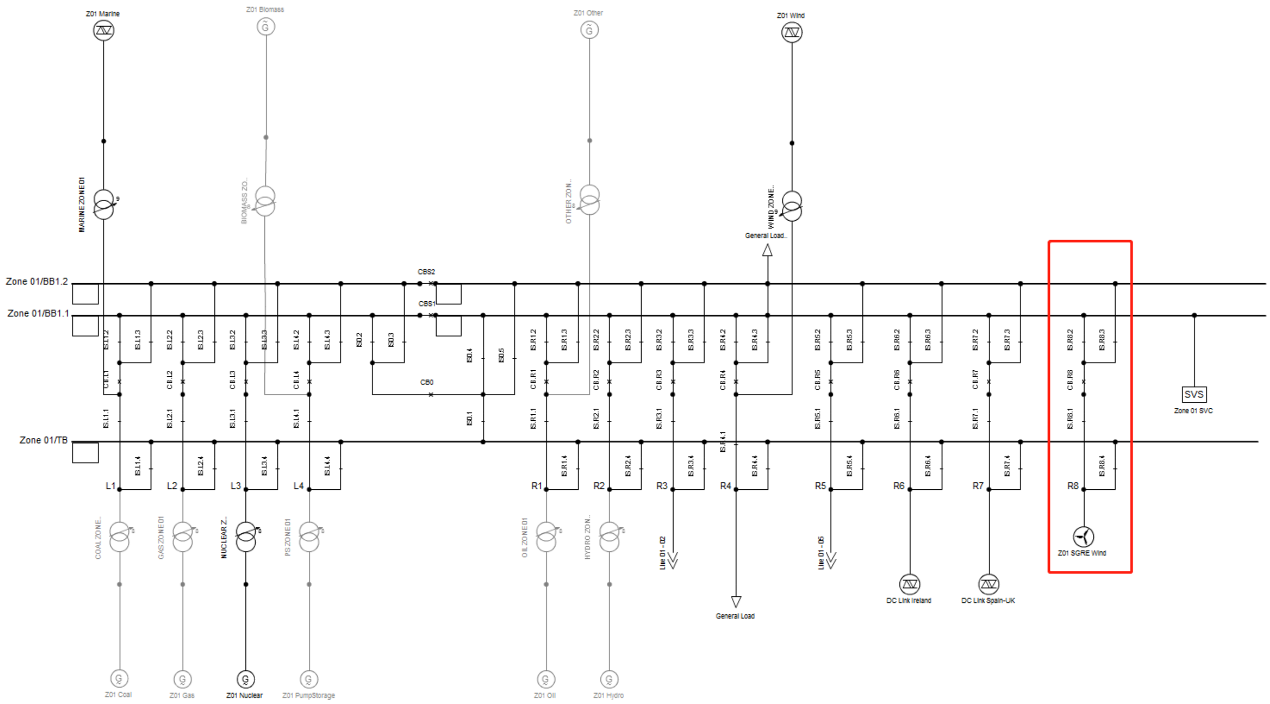


Figure 3-1. Installation of SGRE windfarm static generator in the reduced GB transmission model (Zone 01 as an example)

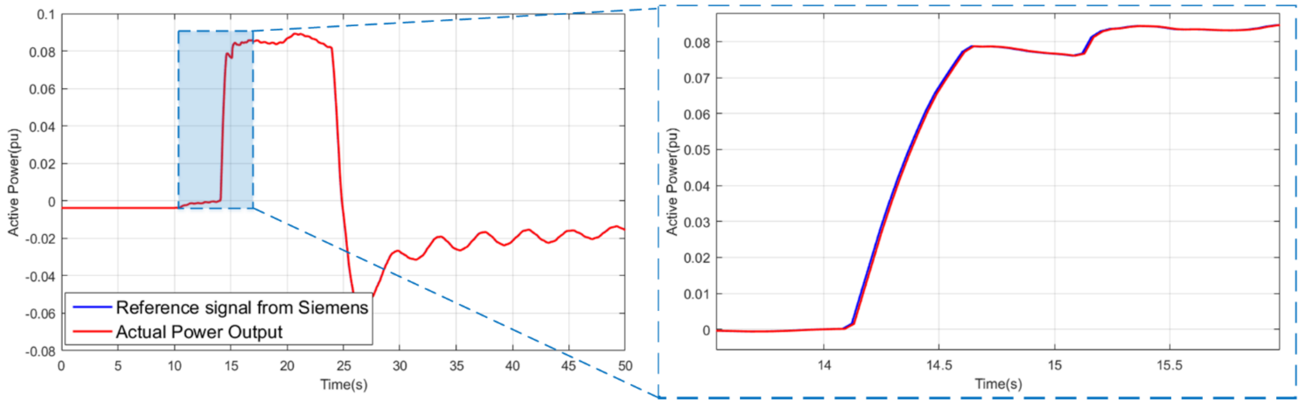
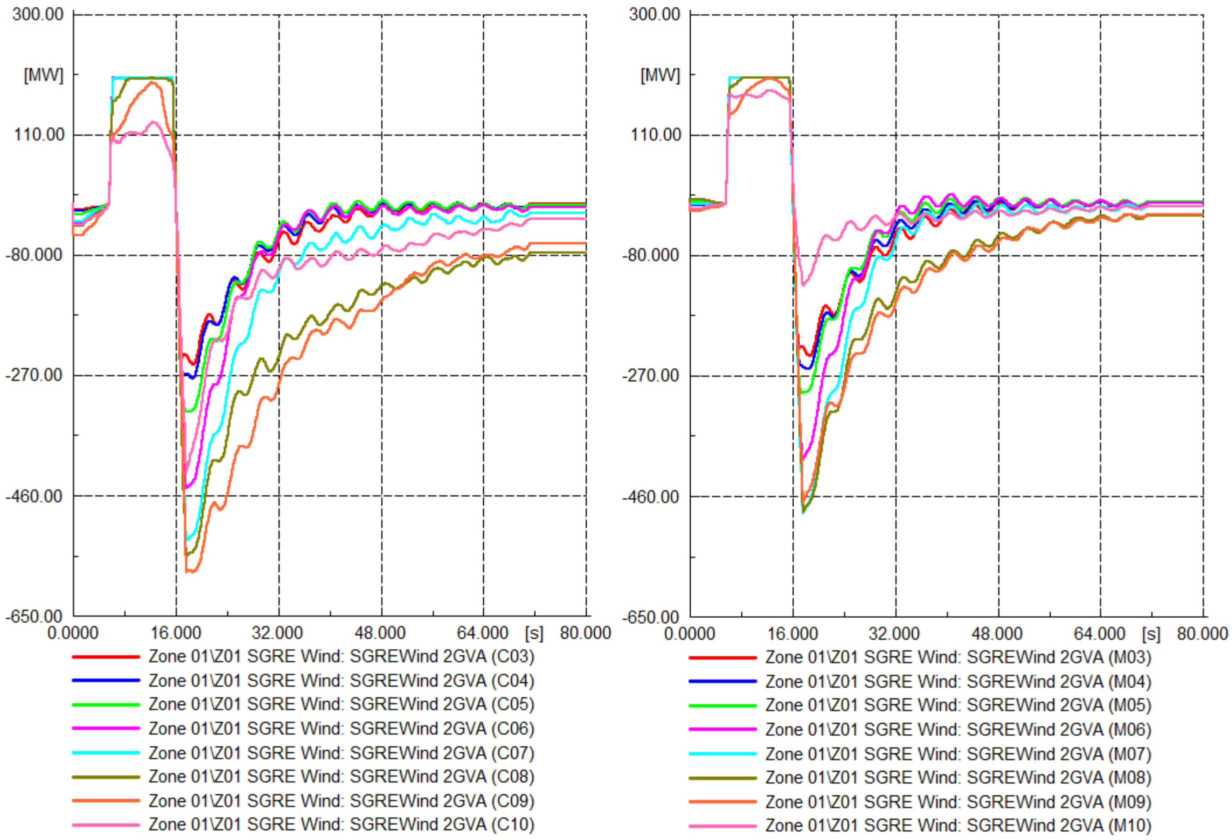


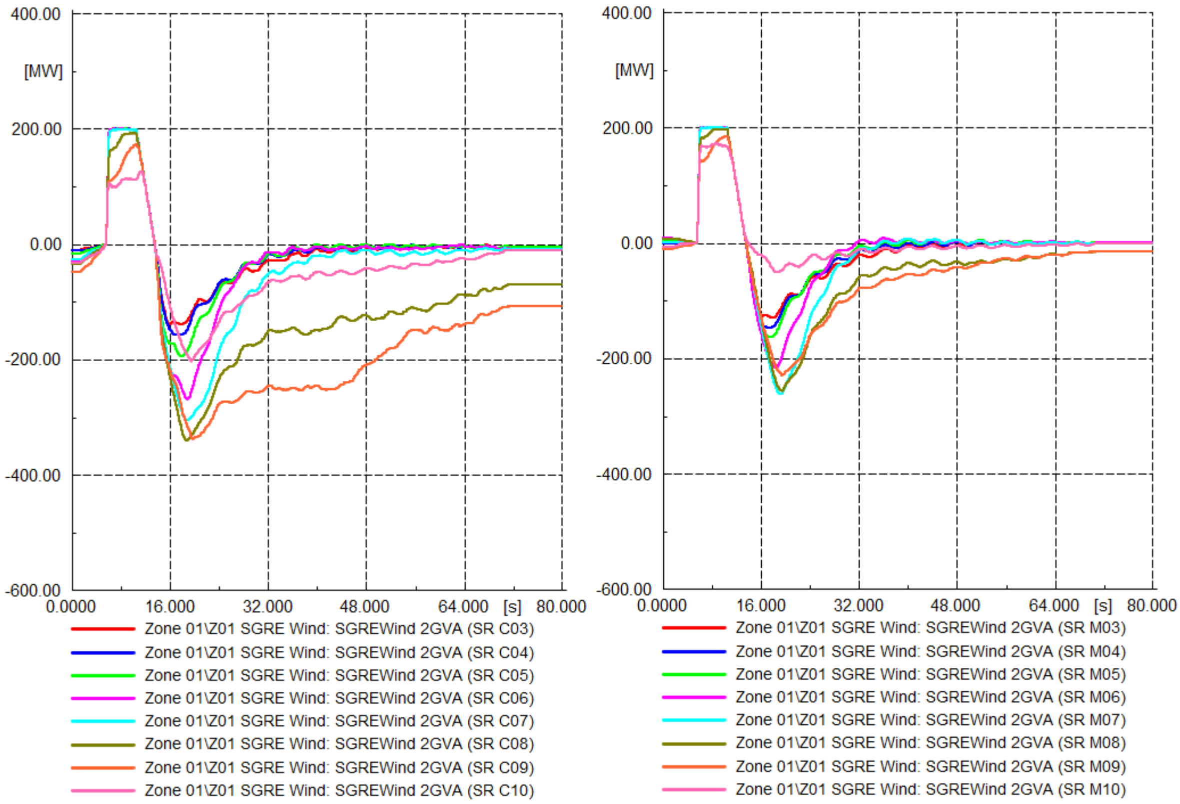
Figure 3-2. Comparison of wind IR raw data provided by SGRE and actual power output from the SGRE static generator in PowerFactory



(a) Conservative (b) Mean

Figure 3-3. IR profiles from a 2 GVA windfarm with the 10 s profiles ranging from 20%-100% loading of rated power [1]

[1] Note that in this report the result graphs for different IR profiles are named in a form as 'Cxx' and 'Mxx' where C stands for conservative data, M stands for mean data, and xx represents the loading level, e.g. 03 means the windfarm is at 20-30% loading.



(a) Conservative (b) Mean

Figure 3-4. IR profiles from a 2 GVA windfarm with the 5 s + SR profiles ranging from 20%-100% loading of rated power

4 SIMULATION RESULTS FROM THE SYSTEM STUDIES

In this report, the impact of the activation time of IR, the capacity and location of the windfarms providing IR on the effectiveness in supporting frequency control are investigated. The simulation cases are summarised below:

- **Comparison of conservative and mean profiles**: this is to investigate the differences and the associated impact on frequency support effectiveness between the conservative and mean IR profiles from SGRE.
- **Impact of activation time of the IR**: this is to investigate how the activation time (ranging from 500 ms to 1000 ms) of the IR activation following the loss-of-infeed events on the effectiveness on supporting the frequency control.
- **Impact of loading and capacity of the windfarms**: this is to investigate the effects of various loading of rated power of the windfarms. Furthermore, the investigation of the suitable range of SGRE windfarm capacity for a range of loading levels in order to contain the frequency degradation at 49.5 Hz during loss-of-infeed events is also conducted.
- **Impact of location of the windfarms providing the IR**: this is to investigate the locational impact of the IR from windfarms on the performance of frequency restoration. The locations investigated include South (Zone 01), Middle (Zone 22), North (Zone 32), and equally distributed across all zones.
- **Frequency event following a fault:** this is to investigate the impact of voltage dip on windfarm IR provision, where faults in both South and North locations have been studied.

For the simulation results to be discussed, the following default settings are applied unless specified:

- Activation time of IR is 500 ms delay after the event (except for the activation time investigation studies);

- Capacity of SGRE windfarm generator(s) is 2 GVA (except for the capacity investigation studies);
- SGRE windfarm generator is loaded with conservative profile at 20%-30% of rated power (except for the loading investigation studies);
- SGRE windfarm generator is activated in the South location in Zone 01 (except for the location investigation studies).

4.1 IR study using data of 10 s duration IR from SGRE windfarms

4.1.1 Comparison of conservative and mean profiles

The simulation results for investigating the impact of conservative and mean profiles on the frequency support performances at different loading levels are presented from Figure 4-1 to Figure 4-5. It can be seen from the results that, the profiles with mean values show better performance than that the ones with conservative values in terms of the second frequency drop due to the smaller power drop after the IR. In consistence with the profiles shown in Figure 2-1 and Figure 2-2, the difference between performance with conservative and mean profiles becomes larger with higher loading levels of SGRE windfarm. The recovery time after the loss-of-infeed event is similar with mean and conservative profiles.

As summarised in Table 4-1, with an increasing loading level for each type of the profiles, the second frequency drop became more severe and the time when the second frequency dip occurred became later. The different frequency dip occurring time (for second frequency drop specifically) needs to be considered while coordinating with other types of frequency support, e.g. power dispatch through techniques such as EFCC.

Table 4-1. Size and time of the frequency drops with 10 s conservative and mean profiles

Case study		First frequency drop		Second frequency drop	
		Min. frequency (Hz)	Time of dip (s)	Min. frequency (Hz)	Time of dip (s)
20-30% loading	Conservative	49.49	8.04	49.64	19.16
	Mean	49.49	8.04	49.63	19.35
30-40% loading	Conservative	49.49	8.04	49.61	19.70
	Mean	49.49	8.04	49.62	19.51
40-50% loading	Conservative	49.49	8.04	49.56	20.25
	Mean	49.49	8.04	49.60	19.76
50-60% loading	Conservative	49.49	8.04	49.44	21.39
	Mean	49.49	8.04	49.51	20.62
60-70% loading	Conservative	49.49	8.04	49.41	21.71
	Mean	49.49	8.04	49.31	22.91

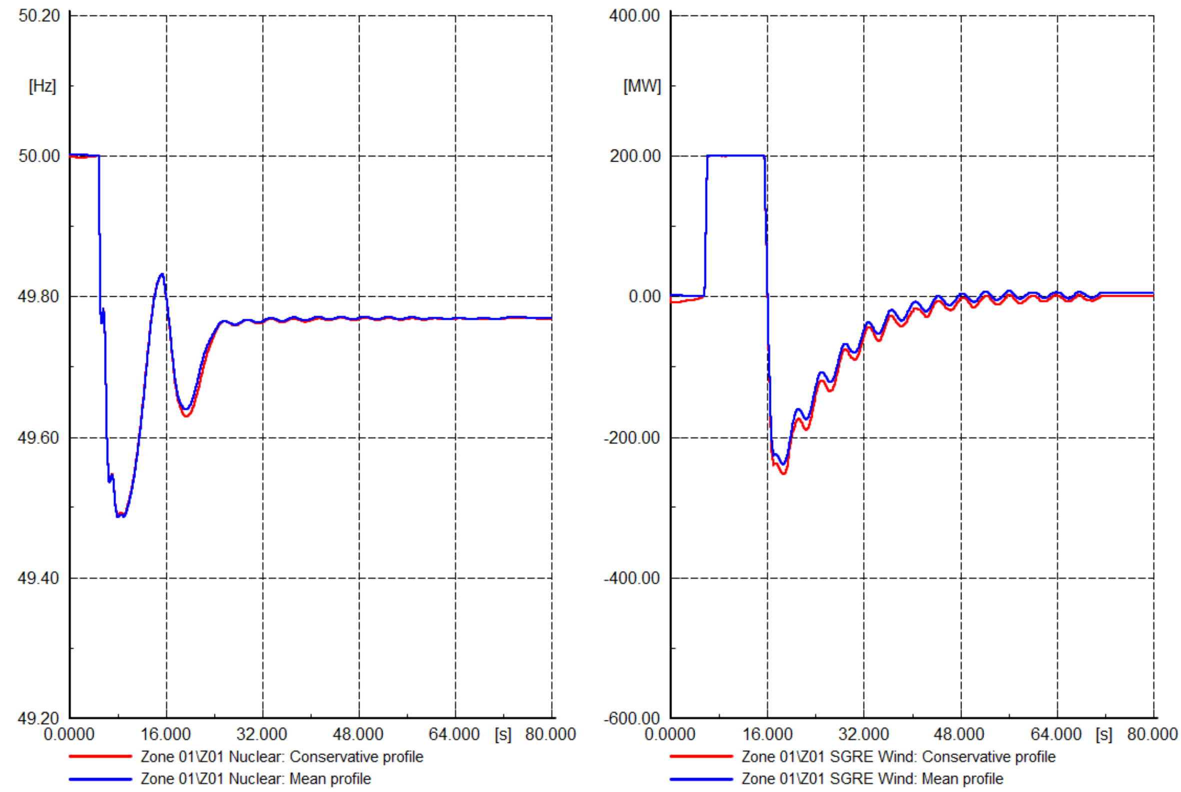


Figure 4-1. Performance of 10 s SGRE windfarm IR with conservative and mean profile at loading of 20%-30%

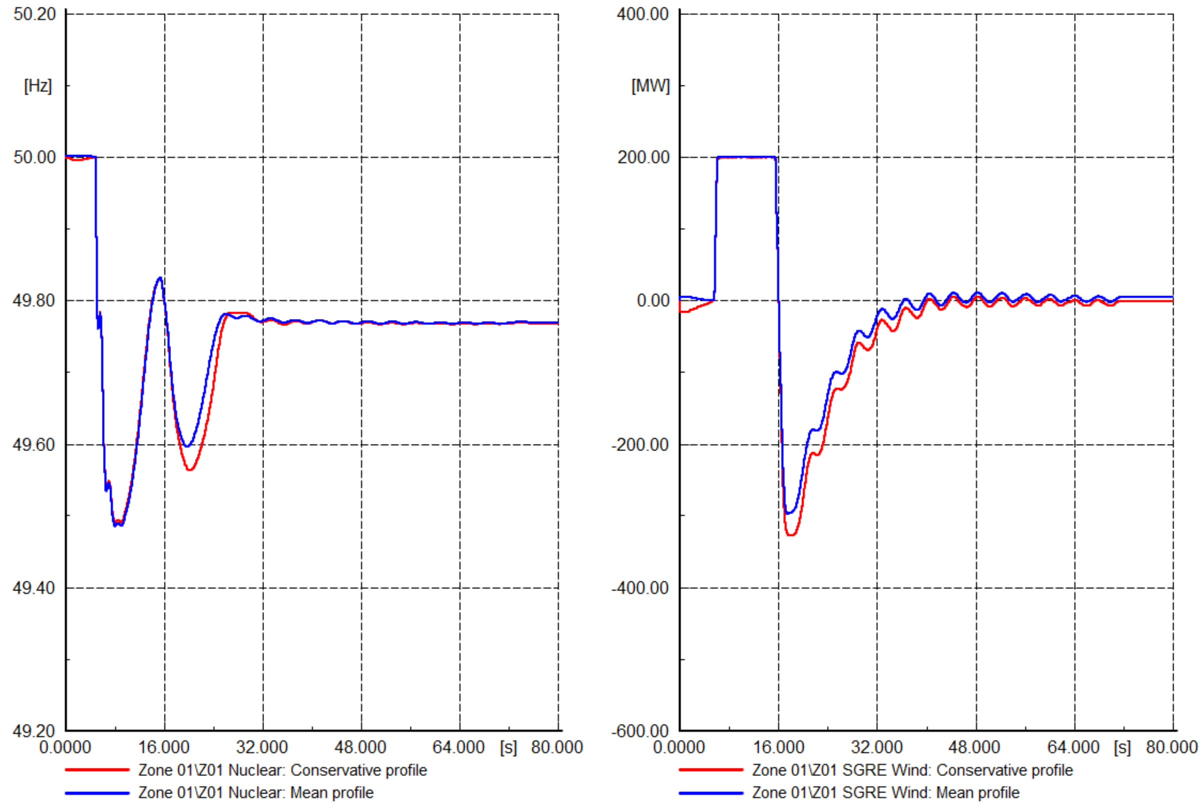


Figure 4-2. Performance of 10 s SGRE windfarm IR with conservative and mean profile at loading of 30%-40%

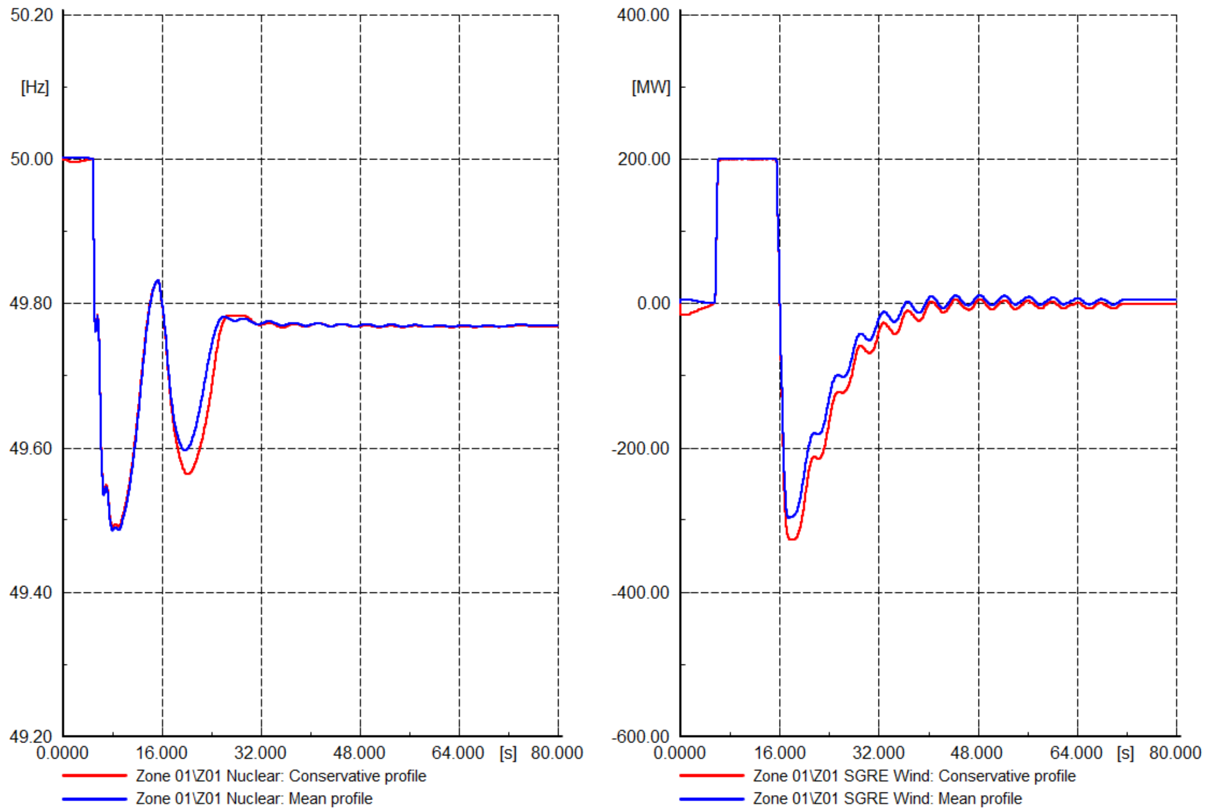


Figure 4-3. Performance of 10 s SGRE windfarm IR with conservative and mean profile at loading of 40%-50%

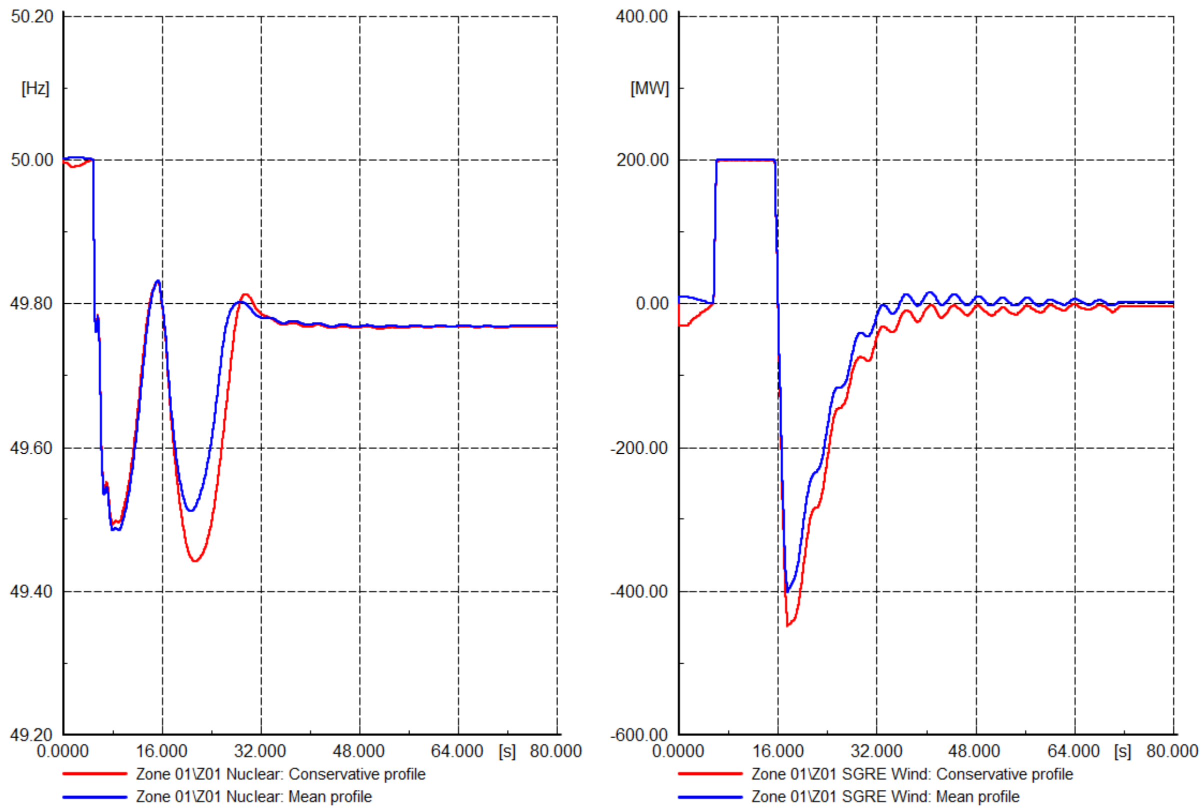


Figure 4-4. Performance of 10 s SGRE windfarm IR with conservative and mean profile at loading of 50%-60%

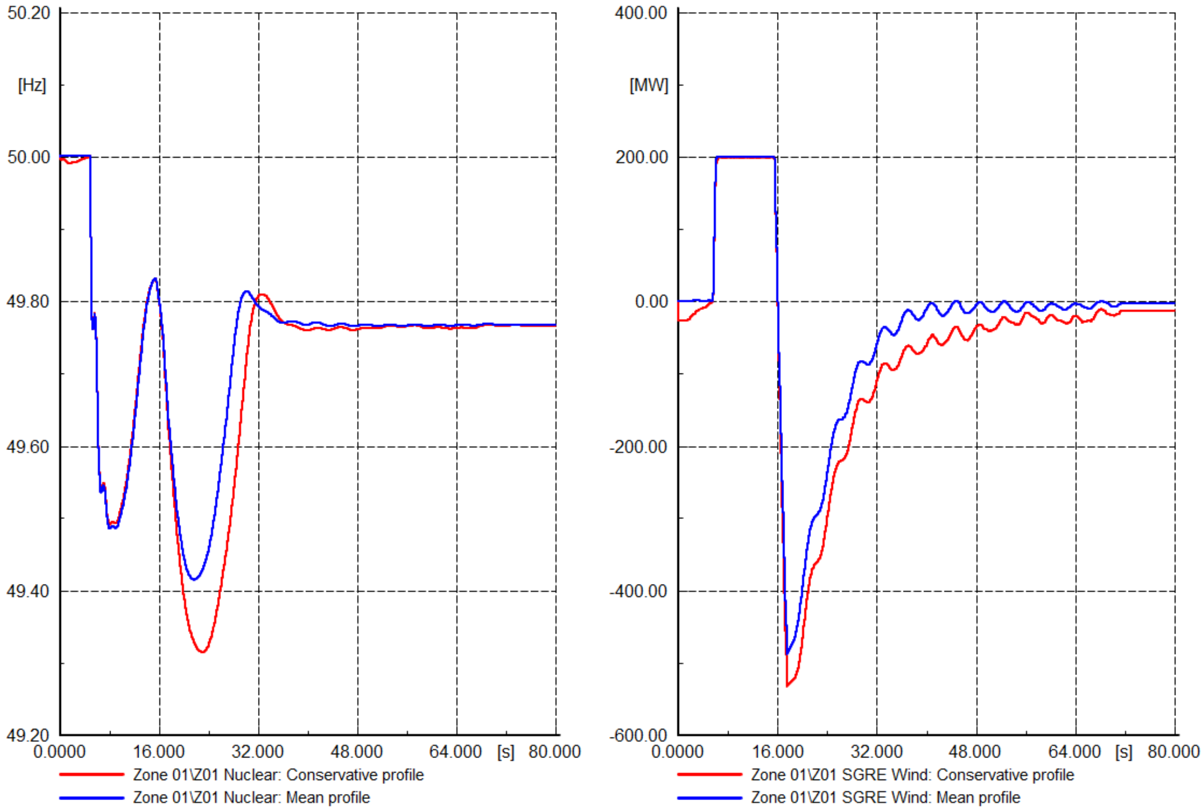


Figure 4-5. Performance of 10 s SGRE windfarm IR with conservative and mean profile at loading of 60%-70%

4.1.2 Impact of IR's activation time

The simulation results for investigating the impact of different activation times of windfarm IR on frequency support performance are shown in Figure 4-6 for conservative data (results with mean data are presented in Appendix A7.1). Table 4-2 summarises the first and second frequency nadirs for the investigated case studies. The governor responses from the operating synchronous generators are attached in Appendix B.

It can be seen that the first frequency drop after the 1320 MW infeed loss is significantly improved compared with the case without wind IR contribution (red line) for both activation time of 500 ms and 1000 ms. It can also be seen that with longer delays in IR activation, the second frequency drop can occur slightly later. Comparing the activation time of 500 ms and 1000 ms, while the first frequency drop became slightly less severe and the recovery time slightly decreased with a shorter delay of IR, there is no significant difference on effectiveness of frequency containment with the activation ranging from 500 ms to 1000 ms. However, it should be noted that this effect is dependent onto the network strength, i.e. different short-circuit ratios, which requires further investigations.

Table 4-2. Size and time of the frequency drops with different activation time for 10 s profiles

Case study		First frequency drop		Second frequency drop	
		Min. frequency (Hz)	Time of dip (s)	Min. frequency (Hz)	Time of dip (s)
No SGRE wind IR		49.25	10.93	-	-
10 s conservative profile, 20-30% loading	500 ms delay	49.49	8.04	49.64	19.16
	1000 ms delay	49.46	8.04	49.64	19.80
10 s mean profile, 20-30% loading	500 ms delay	49.49	8.04	49.63	19.35
	1000 ms delay	49.46	8.04	49.63	19.98

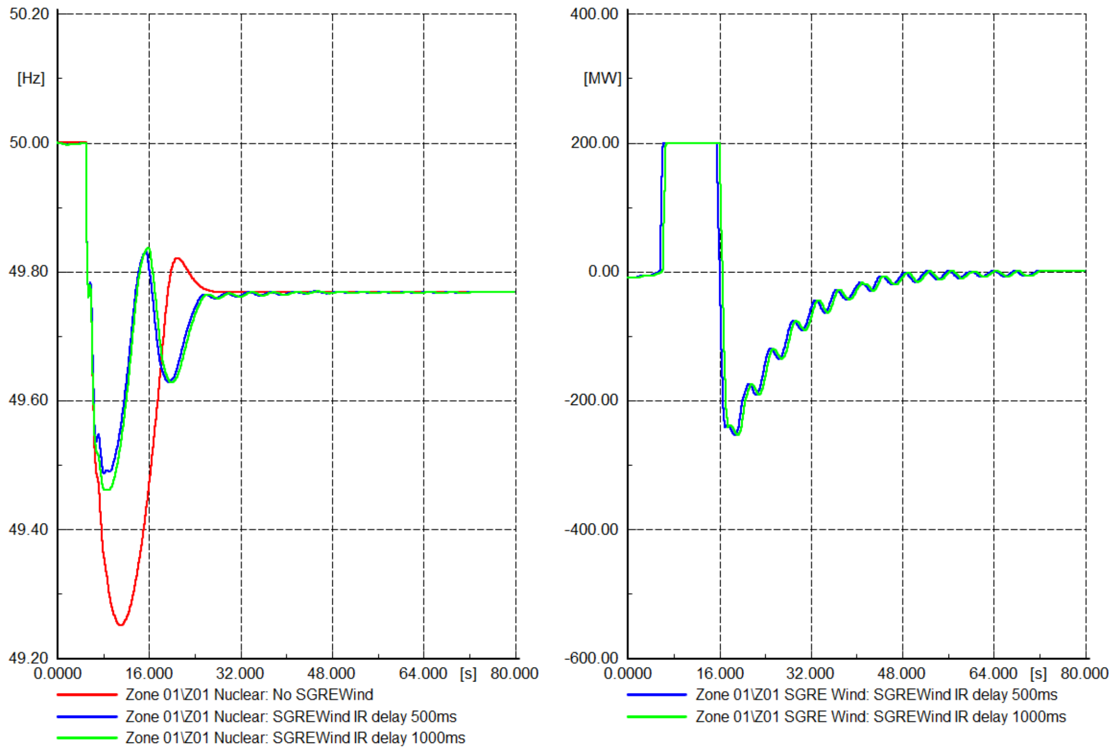


Figure 4-6. Performance of 10 s SGRE windfarm IR with various response activation time (with 20%-30% of rated power and conservative profile)

4.1.3 Impact of the capacity of the windfarms providing IR

This section presents the simulation results for evaluating the impact of the capacity of the windfarms providing IR at different loading levels on the effectiveness of frequency support. The results with conservative data are presented from Figure 4-7 to Figure 4-11 for the loading level from 20%-100% (results with mean data are included in Appendix A7.2). The optimal capacity of windfarms providing IR in order to contain both first and second frequency nadir above the 49.5 Hz limit will also be investigated for both conservative and mean IR profiles. The governor responses from the operating synchronous generators are attached in Appendix B.

