Frequency Response and Its Enhancement Using Synchronous Condensers in Presence of High Wind Penetration

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***Abstract*— In recent years wind power integration has substantially increased in southern states of Australia. At present South Australia has the highest wind generation capacity of any region across the country. This large capacity penetration would likely displace existing synchronous generation fleet. These wind generators have neither enough inertia response nor governor support to control major frequency excursion. Under high wind power availability and cheaper import from neighboring region, South Australian grid could depend on few synchronous machines for frequency regulation. Under such a scenario, a big contingency may produce a severe frequency excursion in the network. Consequently, system may face a considerable amount of load shedding, which may degrade the standard of network service quality. To understand these issues, this paper investigates frequency response of a power system in presence of high wind penetration. The network under consideration loosely represents South Australian power system. Additional frequency control strategy, such as deployment of synchronous condensers to enhance network frequency response is also studied.**

***Index Terms*—Frequency response, Inertia, Headroom, Under frequency load shedding, Wind power.**

I. Introduction

To achieve clean energy target, integration of wind energy has been steadily increasing in many countries. Australia is experiencing a similar development in recent time. This has been largely motivated by climate change policies, which are meant to reduce carbon emissions in Australia. Moreover, technological advancement has made wind energy more cost-effective. Current installed capacity of wind generation in the Australian National Electricity Market is around 3.2 GW [1]. Among different states in Australia, South Australia has the highest wind penetration. Up to now, the installed wind capacity has reached around 1,500 MW [1]. Maximum instantaneous wind generation was around 1,350 MW in 2014 [2], which is approximately at the same level of the total demand during low load conditions.

Growing wind participation continues to economically replace conventional synchronous generators from the South Australian generation mix. Since 2012, average number of committed synchronous machines in the system has declined [2]. Fig. 1 shows a time distribution of the number of synchronous machines online in South Australia between November 2012 and November 2013.

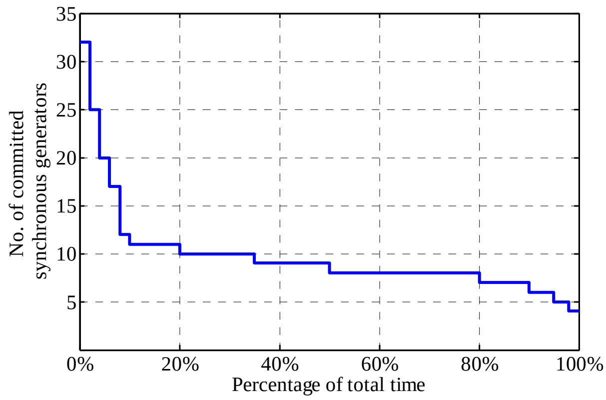

Figure 1. Time distribution of no. of committed synchronous machines [2]

Unlike synchronous generators, modern wind machines do not provide inertia and governor support after a disturbance to control frequency excursion. Thus, presence of large-scale wind generation and consequently few synchronous machines during low demand periods can drastically increase the risk of concerning frequency response in the South Australian network after a major disturbance (such as interconnection trip). Therefore, South Australian network provides a challenging case study for power system frequency response investigation.

A number of studies on power system frequency response due to high wind penetration have been reported in the literature. These papers include frequency response of the Eastern Interconnection, Electric Reliability Council of Texas, California and Western Electricity Coordinating Council and Ireland grid [3-6]. These papers consider the influence of several factors such as inertia, reserve, wind penetration level, interconnection flow and percentage of governor responsive generation on system response. To improve power system frequency response, inertia and governor like support from wind turbines are presented in [7-9]. The proposed methods are developed by considering wind speed variation, non-linear control and tuning of tip speed ratio.

According to a recent report [2] published by Australian Energy Market Operator (AEMO) and ElectraNet, currently there is no process implemented in unit commitment decision process of the South Australian system, which will ensure any minimum number of committed synchronous generators. High availability of wind generation may compel South Australia to rely on few synchronous machines for frequency control after a contingency [2]. As a consequence, system may face substantial under frequency load shedding (UFLS). However, this report does not provide any solution to improve frequency response and reduce UFLS. To meet these gaps, at first, this paper investigates frequency response of a power system, which loosely resembles South Australian system [10]. Then, it proposes a solution by using synchronous condensers to enhance frequency response and decrease UFLS.

