Impact of Short-circuit Ratio on Grid Integration of Wind Farms - A New Zealand Perspective

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***Abstract*—The high wind energy potential sites are increasingly remote from the load centers which create problems in integrating wind power plants into power grids. One of the major issues is the short-circuit ratio (SSR) at the point of common coupling. A lower short-circuit ratio will lead to a weaker grid which in turn creates power system stability problems. The definition of a weak grid depends on short-circuit ratio values. In New Zealand, it is often noted that the definition of a weak grid, based on SSR,is different from that of standard values (of SSR) due to several reasons.**

New Zealands grid is long and slender with arguably major generation at one end and load centers at the other side. Close to 80% of daily consumption of electricity is generated from renewables with 5-8% contributed by Wind generation. Wind farm locations in New Zealand share the same difficulties as shared by many nations in terms of remote locations, far away from load centers and wind variability. However, New Zealand wind farm capacity factor is close to 45% and maximum capacity of around 400 hours a year. Over 20 new wind farms have been consented for future with capacity close to 3GW.

This work shares our experience in connecting future wind farms to New Zealand grid and their effect on the weak grid concept. We will discuss the reasons for our definition of short-circuit ratio in New Zealand scenario and, in support, share some results of our simulations.

I. Introduction

The demand for electricity is dependent on various factors viz. GDP, energy costs, wealth and number of the population [1]. The energy consumption of New Zealand was about 38,800 gigawatt hours (GWh) in 2017 consisting of 1.72 million residential, 175,000 commercial and 123,000 industrial customers. NZ has over 219 generating stations with a mix of generation types, as shown in Fig. 1 [2].

On average, from all the generation in New Zealand, 59% of the generation is from hydro, 17% geothermal, 16% thermal, 5% wind and 3% from co-generation [2]. Wind and solar energy installations are growing rapidly in the past few years. The generation contribution of wind energy is growing at a proportion of nations electricity demand [1]. Currently, 700 MW large-scale wind energy is operational and new wind farms are either in consent and construction phases [2].

Geographically, NZ is divided into two Islands, viz. North Island and South Island. The major load centres of the country are in North Island, as shown in Fig.2 [3]. Historically, NZ's electrical power system was distributed with local generation supplying the load centres until 1950s [3]. The major power generation source was Hydro. Eventually,

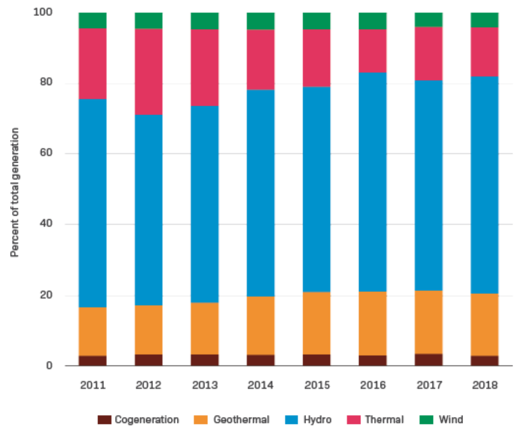

Fig. 1. Energy by technology type in NZ [2].

the load has grown and the power system was connected using high voltage transmission system [3].

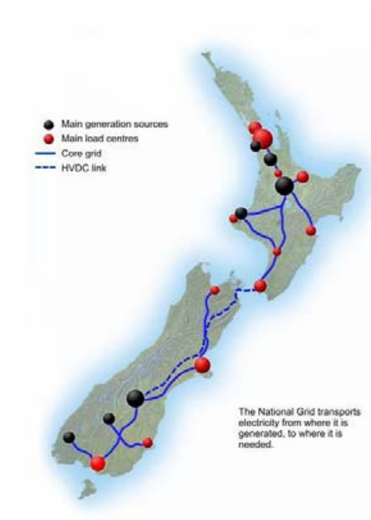

Fig. 2. Map of the New Zealand electricity system showing the main load centres and main generation sources [3].

The first wind farm connected to the power grid in New Zealand was in the year of 2004. Since then, over 16 wind farms have been developed with 490 turbines and a capacity of 690MW [4].

The interconnection of wind farms to the transmission networks can cause the fluctuations in voltage and power flows in the system [5]. Also, the inherent nature of the wind power variability results in the need for reactive power that affects the bus voltages and transformer taps [6]. Hence, the operators of wind farms should regulate the voltage at point of connection (PoC) [7] imposed by system operators.

The impedance and mechanical inertia of a power system determines the strength of any grid [8]. An alternative way of determining the strength is with short circuit ratio (SCR) [9]. SCR does not represent the strength of entire grid but only at specific (measured) nodes of the power grid [10]. Hence, different parts of the grid may have different values of SCR [11].

A grid is defined as a weak grid if its SCR values is less than 3 [12] at the point of connection. The definition is supported by both IEEE [13] and NERC [9]. However, research states there should be a distinction between a weak grid and grid with low SCR [10]. The SCR of a node represents the ability of a bus to withstand the voltage fluctuations in response to a fault. Although, SCR is evaluated based on the steady state parameters of the power system, it represents the capacity of a bus during dynamic system disturbances [14].

This paper presents an analysis of SCR on voltage and active power profiles at PoC and wind turbine terminals during a fault ride through scenario. The transmission system model of the entire New Zealand power grid is used in evaluating the short circuit levels of the system at all the nodes.

II. Methodology

The calculation of short-circuit ratio requires short-circuit levels at the nodes of the power system. The minimum three-phase short-circuit levels are calculated according to IEC 60909 at all the nodes of the NZ power network using System Operator's model in DiGSilent PowerFactory. The single line diagram consists of the complete transmission network of North and South Island along with the interconnecting underwater HVDC link.