As shown in Figure 4-7, for 20%-30% loading of the SGRE windfarm with conservative profiles, with an increasing capacity of SGRE windfarm (thus the active power output from the windfarm IR), the first frequency drop after the loss-of-infeed event is significantly mitigated and the minimum active power output required to fulfil frequency limitation is 200 MW. However, as the windfarm capacity increases, it tends to introduce a negative effect on the second frequency drop. To maintain the second frequency drop to be above 49.5 Hz, i.e. limit the power drop from the windfarms after IR, the maximum windfarm capacity is found to be 3 GVA for both conservative and mean profiles. Therefore, response capacity needs to be carefully chosen to make sure both frequency drops stay in the required limit. In this case, for 20%-30% loading of SGRE windfarm, the optimal capacity of the windfarm is about 2.5 GVA.

Table 4-3 gives the size and time of frequency drops for the test cases with conservative profiles. It can be seen that with higher rating of the windfarm, the first frequency drop is less severe due to the IR contribution and the changes in the occurring time of the first frequency drop is not significant (around 5ms); while the magnitude and occurring time of the second frequency drop can vary significantly due to the sudden power drop from IR windfarm as well as increased rate of the power drop. The various occurring time for the frequency dips can introduce potential challenges to system operators to coordinate other available resources and obtain an acceptable system frequency response. Novel frequency control schemes (such as EFCC) will be required to achieve coordination of various frequency support resources.

The above analysis has been applied to the other levels of loadings of the SGRE windfarms and the results are summarised in Table 4-4. It has been found that a windfarm capacity of around 2 GVA showed to be the most beneficial case for loading below 50%. When the loading of SGRE windfarm is above 50%, it was found that it became unlikely for both of the frequency nadirs to be controlled above 49.5 Hz for a 1320 MW infeed loss. It should be noted that the cases for 70%-100% loading of SGRE windfarm are not tested as it is of certain that the frequency will not be able to stay above 49.5 Hz for both dips based on the previous simulation results.

To maintain the first frequency drop above 49.5 Hz, SGRE wind should output for more than 200 MW during IR, i.e. minimum MVA level of 2 GVA; and the maximum MVA level of the windfarms to ensure the second frequency drop is around 2~3 GVA depending on the loading level (detail available in Table 4-4).

Table 4-3. Size and time of the frequency drops with wind MVA ratings for 10 s profiles with conservative profiles

Case study		First frequency drop		Second frequency drop	
		Min. frequency (Hz)	Time of dip (s)	Min. frequency (Hz)	Time of dip (s)
No SGRE wind IR		49.25	10.93	-	-
20-30% loading	2 GVA	49.49	8.04	49.64	19.16
	2.5 GVA	49.52	7.98	49.54	20.35
	3 GVA	49.55	7.93	49.43	21.71
30-40% loading	2 GVA	49.49	8.04	49.61	19.70
	2.5 GVA	49.52	7.92	49.51	20.60
	3 GVA	49.55	7.92	49.39	21.96
40-50% loading	2 GVA	49.49	8.04	49.56	20.25
	2.5 GVA	49.52	7.96	49.43	21.26
50-60% loading	1.5 GVA	49.44	9.20	49.60	20.02
	2 GVA	49.49	8.04	49.44	21.39
60-70% loading	1.5 GVA	49.44	9.26	49.55	20.68
	2 GVA	49.49	8.04	49.41	21.71

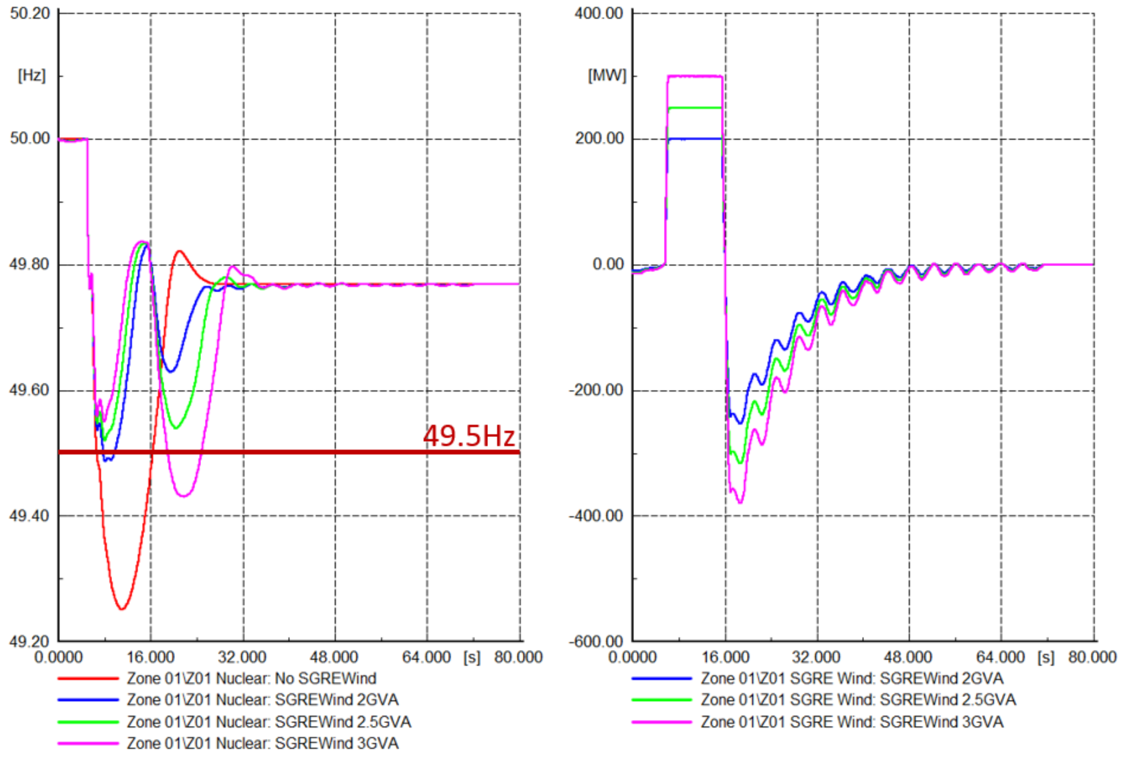


Figure 4-7. Performance of 10 s SGRE windfarm IR with various capacity levels (with 20%-30% of rated power and conservative profile)

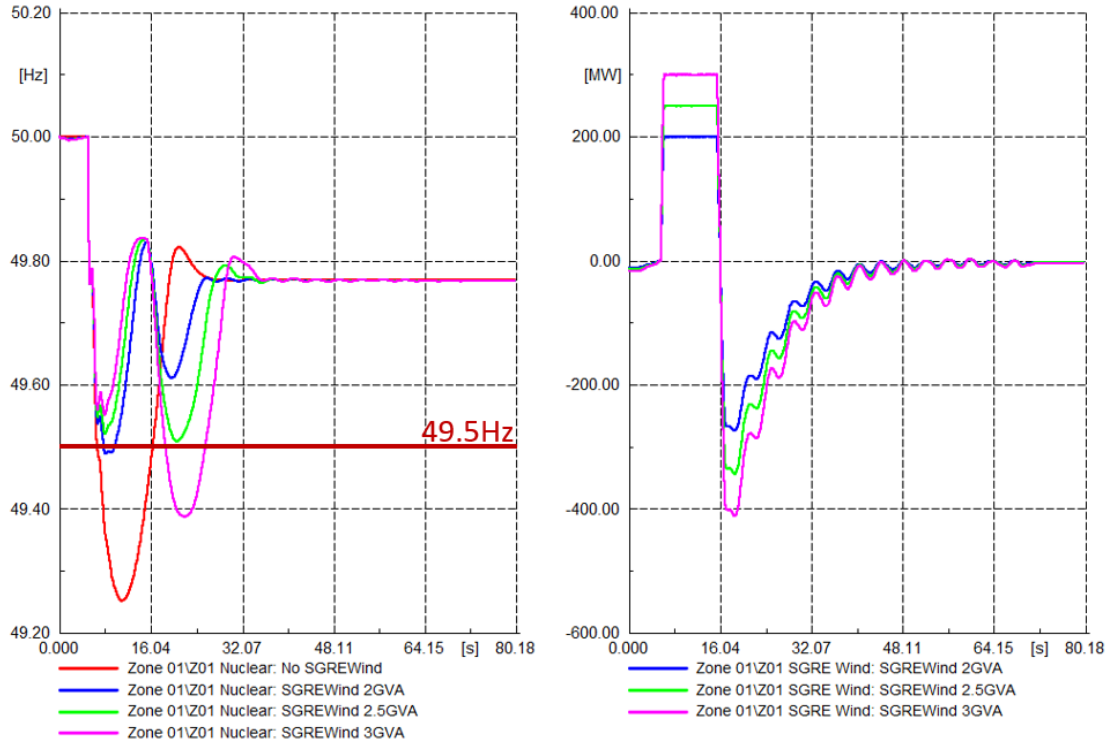


Figure 4-8. Performance of 10 s SGRE windfarm IR with various capacity levels (with 30%-40% of rated power and conservative profile)

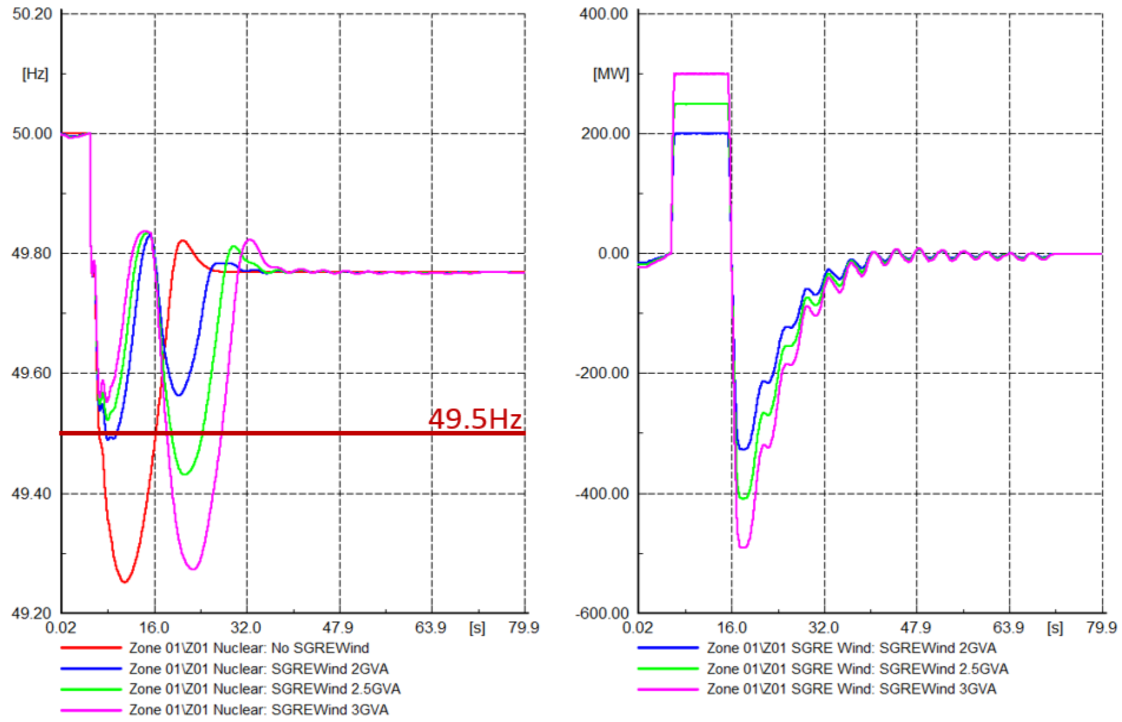


Figure 4-9. Performance of 10 s SGRE windfarm IR with various capacity levels (with 40%-50% of rated power and conservative profile)

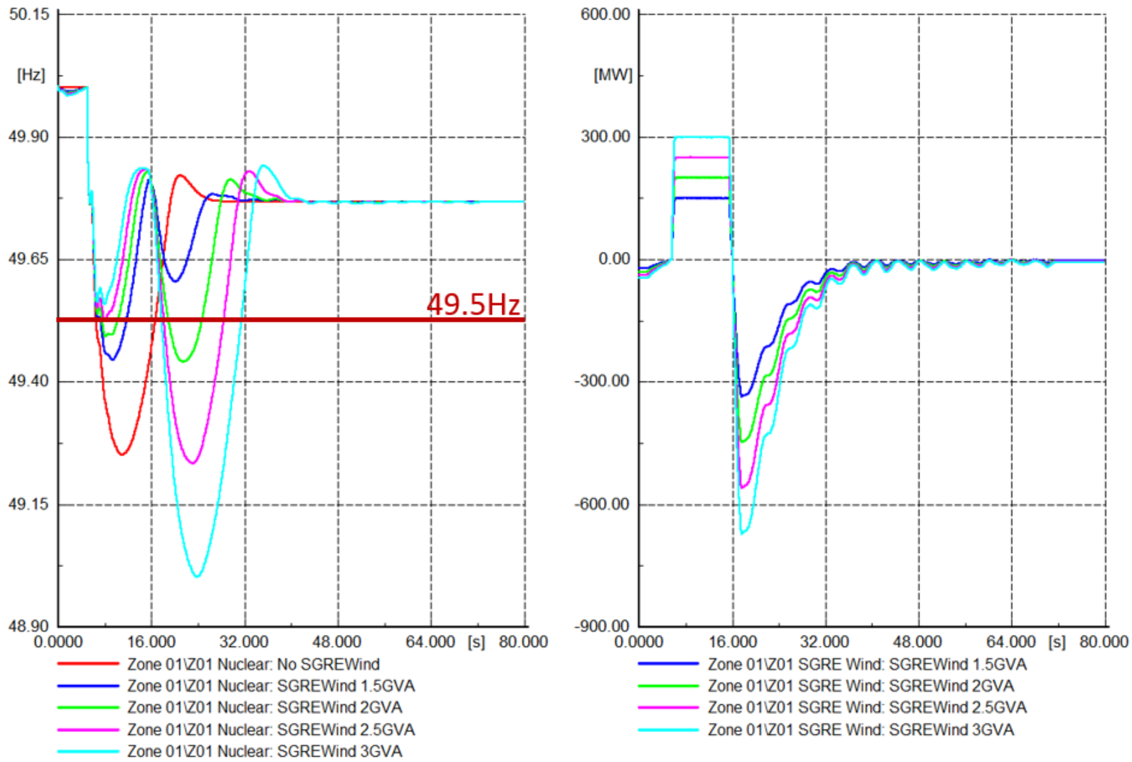


Figure 4-10. Performance of 10 s SGRE windfarm IR with various capacity levels (with 50%-60% of rated power and conservative profile)

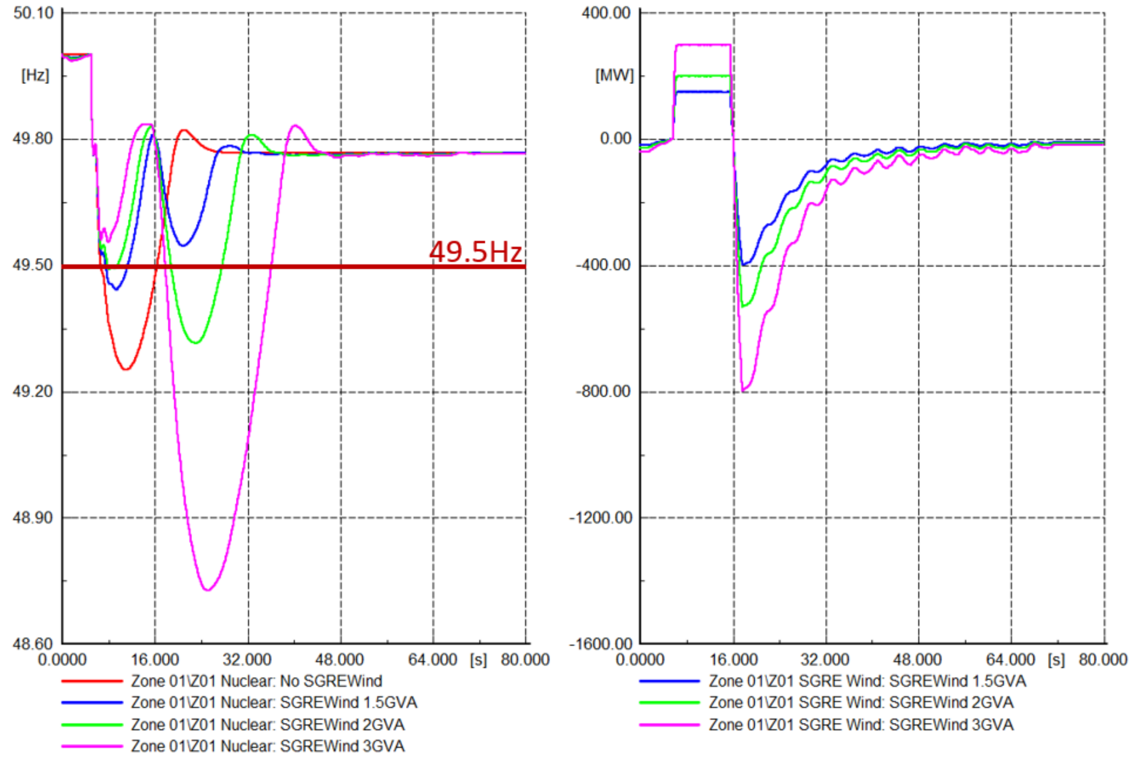


Figure 4-11. Performance of 10 s SGRE windfarm IR with various capacity levels (with 60%-70% of rated power and conservative profile)

Table 4-4. Capability of 10 s SGRE windfarm IR to fulfil frequency limitation with various loading of rated power

Loading (%) of rated power	Data type	Capability to achieve satisfying frequency response?	Best case	Power required from SGRE windfarm IR	
				First drop ⩾ 49.5 Hz	Second drop ⩾ 49.5 Hz
20%-30%	Conservative	Yes	2.5 GVA	>2 GVA	<3 GVA
	Mean	Yes	2.5 GVA	>2 GVA	<3 GVA
30%-40%	Conservative	Yes	2.5 GVA	>2 GVA	<2.5 GVA
	Mean	Yes	2.5 GVA	>2 GVA	<3 GVA
40%-50%	Conservative	Yes	2 GVA	>2 GVA	<2.5 GVA
	Mean	Yes	2-2.5 GVA	>2 GVA	<2.5 GVA
50%-60%	Conservative	No	-	>2.5 GVA	<2 GVA
	Mean	No	-	>2 GVA	<2 GVA
60%-70%	Conservative	No	-	>2 GVA	<2 GVA
	Mean	No	-	>2 GVA	<2 GVA

4.1.4 Impact of the locations of windfarms providing IR

In this study, the windfarm producing IR is located in different parts of the network to evaluate the locational impact of the windfarm IR on the frequency control performance. The following scenarios have been studies for both conservative and mean profiles: the windfarm locating in South (Zone 01), Middle (Zone 22), North (Zone 32), and equally distributed across the network (all 36 zones). Figure 4-12 shows the frequency responses measured in South (Zone 01) from the simulation using the conservative profiles. It can be seen that the location of the IR does not seem to have significant impact on the both of the first and the second frequency nadir. There is one case where frequency event occurs in Zone 01 and the windfarm is located in the North (Zone 32) having relatively more obvious difference in frequency nadirs compared to other cases due to the remote IR contribution from the event location.

Frequency profiles at various parts of the network when SGRE wind IR locates in South (Zone 01), Middle (Zone 22), North (Zone 32), and equally distributed across the system are shown in Figure 4-13. From the results, it can be seen that the locations of SGRE windfarm IR do not appear to have significant effects on system nadir and the level of inter-oscillation when placing the windfarm in different locations does not appear to cause system stability issues. Simulation results for mean profiles are shown in Appendix A7.3. The governor responses from the operating synchronous generators are attached in Appendix B.

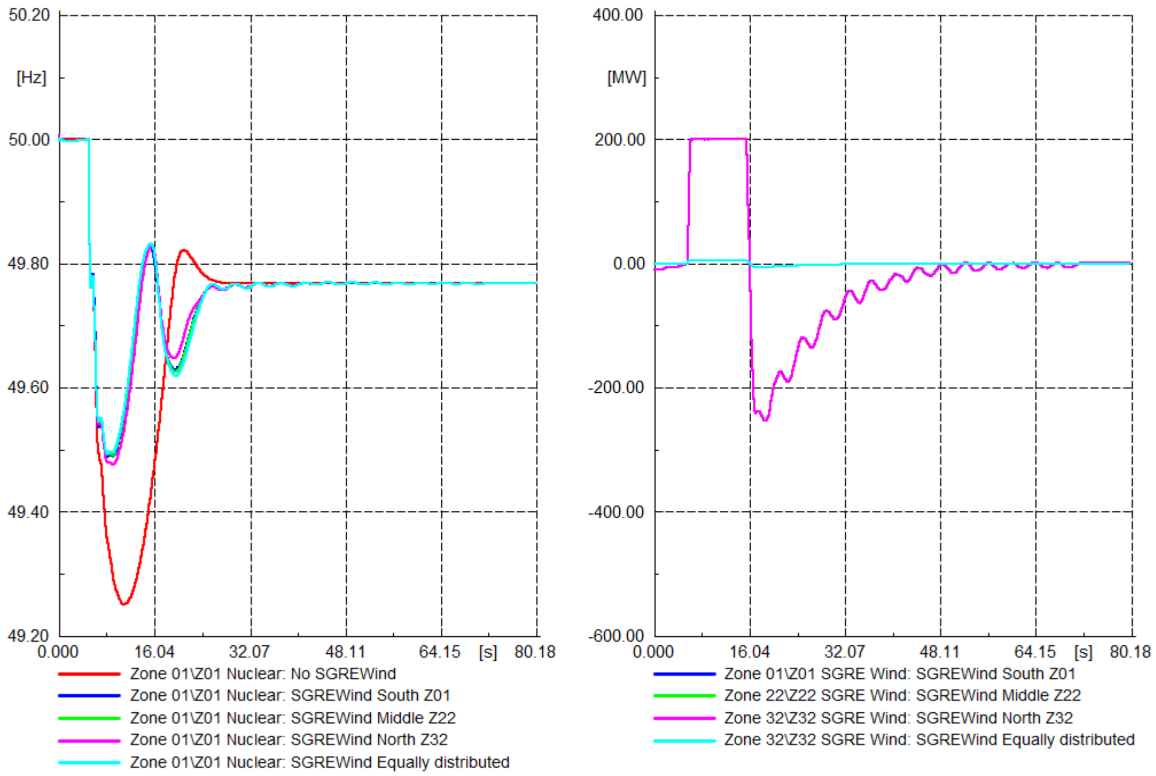


Figure 4-12. Performance of 10 s SGRE windfarm IR with various locations (conservative profile)

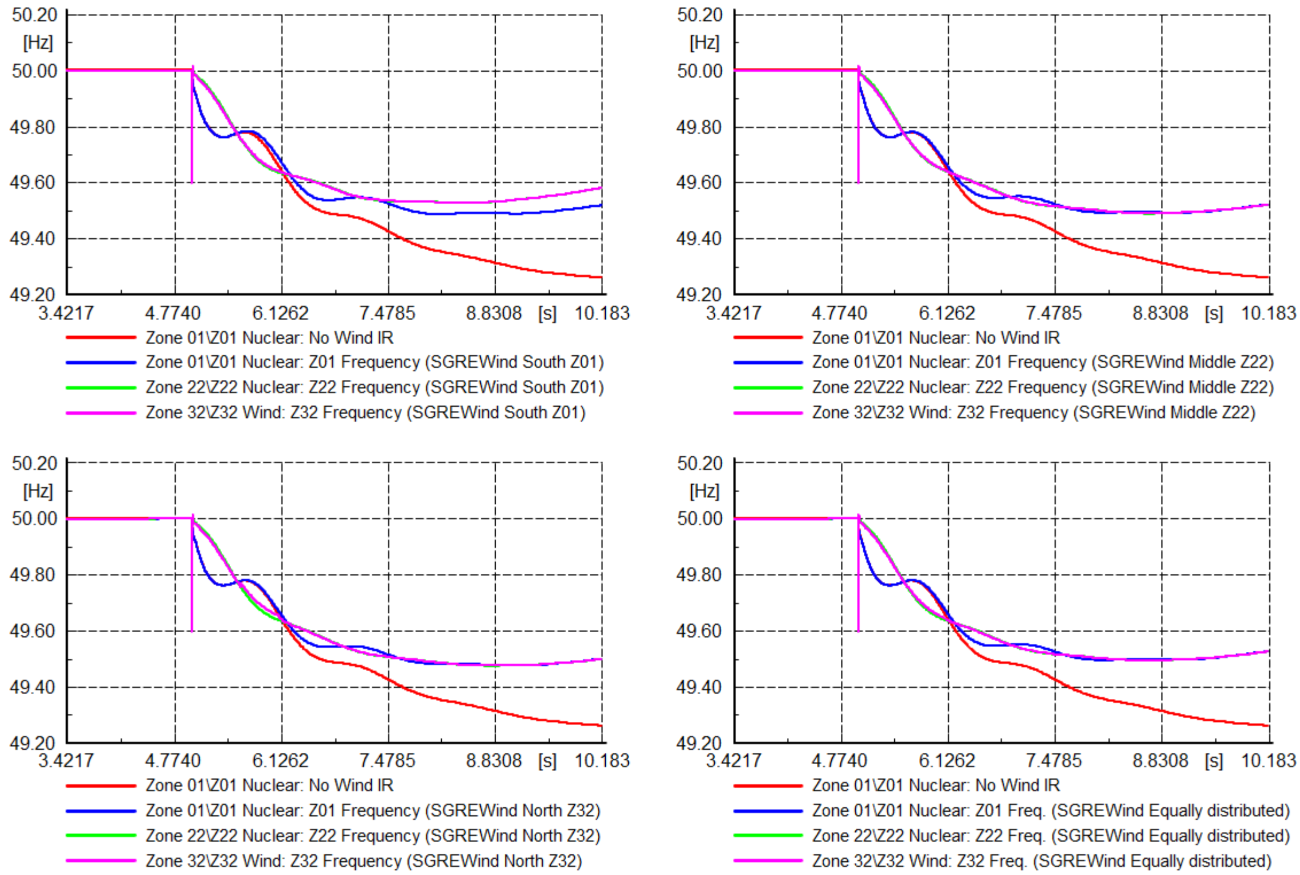


Figure 4-13. Frequency measured at different parts of the system when SGRE wind IR is located at South (Zone 01), Middle (Zone 22), North (Zone 32) and equally distributed (10 s conservative profile for IR with 20-30% loading level and 2GVA rating)

4.2 IR study using data of 5 s duration IR with slow ramping (SR)-down rate

4.2.1 Impact of IR's activation time

The impact of IR's activation time has also been studied for 5 s duration windfarm IR profiles. Similar to what have been found for the 10 s profiles as reported in Section 4.1.2, the activation time of SGRE windfarm IR with a range of 500 ms to 1000 ms does not appear to have significant impact on effectiveness on supporting frequency control. Figure 4-14 show the performance of SGRE windfarm with 5 s conservative profiles with the activation delay of wind IR varying from 500 ms to 1000 ms. Results for the mean profiles are presented in Appendix A7.4 and the governor responses from the operating synchronous generators are attached in Appendix B.

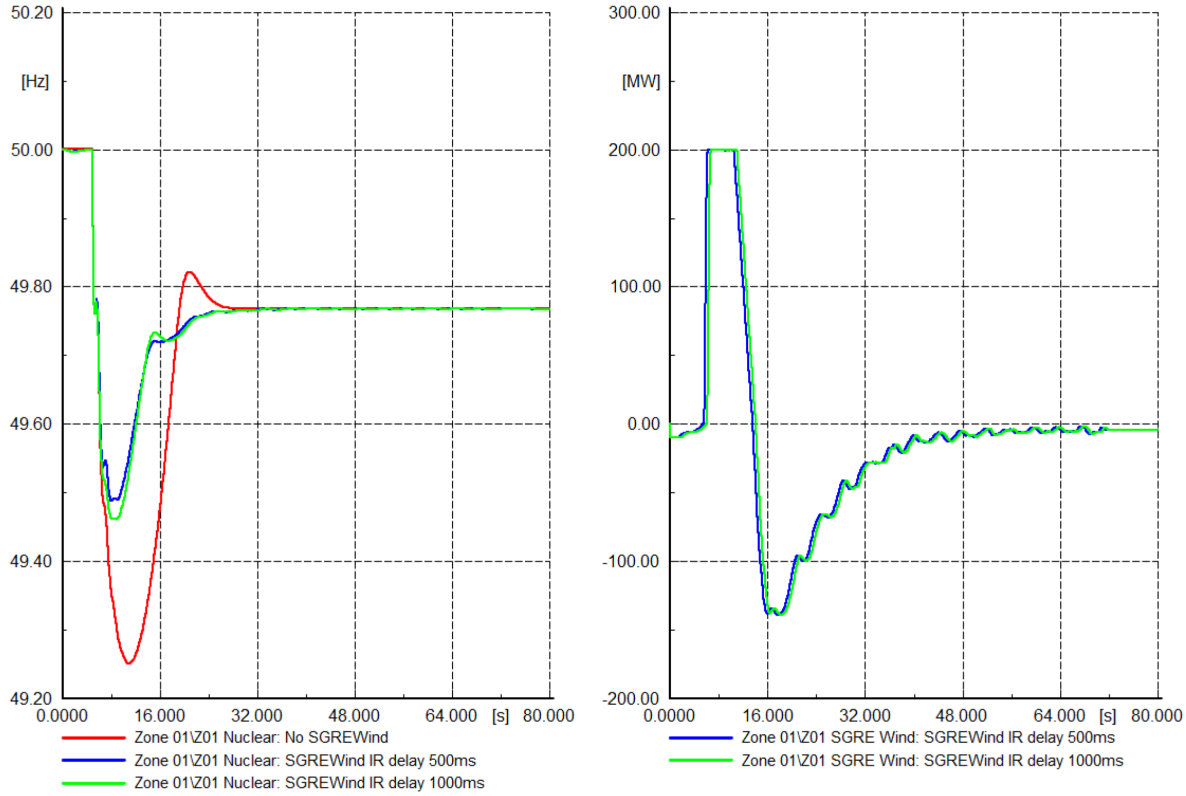


Figure 4-14. Performance of 5 s with SR SGRE windfarm IR with various activation time (conservative profile, 20-30% loading)

4.2.2 Impact of the capacity of the windfarms providing IR

This section presents the studies for investigating IR effectiveness on frequency control with different capacities and loading levels using 5 s duration and slow-ramping down power characteristic. The simulation results for 5 s SR conservative profiles are shown from Figure 4-15 to Figure 4-22 for loading level from 20% to 100%. Results with mean profiles used for the windfarms' IR are shown in Appendix A7.6. All the loading levels from 20-100% are explored with both conservative and mean profiles. And the governor responses from the operating synchronous generators are attached in Appendix B.

It can be seen that, with higher loading levels of the windfarms, the first frequency drop can be significantly improved with IR contribution from SGRE windfarms but the second frequency drop tends to become larger. Such impact becomes more significant with an increased capacity of SGRE windfarm due to higher power drop after IR. However, the slow ramping-down of the power and the less power drop after IR compared with the 10 s profiles lead to much less severe second frequency drops under the same condition. Therefore, this shows significant advantages for applying the power slow-ramp down characteristic after delivering the IR from windfarms.

Table 4-5 gives the size and time of frequency drops for the test cases with conservative profiles. Again, the various occurring time for the frequency dips should be considered while coordinating other resources to support frequency response.

Table 4-6 summarises the results on suitable capacity levels of SGRE windfarm in the network with the aim to ensure both first and the second frequency nadir meet the frequency limit of 49.5 Hz. It can be seen that compared with the results for the 10 s profiles shown in Table 4-4, the capability of SGRE windfarm to assist system frequency response by contributing IR is largely increased with the possibility to achieve satisfying frequency response for all the loading levels of SGRE windfarm. As mentioned previously, allowing more capacity of windfarm providing IR can effectively facilitate the containment of the first frequency nadir. However, due to the power drop after the IR, there is a constraint in further increasing the capacity of wind IR with the 10 s duration profiles. From this studies, it can be seen that the slow-ramp down characteristic after the IR allows a higher capacity of windfarm to provide IR (thus enhancing the first frequency nadir control), while being able to ensure the power drop after the IR will not be too severe to cause the second frequency dip to violate the 49.5 Hz limit.

From the studies, it was found that, to maintain the first frequency drop above 49.5 Hz, SGRE windfarms should output more than 200 MW during IR, i.e. the capacity should be greater than 2 GVA; and the maximum capacity of the windfarms is around 3~5 GVA (depending on the loading level - detail available in Table 4-6) to ensure a satisfactory second frequency nadir. It should be noted that in general, with the increase in loading level, the power drop after the IR will be larger, thus a more severe second frequency dip. However, the cases with 80-100% loading show a greater improvement in terms of the second frequency drop due to a reduced power drop after IR, which, as suggested by SGRE is associated with the specific operating characteristics of the turbines. This is out of the scope of these studies.