II. System Description

The studied power system has been designed based on South East Australian 14-Generator Model [10]. The network used for this study loosely represents southern and eastern Australian high voltage network. Therefore, it does not exactly demonstrate any particular feature of those networks. The results presented in this paper should not be employed to resolve any conclusion involving to the actual performance of the network. The South Australian region (Area-5) of the 14-Generator Model system has been modified to incorporate existing wind generation. Generator models of the studied system are adjusted with generic governors, exciters and stabilizers to facilitate dynamic analysis [11]. Fig. 2 shows a schematic presentation of the studied system.

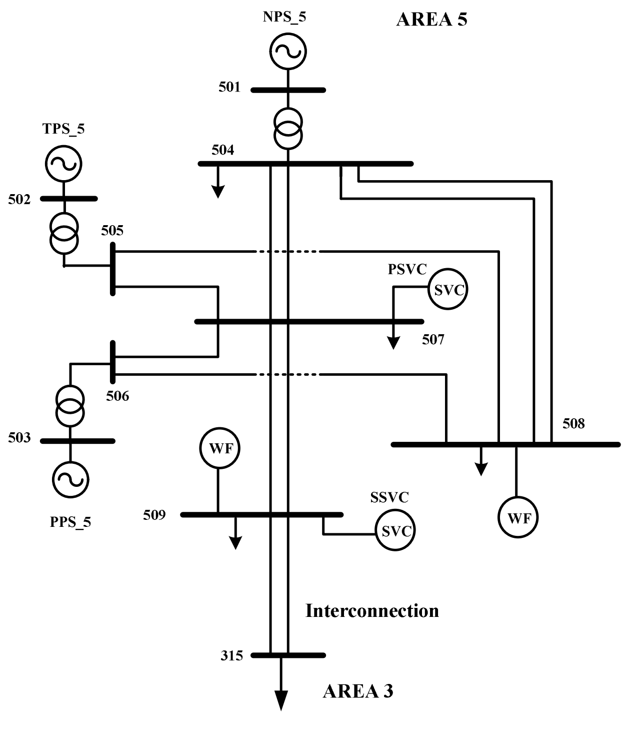

Figure 2. The studied power system [10]

The studied system is connected to its neighboring network through an interconnection. According to the network data of [10], in the studied power system there are 3 power plants with total installed capacity of around 2,300 MW. These are NPS_5, TPS_5 and PPS_5. Table I contains a description of synchronous generators.

Most wind farms in South Australia are located in Upper North, Mid North and in the region between Riverlands and Heywood interconnection [1]. In the simulation network, wind farms are lumped at two buses (ID: 508 and 509) with total power generation capacity of approximately 1,500 MW. Wind farms are modelled as Type-3 wind machines (Doubly-Fed Induction Generator: DFIG).

TABLE I. Synchronous Machine Profile

Name of Power plant	No. of units	Capacity of each unit (MW)	Base MVA of each unit	Inertia constant (H) of each unit (s)
NPS_5	2	300	333	3.50
TPS_5	4	200	250	4.00
PPS_5	6	150	166	7.50

III. Simulation Scenarios

Presence of substantial wind generation and power import from neighboring network may set the studied system to rely on few synchronous machines to control frequency deviation after a major disturbance (such as loss of interconnection) predominantly in low load situations. The studied system is investigated in five simulation scenarios in low load condition. Numbers of committed synchronous generating units are varied from 5 to 1. Each of them is assumed to run at 50% of their maximum rating. However, in reality they can be operated to their minimum stable operating points, if needed to be. It is assumed that cheaper power is imported into the studied region through AC interconnection, which operates around its maximum capacity of 460 MW. System load is set around its minimum level, which is 1200 MW. Power import and demand are kept fixed for all simulation cases.