Based on the short-circuit levels observed, the point of connections for wind farm interconnection were selected for this study. The lower and higher short-circuit capacity nodes were selected to compare the system performance for different short circuit ratios. The short circuit ratios were evaluated based on the short circuit levels and the wind farm name plate ratings.

At PoC, an infinite grid with the selected short circuit capacity is modelled to connect the wind farm. The wind farm with different name plate ratings were modelled and connected at the PoC to create a low and high SCR scenarios. This completes the modelling of case to be studied in DigSilent Powerfactory. The load data included in the study was for 13 December 2018.

The fault ride through (FRT) studies were carried as follows:

1) The FRT study shall be carried out by keeping the park controller in V control mode.
2) The OLTC of the WF Transformer (if any) shall be locked at a nominal position.
3) In pre-fault condition, the power dispatch at the PoC should be Maximum Real power with Zero Reactive power output.
4) Create a solid 3-phase fault at the PoC with a fault clearance time of 140 ms.
5) Record the V, P and Q graphs at the PoC and WF terminals.
6) Repeat the study for different values of SCR.

III. Case Study

A. System model

The wind farm used in this study was a type 4 model from Powerfactory, as shown in Fig. 3 The base model consist of six wind turbines with a rating of 2.5 MW. Each wind turbine has a step-up transformer of 0.69/20 kV. The wind turbines are connected to a wind farm substation which has a capacitor bank to support the reactive power. A park controller at PoC has been used to operate the farm in Voltage/Reactive Power/Power Factor mode, as depicted in Fig. 4 [15]. An individual controller at each Wind Turbine has been to control the active/reactive power output from the wind turbines, as shown in Fig. 5 [15]. A Master-Slave control approach is applied by selecting the park controller in Voltage control mode and the individual wind turbines in reactive power mode such that the wind farm will support the grid at PoC for any voltage variations. At the wind farm substation, a step-up transformer of 20/110(220) kV is modelled at the PoC. Wind farm rating is scaled up to 150 MW to perform wider SCR scenarios.

B. Short circuit ratio calculations

A three-phase short circuit analysis was performed on the NZ transmission network model to identify the short-circuit capacities. The short circuit capacities varied from 222 MVA to 3376 MVA across the country. However, only three cases with least short circuit capacity from each North and South Island are considered for this analysis. The wind farm name plate rating of 15 MW to 150 MW (Capacities currently under operation in NZ) were connected to calculate the SCR. SCRs evaluated using eq(1), are summarised in Tables-I to VI.

$$SCR = \frac{S_{cc}}{S_{wf}} \tag{1}$$

where S_{cc} is the short circuit level at the bus without connecting the wind farm and S_{wf} is the wind farm name plate rating in MW [7].

TABLE I: Short Circuit Ratios for Westport node of South Island.

S.No.	SC (MVA)	Wind farm rating (MW)	SCR
1	222.68	10	22.27
2	222.68	15	14.85
3	222.68	30	7.42
4	222.68	45	4.95
5	222.68	60	3.71
6	222.68	75	2.97
7	222.68	90	2.47
8	222.68	105	2.12
9	222.68	120	1.86
10	222.68	135	1.65
11	222.68	150	1.48