Table 4-5. Size and time of the frequency drops with wind MVA ratings for 5 s profiles with conservative profiles

Case study		First frequency drop		Second frequency drop	
		Min. frequency (Hz)	Time of dip (s)	Min. frequency (Hz)	Time of dip (s)
No SGRE wind IR		49.25	10.93	-	-
20-30% loading	2 GVA	49.49	8.04	49.72	15.77
	3 GVA	49.55	7.81	49.66	16.74
	4 GVA	49.58	6.62	49.56	18.63
	4.5 GVA	49.59	6.60	49.49	19.32
	5 GVA	49.60	6.60	49.41	19.79
30-40% loading	2 GVA	49.49	8.04	49.71	16.75
	3 GVA	49.55	7.92	49.65	17.38
	4 GVA	49.58	6.62	49.52	19.11
	5 GVA	49.60	6.56	49.35	20.10
40-50% loading	2 GVA	49.49	8.04	49.70	17.00
	2.5 GVA	49.52	7.93	49.67	16.93
	3 GVA	49.55	7.87	49.61	18.53
	3.5 GVA	49.57	6.68	49.52	19.36
	4 GVA	49.58	6.6	49.42	19.95
50-60% loading	2 GVA	49.49	8.02	49.69	17.32

	2.5 GVA	49.49	8.04	49.69	17.06
	3 GVA	49.56	7.92	49.49	20.36
	4 GVA	49.59	6.60	49.18	21.95
60-70% loading	2 GVA	49.49	8.04	49.67	18.47
	2.5 GVA	49.52	7.98	49.58	20.64
	3 GVA	49.55	7.92	49.41	22.28
70-80% loading	2 GVA	49.47	9.08	49.66	19.17
	2.5 GVA	49.51	7.93	49.53	21.42
	3 GVA	49.53	7.93	49.33	22.90
80-90% loading	2 GVA	49.44	9.20	49.68	20.22
	2.5 GVA	49.47	8.98	49.59	22.00
	3 GVA	49.49	7.99	49.37	24.07
90-100% loading	2 GVA	49.41	9.40	49.73	20.26
	3 GVA	49.47	9.20	49.68	19.47
	4 GVA	49.51	7.98	49.57	21.27
	4.5 GVA	49.53	7.92	49.48	22.22
	5 GVA	49.55	7.92	49.37	23.02

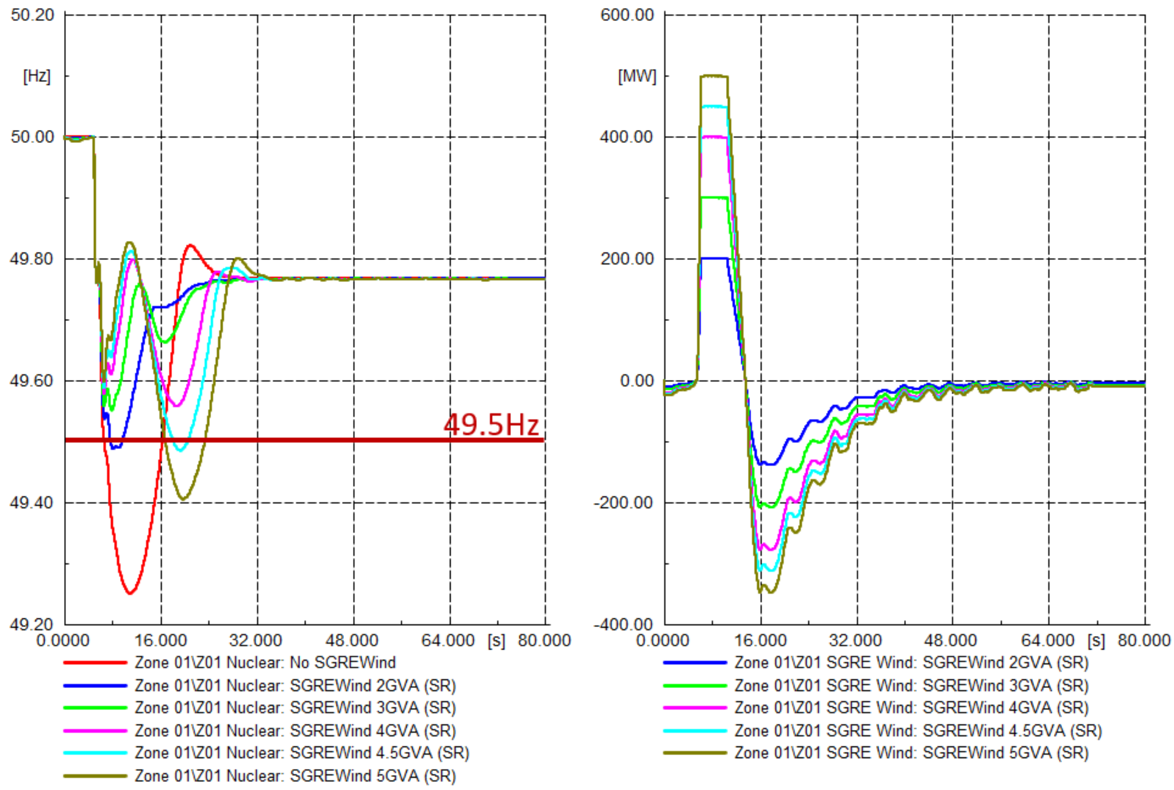


Figure 4-15. Performance of 5 s with SR SGRE windfarm IR with various capacity levels (with 20%-30% of rated power and conservative profile)

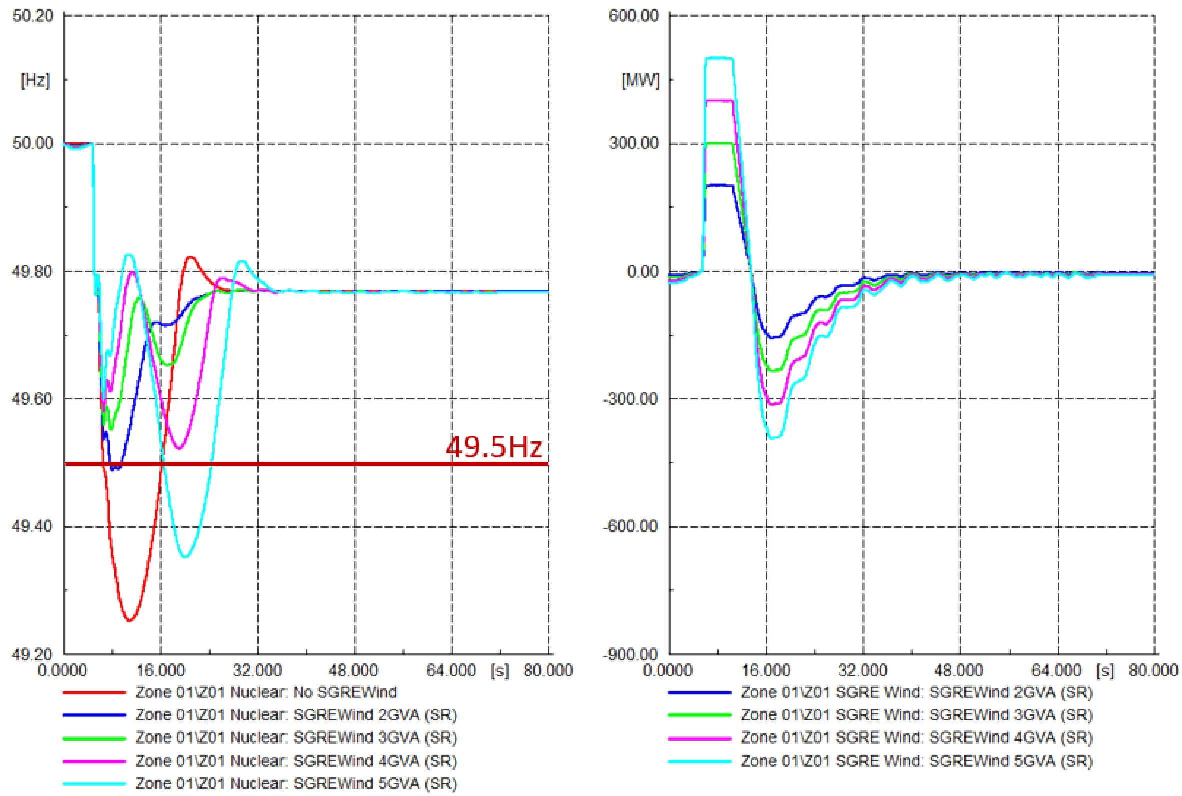


Figure 4-16. Performance of 5 s with SR SGRE windfarm IR with various capacity levels (with 30%-40% of rated power and conservative profile)

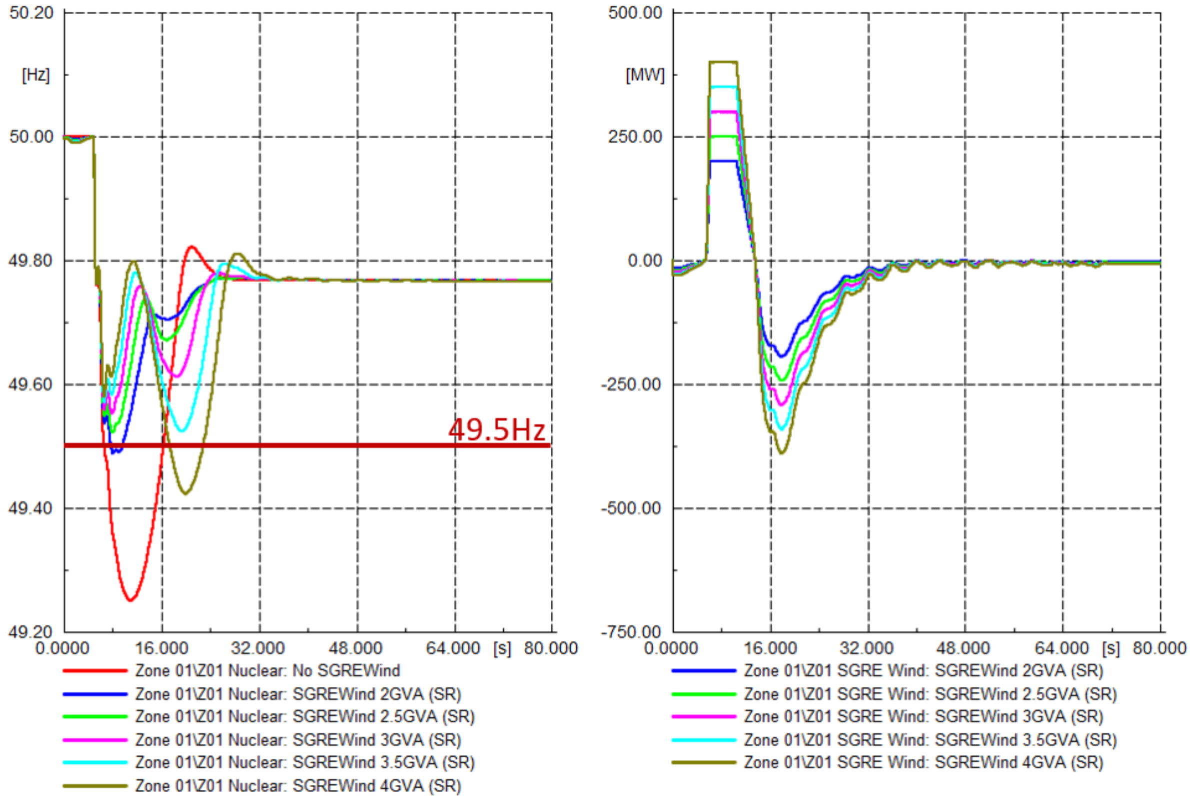


Figure 4-17. Performance of 5 s with SR SGRE windfarm IR with various capacity levels (with 40%-50% of rated power and conservative profile)

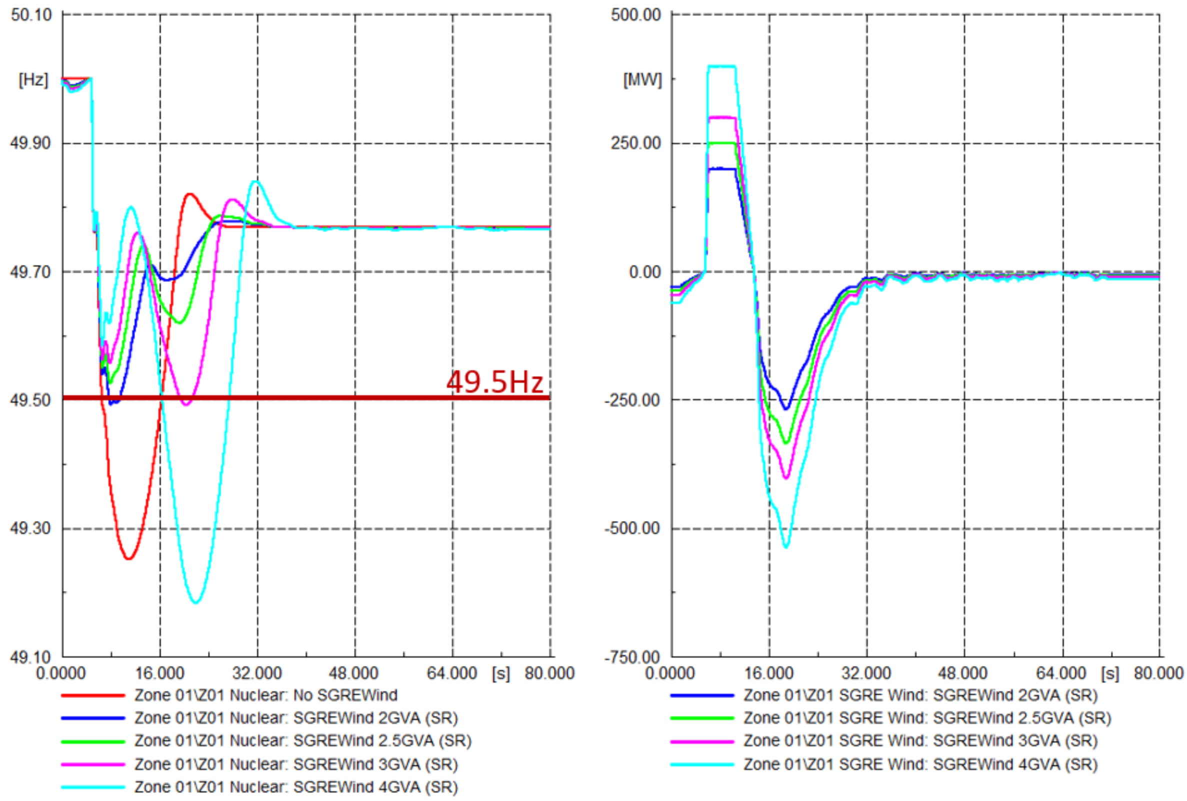


Figure 4-18. Performance of 5 s with SR SGRE windfarm IR with various capacity levels (with 50%-60% of rated power and conservative profile)

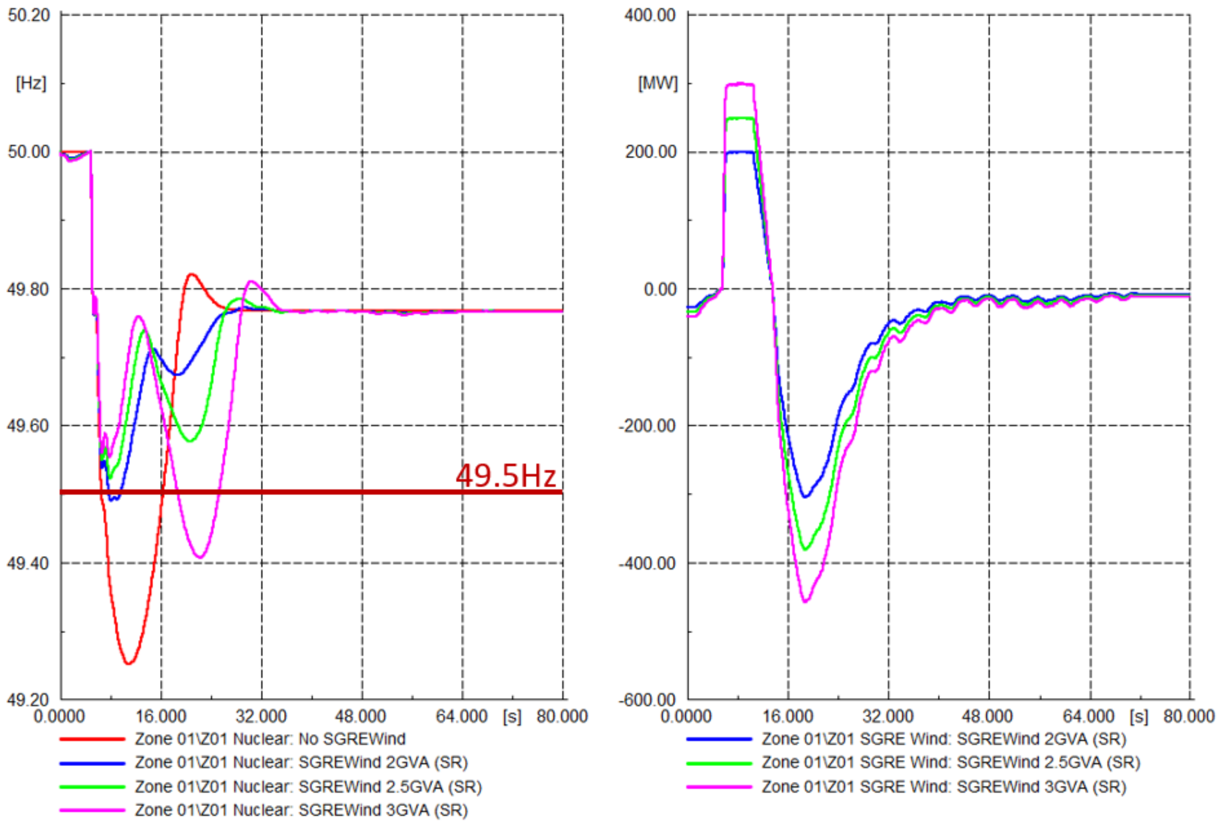


Figure 4-19. Performance of 5 s with SR SGRE windfarm IR with various capacity levels (with 60%-70% of rated power and conservative profile)

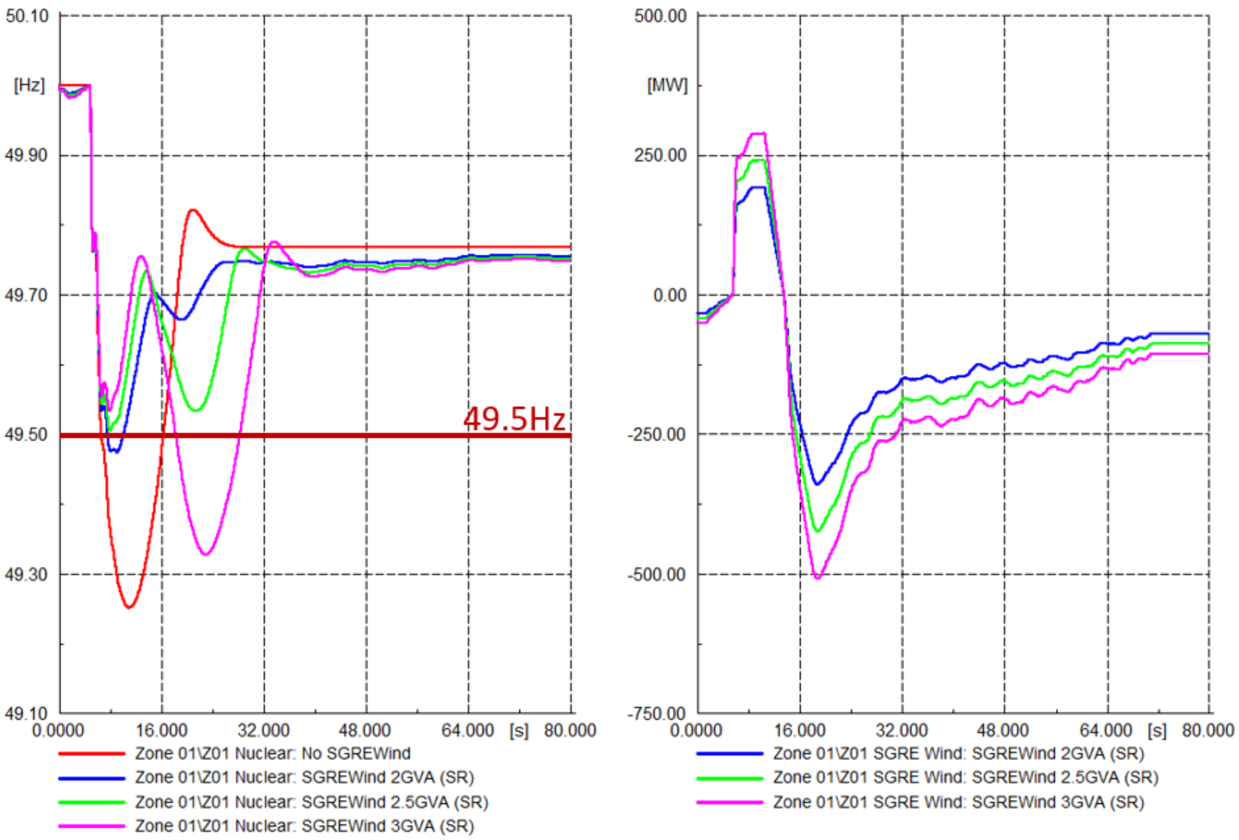


Figure 4-20. Performance of 5 s with SR SGRE windfarm IR with various capacity levels (with 70%-80% of rated power and conservative profile)

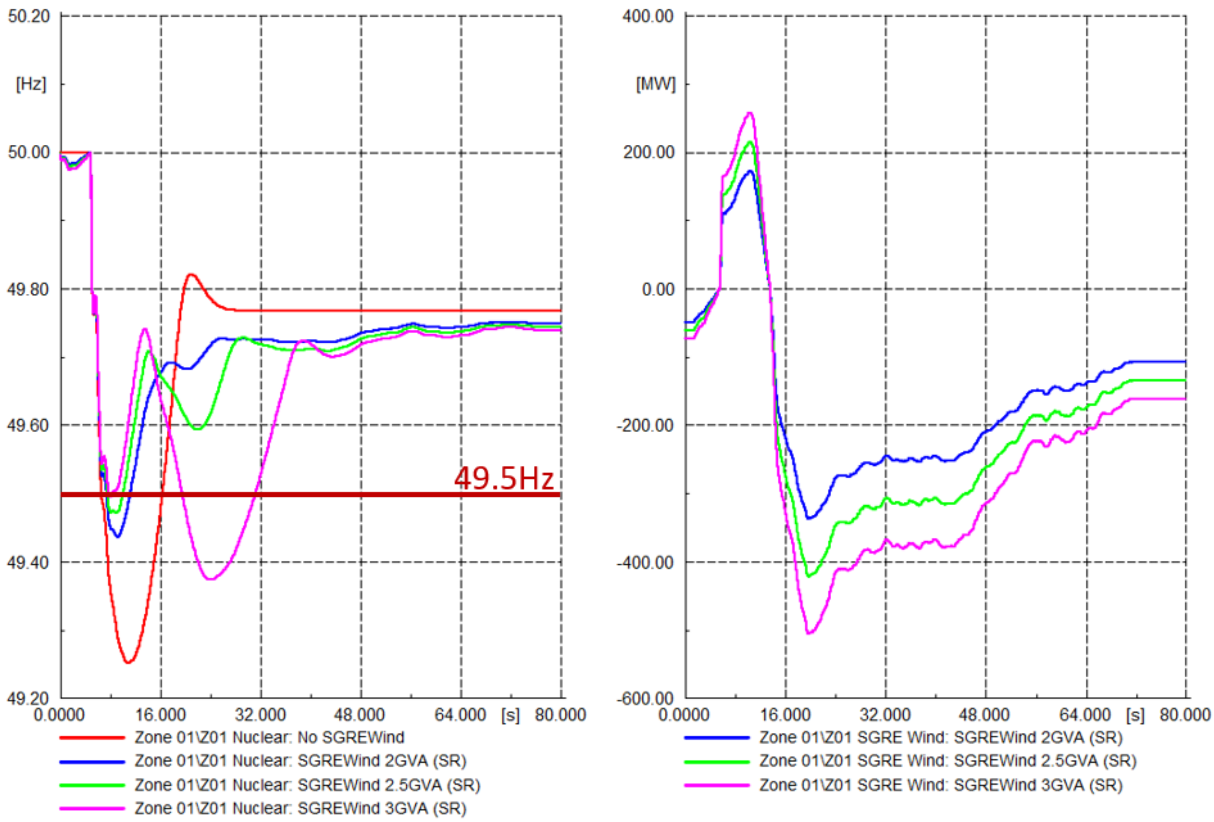


Figure 4-21. Performance of 5 s with SR SGRE windfarm IR with various capacity levels (with 80%-90% of rated power and conservative profile)

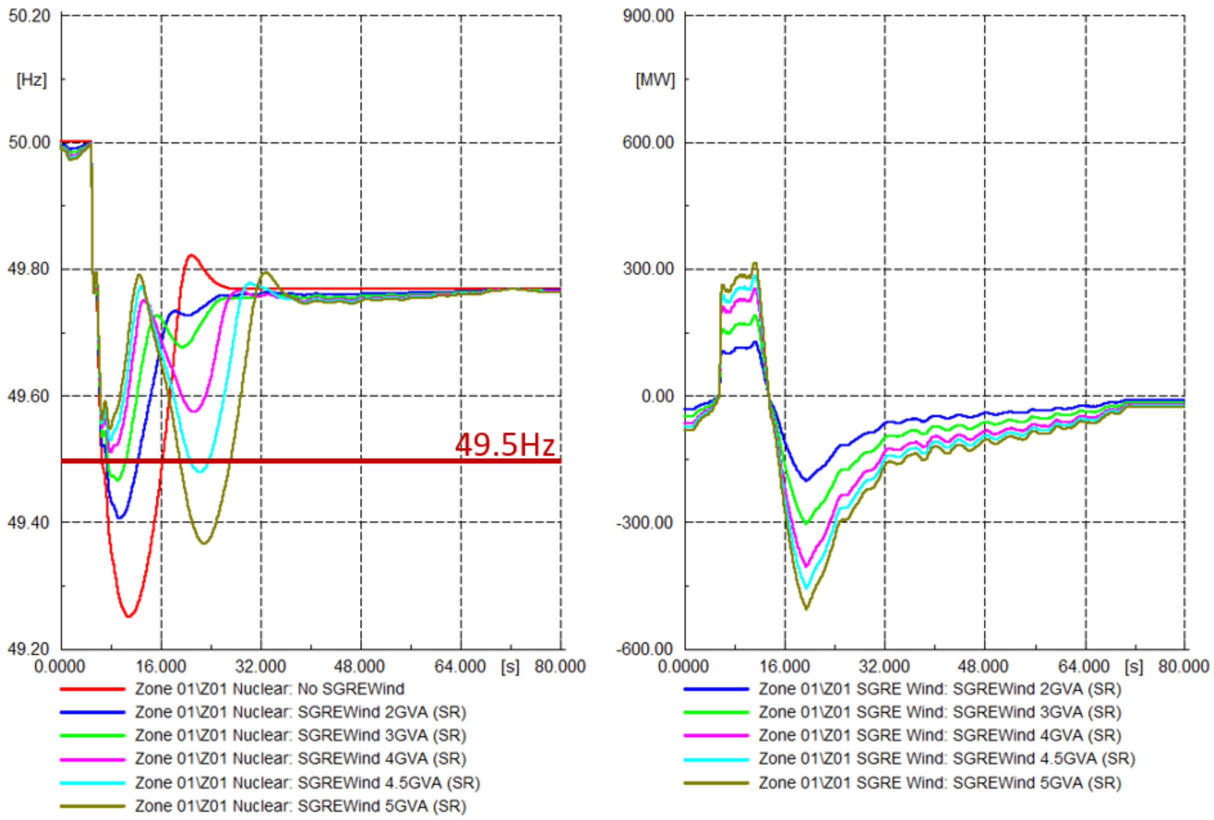


Figure 4-22. Performance of 5 s with SR SGRE windfarm IR with various capacity levels (with 90%-100% of rated power and conservative profile)

Table 4-6. Capability of 5 s with SR SGRE windfarm IR to fulfil frequency limitation with various loading of rated power

Loading (%) of rated power	Data type	Capability to achieve satisfying frequency response?	Best case	Power required from SGRE windfarm IR	
				First drop ⩾ 49.5 Hz	Second drop ⩾ 49.5 Hz
20%-30%	Conservative	Yes	4 GVA	>2 GVA	<4.5 GVA
	Mean	Yes	4.5 GVA	>2 GVA	<5 GVA
30%-40%	Conservative	Yes	4 GVA	>2 GVA	<4.5 GVA
	Mean	Yes	4 GVA	>2 GVA	<4.5 GVA
40%-50%	Conservative	Yes	3.5 GVA	>2 GVA	<4 GVA
	Mean	Yes	4 GVA	>2 GVA	<4.5 GVA
50%-60%	Conservative	Yes	2.5 GVA	>2 GVA	<3 GVA
	Mean	Yes	3.5 GVA	>2 GVA	<3.5 GVA
60%-70%	Conservative	Yes	2.5 GVA	>2 GVA	<3 GVA
	Mean	Yes	3 GVA	>2 GVA	<3.5 GVA
70%-80%	Conservative	Yes	2.5 GVA	>2 GVA	<3 GVA
	Mean	Yes	3 GVA	>2 GVA	<3.5 GVA
80%-90%	Conservative	Yes	2.5 GVA	>2.5 GVA	<3 GVA
	Mean	Yes	3.5 GVA	>2 GVA	<4 GVA
90%-100%	Conservative	Yes	4 GVA	>2.5 GVA	<4.5 GVA
	Mean	Yes	9 GVA	>2 GVA	<9.5 GVA

4.2.3 Impact of the locations of windfarms providing the IR

This section presents the simulation results for investigating the locational impact of the IR on frequency control using 5 s windfarm IR profiles. In the studies, SGRE windfarms were located in the following locations, South (Zone 01), Middle (Zone 22), North (Zone 32) and equally distributed across the system (all 36 zones). Figure 4-23 shows the simulation results using IR conservative profiles with a total capacity of the windfarm(s) providing IR being 2 GVA and a loading level of 20-30%. Frequency is measured at South (Zone 01). The simulation results using IR mean profiles are presented in Appendix A7.7. The governor responses from the operating synchronous generators are attached in Appendix B.

Similar to the results for 10 s profiles as presented in Section 4.1.4, the location of IR in the network does not appear to have significant impact on the frequency nadir during the simulated frequency disturbances with the 5 s profiles. The case with the SGRE windfarm located in the North (Zone 32) and the frequency event occurred in Zone 01 has relatively more obvious difference in frequency nadirs compared to other cases due to the remote IR contribution from the event location.

Frequency profiles at different parts of the network when SGRE wind IR locates in South (Zone 01), Middle (Zone 22), North (Zone 32), and equally distributed across the system are shown in Figure 4-24. However, from the results, it can be seen that the locations of SGRE windfarm IR do not appear to have significant effects on system nadir and the level of inter-oscillation when placing the windfarm in different locations does not appear to cause system stability issues.

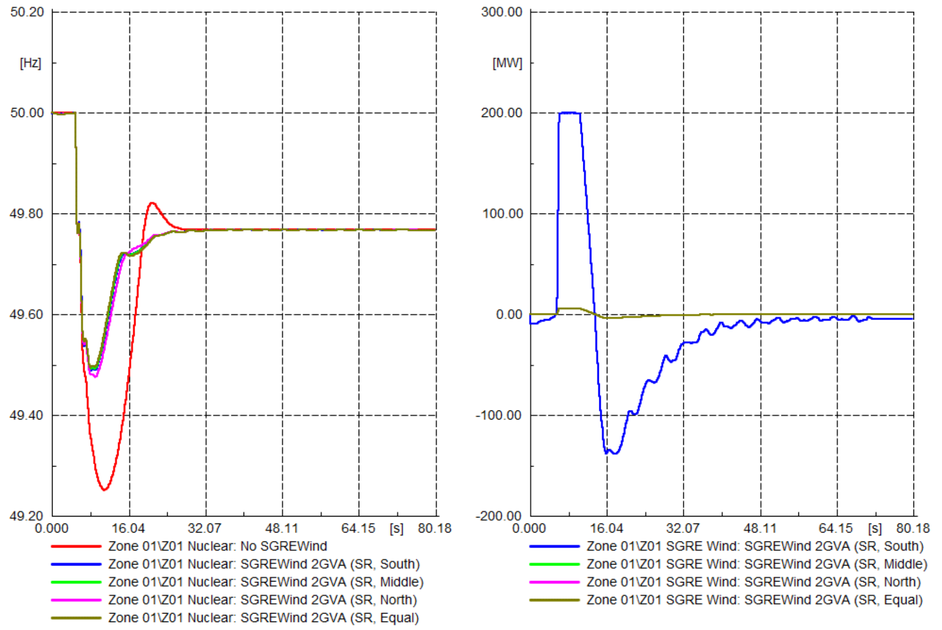


Figure 4-23. Performance of 5 s with SR SGRE windfarm IR with various location (conservative profile)

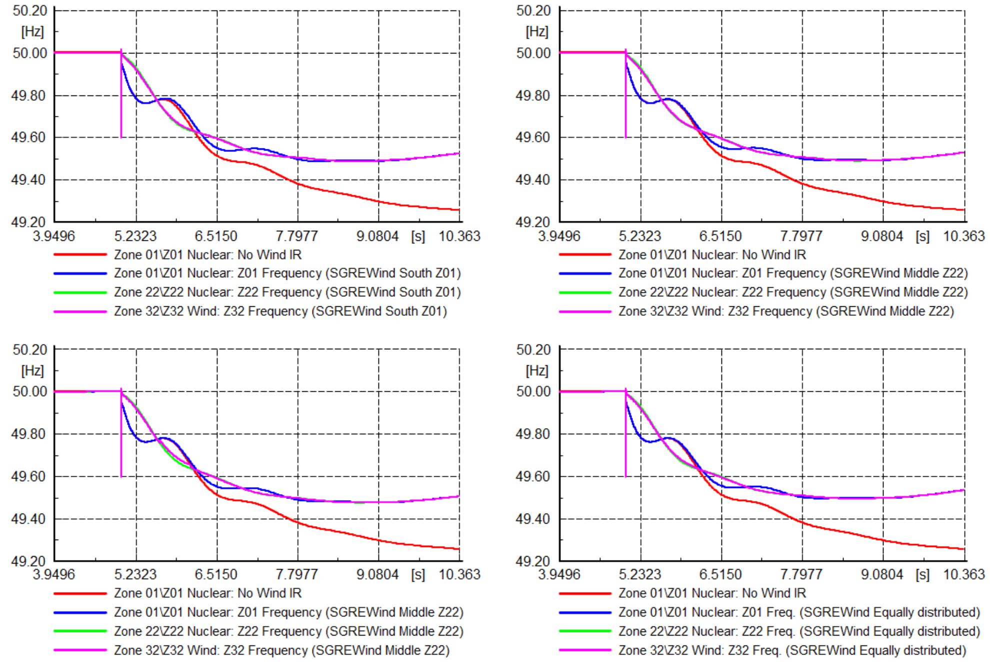


Figure 4-24. Frequency measured at different parts of the system when SGRE wind IR is located at South (Zone 01), Middle (Zone 22), North (Zone 32) and equally distributed (5 s conservative profile for IR with 20-30% loading level and 2GVA rating)

4.3 Investigation of windfarm IR with different profiles

4.3.1 Comparison of 10 s and 5 s profiles

Compared with the 10 s wind IR profiles, the 5 s duration IR has a shorter response duration but it gradually ramps down the power during the wind turbine recovery period after the IR.