System inertia (*IR*), primary reserve or headroom (*HR*) and instantaneous wind penetration level (*WPL*) are expressed by (1)-(3) [12]

$$IR = \sum_{i=1}^{i=n} (S_i \times H_i) \tag{1}$$

$$HR = \sum_{i=1}^{i=ng} (P_{max,i} - P_{gen,i}) \tag{2}$$

$$WPL = \frac{P_{wind}}{P_{sync} + P_{wind} + P_{import}} \tag{3}$$

where S_i denotes the rated MVA of i-th synchronous generator, H_i refers to the inertia constant of i-th synchronous generator (in s), n is the total number of committed synchronous generators, $P_{max,i}$ is the rated capacity of i-th synchronous machine (in MW), $P_{gen,i}$ denotes the power generation of i-th synchronous machine (in MW), ng refers to the total number of governor responsive synchronous generators, P_{wind} stands for the total power generation from wind (in MW), P_{sync} refers to the total power generation from synchronous generators (in MW) and P_{import} denotes the power import through interconnection (in MW). Simulation scenarios considered in this paper are summarized in Table II.

To examine the worst case frequency response, interconnection trip contingency is studied in this paper. Load shedding is assumed to start when frequency goes below 49 Hz [13]. For each 0.1 Hz drop, 3% load shedding is presumed.

TABLE II. SIMULATION SCENARIOS

No. of synchronous generators	P_{sync} (MW)	P_{wind} (MW)	*IR* (MWs)	*HR* (MW)	*WPL* (%)
5	570	220	5575	765	18
4	470	320	4575	615	26
3	320	470	3400	430	38
2	165	660	2245	250	52
1	90	770	1000	160	59

IV. SIMULATION METHODS AND RESULTS

This section presents necessary simulation techniques and results with relevant discussions.

A. Simulation Methods

Frequency response after interconnection trip is manifested via two parameters. One is frequency nadir, which is minimum frequency after a disturbance. The other is rate of change of frequency, which represents initial degree of frequency decline followed by a contingency.

In order to clearly show the network frequency behavior, this paper adopted an expression of equivalent system frequency shown in (4) [5], which eliminates small signal oscillations in measured frequency.

$$f_{eq} = [\sum_{i=1}^{i=n} (H_i \times S_i \times \omega_i)] / [\sum_{i=1}^{i=n} (H_i \times S_i)] \tag{4}$$

where ω_i refers to the speed of i-th synchronous generator and n is the total number of committed synchronous generators.

Rate of change of frequency (*ROCOF*) after a disturbance is computed by (5) [12]

$$ROCOF = \frac{1}{2} \times \frac{\Delta P}{IR} f_0 \tag{5}$$

where ΔP denotes the trip size (in MW) and f_0 stands for the nominal system frequency (in Hz).

Dynamic simulations of the studied power system network are performed in PSS®E simulation platform [14]. PSS®E software is widely used by power utilities of Australia and many other countries.

B. Simulation Results

In this sub-section, at first base case simulation results are presented and analyzed. In the next step, frequency responses with synchronous condensers are discussed.

(i) Base case: For 5 synchronous machines scenario, when the interconnection trips, frequency nadir becomes 48.55 Hz. The same contingency results in more drop in system frequency as the number of committed synchronous machines reduces. Fig. 3 shows a plot of frequency response for different number of online synchronous generators. It is observed that frequency nadirs may vary from 48.55 Hz to 47.50 Hz for 5 machines case to 1 machine case.

When 5 synchronous machines are committed, system has reasonably large amount of inertia and headroom in comparison with other cases. These values are lowest for 1 machine case. Since frequency nadir after a disturbance depends on both inertia and headroom, five machines scenario has minimum frequency deviation. Frequency deviation starts increasing as the number of committed machines falls and becomes maximum for the one machine scenario.

To examine the effect of wind power on frequency response, Fig. 4 is plotted to present a correlation between wind penetration level and frequency nadir. It is observed that with an increase of wind power contribution into the grid with fixed demand and power import, frequency nadir value shows a decreasing trend (which means frequency drop is increasing). When wind penetration level increases, it displaces synchronous generators. Wind generators in this network are assumed to not contribute to system inertia and headroom. Consequently, with a growth of wind generation, frequency response of the network becomes more susceptible. It is evident from frequency response analysis that in all cases, frequency nadirs after the interconnection trip breach the 49 Hz margin, which is UFLS triggering threshold. Consequently, it is likely that the system will experience load shedding.