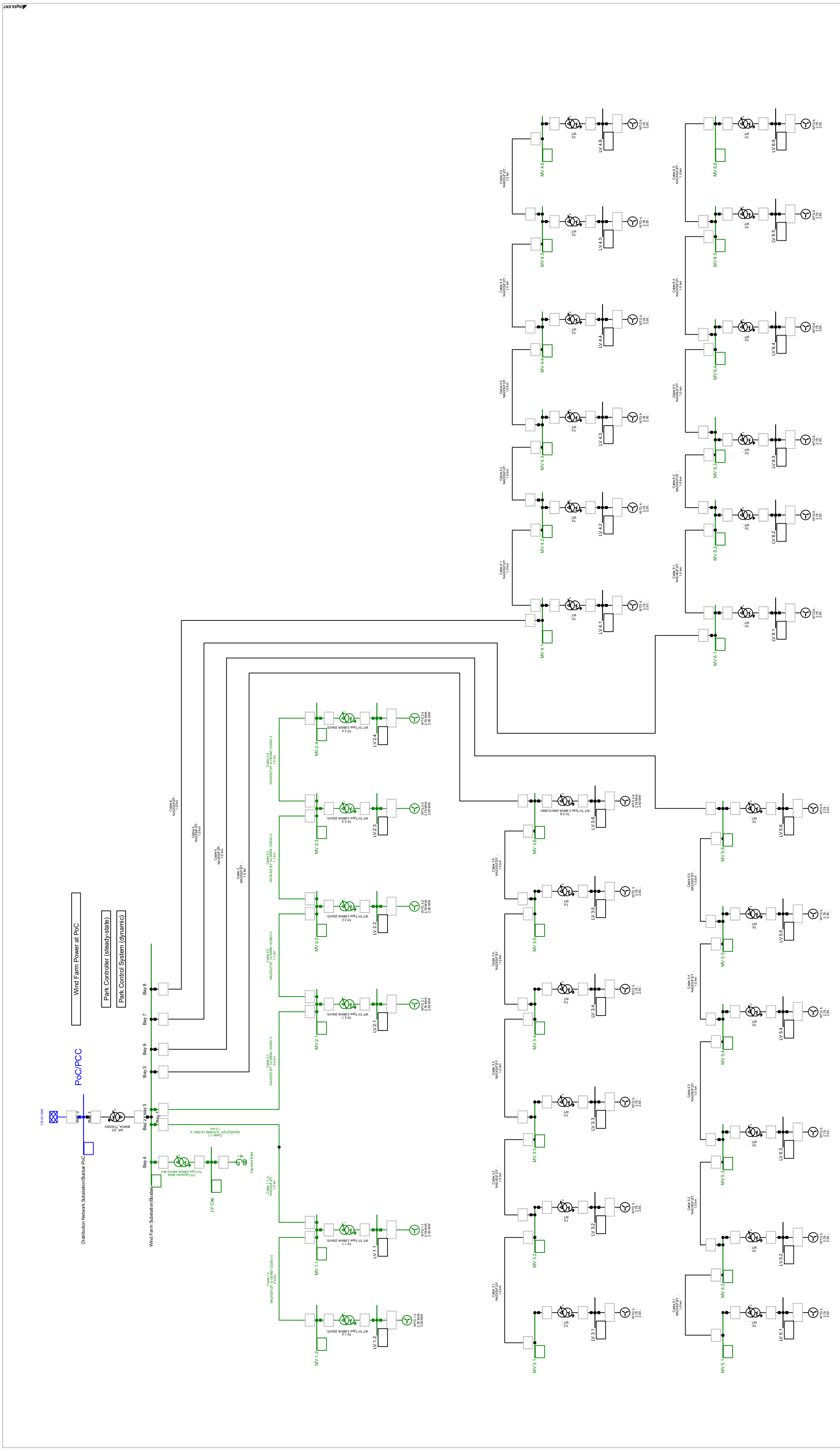

Fig. 3. Wind farm model in Powerfactory.

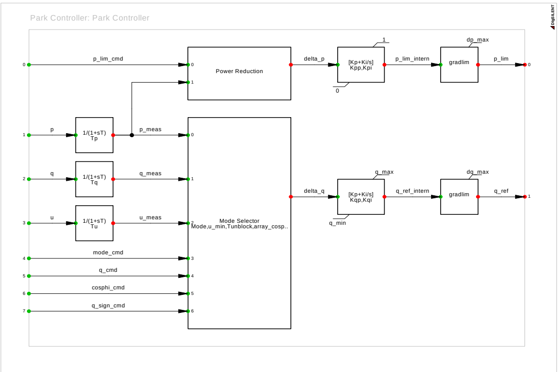

Fig. 4. Wind farm park controller [15].

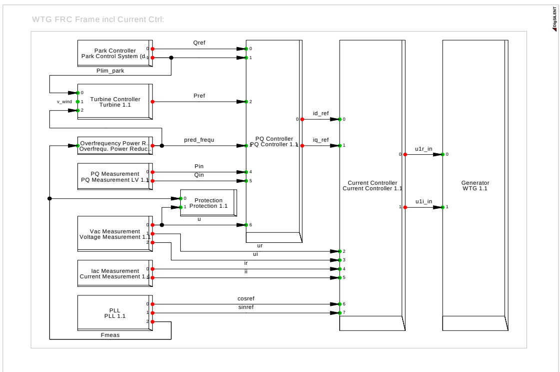

Fig. 5. Wind turbine controller [15].

TABLE II: Short Circuit Ratios for Reefton node of South Island.

S.NO.	SC (MVA)	Wind farm rating (MW)	SCR
1	275.17	15	18.34
2	275.17	30	9.17
3	275.17	45	6.11
4	275.17	60	4.59
5	275.17	75	3.67
6	275.17	90	3.06
7	275.17	105	2.62
8	275.17	120	2.29
9	275.17	135	2.04
10	275.17	150	1.83

TABLE III: Short Circuit Ratios for Oamaru node of South Island.

S.No.	SC (MVA)	Wind farm rating (MW)	SCR
1	321.23	15	21.42
2	321.23	30	10.71
3	321.23	45	7.14
4	321.23	60	5.35
5	321.23	75	4.28
6	321.23	90	3.57
7	321.23	105	3.06
8	321.23	120	2.68
9	321.23	135	2.38
10	321.23	150	2.14

TABLE IV: Short Circuit Ratios for Kaitaia node of North Island.

S.No.	SC (MVA)	Wind farm rating (MW)	SCR
1	238.57	15	15.90
2	238.57	30	7.95
3	238.57	45	5.30
4	238.57	60	3.98
5	238.57	75	3.18
6	238.57	90	2.65
7	238.57	105	2.27
8	238.57	120	1.99
9	238.57	135	1.77
10	238.57	150	1.59

TABLE V: Short Circuit Ratios for National Park node of North Island.

S.No.	SC (MVA)	Wind farm rating (MW)	SCR
1	297.11	15	19.81
2	297.11	30	9.90
3	297.11	45	6.60
4	297.11	60	4.95
5	297.11	75	3.96
6	297.11	90	3.30
7	297.11	105	2.83
8	297.11	120	2.48
9	297.11	135	2.20
10	297.11	150	1.98

TABLE VI: Short Circuit Ratios for Gisborne node of North Island.

S.No.	SC (MVA)	Wind farm rating (MW)	SCR
1	367.15	15	24.48
2	367.15	30	12.24
3	367.15	45	8.16
4	367.15	60	6.12
5	367.15	75	4.90
6	367.15	90	4.08
7	367.15	105	3.50
8	367.15	120	3.06
9	367.15	135	2.72
10	367.15	150	2.45

C. *Transient stability studies*

The aim of this transient stability studies is to analyse the performance of Wind farm on a sudden disturbance at the PoC under different SCR scenarios. In this study, the sudden disturbance is modelled as a solid three-phase short circuit with fault clearance time of 140 ms. The Wind farm responses (Voltage and Active Power) at the PoC and at wind turbine level are analysed during and after clearing the fault for selected SCR values.