Figure 4-25 gives presents the simulation results using the 10 s and 5 s profiles with conservative data while the SGRE wind is rated at 2 GVA with 20-30% loading. During the initial 5 s of power ramp-up period, both profiles have almost the same power output and therefore the initial frequency drop. The first frequency nadirs after the event are similar. However, the IR with 5 s duration and SR characteristic retrieves a smaller amount of power with a slower rate. As a result, the frequency drop during the recovery period was largely mitigated. While the 10 s profile has a longer duration in outputting the 200 MW IR power, the sharp drop in output power, from 200 MW (injecting power to the grid) to approximately -250 MW (consuming power from the grid), introduced a severe second frequency drop. It can be concluded that the 5 s profile with SR characteristic gives additional room for the wind IR to assist system frequency response whereas reduce the negative effect introduced by the power drop from windfarms after IR. Table 4-7 gives the size and time of frequency drops for the 10 s and 5 s conservative profiles at different loading levels with the capacity of the windfarm being 2 GVA.

Results for higher loading levels of the SGRE windfarm are similar and also indicate benefits of 5 s SR profiles for IR over the 10 s profiles. Figures from Figure 4-26 to Figure 4-32 show comparisons of 10 s and 5 s profiles with loading levels of 30-100% (conservative profiles). Results with the mean profiles applied for windfarms' IR are presented in Appendix A7.8.

While for the loading levels between 20-80%, higher loading levels generally introduce larger power drop after the IR and therefore larger second frequency drop, for the load level of 80-100% as shown in Figure 4-31 and Figure 4-32, the power drop is smaller. It was suggested by SGRE that this is dependent on the specific operating point on the power curve for the windfarm.

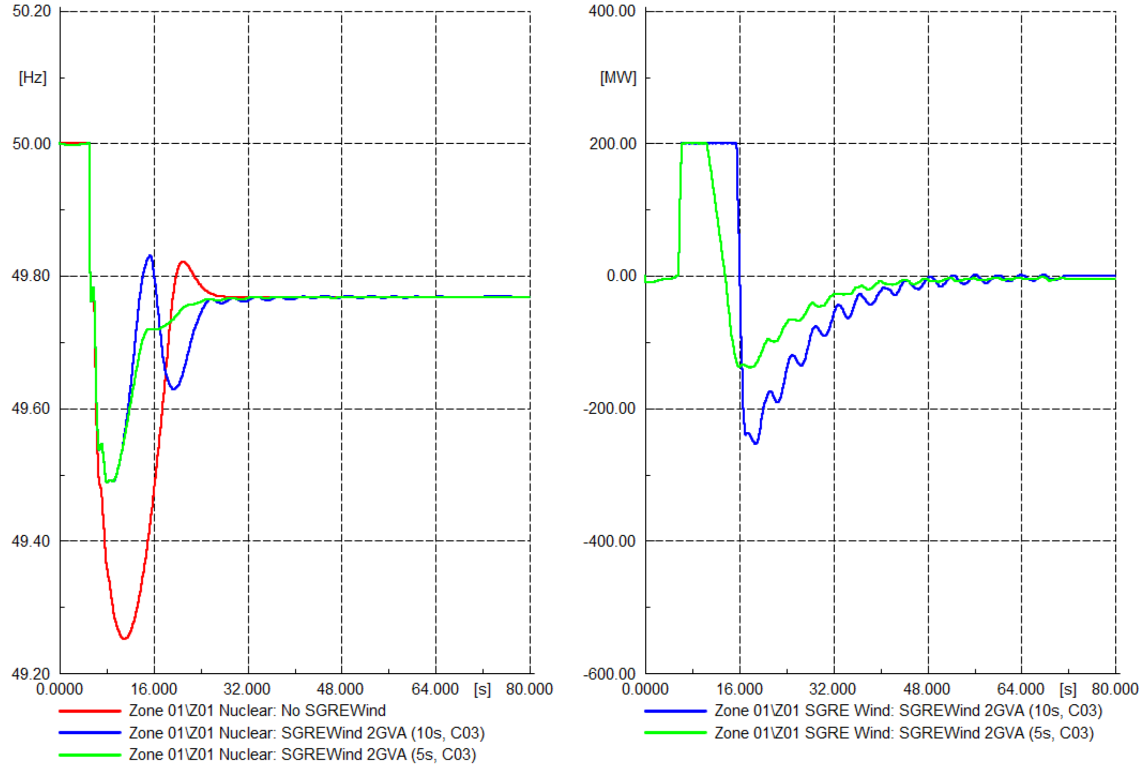


Figure 4-25. Comparison of 10 s and 5 s SGRE windfarm profiles (conservative profile and 20-30% loading)

Table 4-7. Size and time of the frequency drops with 10 s and 5 s conservative profiles

Case study (conservative profiles only)		First frequency drop		Second frequency drop	
		Min. frequency (Hz)	Time of dip (s)	Min. frequency (Hz)	Time of dip (s)
20-30% loading	10 s profile	49.49	8.04	49.64	19.16
	5 s profile	49.49	8.04	49.72	15.77
30-40% loading	10 s profile	49.49	8.04	49.61	19.70
	5 s profile	49.49	8.04	49.71	16.75
40-50% loading	10 s profile	49.49	8.04	49.56	20.25
	5 s profile	49.49	8.04	49.70	17.00
50-60% loading	10 s profile	49.49	8.04	49.44	21.39
	5 s profile	49.49	8.04	49.69	17.06
60-70% loading	10 s profile	49.49	8.04	49.41	21.71
	5 s profile	49.49	8.04	49.67	18.47

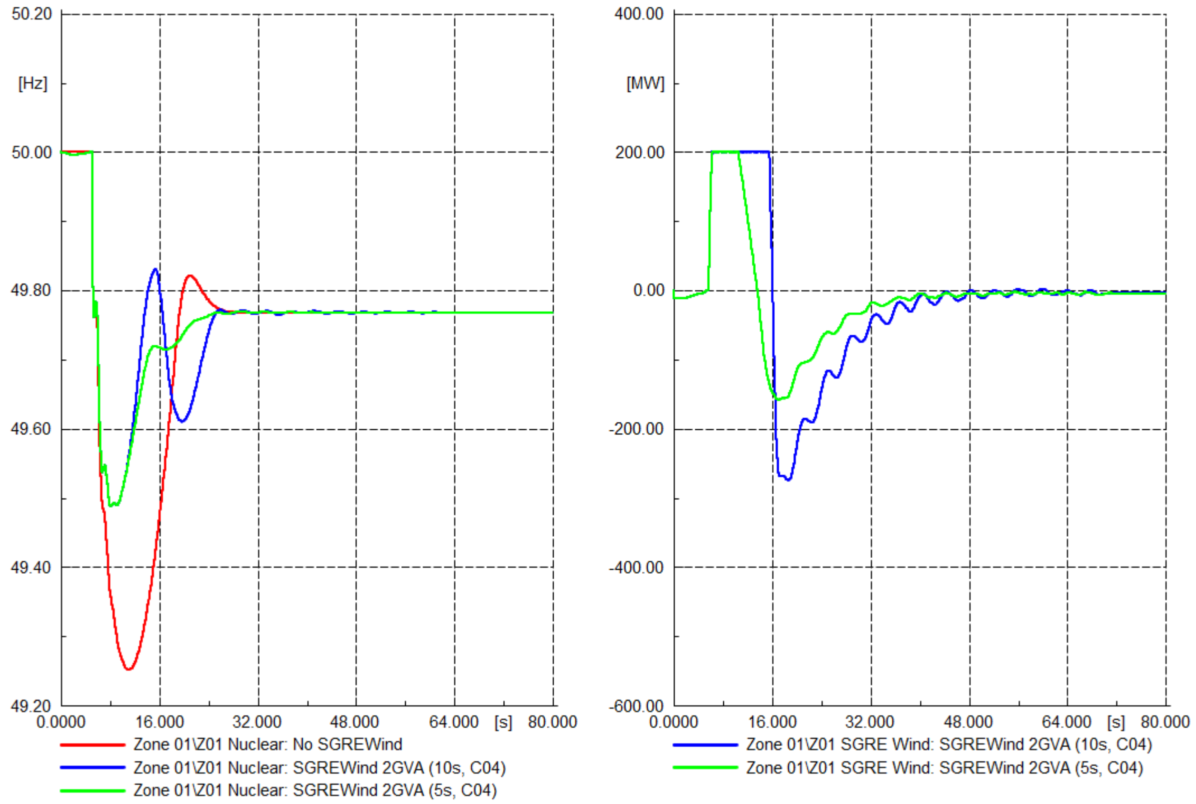


Figure 4-26. Comparison of 10 s and 5 s SGRE windfarm profiles (conservative profile and 30-40% loading)

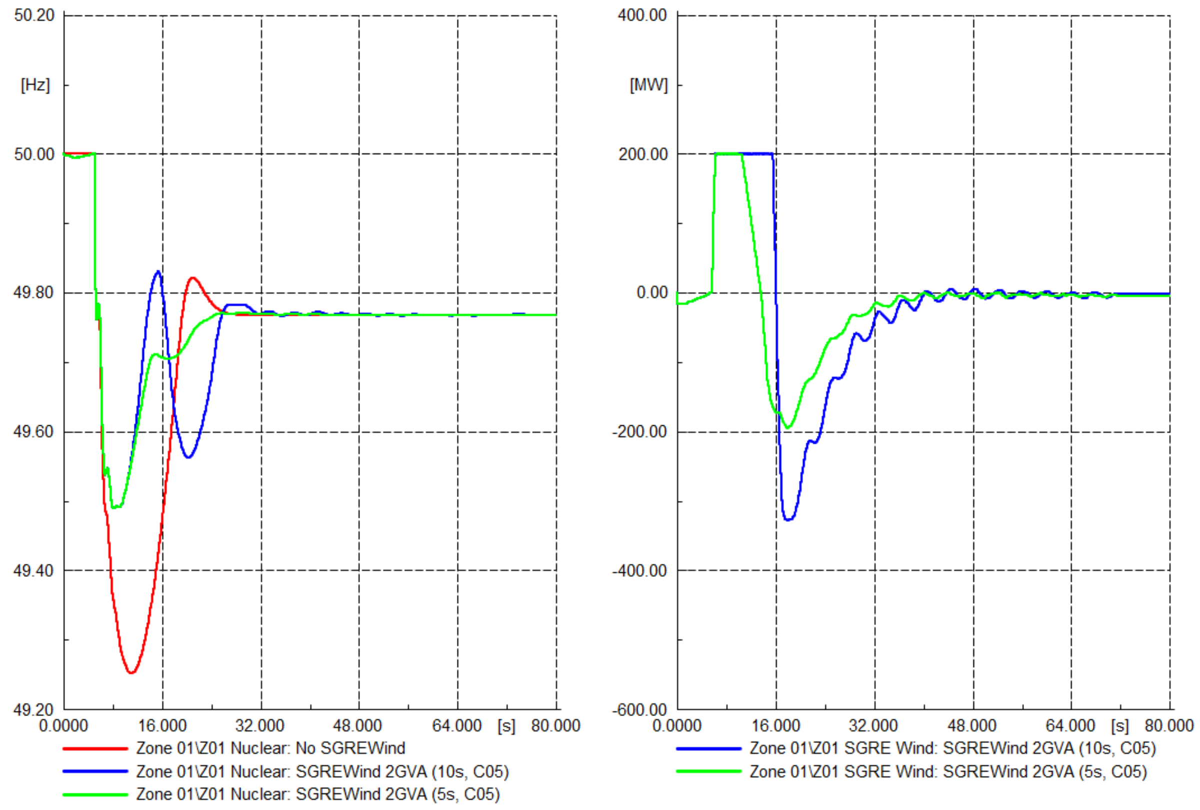


Figure 4-27. Comparison of 10 s and 5 s SGRE windfarm profiles (conservative profile and 40-50% loading)

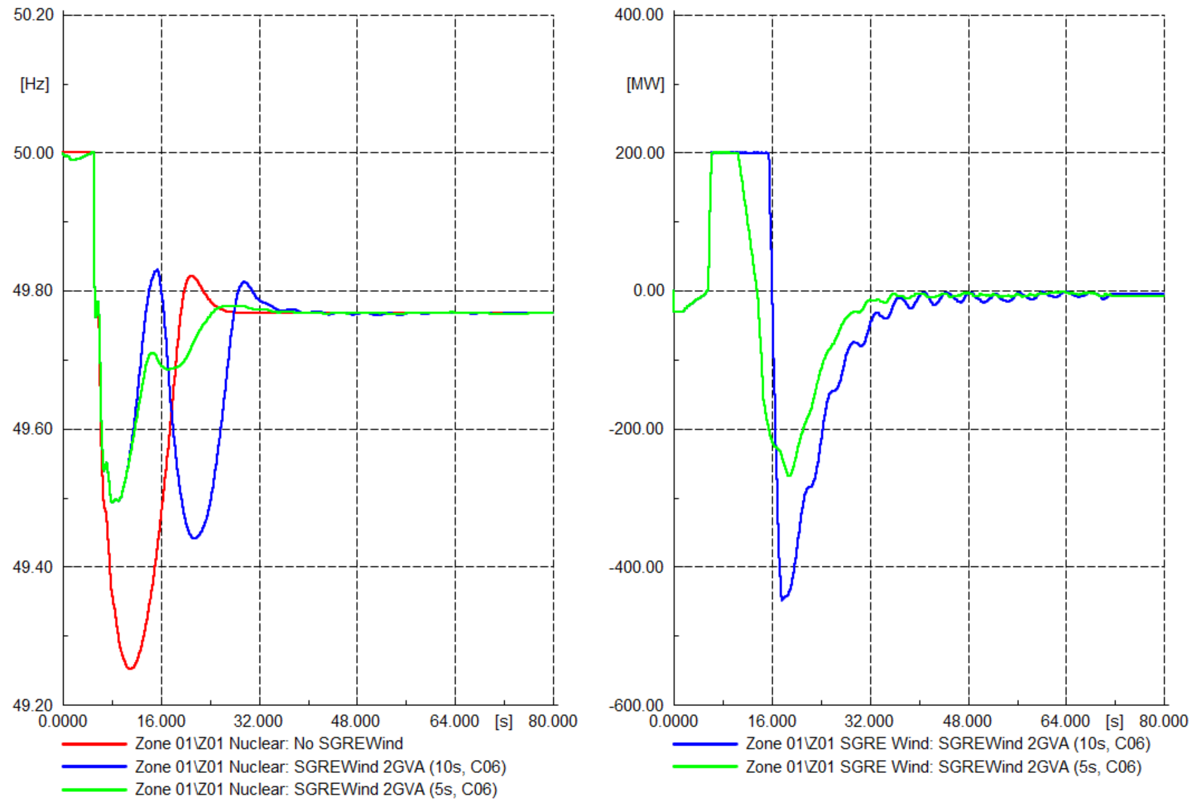


Figure 4-28. Comparison of 10 s and 5 s SGRE windfarm profiles (conservative profile and 50-60% loading)

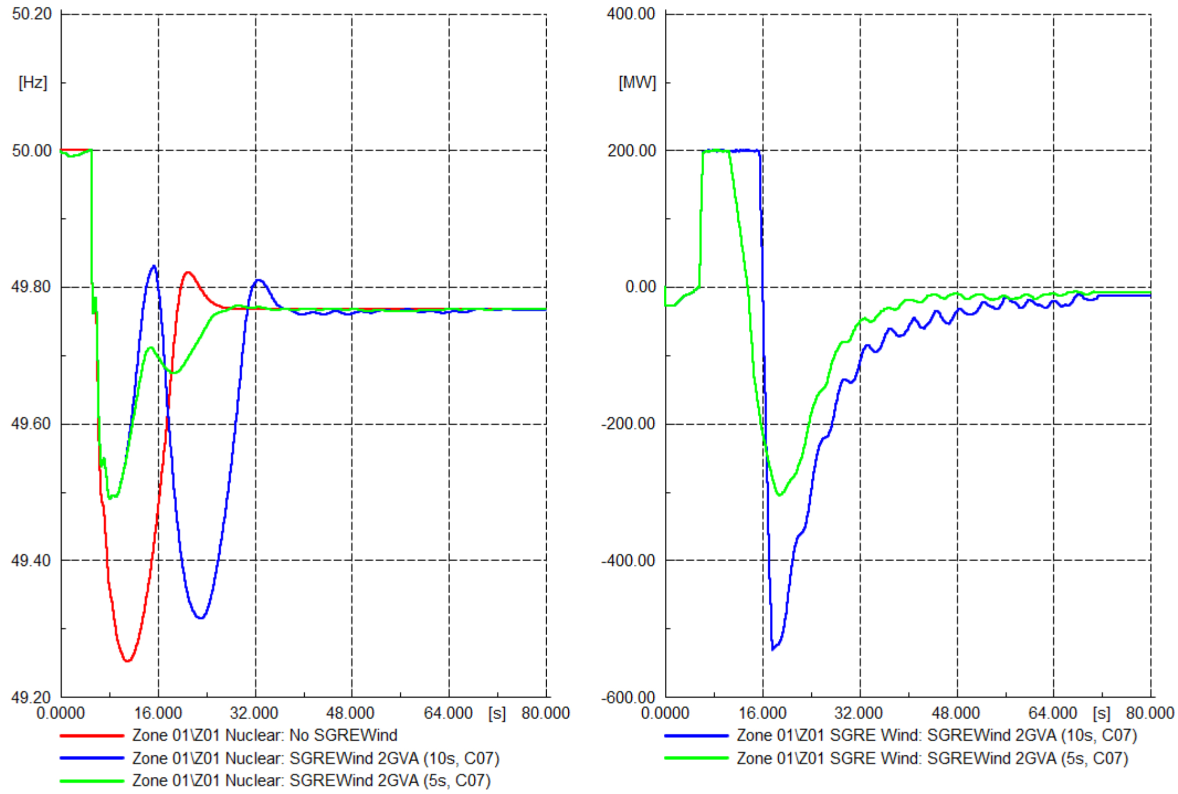


Figure 4-29. Comparison of 10 s and 5 s SGRE windfarm profiles (conservative profile and 60-70% loading)

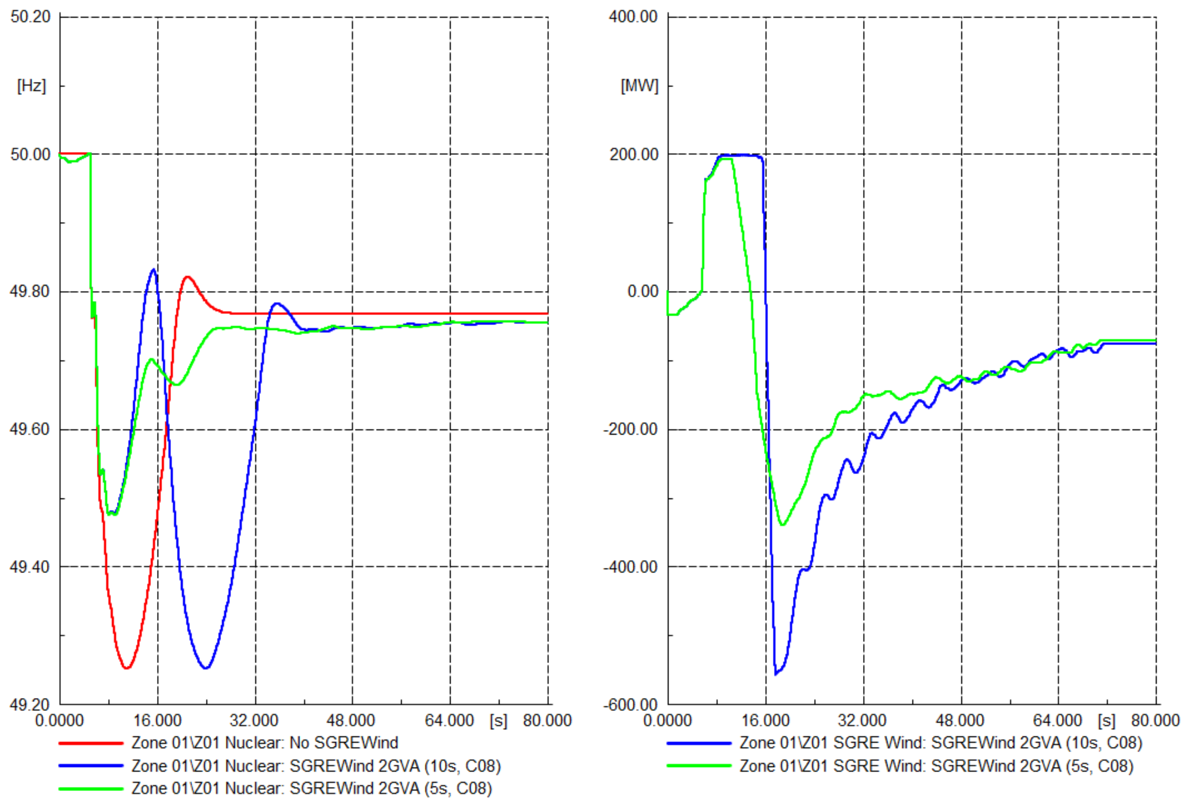


Figure 4-30. Comparison of 10 s and 5 s SGRE windfarm profiles (conservative profile and 70-80% loading)

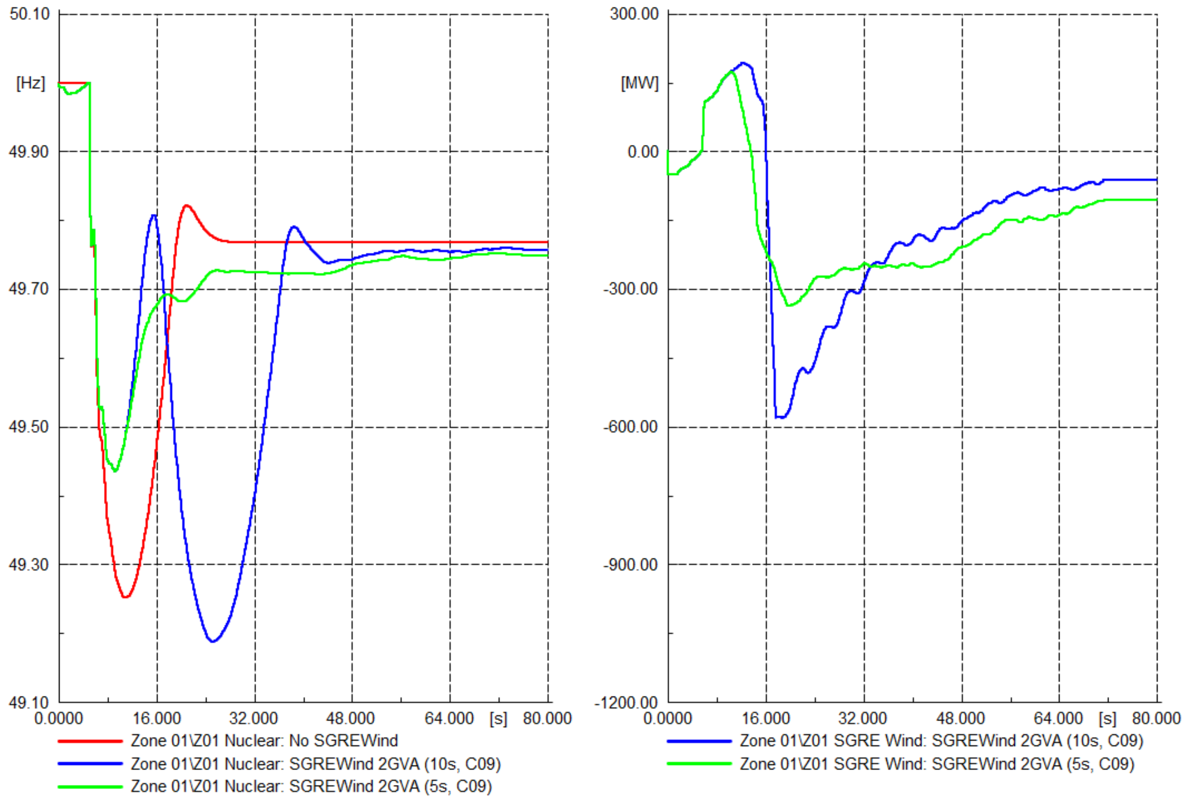


Figure 4-31. Comparison of 10 s and 5 s SGRE windfarm profiles (conservative profile and 80-90% loading)

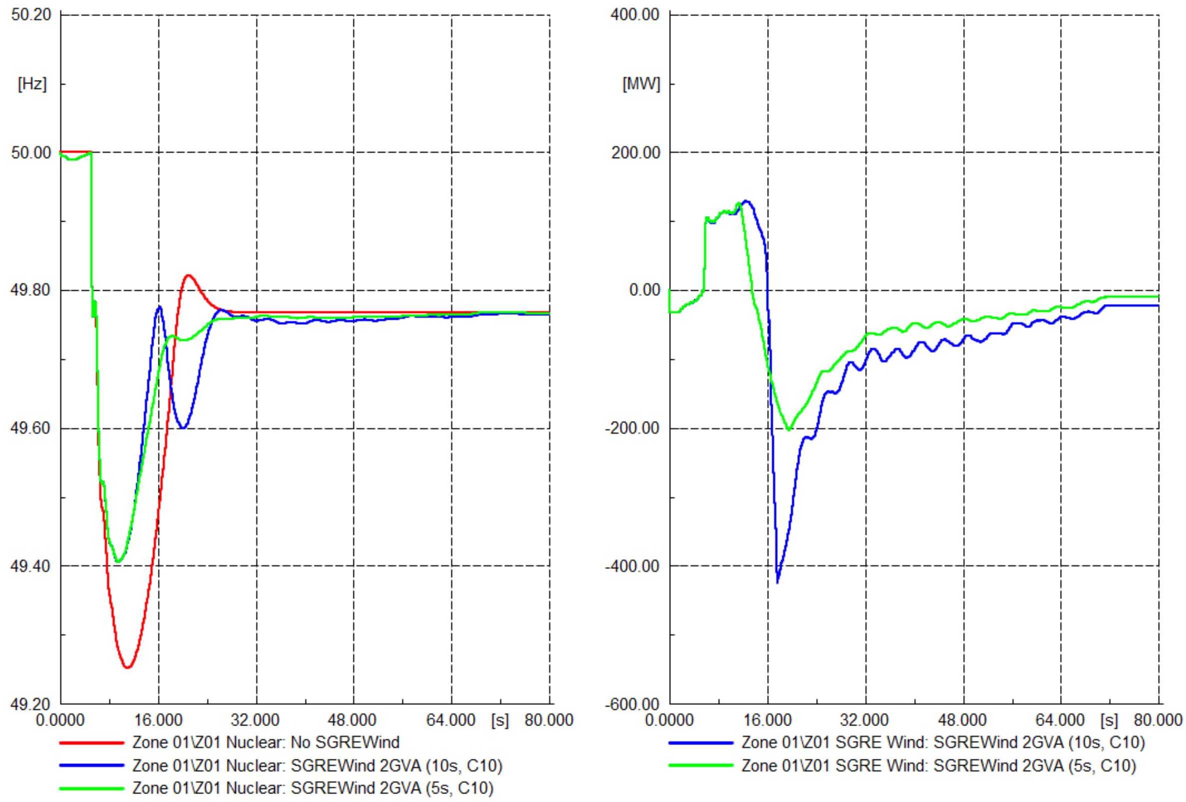


Figure 4-32. Comparison of 10 s and 5 s SGRE windfarm profiles (conservative profile and 90-100% loading)

4.3.2 Mix of windfarms with 10 s and 5 s profiles

From the perspective of the system operator, it is important to consider the coordination of various resources available in order to obtain most satisfactory frequency response. In this section, the performance of a mix of windfarms with 10 s and 5 s profiles providing IR is explored and compared with the ones that only have one type of profile (i.e. 10 s duration or 5 s duration).

In Zone 01 of the 36-bus system model, two SGRE wind static generators are connected, while one of them is configured to export power based on 10 s profile and the other one employs the 5 s profile. Both 10 s and 5 s profiles are conservative profiles with a loading level of 20-30%. The two wind static generators are configured with the same rating, e.g. for a total 2 GVA of windfarm capacity in the network, each of the static generators is rated at 1 GVA. The performance with conservative profiles is shown in Figure 4-33 while that with the mean profiles is included in the Appendix A7.8.

Compared with the case with only10 s profiles (red line) and only with 5 s profiles (blue line), the performance of the combination of 10 s and 5 s profiles (green line) sits in the Middle of the former cases. Compared with the 10 s profile, it has similar first frequency drop and frequency nadir as the initial power output is almost the same, while the frequency overshoot and second frequency drop is less due to the contribution from the 5 s profile. The maximum rating of SGRE windfarm with such mixture of 10 s and 5 s profiles in order to ensure both first and second frequency nadir to be above 49.5 Hz is in the range of 3-4 GVA for this case.

In conclusion, it is most beneficial and desirable to have IR from windfarms with the 5 s SR characteristic, while a combination of 10 s and 5 s SR profiles, and all response from 10 s profile can still provide a level of improvement to the frequency control effectiveness. From the perspective of system operators, it is important to effectively coordinate various resources with different characteristics in order to obtain desirable frequency control performance, where novel frequency control scheme with wide monitoring and control capability such as EFCC could play a key role in enabling such coordination.

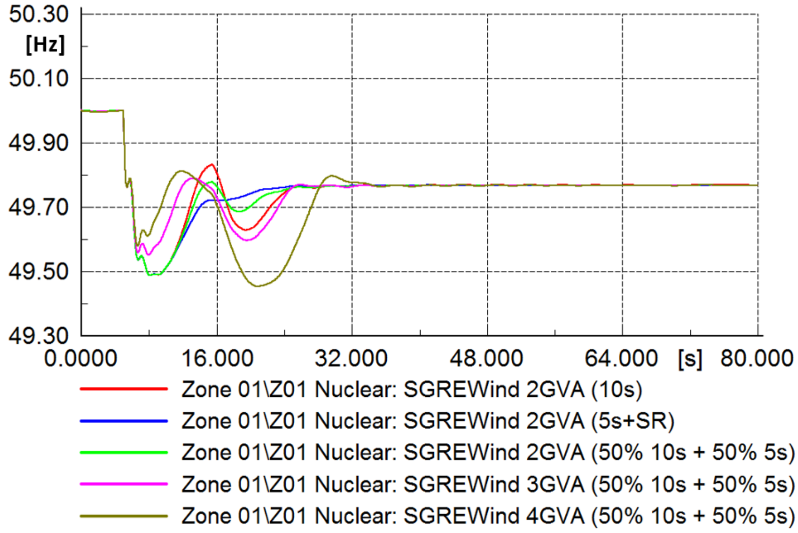


Figure 4-33. Performance of system frequency (measured at Zone 01) with 50% 10 s SGRE wind IR and 50% 5 s SGRE wind IR (SGRE wind with 20-30% loading and conservative profiles)

4.3.3 Mix of windfarms with different IR activation times

This section investigates the impact of windfarms having different IR activation times on the system frequency control. In Zone 01 of the network model, two SGRE wind static generators (rated at 1GVA each) are implemented with one having 500 ms of IR activation time and the other with 1000 ms activation time. Both 10 s and 5 s profiles are tested with conservative profiles and a loading level of 20-30%.

The performance are shown in Figure 4-34 and Figure 4-35 for 10 s and 5 s profiles respectively. It can be seen that the mix of two different activation delays result in a response which sits between the responses of only 500 ms delay and only 1000 ms delay which is as expected. Overall, the impact of having a combination of different activation time in the range of 500 ms to 1000 ms does not appear to be significant on the system frequency nadir.