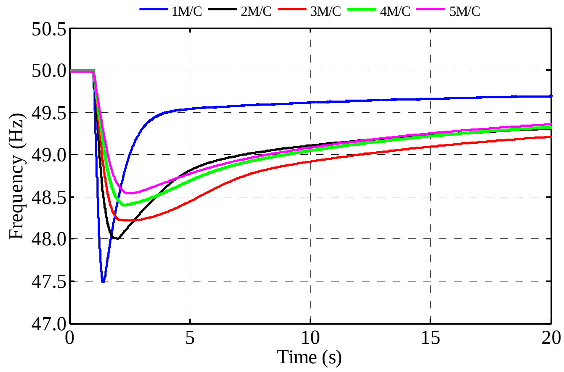

Figure 3. Frequency nadir for different cases

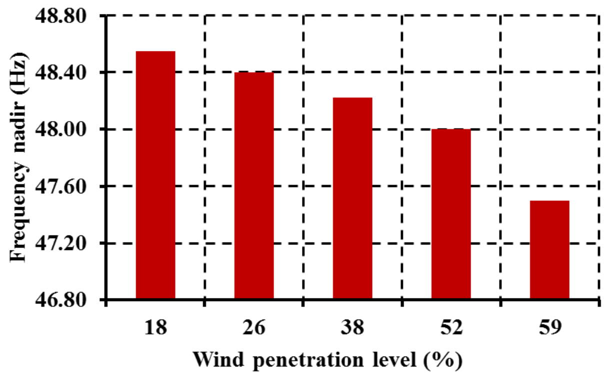

Figure 4. Frequency nadir vs. wind penetration level

For a fixed power outage, *ROCOF* is inversely proportional to the total inertia. 5 machines case corresponds to the largest inertia and 1 machine case has the lowest inertia among the five simulation scenarios. For interconnection trip contingency, *ROCOF* differs from 2 Hz/s to 11.25 Hz/s for different number of committed synchronous generators. Percentage and amount of load shedding and *ROCOF* for different simulation scenarios are shown in Table III.

Impacts of wind penetration level on UFLS and *ROCOF* are illustrated in Fig. 5. It is observed that there is a positive correlation between wind generation and UFLS. A similar trend is exhibited for wind penetration level and *ROCOF*.

TABLE III. PERCENTAGE AND AMOUNT OF UFLS AND *ROCOF*

No. of synchronous generators	UFLS (%)	Load shed (MW)	*ROCOF* (Hz/s)
5	12%	144	2
4	15%	180	2.45
3	18%	216	3.3
2	24%	288	5
1	30%	360	11.25

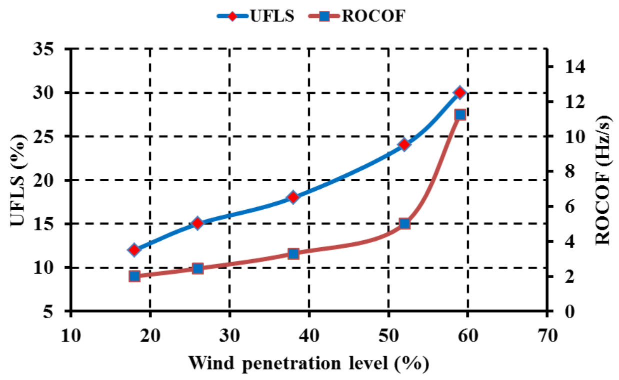

Figure 5. Effects of wind penetration level on UFLS and *ROCOF*

According to the adopted grid code of the studied system, *ROCOF* after a disturbance should not exceed 1 Hz/s [2]. Changes of frequency at a rate greater than 1 Hz/s may become a concern for protection devices [2]. It is observed from the base case simulations that *ROCOF* values in all 5 scenarios violate the permitted limit. Moreover, system may face a substantial amount of load shedding due to interconnection trip, which can deteriorate service quality and reliability. Thus, an enhancement of system frequency response is essential.