IV. Results and Discussion

Simulations were performed to test the network stability for different SCR levels by varying the wind power generation. The wind farm output was varied to create different SCR scenarios in the power system network. The simulations were performed in DIgSILENT Powerfactory tool [15]. A three-phase solid fault is created at 2 s of and fault is cleared after 140 ms.

The SCR values are calculated at six nodes of the network by increasing the wind farm output in steps of 15 MW. As the short-circuit level at each node is fixed, it is observed that the SCR will decrease with increase in the wind farm output, as illustrated in Fig. 6. The nodes with low short-circuit capacity will see low SCR values for the increased wind farm output.

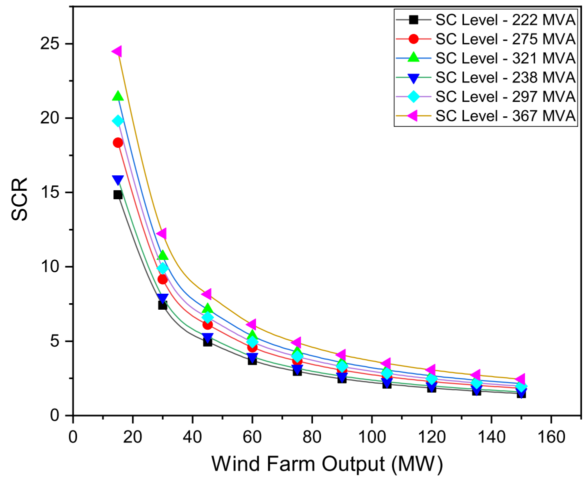

Fig. 6. Variation of SCR for short-circuit capacity and wind farm output.

Stability of the power system for selected nodes is tested for different SCR values. Fig. 7 shows the voltage profiles at the PoC for SCR of 1.48. It is observed that the voltage profile resumes to pre-fault condition after 1029 ms of the fault clearance. Also, during the restoration phase, the voltage overshoot of 41.75%.

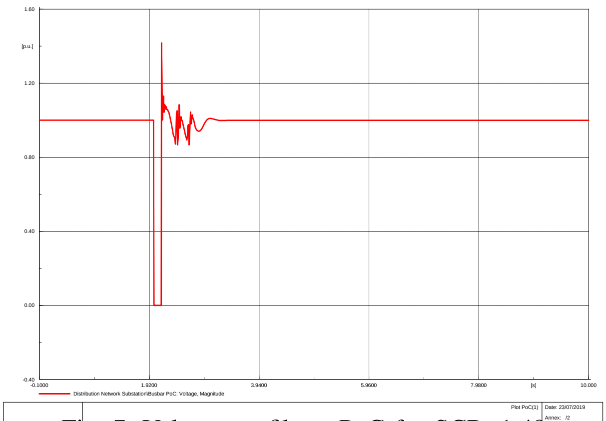

Fig. 7. Voltage profile at PoC for SCR=1.48.

Fig. 8 depicts the voltage profile at the PoC for a short circuit ratio of 1.65. The voltage over-shoot reduces to 38.9% with a restoration of time of 516 ms after the fault clearance. Figs. 9 to 14 illustrate the voltage profile for SCR values from 1.86 to 4.95. The voltage overshoot ranges from 34.7% to 15.44% and restoration times are between 420 ms and 230 ms.

Voltage profiles for SCR values beyond 5 are not demonstrated in this paper, as the percentage over-shoot is within 10% and restoration times in 200 ms after the fault clearances.

Fig. 15 shows the effect of reactive power support at the PoC. It is observed that with the reactive power using the capacitor bank at the PoC improves system stability. The restoration time of 1679 ms is noted without the reactive

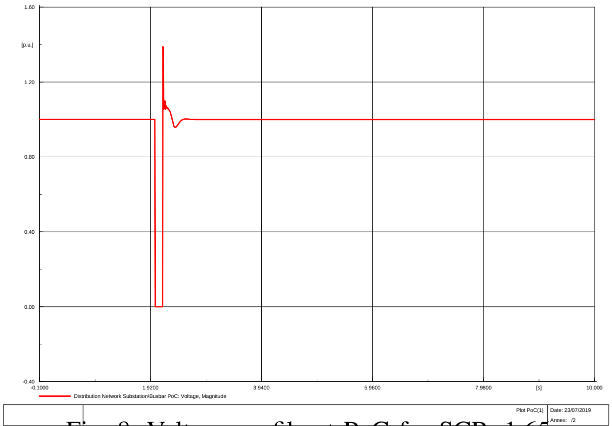

Fig. 8. Voltage profile at PoC for SCR=1.65.

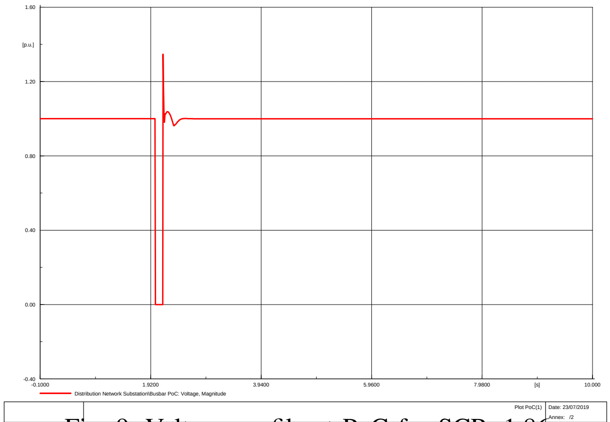

Fig. 9. Voltage profile at PoC for SCR=1.86.