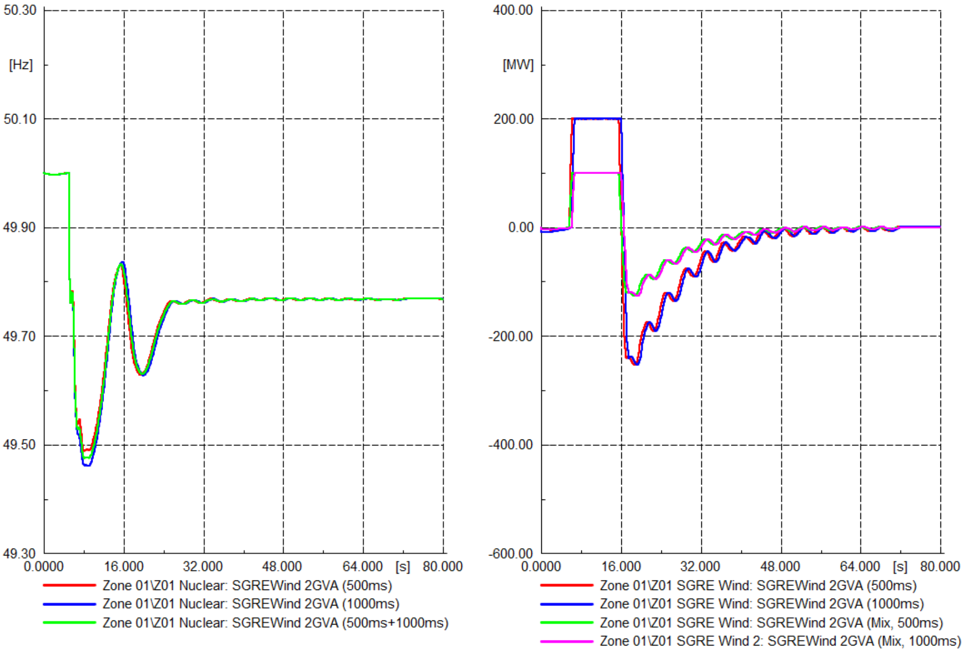


Figure 4-34. Performance of a mix of 500 ms and 1000 ms delay in IR activation time (SGRE wind rated at 2 GVA with 20-30% loading and 10 s conservative profile)

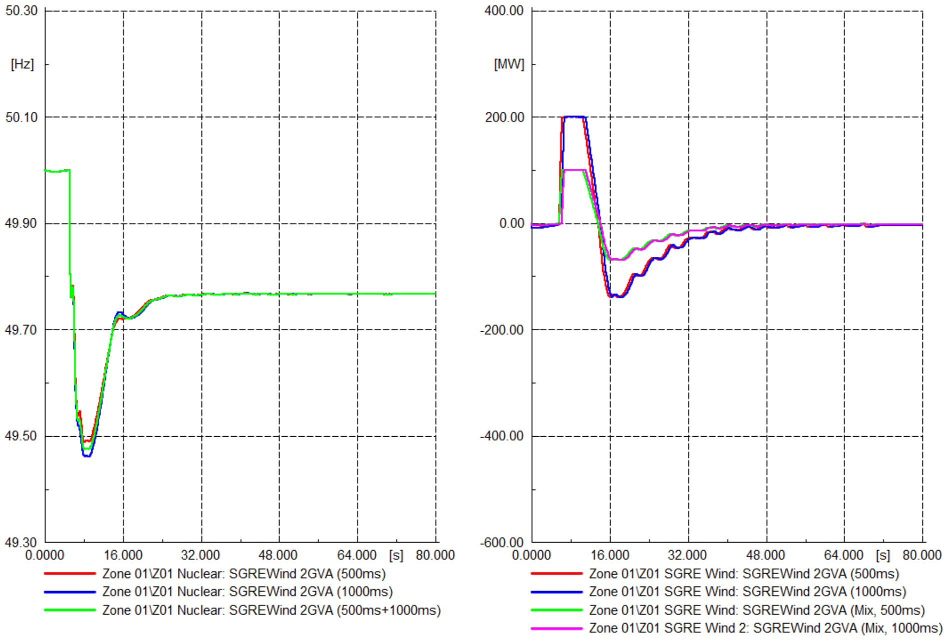


Figure 4-35. Performance of a mix of 500 ms and 1000 ms delay in IR activation time (SGRE wind rated at 2 GVA with 20-30% loading and 5 s conservative profile)

4.4 System studies of frequency events following faults

This study investigates whether the voltage will recover to above 90% within 500 ms following faults, which will determine whether the windfarms will be capable of providing IR after faults. The following events have been simulated:

- A three-phase fault in the middle of a transmission line connected with a generation plant is applied at 4.9 s and cleared at 5 s with a fault duration of 100 ms. The magnitude of the fault impedance is around 14 Ω. The reason to use resistive fault is because the network model is a simplified form of the actual system, so each feeder in this model could be the equivalent of a number of lines in the actual system.

Therefore, when applying a fault in a line in the simplified network model, it has relatively larger impact compared with a fault in a line the actual system. In the study, if a bolted fault is applied, the system will become unstable and it was found that when the magnitude of the fault impedance increased to around 14 Ω, it would avoid the system becoming unstable following the fault clearance. That's why a fault with impedance of 14 Ω is used in the studies;

- Following the fault clearance, a 1320 MW loss-of-infeed event is triggered near the fault location - this is to emulate an protection action that leads to a transmission line connected to a generation plant or an infeed being tripping, leading to subsequent frequency disturbances;
- IR from SGRE windfarm is activated at 5.5 s with a 500 ms delay after the loss-of-infeed event.

The fault locations considered in this study include South and North of the network, which are stated in details below:

- South: a three-phase fault on line 11-12 and loss of 1320 MW static generator in Zone 12;
- North: a three-phase fault on line 32-33 and loss of 1320 MW static generator in Zone 32.

The studies tested for 10 s and 5 s conservative and mean profiles employed for windfarm IR and the loading level of the SGRE windfarms is 20-30%. Figure 4-36~Figure 4-39 show the regional voltage behaviour in the 36 zones for the test cases stated above with the windfarms providing IR evenly distributed across the system in all zones with a total capacity of 2 GVA and conservative profiles. Results with mean profiles are presented in Appendix A7.10.

As shown in the simulation results in Figure 4-36, when the fault occurred at 4.9 s, the voltage disturbances closer to Zone 12 (where the fault is located) tend to be more severe, while those at remote locations tends to be smaller. At the instance of the fault, voltage dips are observed across the system but the voltages recover quickly to above 90% within 500 ms, which indicate that the windfarms will be available to provide IR after 500 ms after the fault occurrence. This also applies to the period after the fault clearance where the voltage depression were also recovered relatively quickly. Responses for the other test cases are similar and indicate the same conclusion. As suggested by SGRE, the current wind turbine control system could potentially experience issues in offering the IR service when voltage goes below 0.9 pu and further investigation on capability of SGRE windfarm to provide IR response under low voltage situations is to be expected.

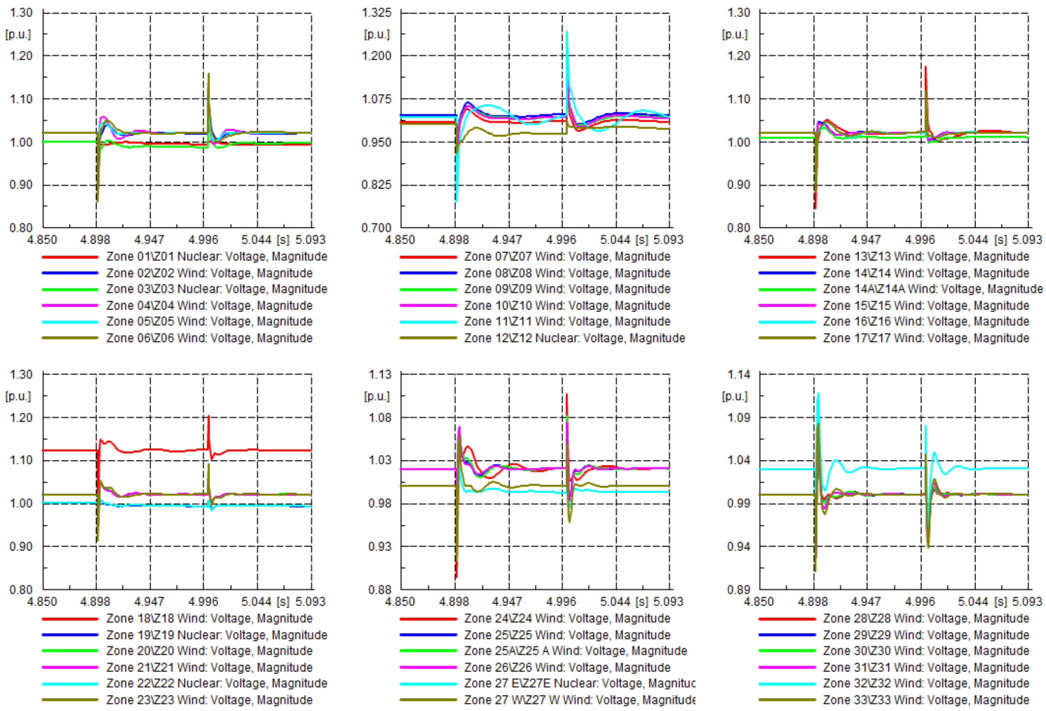


Figure 4-36. Responses of local voltage with Zone 11-12 generation line fault followed by a loss-of-infeed in Zone 12 (2 GVA SGRE wind equally distributed across the system with conservative 10 s profile and 20-30% loading)

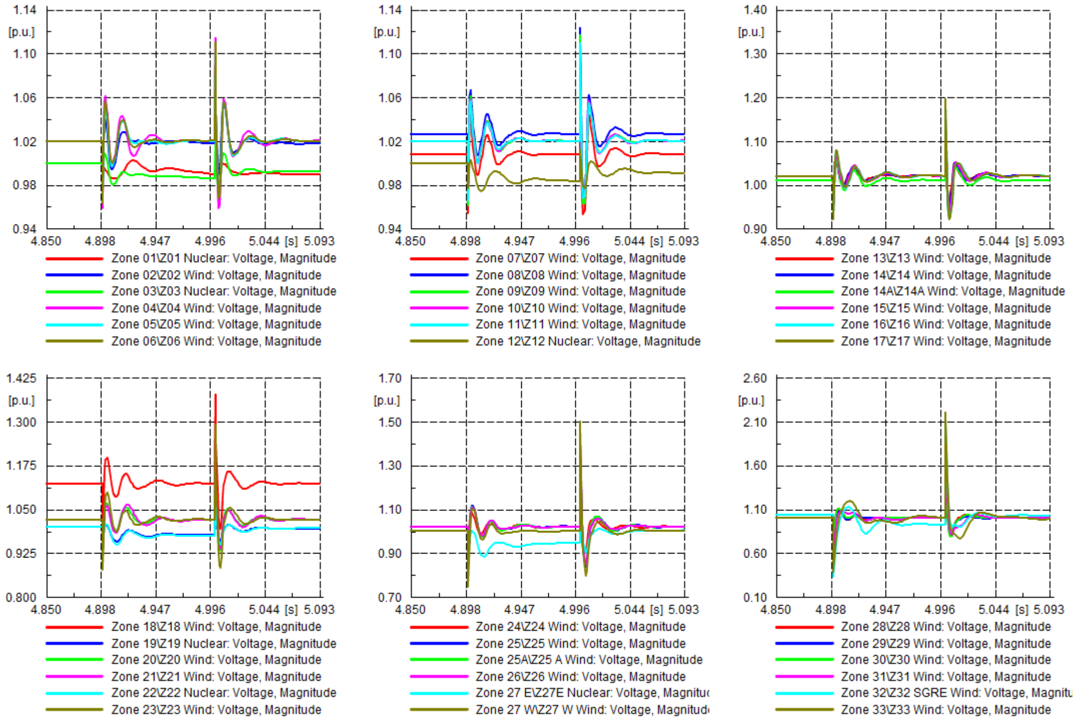


Figure 4-37. Responses of local voltage with Zone 32-33 generation line fault followed by a loss-of-infeed in Zone 32 (2 GVA SGRE wind equally distributed across the system with conservative 10 s profile and 20-30% loading)

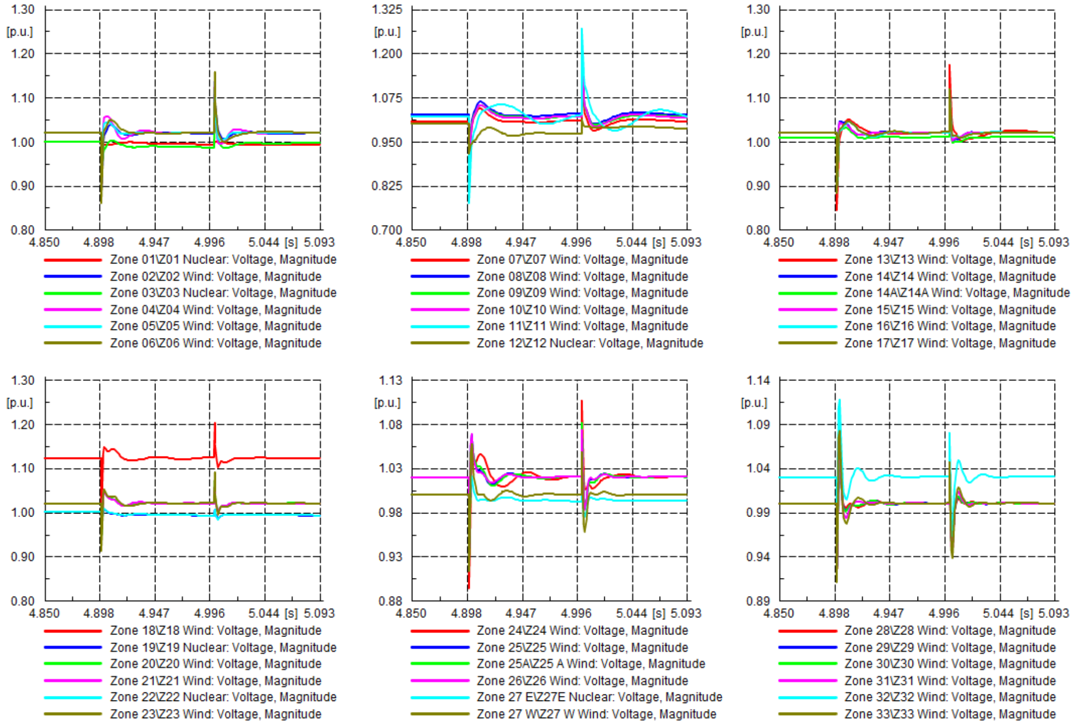


Figure 4-38. Responses of local voltage with Z11-12 generation line fault followed by a loss-of-infeed in Zone 12 (2 GVA SGRE wind equally distributed across the system with conservative 5 s profile and 20-30% loading)

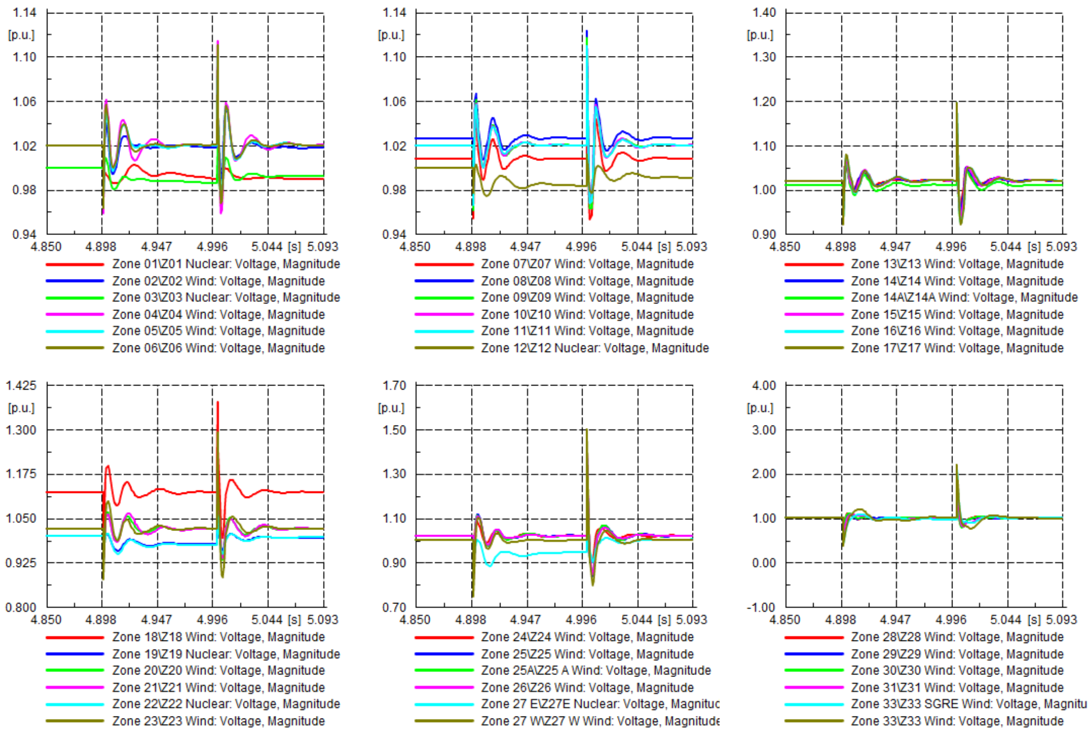


Figure 4-39. Responses of local voltage with Zone 32-33 generation line fault followed by a loss-of-infeed in Zone 32 (2 GVA SGRE wind equally distributed across the system with conservative 5 s profile and 20-30% loading)

5 CONCLUSIONS

In this report, the capability of IR contribution from SGRE windfarms in supporting frequency control has been evaluated using windfarm IR profile data from SGRE and the 36-bus reduced GB model from NG. From the extensive system studies conducted, the following conclusions have been drawn:

- Due to the fast acting response time (typically between 500 ms and 1000 ms) and the fast power ramp-up capability, the IR from windfarms has shown a great potential in playing an important role in supporting the frequency control in systems with low inertia. It was found that, the windfarm can provide fast frequency response following a frequency disturbance upon instruction and thus greatly improve the frequency deviation containment performance.
- The IR from windfarm can only sustain for a certain period, after which it will not be able to continue the IR and will need to reduce the generating power to recover the turbines to avoid stalling. This change in output power could introduce a second frequency drop after the IR response.
- According to the windfarm IR profiles provided by SGRE, although windfarms with higher loading levels output similar amount of power during IR, the power dip after the IR tend to be larger, thus a more severe second frequency drop.
- With larger windfarm capacities, the IR from windfarms tend to be more effective in mitigating the first frequency drop, while it will lead to more severe second frequency drops after the IR. Therefore, the capacity of windfarms in providing IR has to be carefully chosen to keep the second frequency drop above the required 49.5 Hz limit. In this report, the optimal capacity range for different loading conditions to ensure both first and second frequency nadirs are above 49.5 Hz have been found for the 82 GVAs inertia level.
- The occurring time of the second frequency drop can vary and is dependent on the output from the windfarms, which is subject to a number for factors, e.g. windfarm ratings, IR profiles, etc. Such variation in the occurring time of second frequency dip could potentially introduce challenges to system

operators when coordinating wind IR with other available resources to obtain a desirable system frequency response. Therefore, novel frequency control schemes (such as EFCC) will be required to achieve such coordination of various frequency support resources.

- Performance of SGRE windfarm IR with mean data generally outstands that with the conservative data.
- While a shorter delay in activation time for windfarm IR is preferred, the studies have shown that the impact of IR activation time (in the range of 500 ms to 1000 ms) do not show an significant impact on the first and second frequency nadir.
- Locations of SGRE windfarm IR do not appear to have significant effects on the system frequency nadir. In the system being studied (82 GVA - the minimum inertia level in 2021/2022), the level of inter-oscillation when placing the windfarm in different locations does not appear to cause system stability issues. However, this only shows the location of the IR from windfarm is not a significant issue for the system in the near future. For the long term future system operation, more detailed analysis will be required to access the impacts.
- It has been shown that voltages across the network are able to recover to above 90% of the nominal voltage within 500 ms when a frequency event is introduced following a generation-line fault. Therefore, it allows the windfarms to provide IR under such circumstances. Further investigation on capability of SGRE windfarm to provide IR under low voltage situations (e.g. below 0.9 pu) is necessary.
- Compared with the 10 s profiles, which introduces sharper power drops after the IR contribution, the 5 s profiles has a shorter duration of IR but a slower ramp-down rate during the recovery period, which has shown to be significantly beneficial for mitigating the second frequency drop. Performance of 10 s and 5 s regarding the first frequency drop are generally similar during IR under the same conditions.
- Compared with the case where all windfarms are with the 10 s, a mix of 10 s and 5 s profiles has similar performance for the first frequency dip due to the similar IR injection characteristic while it improves the second frequency drop. It is most beneficial and desirable to have IR from windfarms with the 5 s SR characteristic, while a combination of 10 s and 5 s SR profiles, and all response from 10 s profile can still provide a level of improvement to the frequency control effectiveness. From the perspective of system operators, it is important to effectively coordinate various resources with different characteristics in order to obtain desirable frequency control performance, where novel frequency control scheme with wide monitoring and control capability such as EFCC could play a key role in enabling such coordination.
- Impact of having windfarms with a mix of 500 ms and 1000 ms IR activation time does not distinct significantly from the case where all windfarms have uniform activation time (i.e. either all with 500 ms or 1000 ms).

In summary, IR contribution from windfarms showed a great potential to support system frequency control. To enable the windfarm IR in an actual system, the second frequency drop introduced by the windfarms due to the power drop after IR should be carefully considered to ensure the frequency limits are met for both first and second frequency dip. This can be achieved by enabling the windfarms to ramp down the power slowly after the IR and carefully selecting appropriate windfarm capacity in providing IR.

In this report, extensive studies have been conducted for the 82 GVAs inertia level. It is suggested that future work could be conducted to develop a general approach for quantifying the requirements for windfarm IR characteristic (e.g. capacity, duration, power ramp-down rate, etc.) for different inertia levels and system operating conditions. It is expected that the outcome of the future work will facilitate the decision making for the control room to determine when and how much they should enable IR from the windfarm. It is also suggested that future work could also investigate how windfarms can be combined with other technologies, e.g. gas turbines, to provide a smooth power transition from wind IR to power outputs from other sources.

6 REFERENCES

[1] National Grid (GB), "System Operability Framework," 2016. Available: http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/System-Operability-Framework/, accessed in 2018/12/10.

7 APPENDIX A: SYSTEM STUDIES OF WINDFARMS' IR WITH MEAN PROFILE DATA

7.1 Impact of IR's activation time with 10 s profiles

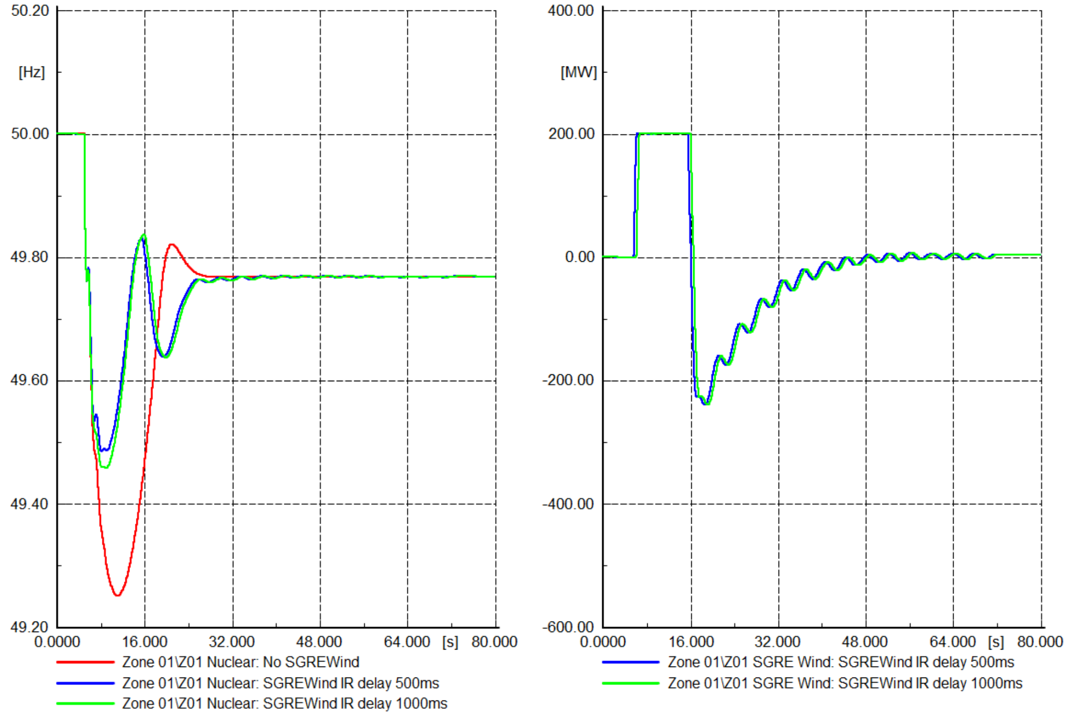


Figure 7-1. Performance of 10 s SGRE windfarm IR with various response activation time (with 20%-30% of rated power and mean profile)

7.2 Impact of capacity of windfarm providing IR with 10 s profiles

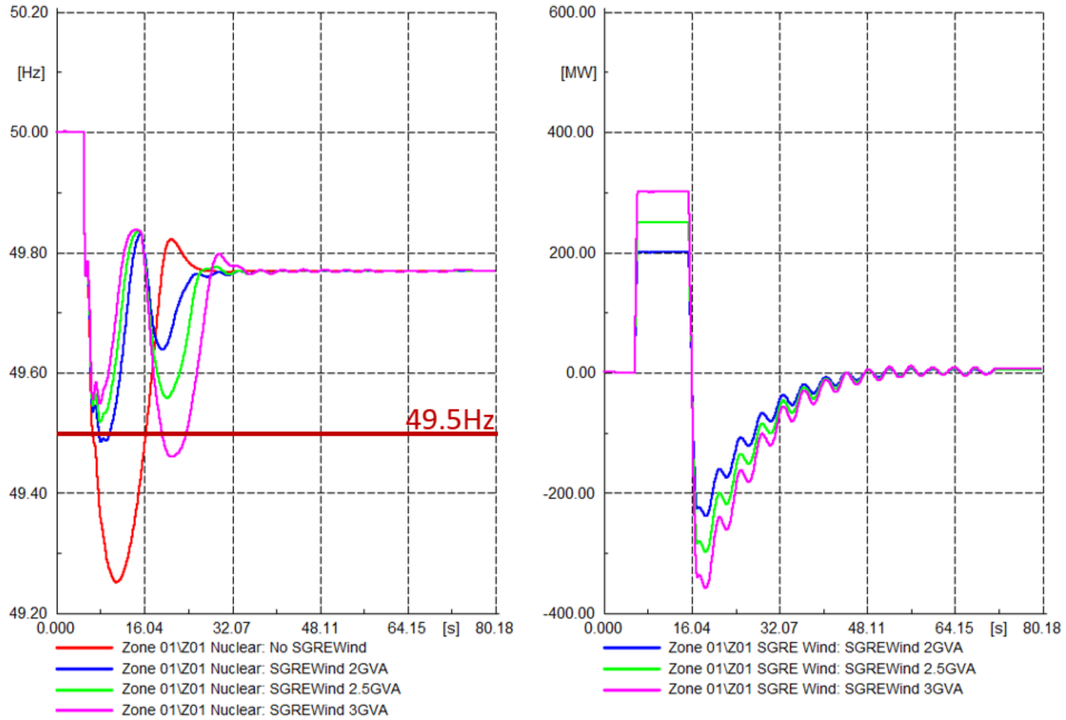


Figure 7-2. Performance of 10 s SGRE windfarm IR with various capacity levels (with 20%-30% of rated power and mean profile)

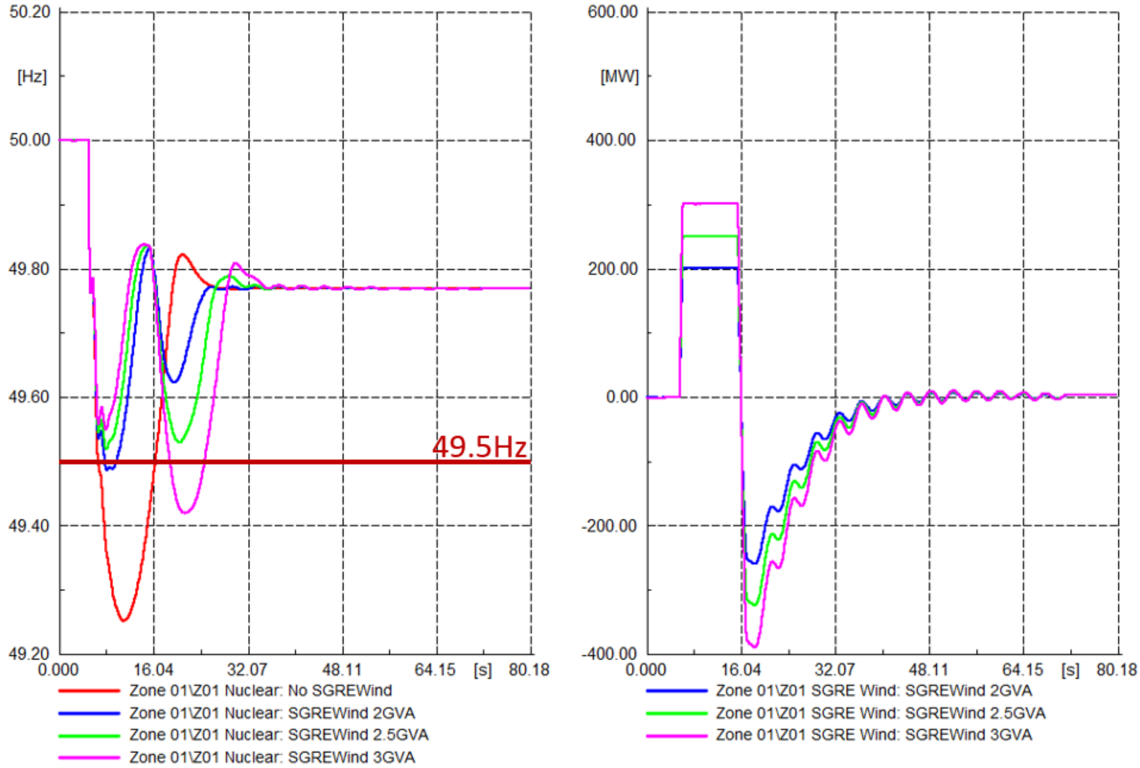


Figure 7-3. Performance of 10 s SGRE windfarm IR with various capacity levels (with 30%-40% of rated power and mean profile)

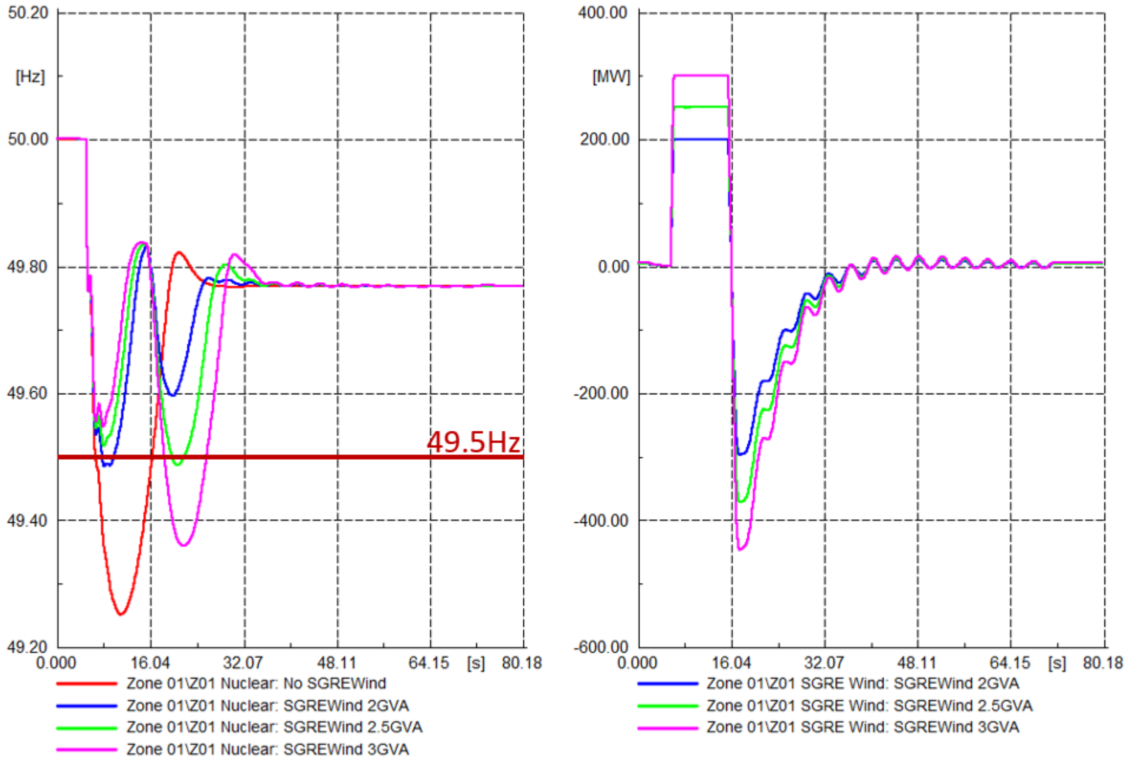


Figure 7-4. Performance of 10 s SGRE windfarm IR with various capacity levels (with 40%-50% of rated power and mean profile)

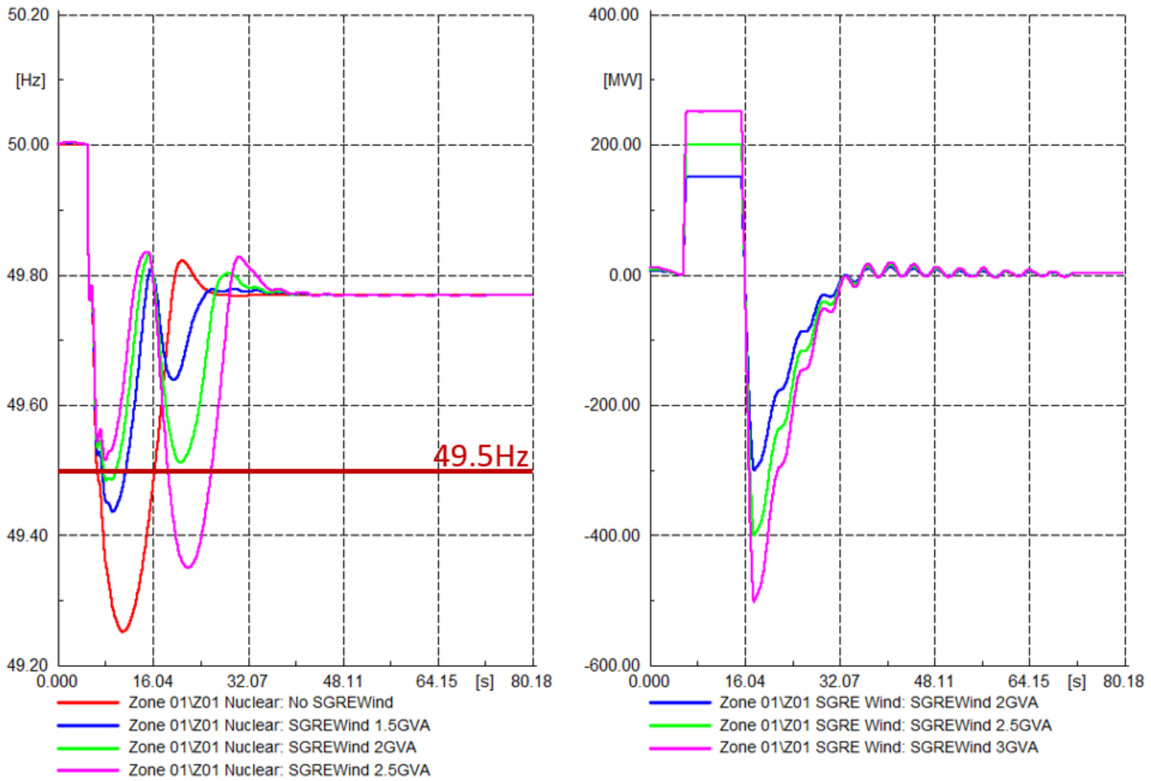


Figure 7-5. Performance of 10 s SGRE windfarm IR with various capacity levels (with 50%-60% of rated power and mean profile)