To improve frequency response and reduce UFLS, one viable solution can be deployment of synchronous condensers. According to the 14-Generator Model, the studied system has 12 synchronous generators. Assuming that when n_c number of generators are committed, maximum (12-n_c) number of machines can be converted to run in synchronous condenser mode to provide additional inertia support. The following sub-section presents frequency response of the studied network when different numbers of synchronous condensers are employed in the grid. Loss of interconnection is applied for all cases.

(ii) Frequency response with synchronous condensers: For various machines case (5 to 1 synchronous generator) the studied network is simulated with multiple numbers of synchronous condensers. As the number of synchronous condensers gradually increases, frequency nadir starts to get better. The rate of frequency excursion slows down with an increase of system inertia. So, more time is allowed to deploy headroom, which in turn recovers frequency nadir.

Table IV summarize frequency response performance with placement of synchronous condensers. Fig. 6 shows an improvement in frequency nadir (i.e. decrease in frequency drop) from base case to maximum additional inertia support for different number of committed synchronous generators. It is observed from simulations that with an equal amount of inertia (13,800 MWs) in the grid, frequency nadir becomes 48.64 Hz when 5 synchronous generating units are online. It becomes 48.08 Hz when only 1 unit is committed. In other words, 5 machines scenario has the minimum frequency drop, whereas 1 machine case has the maximum deviation in spite of equal system inertia.

The reason for this variation is amount of headroom. For 5 machines case, wind penetration level is lowest (18%) and headroom is maximum (765 MW). On the other hand, 1machine case has highest wind penetration level (59%) and minimum headroom, which is only 160 MW.

TABLE IV. SYSTEM PERFORMANCE WITH SYNCHRONOUS CONDENSERS

No. of committed synchronous generators	No. of synchronous condensers employed	Total Inertia with additional synchronous condensers (MWs)	Frequency nadir (Hz)
5	1-7	6820-13800	48.56-48.64
4	1-8	5820-13800	48.41-48.53
3	1-9	4645-13800	48.23-48.36
2	1-10	3490-13800	48.03-48.19
1	1-11	2245-13800	47.85-48.08

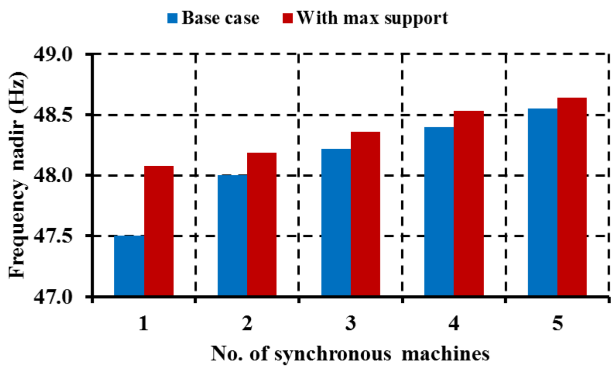

Figure 6. Improvement of frequency nadir

From Fig. 6, it is noticed that improvement in frequency nadir at maximum inertia provision becomes largest for single machine scenario, which is 0.58 Hz. It shows a saturated behavior as number of committed synchronous machines increases. One reason may be the percentage increase of supplementary inertia. When reasonable numbers of synchronous generators are already connected to a grid, any additional inertia from synchronous condenser does not significantly change grid strength. Accordingly, enhancement in frequency nadir slows down.

Added inertia contributions from synchronous condensers assist to upgrade frequency response performance. As a result, amount and percentage of UFLS in the studied system decrease. Fig. 7 depicts a comparison between UFLS in base case and with maximum supplementary inertia. It is noticed that UFLS considerably reduces due to placement of synchronous condensers. Highest reduction is 9%, which means that load shedding decreases by 108 MW (total load is 1,200 MW).