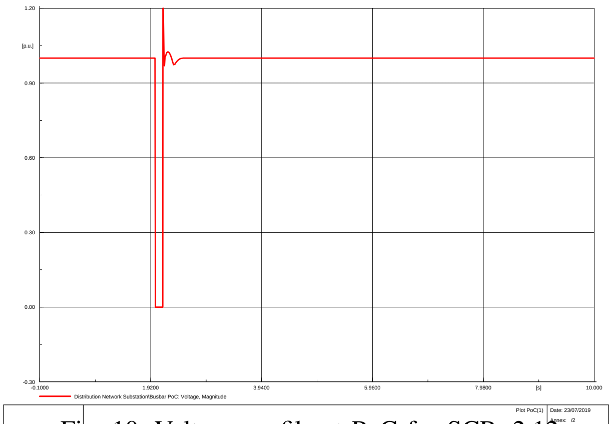

Fig. 10. Voltage profile at PoC for SCR=2.12.

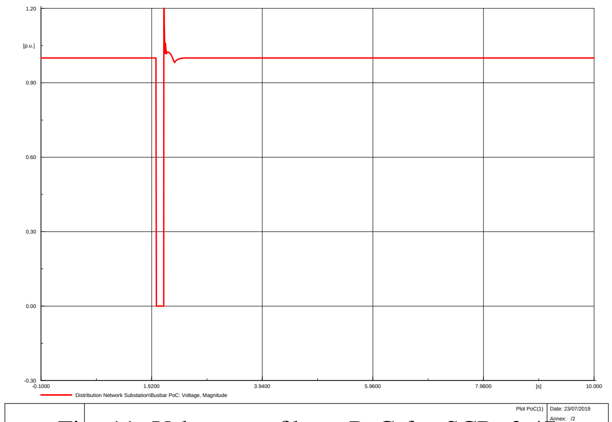

Fig. 11. Voltage profile at PoC for SCR=2.47.

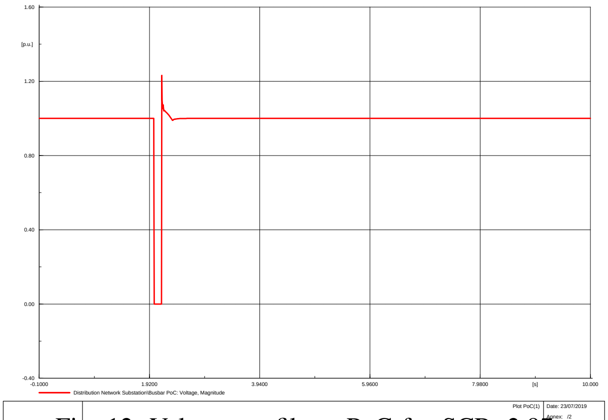

Fig. 12. Voltage profile at PoC for SCR=2.97.

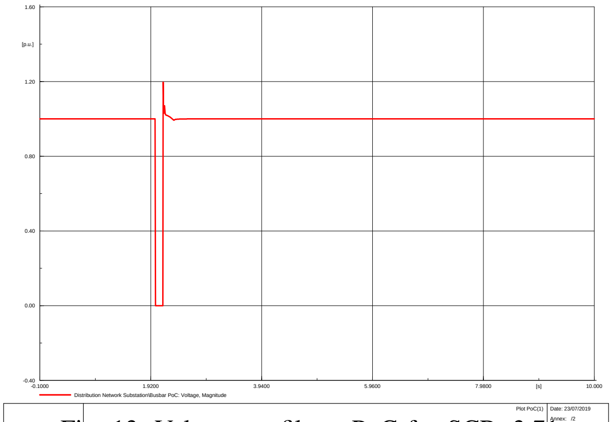

Fig. 13. Voltage profile at PoC for SCR=3.71.

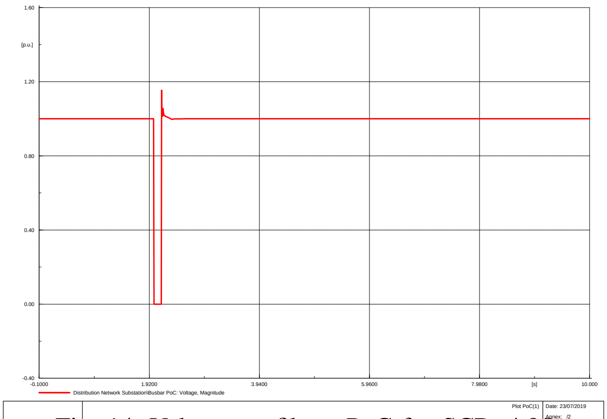

Fig. 14. Voltage profile at PoC for SCR=4.95.

power support as compared to 1029 ms with the reactive power support.

Voltage profile at the PoC for a SCR value of 2.45 at a different node and short circuit capacity is depicted in Fig. 16. It is important to note here that although the SCR is same but with different short circuit capacity, the voltage overshoot is same as that of SCR of 2.47. Hence, it is observed that SCR plays a predominant role in the stability of the system.

Figs. 17 to 24 show the voltage profiles at one of the wind turbines low-voltage terminal. It can be observed that the voltage profile resumes to pre-fault condition after clearance of the fault with an increased voltage overshoot and settling time at PoC, for all SCR values. For low SCR conditions

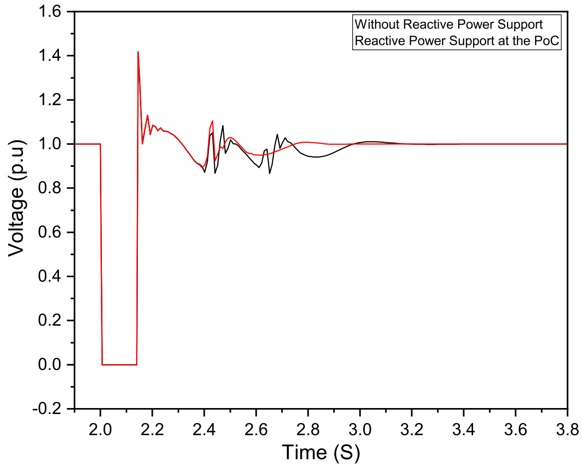

Fig. 15. Effect of reactive power support on the voltage profile at PoC for SCR=1.48.