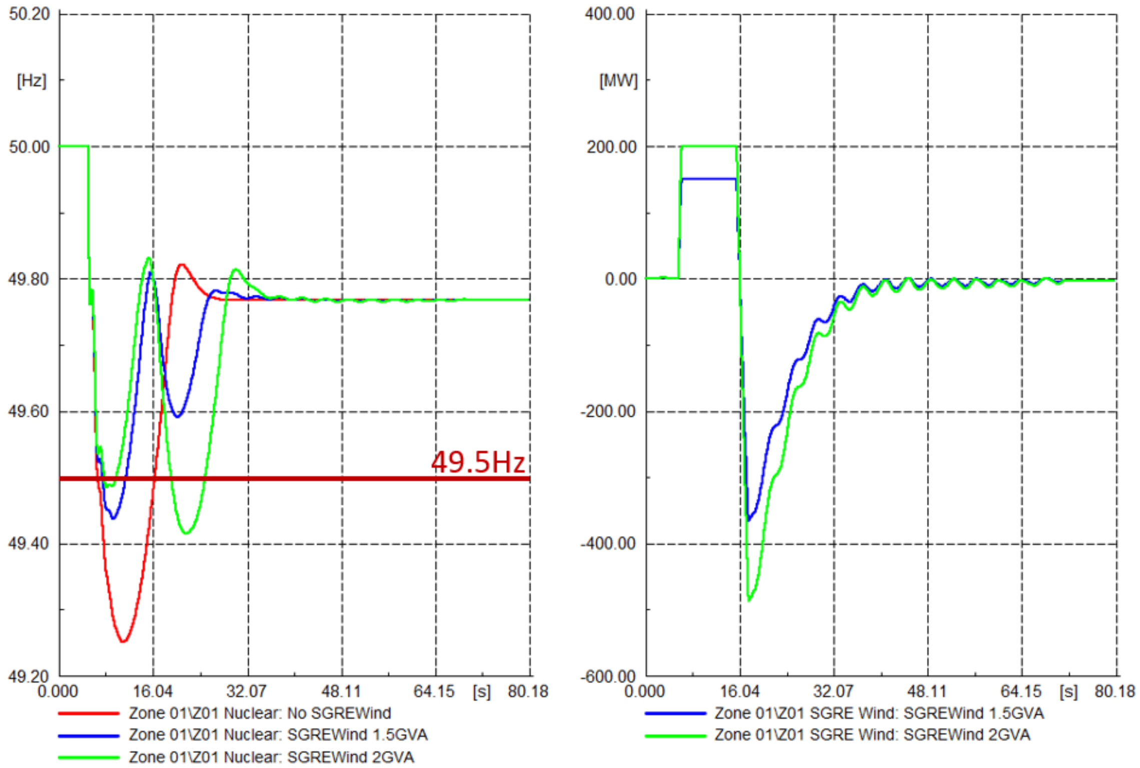


Figure 7-6. Performance of 10 s SGRE windfarm IR with various capacity levels (with 60%-70% of rated power and mean profile)

7.3 Impact of locations of windfarm providing IR with 10 s profiles

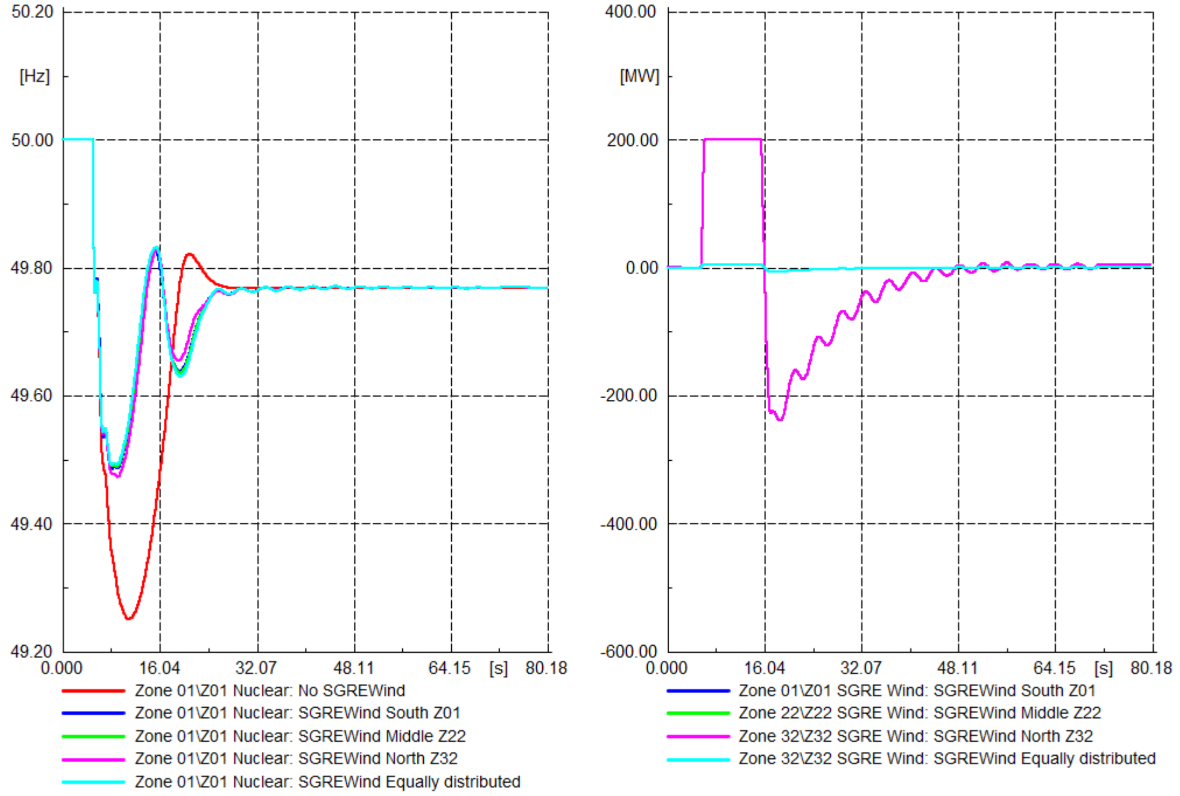


Figure 7-7. Performance of 10 s SGRE windfarm IR with various locations (mean profile)

7.4 Impact of IR's activation time with 5 s profiles

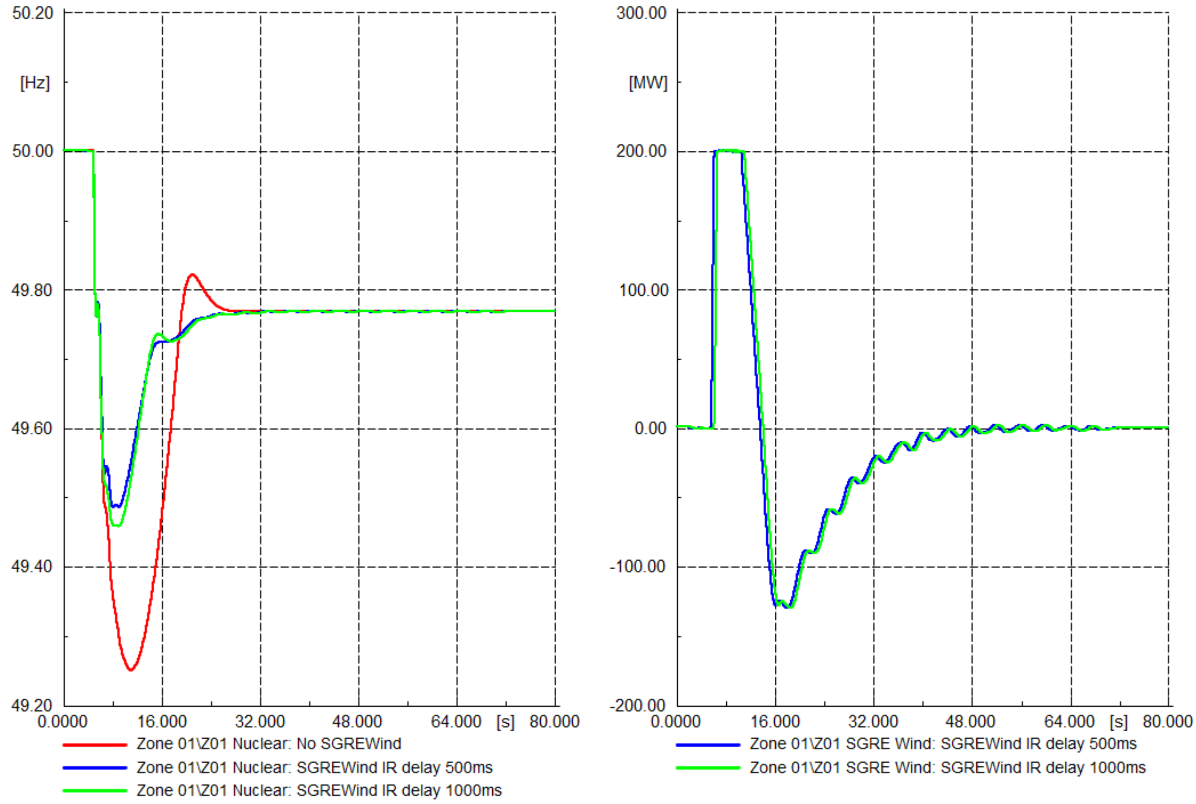


Figure 7-8. Performance of 5 s with SR SGRE windfarm IR with various activation time (mean profile, 20-30% loading)

7.5 Impact of activation time of windfarm providing IR with 5 s profiles

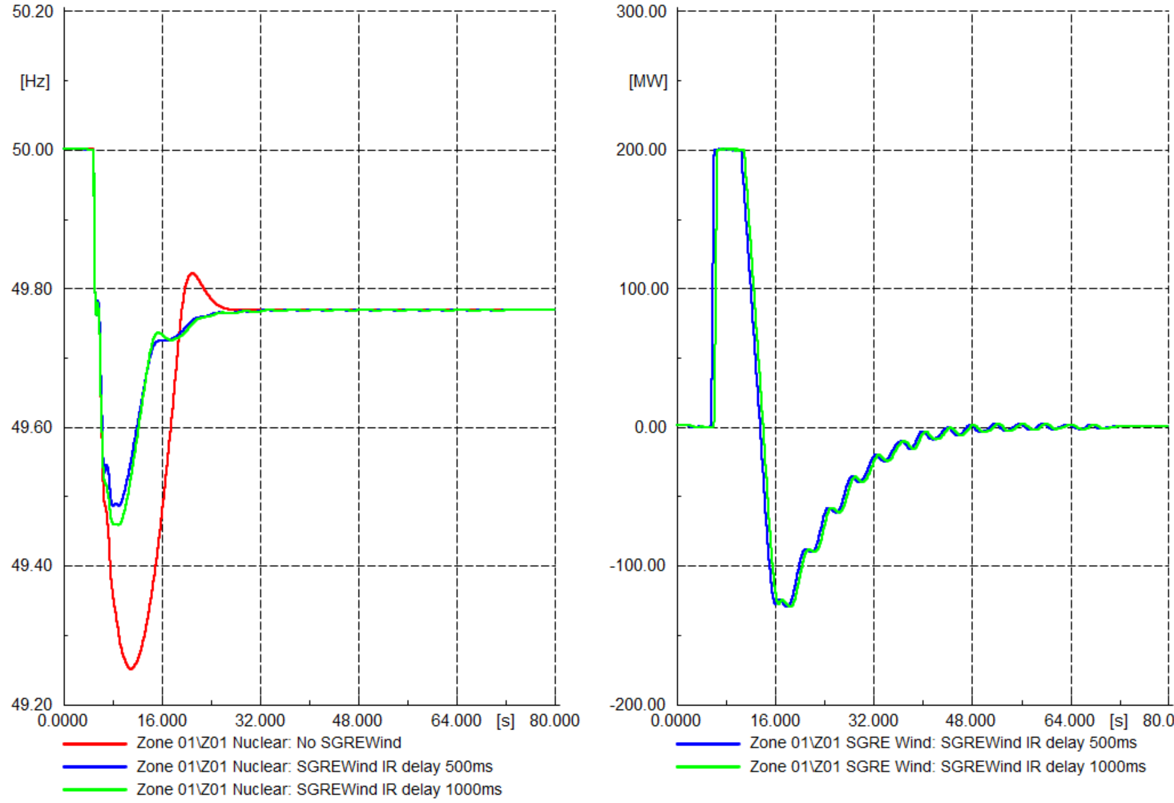


Figure 7-9. Performance of 5 s with SR SGRE windfarm IR with various activation time (mean profile, 20-30% loading)

7.6 Impact of capacity of windfarm providing IR with 5 s profiles

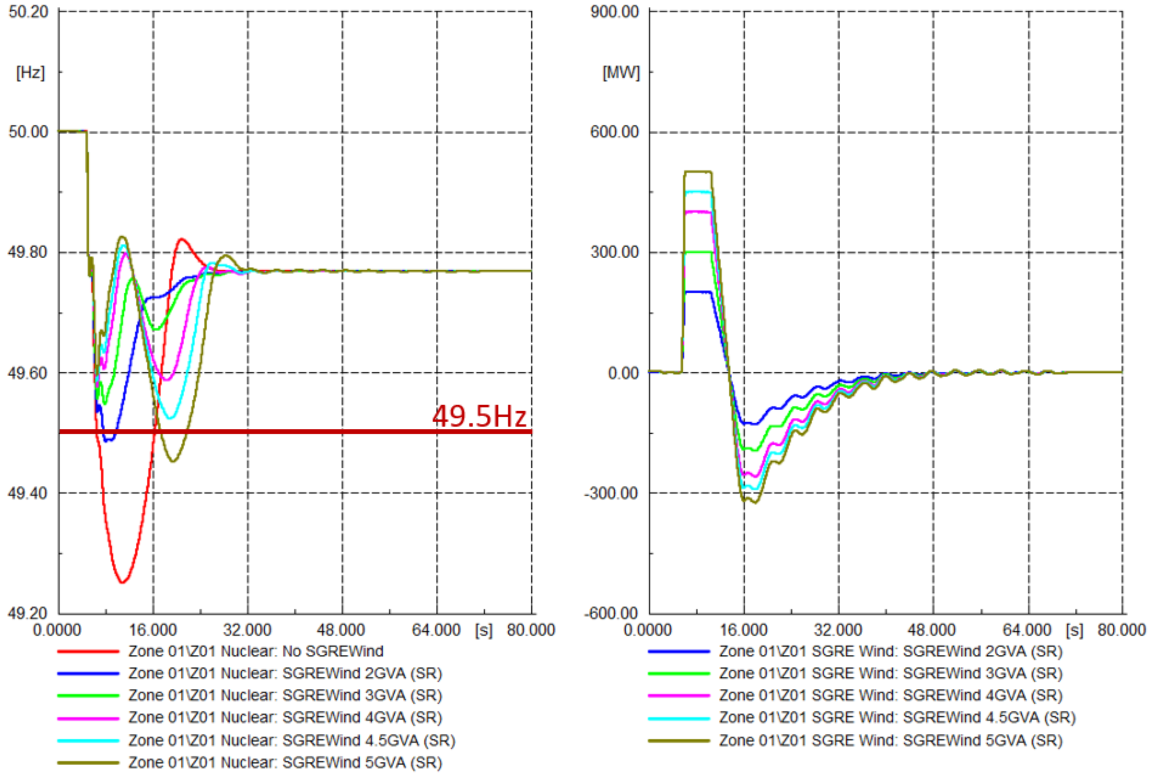


Figure 7-10. Performance of 5 s with SR SGRE windfarm IR with various capacity levels (with 20%-30% of rated power and mean profile)

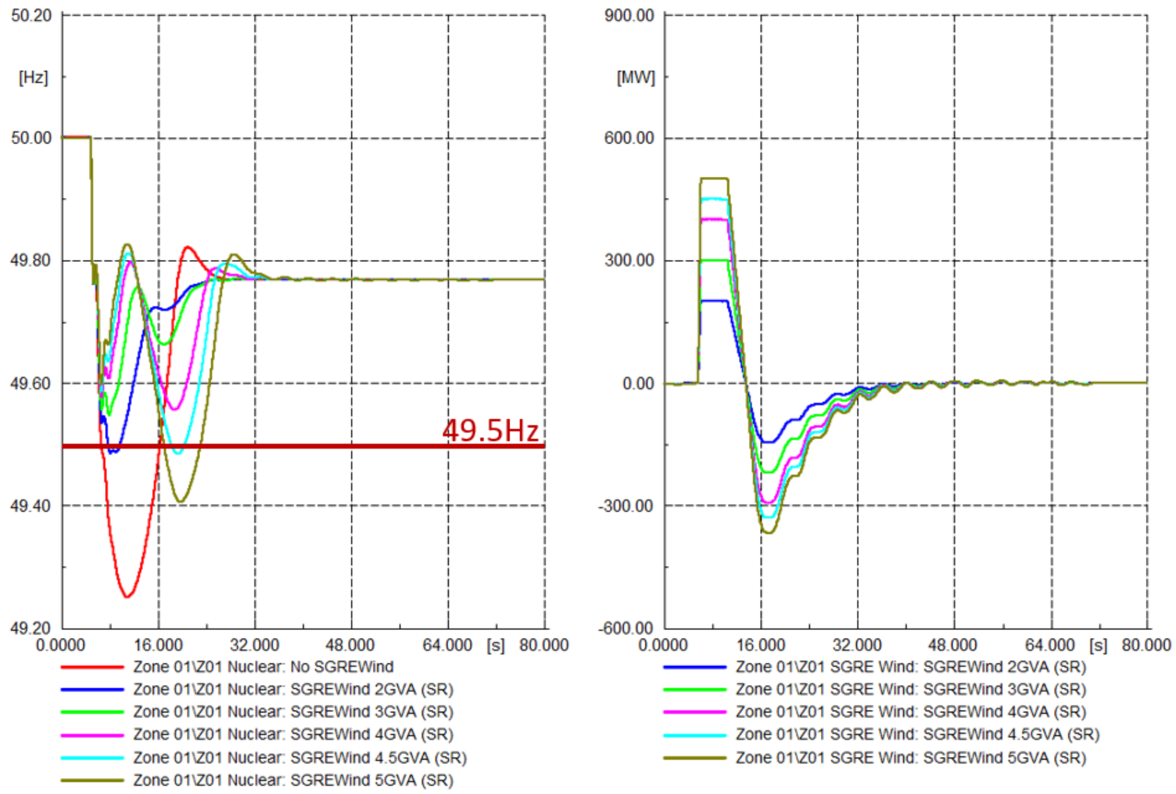


Figure 7-11. Performance of 5 s with SR SGRE windfarm IR with various capacity levels (with 30%-40% of rated power and mean profile)

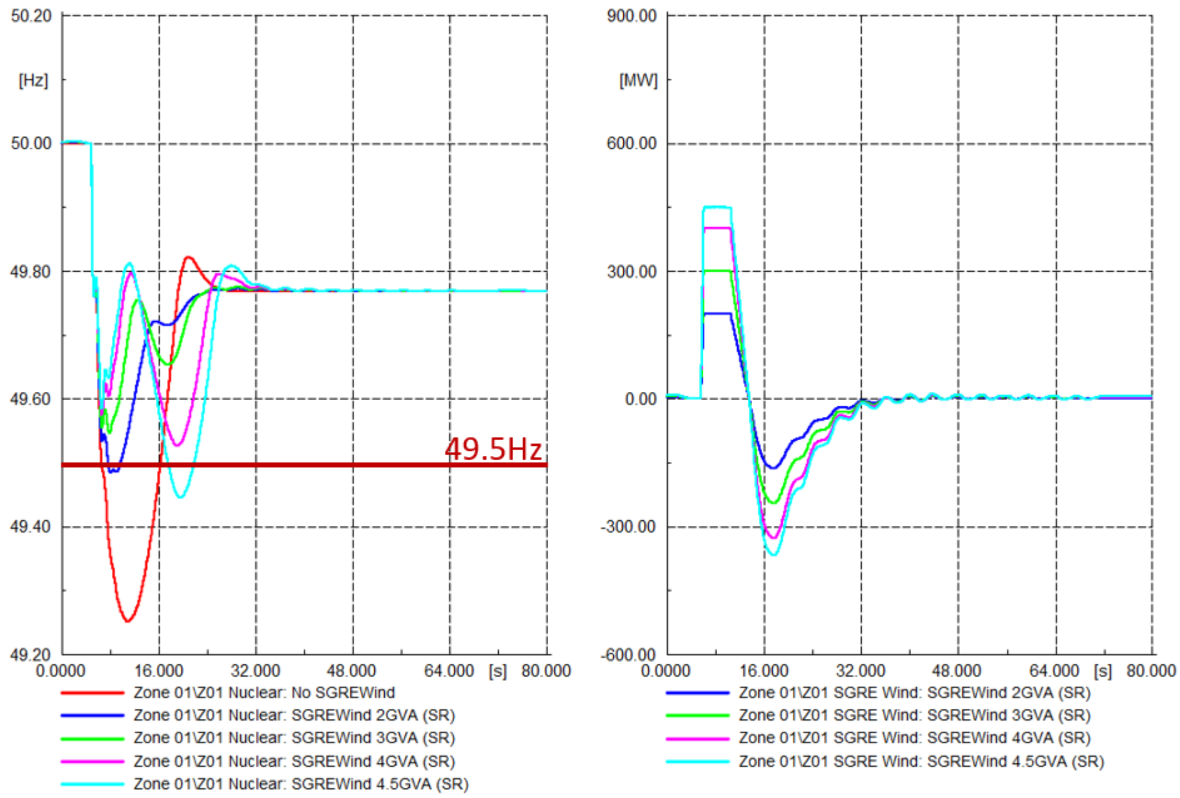


Figure 7-12. Performance of 5 s with SR SGRE windfarm IR with various capacity levels (with 40%-50% of rated power and mean profile)

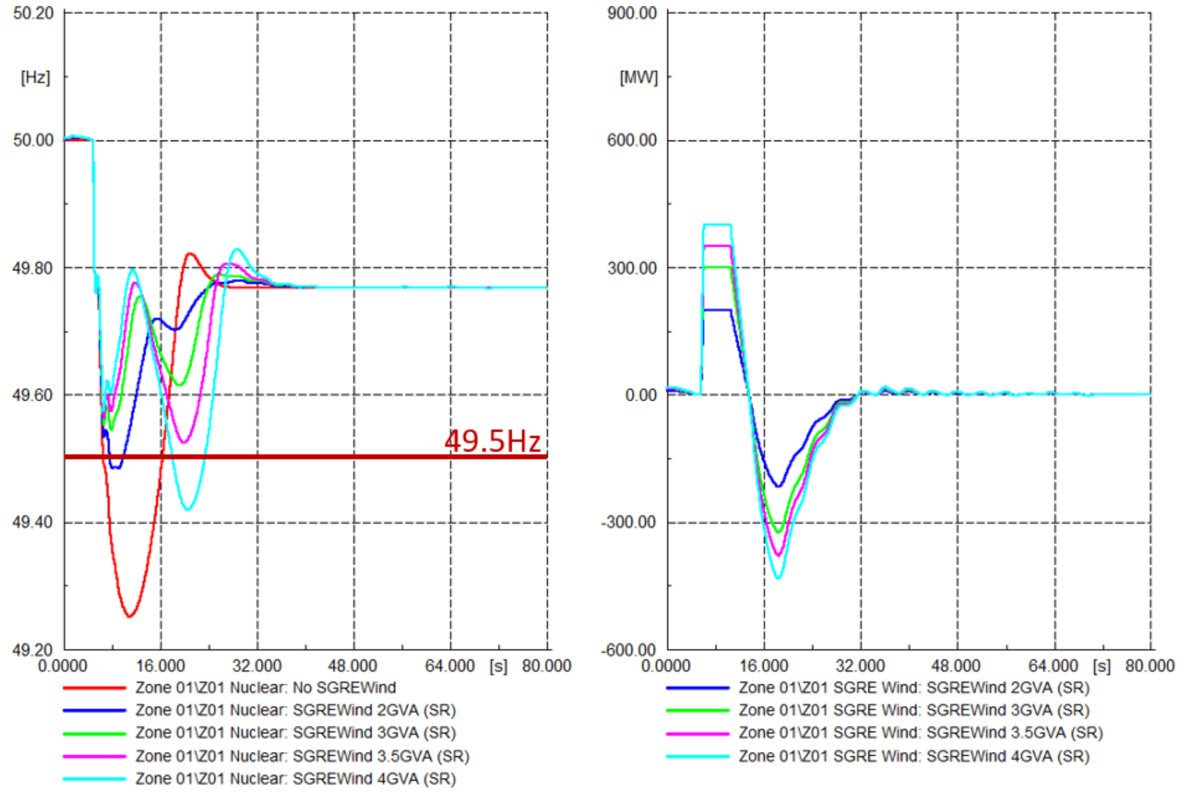


Figure 7-13. Performance of 5 s with SR SGRE windfarm IR with various capacity levels (with 50%-60% of rated power and mean profile)

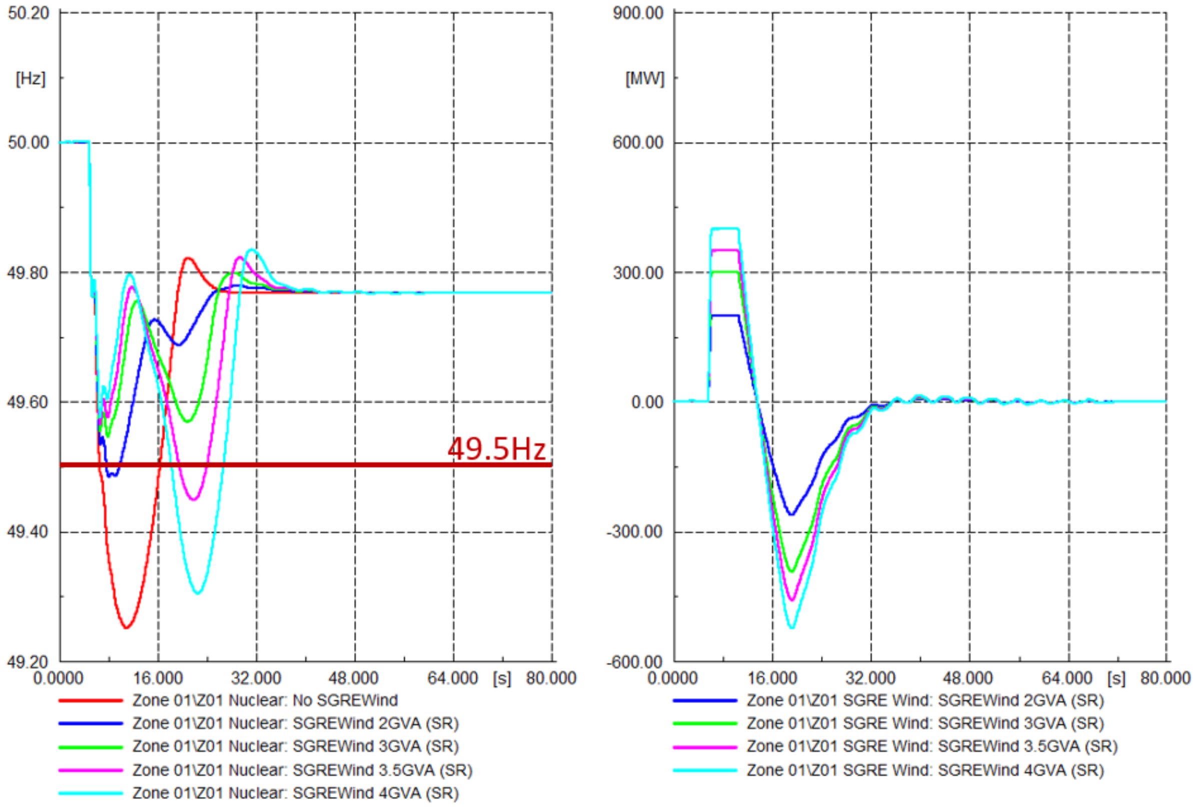


Figure 7-14. Performance of 5 s with SR SGRE windfarm IR with various capacity levels (with 60%-70% of rated power and mean profile)

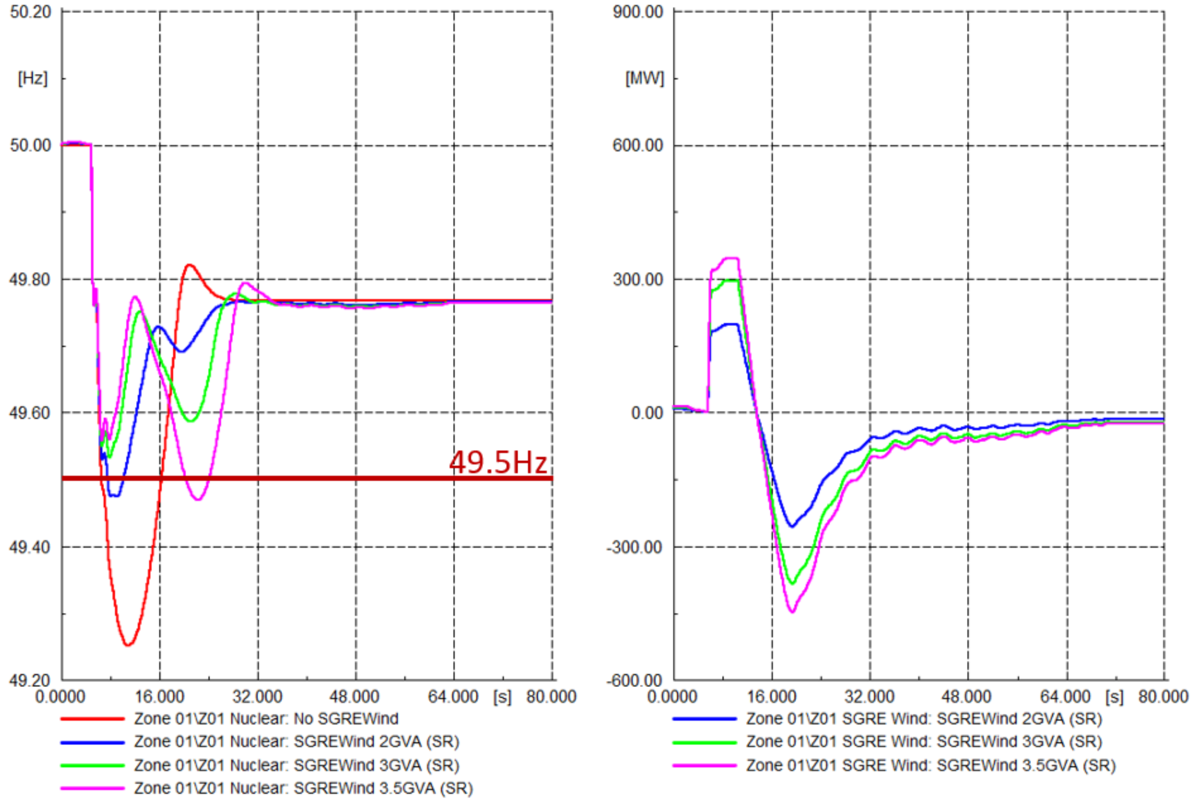


Figure 7-15. Performance of 5 s with SR SGRE windfarm IR with various capacity levels (with 70%-80% of rated power and mean profile)

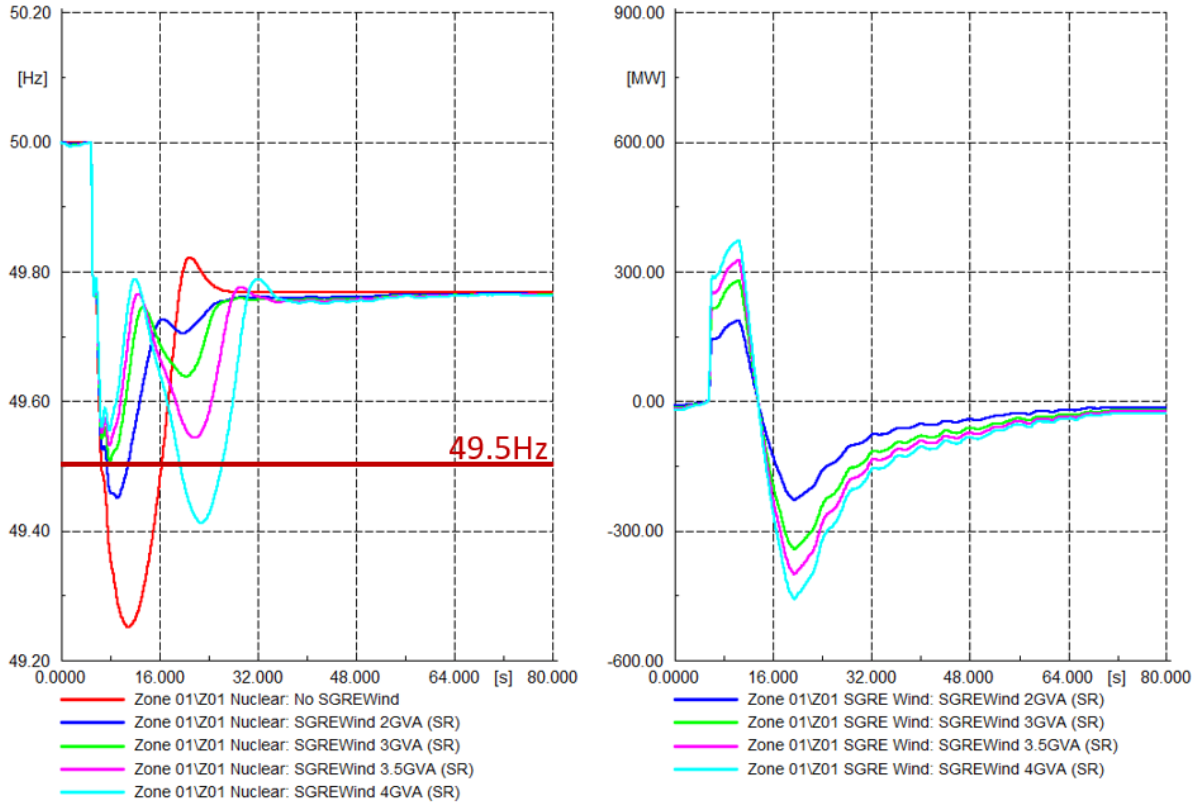


Figure 7-16. Performance of 5 s with SR SGRE windfarm IR with various capacity levels (with 80%-90% of rated power and mean profile)