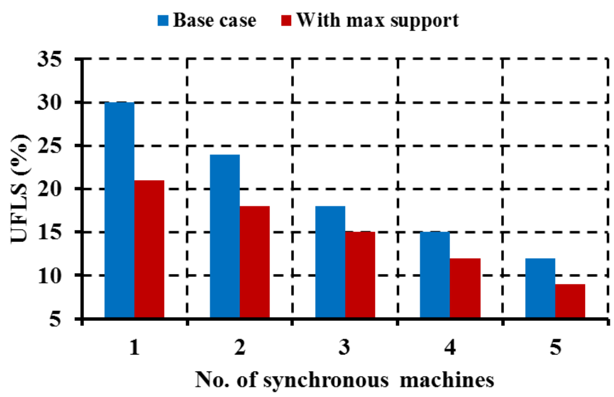

Figure 7. Comparison of UFLS

ROCOF values significantly drop due to inertia support from synchronous condensers. Fig. 8 shows a plot between

ROCOF vs. inertia for 1 machine case. It is seen that *ROCOF* falls to 0.82 Hz/s (with maximum inertia of 13,800 MWs) from 11.25 (base case inertia is 1,000 MWs) for 1 machine scenario. To attain the acceptable margin of *ROCOF* (less than or equal to 1 Hz/s), minimum system inertia is calculated using (5) and its value is 11,250 MWs. From the simulations, it is found that during single machine case, minimum 9 synchronous condensers are required to avoid unexpected rate of change of frequency after interconnection trip.

Highest reduction in *ROCOF* at each machine scenario is evaluated by computing the difference between *ROCOF* at base case (shown in Table II) and that with maximum inertia condition. Table V presents a summary of *ROCOF* analysis with gradual increase of synchronous condensers. It also contains minimum number of synchronous condensers, which are required to maintain a rate less than 1 Hz/s. It is observed that, as expected, minimum number of required synchronous condenser increases with a decrease in committed synchronous generators and vice versa.

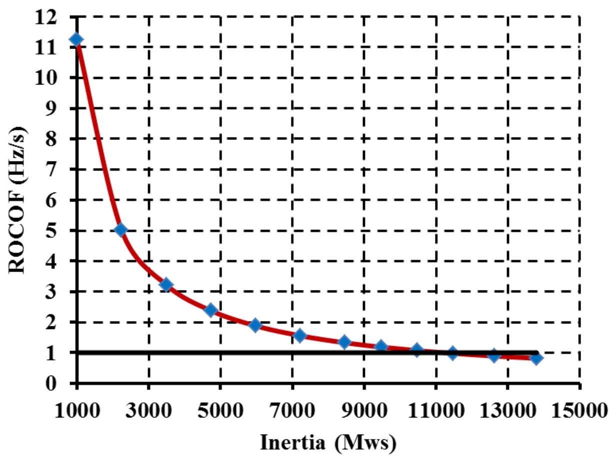

Figure 8. *ROCOF* vs. inertia for single machine case

TABLE V. SUMMARY OF *ROCOF* ANALYSIS

No. of committed synchronous generators	*ROCOF* with gradual increase of synchronous condensers (Hz/s)	Highest reduction of *ROCOF* (Hz/s)	Minimum no. of synchronous condensers to keep *ROCOF*<1 Hz/s
5	1.65-0.82	1.18	5
4	1.93-0.82	1.63	6
3	2.42-0.82	2.48	7
2	3.22-0.82	4.18	8
1	5.01-0.82	10.43	9

V. CONCLUSIONS

This paper analyzes frequency response of a network, which has substantial wind power penetration and few online synchronous generators. The existing 14-Generator SE Australian system has been suitably modified to loosely represent South Australian network and its interconnection to neighboring region. Due to UFLS relay, system can be rescued after a severe contingency like interconnection trip. Frequency nadir, amount of load shed and *ROCOF* mostly depend on wind penetration level, the number of synchronous generators online, system inertia, headroom, interconnection flow and contingency size.

Additional frequency support from synchronous condensers can enhance frequency response performances, which in turn reduces the amount of UFLS. *ROCOF* can be maintained within its acceptable limit by employing a certain number of synchronous condensers. This number depends on how many synchronous machines are already committed to the system. Utilization of synchronous condensers upgrades grid performances and service reliability; however, cost of such frequency control ancillary services may be imposed. In future work, frequency response of the studied system will be investigated by incorporating synthetic inertia and active power control features of wind farms.

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