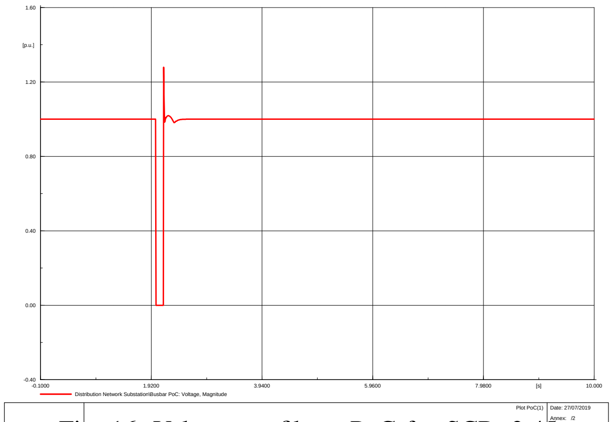

Fig. 16. Voltage profile at PoC for SCR=2.45.

(i.e. SCR=1.48), there is an overshoot of 44.63% and the settling time is around 1800 ms. For high SCR condition (i.e. SCR=22.27), there is an overshoot of 9.47% and the setting time is around 480 ms. The large spikes can drive the wind turbines into over-voltage ride through (OVRT) mode. The measured voltage disturbances can also be fatal for the power electronic components in the WTG converters.

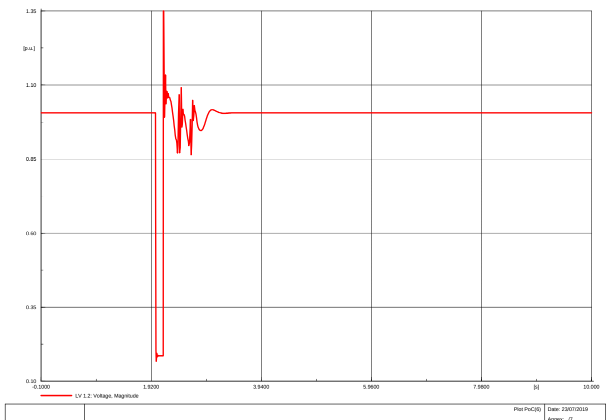

Fig. 17. Voltage profile at WTG for SCR=1.48.

Figs. 25 to 27 illustrate the active power response at the PoC for SCRs of 1.48, 1.65 and 14.85. During pre-fault condition, at PoC, the wind farm was injecting 145.34 MW

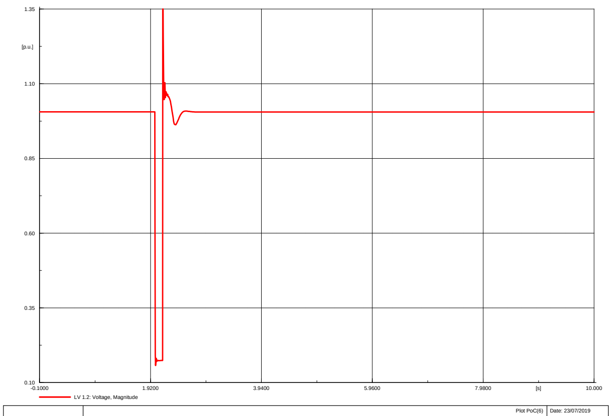

Fig. 18. Voltage profile at WTG for SCR=1.65.

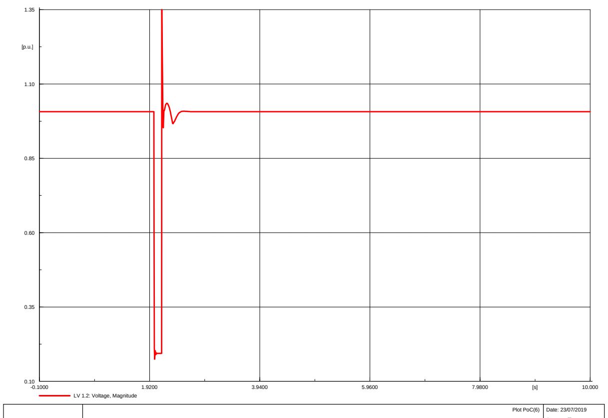

Fig. 19. Voltage profile at WTG for SCR=1.86.

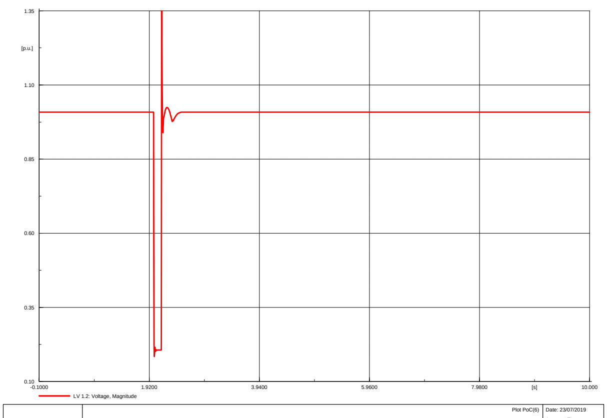

Fig. 20. Voltage profile at WTG for SCR=2.12.