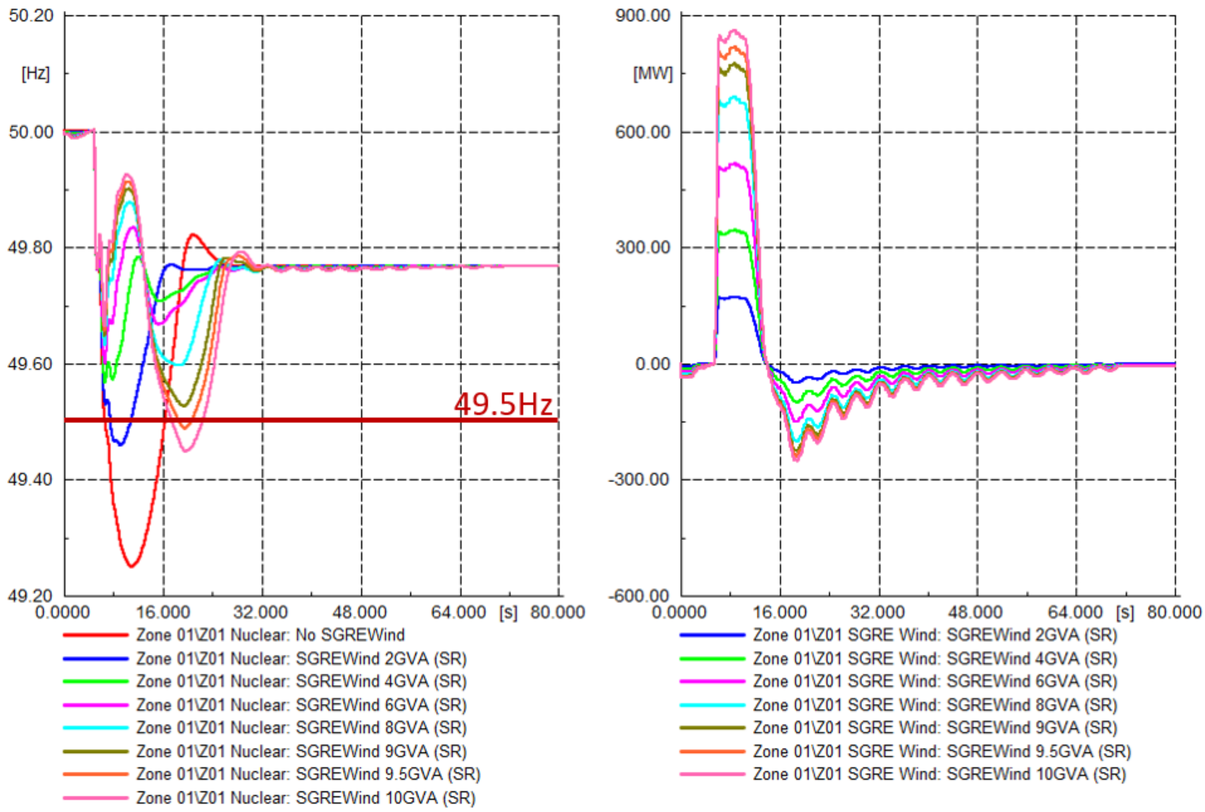


Figure 7-17. Performance of 5 s with SR SGRE windfarm IR with various capacity levels (with 90%-100% of rated power and mean profile)

7.7 Impact of locations of windfarms providing IR with 5 s profiles

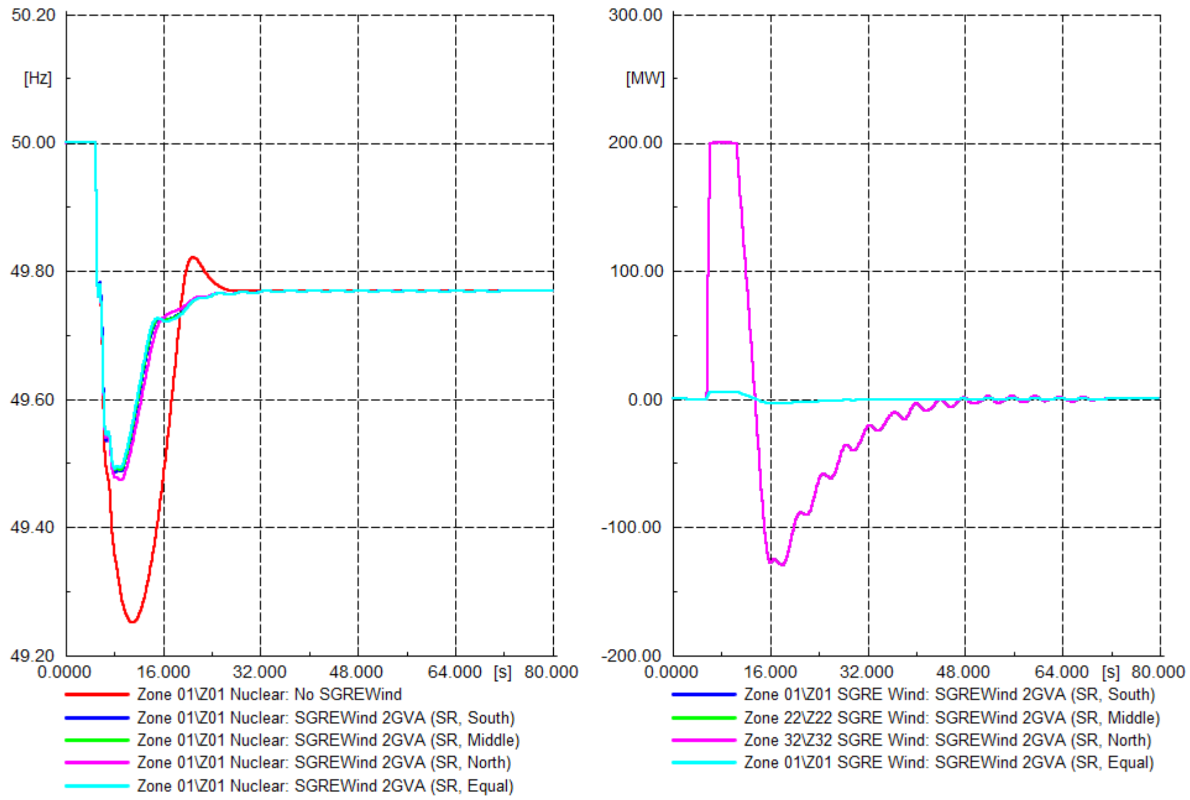


Figure 7-18. Performance of 5 s with SR SGRE windfarm IR with various location (mean profile)

7.8 Comparisons of 10 s and 5 s profiles

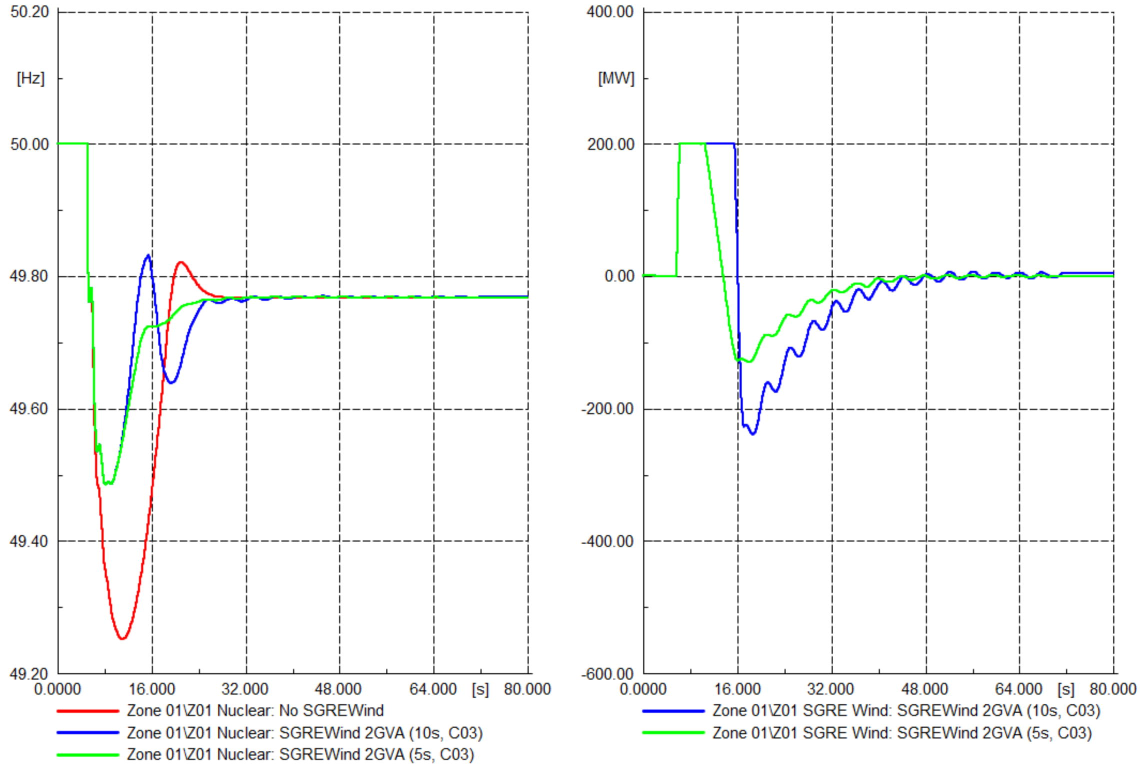


Figure 7-19. Comparison of 10 s and 5 s SGRE windfarm profiles (mean profile and 20-30% loading)

7.9 IR from windfarms with different activation times

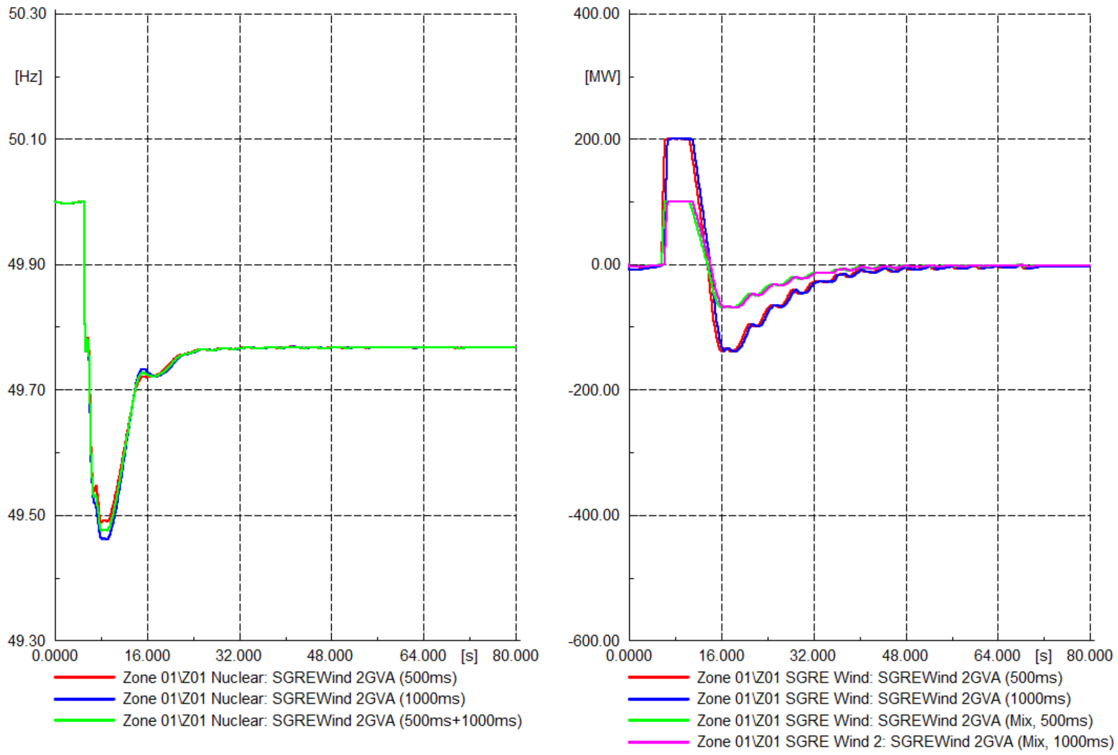


Figure 7-20. Performance of a mix of 500 ms and 1000 ms delay in IR activation time (SGRE wind rated at 2 GVA with 20-30% loading and 5 s mean profile)

7.10 Frequency events following faults

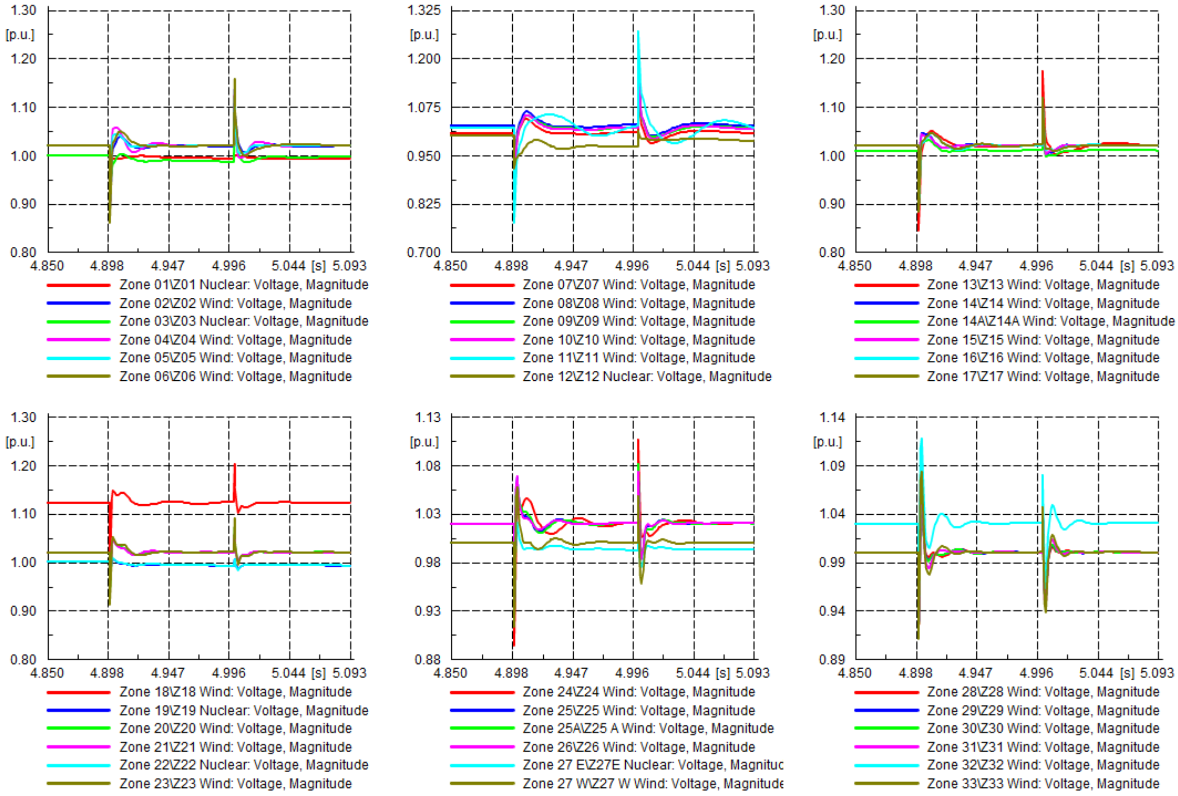


Figure 7-21. Responses of local voltage with Zone 11-12 generation line fault followed by a loss-of-infeed in Zone 12 (2 GVA SGRE wind equally distributed across the system with mean 10 s profile and 20-30% loading)

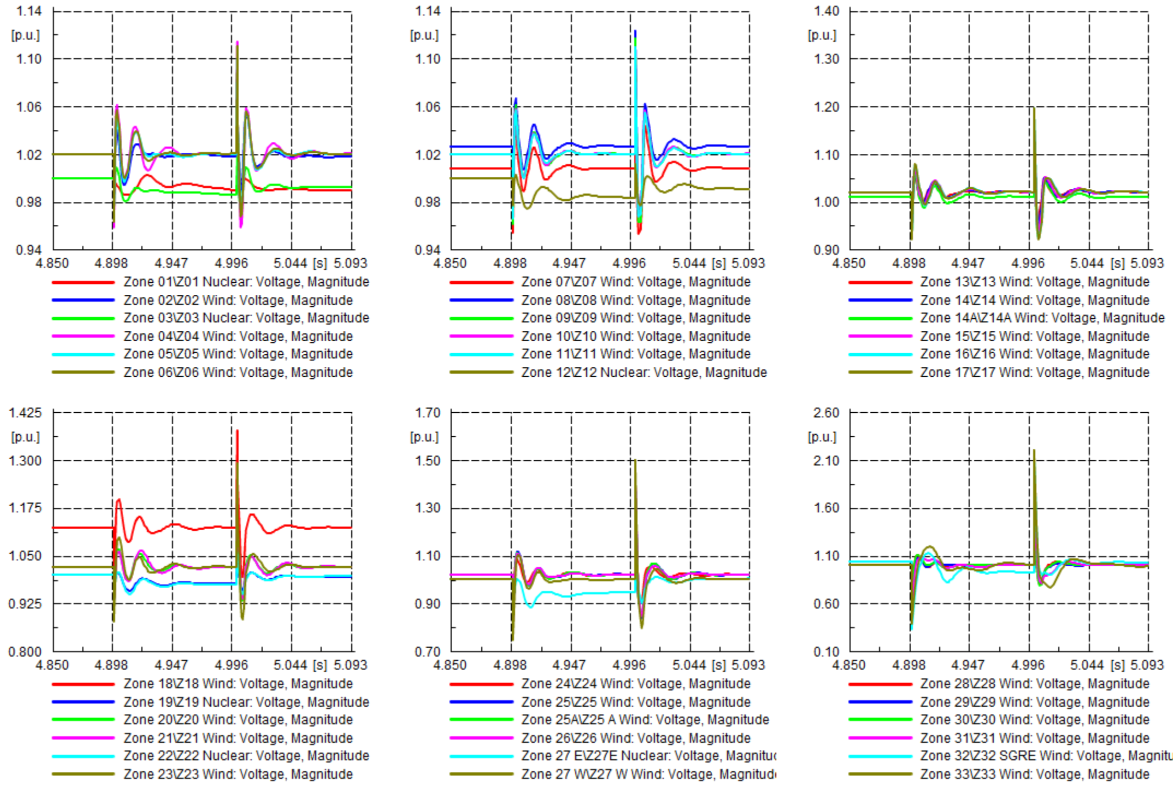


Figure 7-22. Responses of local voltage with Zone 32-33 generation line fault followed by a loss-of-infeed in Zone 32 (2 GVA SGRE wind equally distributed across the system with mean 10 s profile and 20-30% loading)

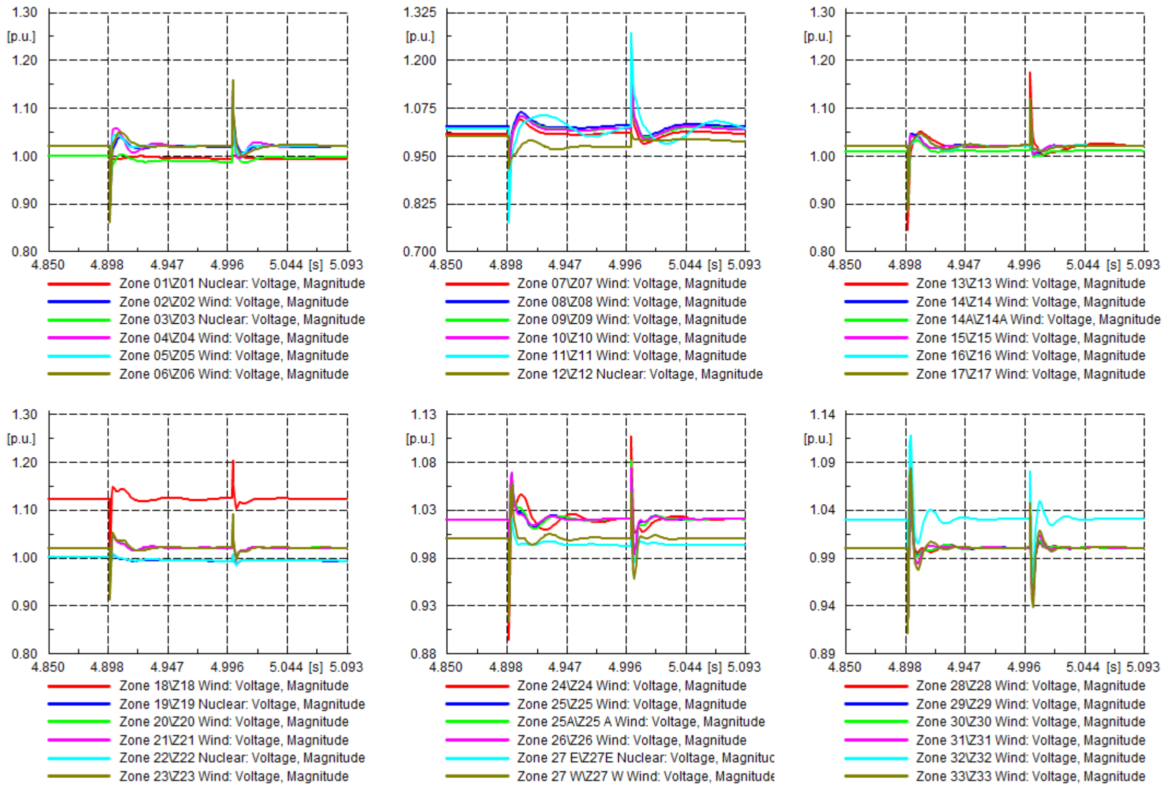


Figure 7-23. Responses of local voltage with Zone 11-12 generation line fault followed by a loss-of-infeed in Zone 12 (2 GVA SGRE wind equally distributed across the system with mean 5 s profile and 20-30% loading)

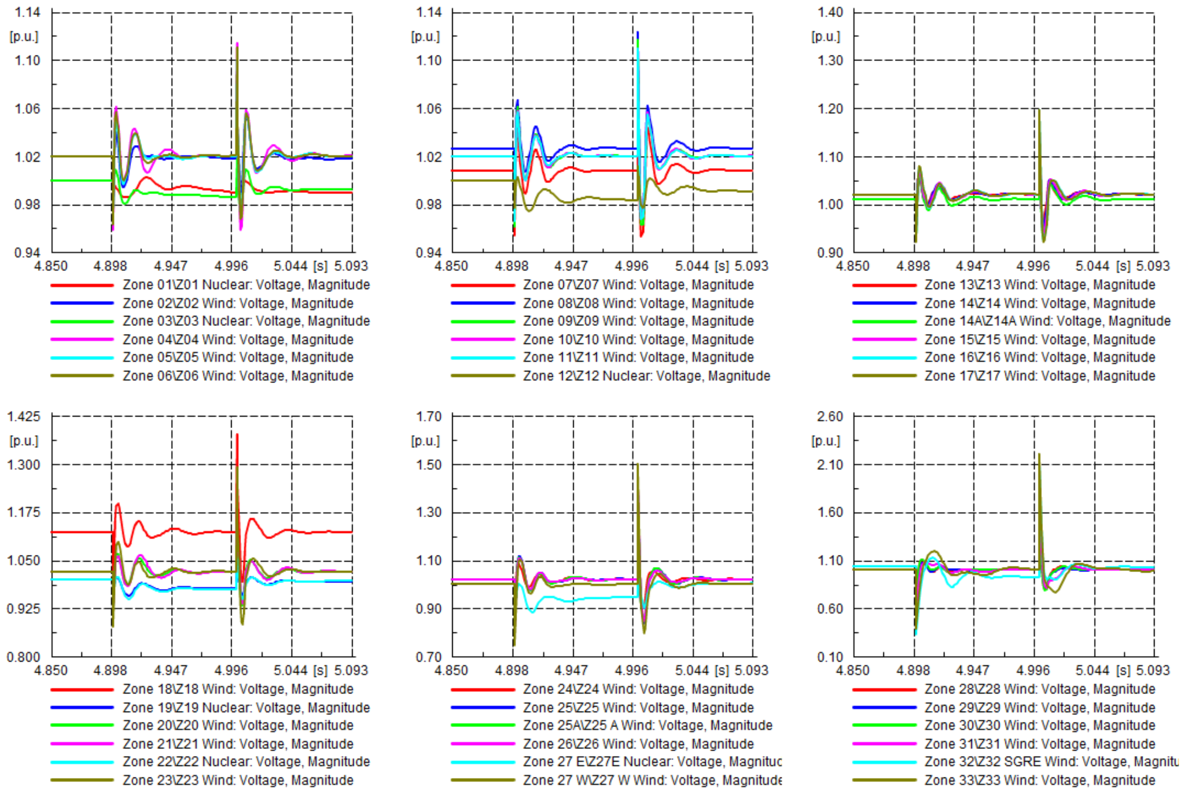


Figure 7-24. Responses of local voltage with Zone 32-33 generation line fault followed by a loss-of-infeed in Zone 32 (2 GVA SGRE wind equally distributed across the system with mean 5 s profile and 20-30% loading)

8 APPENDIX B: GOVERNOR RESPONSES IN THE STUDIED CASES

Table 8-1. Summary of governor response graphs associated with test case scenarios

Figure No.	IR Duration	Data type	Wind Rating	Wind loading	IR Acti. Delay	IR Location
Figure 8-1	10 s	Conservative	2 GVA	20-30%	500 ms	South
Figure 8-2		Conservative	2 GVA	20-30%	1000 ms	South
Figure 8-3		Conservative	2.5 GVA	20-30%	500 ms	South
Figure 8-4		Mean	2.5 GVA	20-30%	500 ms	South
Figure 8-5		Conservative	2.5 GVA	30-40%	500 ms	South
Figure 8-6		Mean	2.5 GVA	30-40%	500 ms	South
Figure 8-7		Conservative	2 GVA	40-50%	500 ms	South
Figure 8-8		Mean	2 GVA	40-50%	500 ms	South
Figure 8-9		Conservative	2 GVA	20-30%	500 ms	North
Figure 8-10	5 s	Conservative	2 GVA	20-30%	500 ms	South
Figure 8-11		Conservative	2 GVA	20-30%	1000 ms	South
Figure 8-12		Conservative	4 GVA	20-30%	500 ms	South
Figure 8-13		Mean	4.5 GVA	20-30%	500 ms	South
Figure 8-14		Conservative	4 GVA	30-40%	500 ms	South
Figure 8-15		Mean	4 GVA	30-40%	500 ms	South
Figure 8-16		Conservative	3 GVA	40-50%	500 ms	South
Figure 8-17		Mean	4 GVA	40-50%	500 ms	South
Figure 8-18		Conservative	2.5 GVA	50-60%	500 ms	South
Figure 8-19		Mean	3.5 GVA	50-60%	500 ms	South
Figure 8-20		Conservative	2.5 GVA	60-70%	500 ms	South
Figure 8-21		Mean	3 GVA	60-70%	500 ms	South
Figure 8-22		Conservative	2.5 GVA	70-80%	500 ms	South
Figure 8-23		Mean	3 GVA	70-80%	500 ms	South
Figure 8-24		Conservative	2.5 GVA	80-90%	500 ms	South
Figure 8-25		Mean	3.5 GVA	80-90%	500 ms	South
Figure 8-26		Conservative	4 GVA	90-100%	500 ms	South
Figure 8-27		Mean	8 GVA	90-100%	500 ms	South
Figure 8-28		Conservative	2 GVA	20-30%	500 ms	North

In the 36-bus system model, it is assumed that there is sufficient primary and secondary reserve available to the loss of generation events simulated.

Governor responses for the selected case studies are shown in this section. Table 8-1 gives a summary of the test case scenarios associated with the governor response graphs shown in this section.

Figure 8-1 gives an example of the responses from synchronous generators in the system with respect to the loss-of infeed event (the corresponding response of SGRE wind IR is shown in Figure 4-6). In this example, the SGRE windfarm is rated at 2 GVA, i.e. maximum of 200 MW output during wind IR, with 10 s conservative profile and a loading level of 20-30%. It can be seen that the synchronous generators starts to ramp up power after the loss of infeed event at 5s. With the IR being activated after 500ms of the frequency event and outputting 200MW of power for 10s, it suddenly drops its power at around 16s after providing IR and this is when the synchronous generators (with available reserve) start to react automatically by increasing their power output to contain the second frequency deviation. The total active power output from the activated synchronous generators before the loss-of-infeed event is about 12126 MW, and after the 1320 MW loss-of-infeed event and SGRE wind IR contribution (maximum of 200 MW with a duration of 10 s during IR), it is increased to 13170 MW (increment of 1044 MW). It should be noted that the power increment from synchronous generation is less than 1120MW (event size 1320 MW minus wind IR output 200 MW) due to the regional voltage variations thus different power required as seen by the synchronous generators across the system.