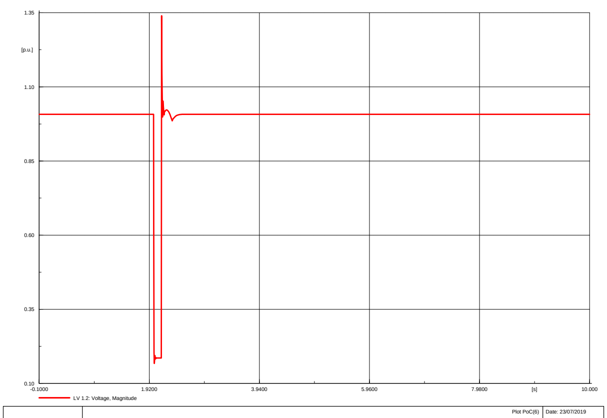

Fig. 21. Voltage profile at WTG for SCR=2.47.

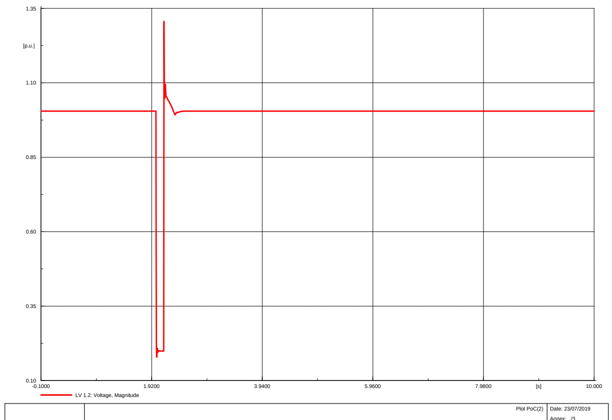

Fig. 22. Voltage profile at WTG for SCR=2.97.

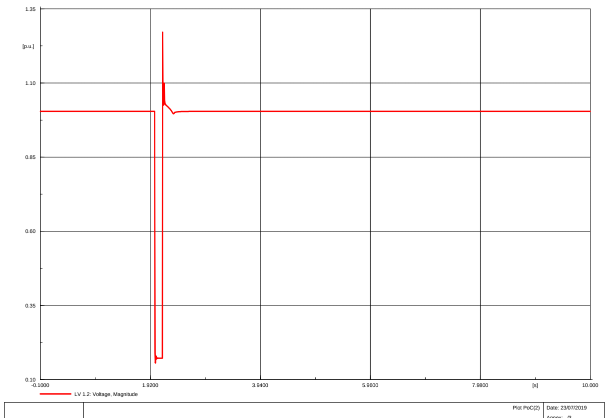

Fig. 23. Voltage profile at WTG for SCR=3.71.

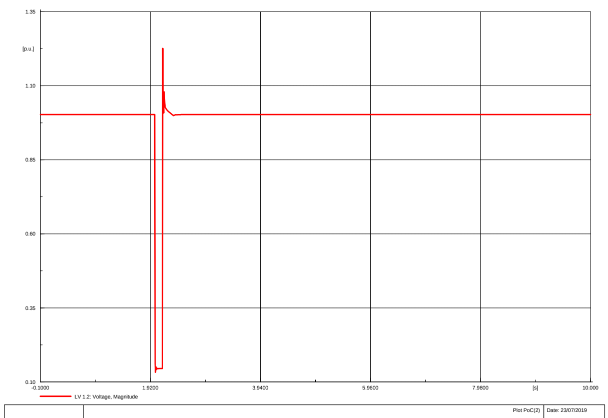

Fig. 24. Voltage profile at WTG for SCR=4.95.

of active power and zero reactive power with SCR of 1.48. It seen that the wind farms are marginally stable and the active power reduces to zero during the disturbance for all SCR values. It is also observed that the active power recovered to its pre-fault level once the fault is cleared for all SCR values. For low SCR condition (i.e. SCR=1.48), the recovery time is around 2200 ms, and for high SCR condition (i.e. SCR=14.85), it is around 420 ms.

The percentage overshoot of voltage profiles at PoC and WTG terminal are depicted in Fig. 28. It is observed that the WTG terminals experiences higher voltage dynamics compared to the PoC. Also, an increase in SCR reduces the voltage overshoots and are within 20% (for SCR values above 5).

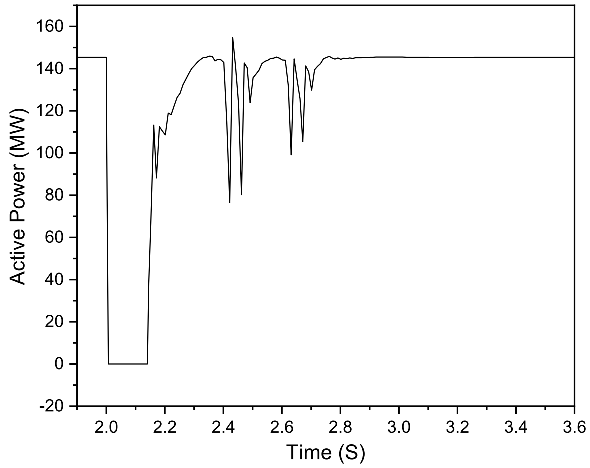

Fig. 25. Active power profile at PoC for SCR=1.48.

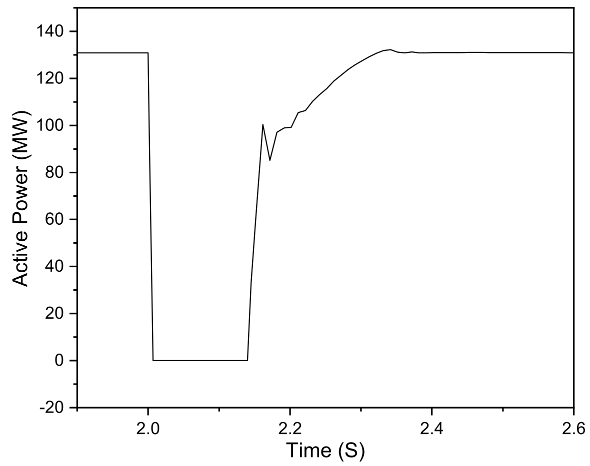

Fig. 26. Active power profile at PoC for SCR=1.65.