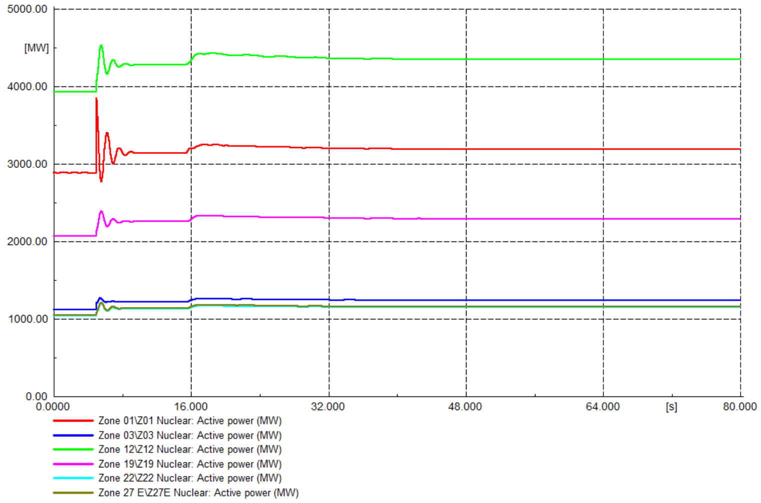


Figure 8-1. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (2 GVA SGRE wind with 10 s conservative profile, 20-30% loading, 500 ms delay in IR activation, and located in South Zone 01)

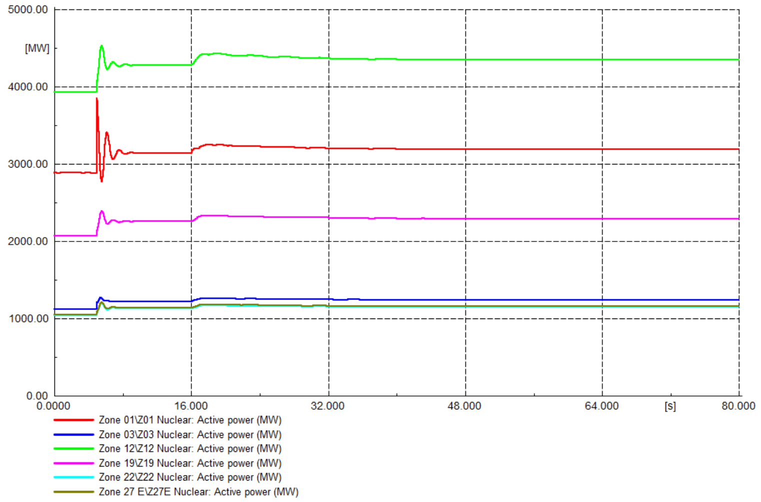


Figure 8-2. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (2 GVA SGRE wind with 10 s conservative profile, 20-30% loading, 1000 ms delay in IR activation, and located in South Zone 01)

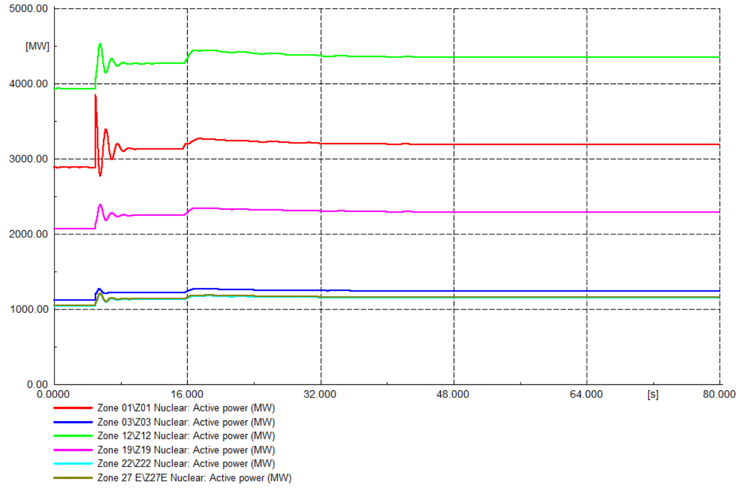


Figure 8-3. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (2.5 GVA SGRE wind with 10 s conservative profile, 20-30% loading, 500 ms delay in IR activation, and located in South Zone 01)

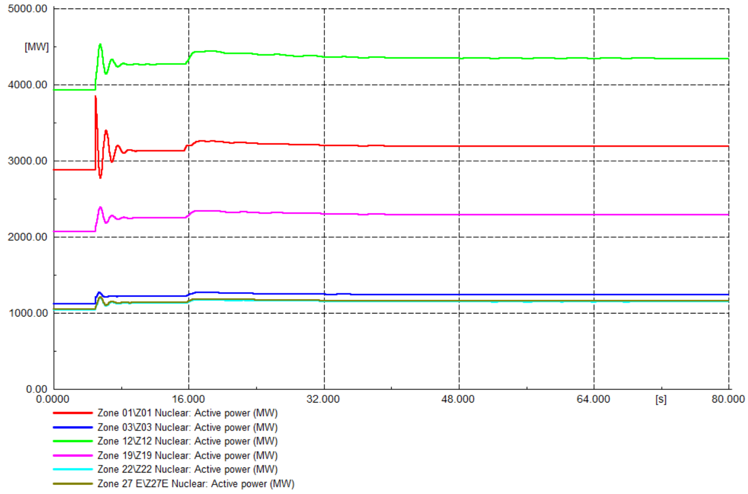


Figure 8-4. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (2.5 GVA SGRE wind with 10 s mean profile, 20-30% loading, 500 ms delay in IR activation, and located in South Zone 01)

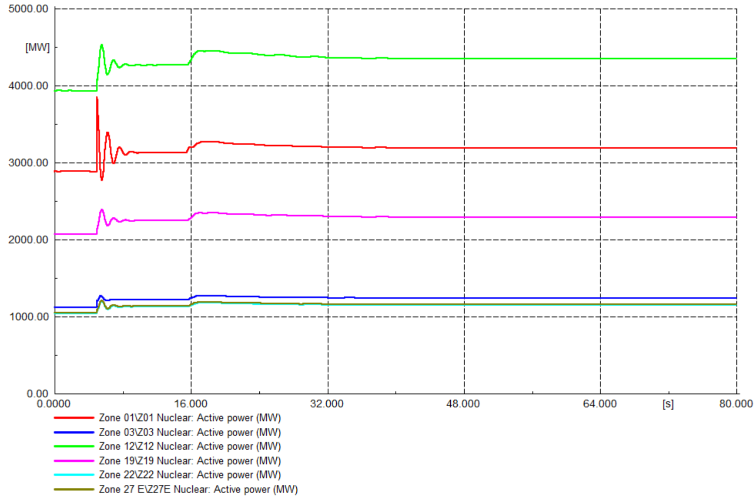


Figure 8-5. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (2.5 GVA SGRE wind with 10 s conservative profile, 30-40% loading, 500 ms delay in IR activation, and located in South Zone 01)

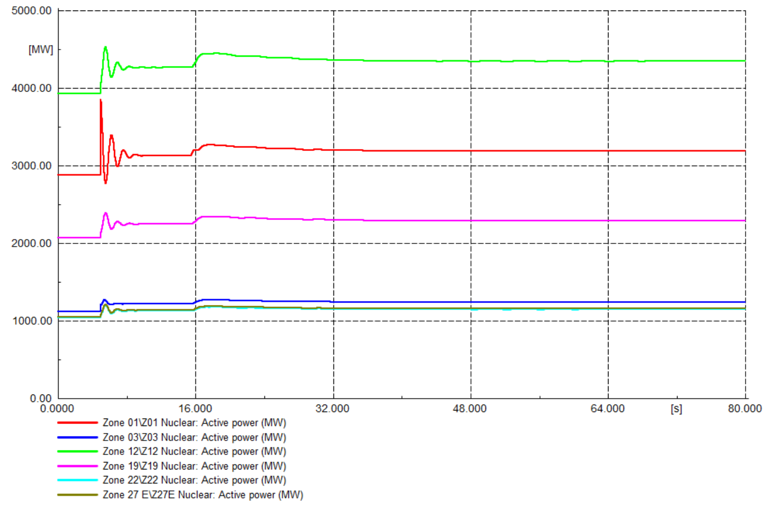


Figure 8-6. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (2.5 GVA SGRE wind with 10 s mean profile, 30-40% loading, 500 ms delay in IR activation, and located in South Zone 01)

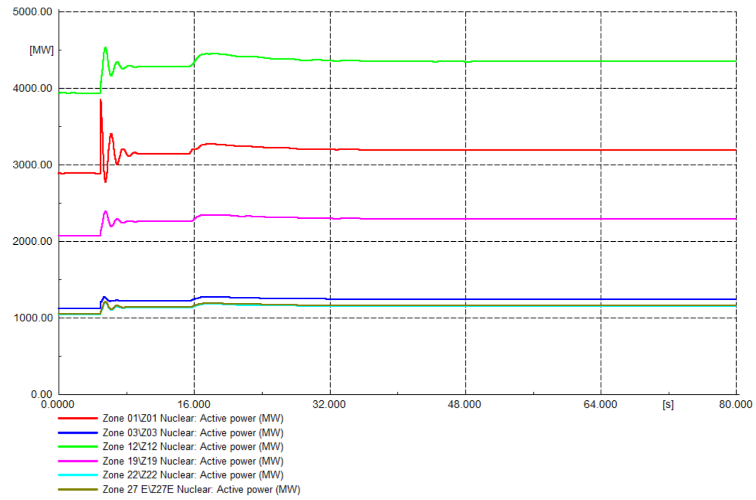


Figure 8-7. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (2 GVA SGRE wind with 10 s conservative profile, 40-50% loading, 500 ms delay in IR activation, and located in South Zone 01)

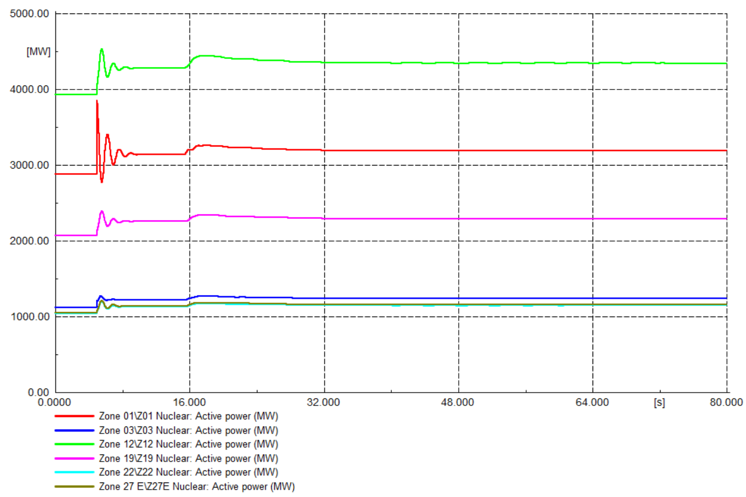


Figure 8-8. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (2 GVA SGRE wind with 10 s mean profile, 40-50% loading, 500 ms delay in IR activation, and located in South Zone 01)

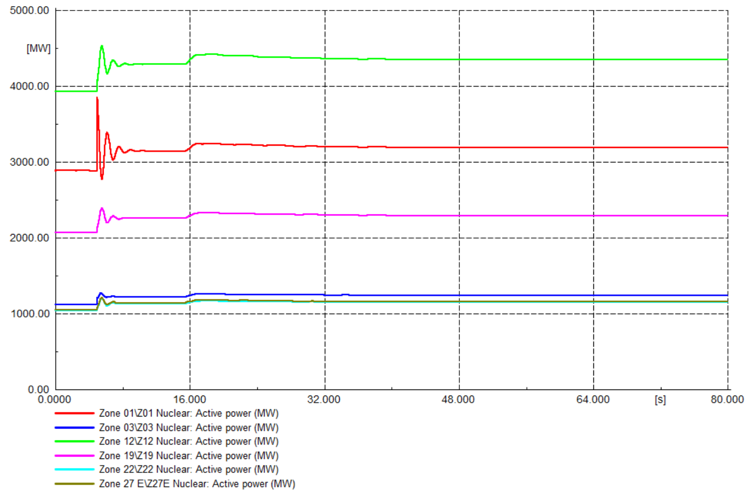


Figure 8-9. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (2 GVA SGRE wind with 10 s conservative profile, 20-30% loading, 500 ms delay in IR activation, and located in North Zone 32)

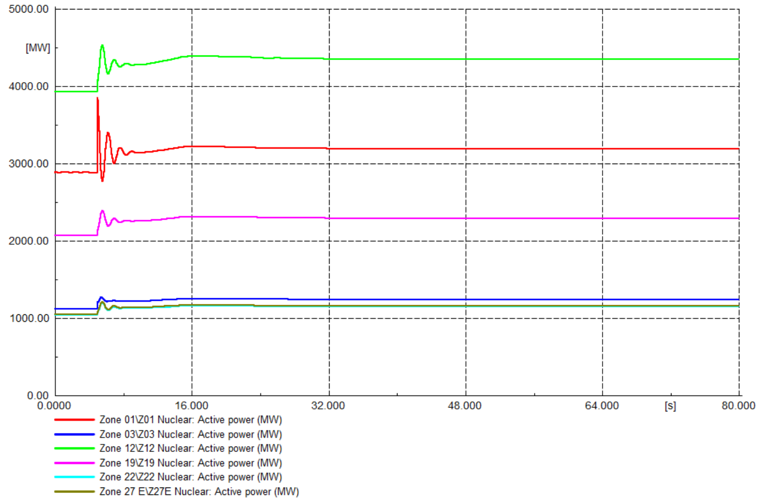


Figure 8-10. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (2 GVA SGRE wind with 5 s conservative profile, 20-30% loading, 500 ms delay in IR activation, and located in South Zone 01)

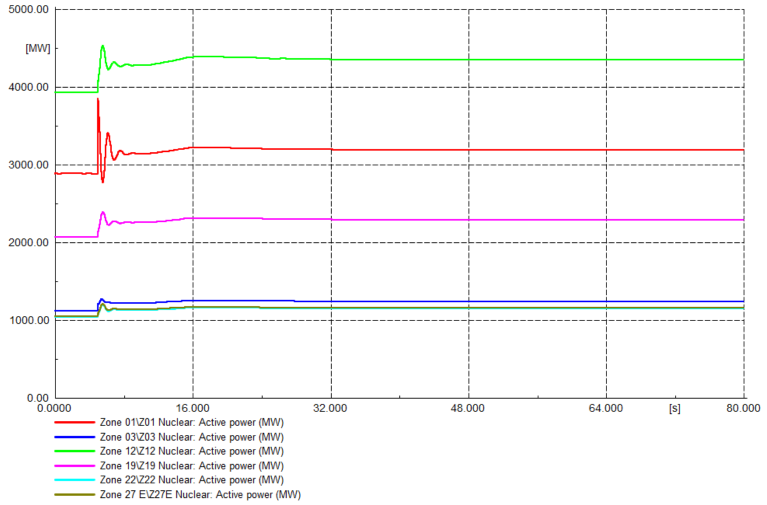


Figure 8-11. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (2 GVA SGRE wind with 5 s conservative profile, 20-30% loading, 1000 ms delay in IR activation, and located in South Zone 01)

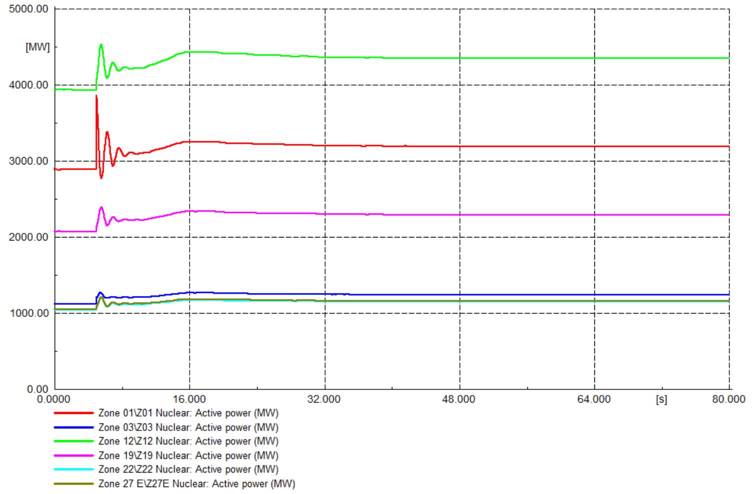


Figure 8-12. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (4 GVA SGRE wind with 5 s conservative profile, 20-30% loading, 500 ms delay in IR activation, and located in South Zone 01)

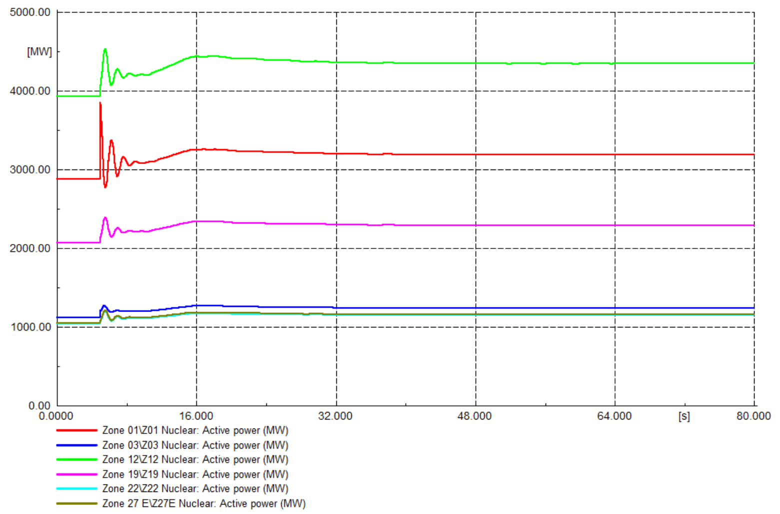


Figure 8-13. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (4.5 GVA SGRE wind with 5 s mean profile, 20-30% loading, 500 ms delay in IR activation, and located in South Zone 01)

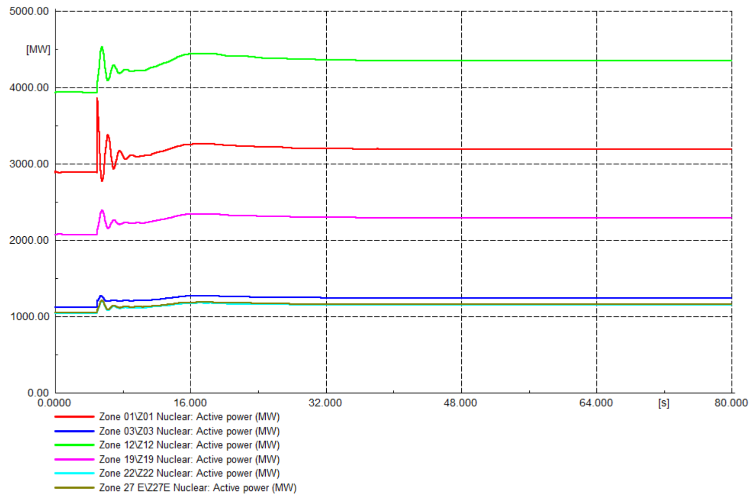


Figure 8-14. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (4 GVA SGRE wind with 5 s conservative profile, 30-40% loading, 500 ms delay in IR activation, and located in South Zone 01)

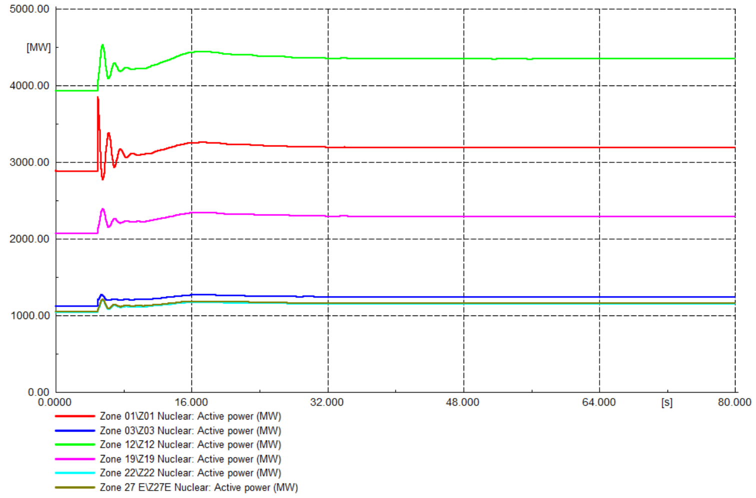


Figure 8-15. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (4 GVA SGRE wind with 5 s mean profile, 30-40% loading, 500 ms delay in IR activation, and located in South Zone 01)

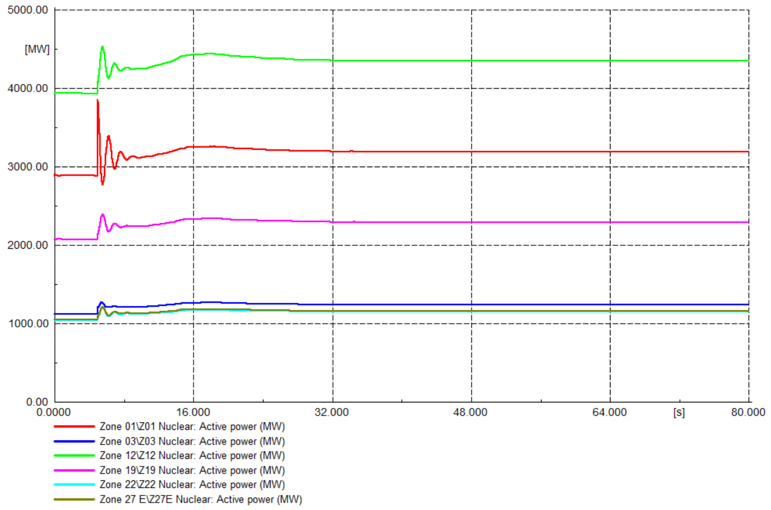


Figure 8-16. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (3 GVA SGRE wind with 5 s conservative profile, 40-50% loading, 500 ms delay in IR activation, and located in South Zone 01)

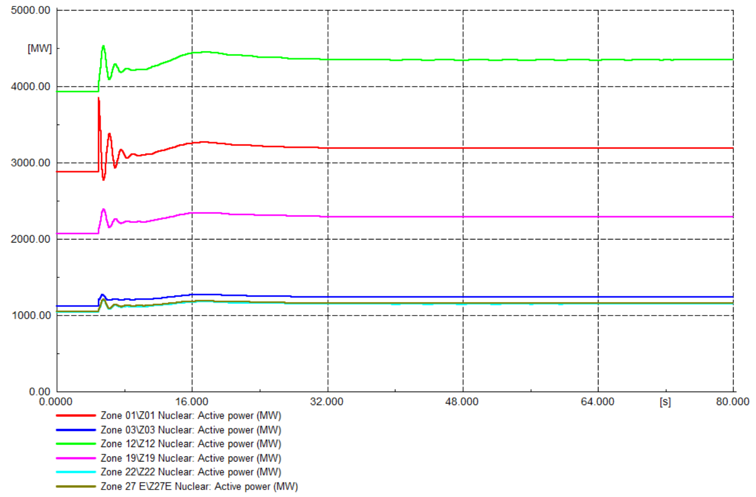


Figure 8-17. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (4 GVA SGRE wind with 5 s mean profile, 40-50% loading, 500 ms delay in IR activation, and located in South Zone 01)

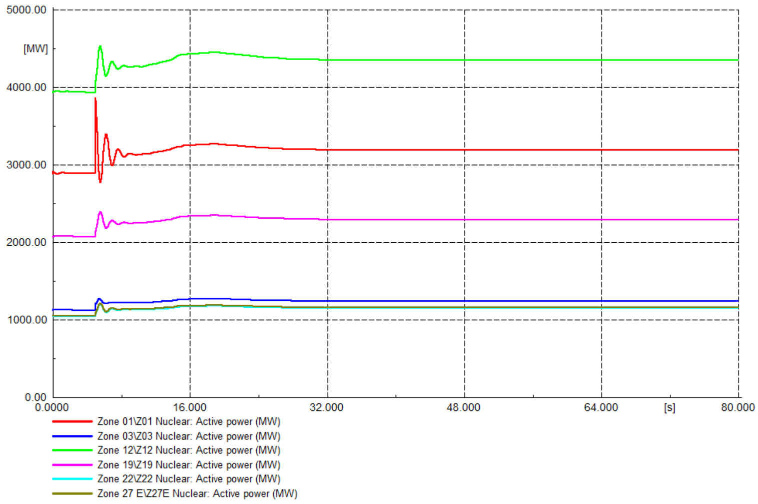


Figure 8-18. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (2.5 GVA SGRE wind with 5 s conservative profile, 50-60% loading, 500 ms delay in IR activation, and located in South Zone 01)

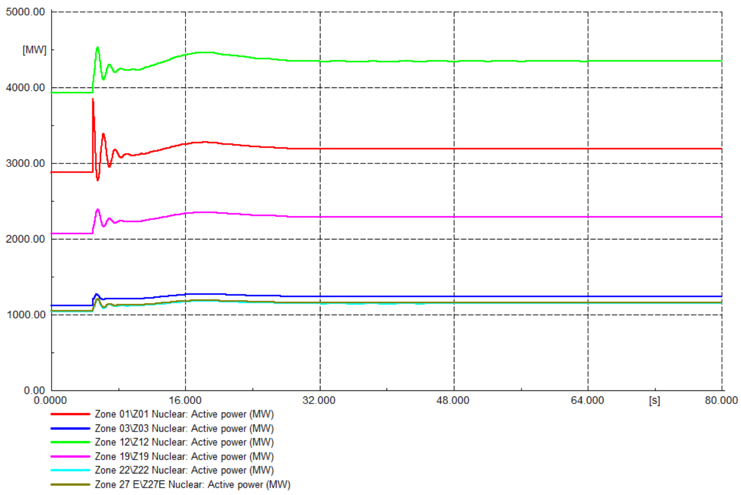


Figure 8-19. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (3.5 GVA SGRE wind with 5 s mean profile, 50-60% loading, 500 ms delay in IR activation, and located in South Zone 01)

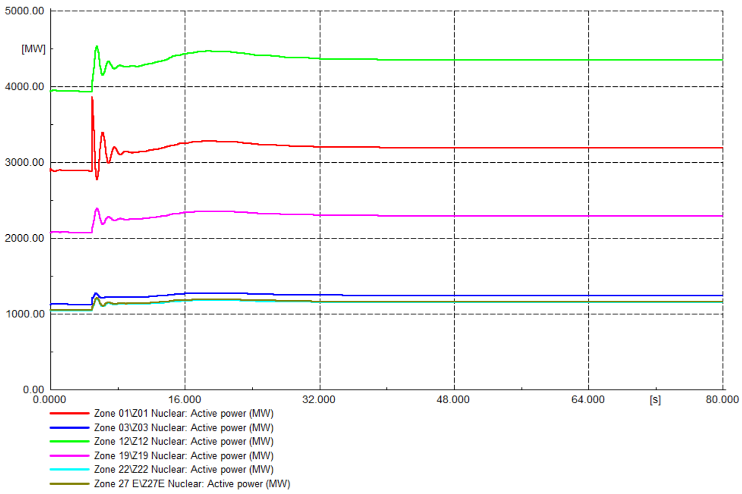


Figure 8-20. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (2.5 GVA SGRE wind with 5 s conservative profile, 60-70% loading, 500 ms delay in IR activation, and located in South Zone 01)

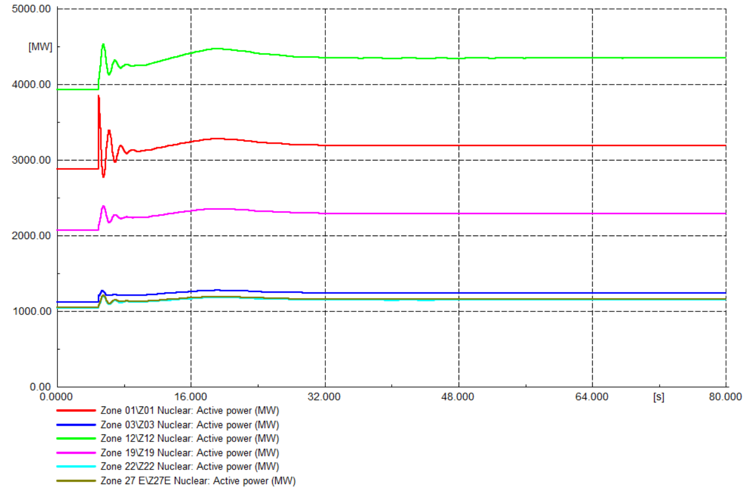


Figure 8-21. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (3 GVA SGRE wind with 5 s mean profile, 60-70% loading, 500 ms delay in IR activation, and located in South Zone 01)

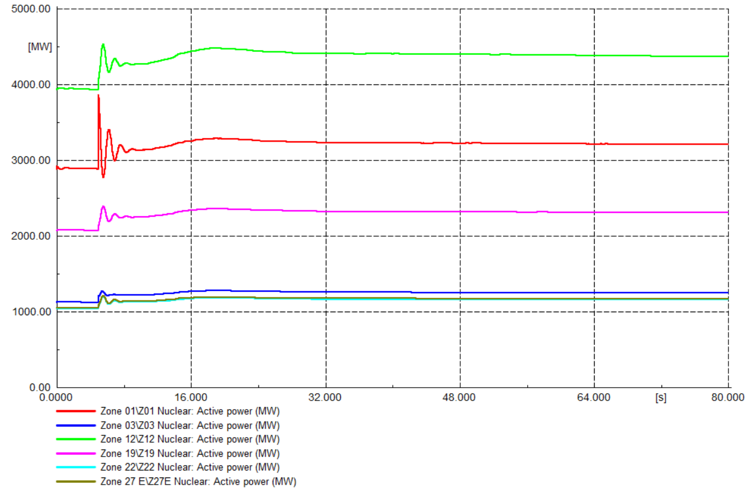


Figure 8-22. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (2.5 GVA SGRE wind with 5 s conservative profile, 70-80% loading, 500 ms delay in IR activation, and located in South Zone 01)

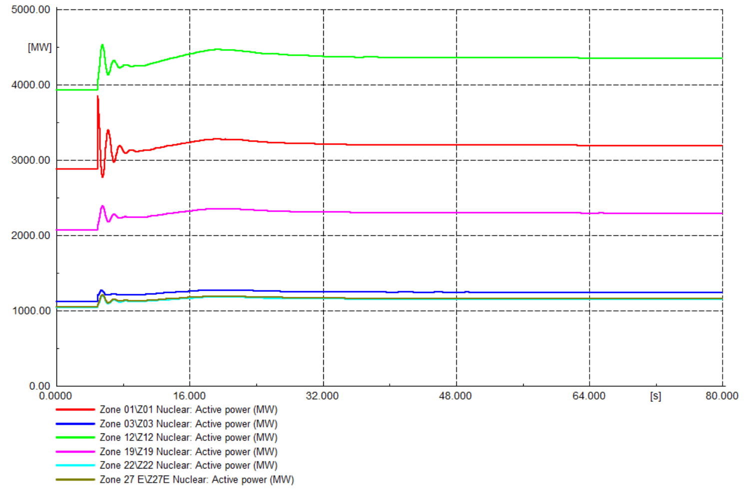


Figure 8-23. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (3 GVA SGRE wind with 5 s mean profile, 70-80% loading, 500 ms delay in IR activation, and located in South Zone 01)

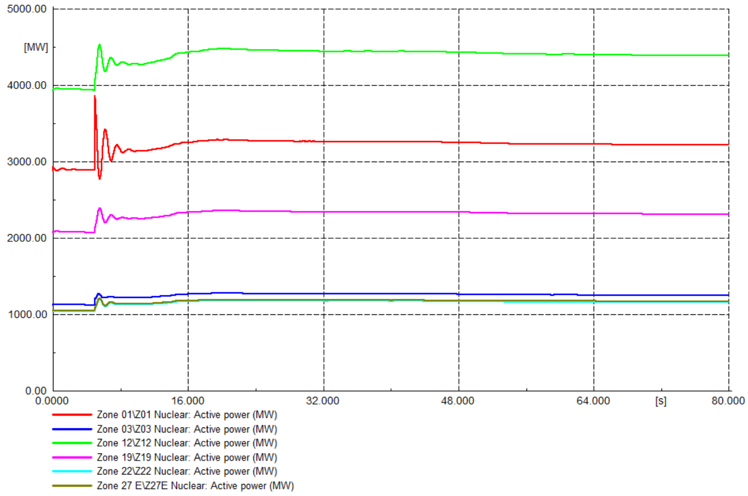


Figure 8-24. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (2.5 GVA SGRE wind with 5 s conservative profile, 80-90% loading, 500 ms delay in IR activation, and located in South Zone 01)

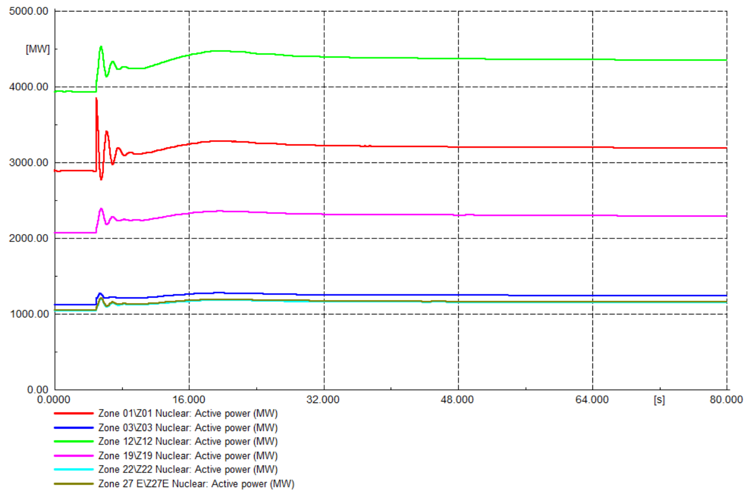


Figure 8-25. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (3.5 GVA SGRE wind with 5 s mean profile, 80-90% loading, 500 ms delay in IR activation, and located in South Zone 01)

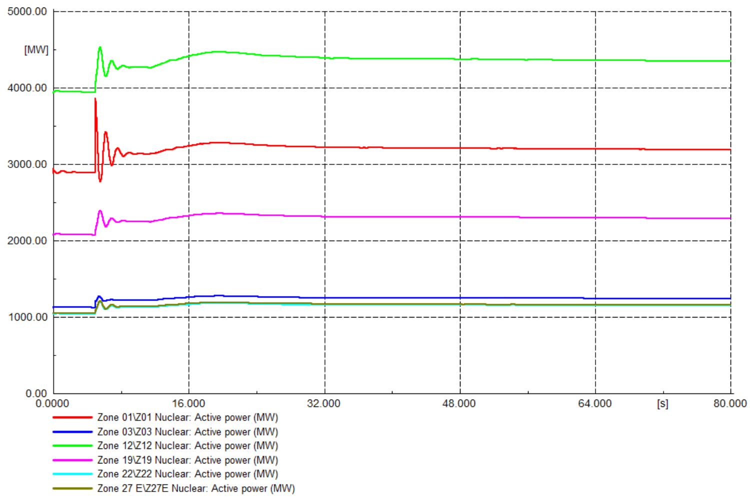


Figure 8-26. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (4 GVA SGRE wind with 5 s conservative profile, 90-100% loading, 500 ms delay in IR activation, and located in South Zone 01)

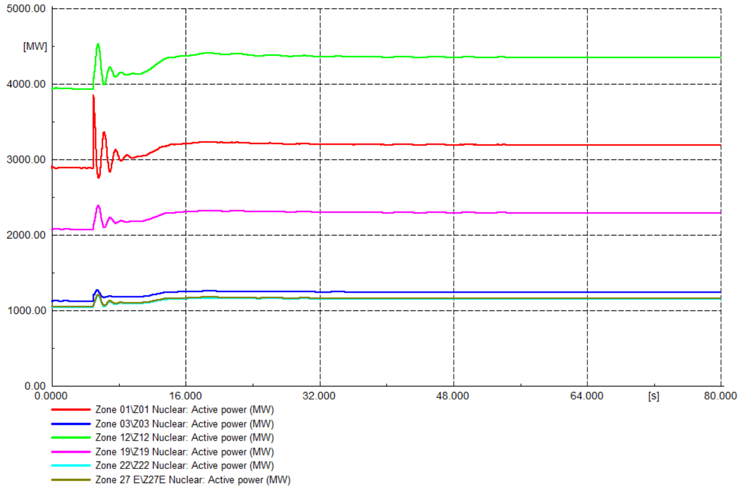


Figure 8-27. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (8 GVA SGRE wind with 5 s mean profile, 90-100% loading, 500 ms delay in IR activation, and located in South Zone 01)

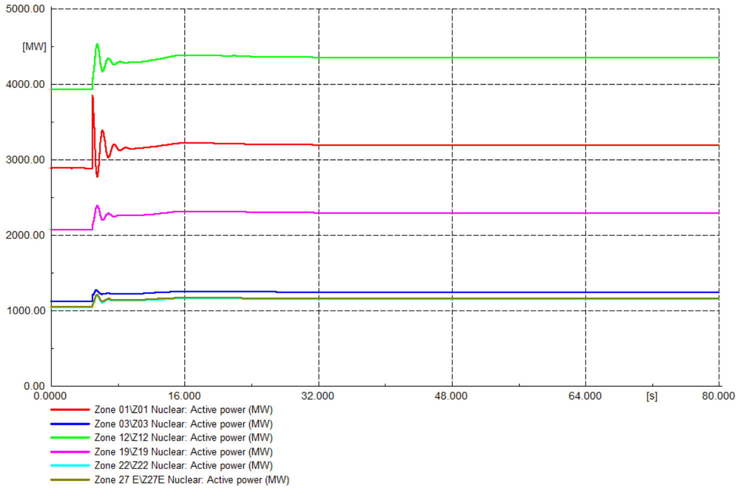


Figure 8-28. Responses of synchronous generators in the system to the loss-of-infeed event and SGRE wind IR (2 GVA SGRE wind with 5 s conservative profile, 20-30% loading, 500 ms delay in IR activation, and located in North Zone 32)