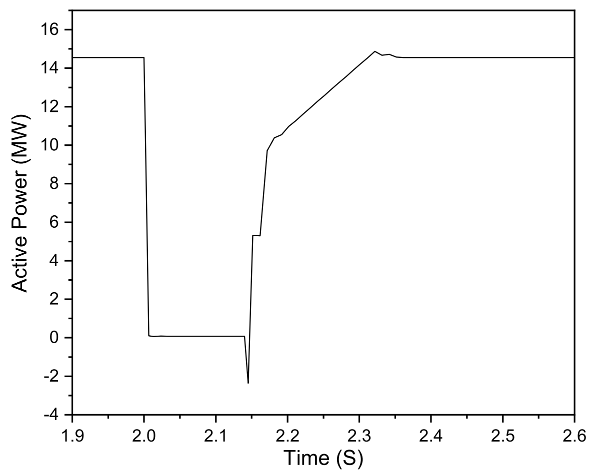

Fig. 27. Active power profile at PoC for SCR=14.85.

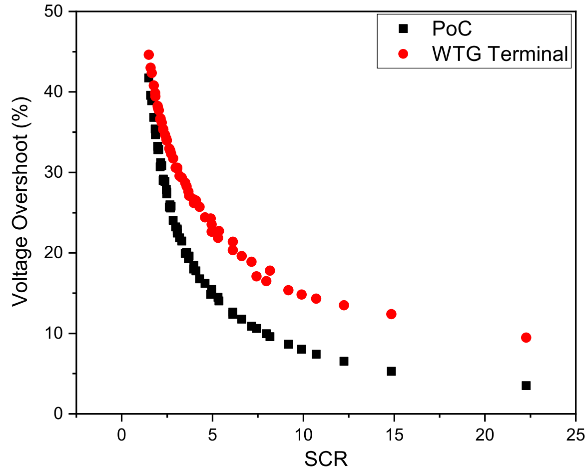

Fig. 28. Voltage overshoot for different SCR values.

Fig. 29 shows the restoration time for voltage at PoC and WTG low-voltage terminal. The settling time decreases with increase in SCR values at both PoC and WTG terminal, however, the restoration times at WTG terminal are greater compared to PoC.

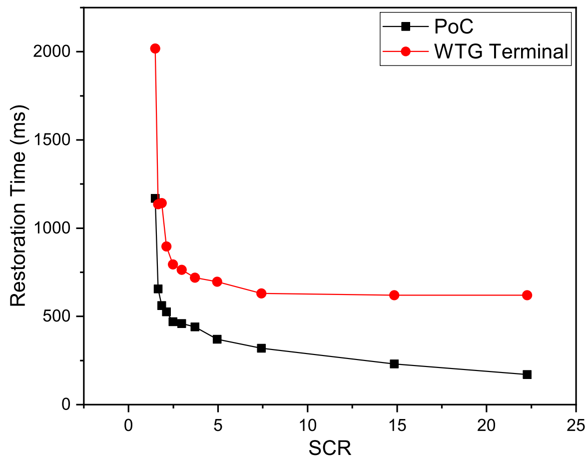

Fig. 29. Voltage restoration time for different SCR values.

V. Discussion

The short circuit ratios are lower for South Island of New Zealand compared to North Island mainly due to longer transmission lines connecting the generation to the load centres. For this study, we have chosen two locations of interest (Reefton and Oamaru) in South Island and three locations (Kaitaia, National Park and Gisborne) in North island using a specific criteria in confidence.

All nodes exhibit SCR of 5 or less beyond 60 MW of wind farm output rating; a medium size farm for New Zealand installations. The voltage overshoot analysis suggests over 15% below SCR of 4 and increases sharply below SCR of 3. The overshoots are worse at WTG terminal level where the levels are around 20% even at SCR of 10. Similar conclusions can be made for the restoration times where they are very high below SCR of 3 (the weak grid defined value). From the analysis, it is evident that many nodes of

NZ transmission network need a detailed design study of WTG farm installations beyond 60 MW.

As seen from above, nodes with low SCRs will have large impact on the voltage response i.e. large initial spikes and slower stabilisation. It can also cause the Wind turbines to operate in OVRT mode. Grids with low SCRs will also have larger impact on the active power recovery response with higher times which in-turn affecting stability of the system.

The analysis shows that disturbances at the WTGs are higher compared to PoC which can potentially affect the low-voltage side and power electronic components in the WTG. This can also be significant for NZ scenario due to the large HVDC network connecting North and South Island networks.

VI. Conclusion

The effect of SCR on voltage and active power profiles are analysed when integrating the wind energy to New Zealand's transmission grid. With a maximum capacity of 150 MW (NZ's largest wind farm), it is observed that the NZ grid is not entirely a weak grid with some strong nodes but there are several nodes with SCR values less than 3. From the results we can also conclude that the system performance needs attention below the SCR values of 5. The low SCR at a bus represents its inability to maintain the voltage profile during the power system disturbances. Hence, the evaluation of SCR and its affect on the wind farm interconnection at individual nodes need to be analysed. We also conclude that many nodes of NZ transmission network need a detailed design study of WTG farm installations beyond 60 MW.

Acknowledgment

The authors gratefully acknowledge the support of the Victoria University of Wellington for this work through the VUW Research trust. The authors also would like to thank Dr. Nyuk-Min Vong of Transpower NZ Limited for initial discussions on the project and Electricity Authority for the system model and load data.

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