IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received January 28, 2020, accepted February 24, 2020, date of publication March 3, 2020, date of current version March 16, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2977941

Optimal Allocation of Synchronous Condensers in Wind Dominated Power Grids

LUCAS RICHARD[1,3], (Student Member, IEEE), NAHID-AL-MASOOD[2,3], (Senior Member, IEEE), TAPAN KUMAR SAHA[3], (Fellow, IEEE), WAYES TUSHAR[3], (Senior Member, IEEE), AND HUAJIE GU[3], (Student Member, IEEE)

[1] Applied Physics–Electrical and Information Engineering (EEA) Department, École Normale Supérieure Paris-Saclay, 91190 Gif-sur-Yvette, France
[2] Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh
[3] School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane, QLD 4072, Australia

Corresponding author: Nahid-Al-Masood (n.masood@uq.edu.au)

ABSTRACT System strength (also known as short-circuit performance) indicates the capability of a power system to recover a fault. Renewable energy integration in power grids causes replacement and retirement of synchronous generators from generation fleet, which tends to reduce system strength. As such, a pre-defined number of synchronous generators are intentionally kept online to ensure adequate system strength in some power systems (e.g. South Australia). It results in the curtailment of wind power which eventually introduces financial concerns. To mitigate this issue, synchronous condensers can be a worthwhile choice. These devices contribute to fault level and provide voltage support to enhance system strength. Since synchronous condensers are costly, the best strategy for their allocation is a major query to investigate. To address this concern, this paper proposes an optimisation algorithm to allocate synchronous condensers to enhance system strength in a wind dominated power system by taking into account the long-term economic profitability of synchronous condensers installation. System strength calculations are based on Time Domain Dynamic Simulations with dynamic models which include current saturation limit of power electronics converters of wind farms. The proposed optimisation algorithm provides the most technically as well as economically viable solution to enhance system strength by utilising synchronous condensers.

INDEX TERMS Optimal allocation, short-circuit ratio, synchronous condenser, system strength, wind power integration.

I. INTRODUCTION

In the past decades, many power systems have experienced major changes due to the prolific integration of renewable energy resources such as wind and solar photovoltaic [1], [2]. For instance, in South Australia (SA), the wind and solar generation has already reached the level of demand during low-load conditions [3], [4]. Furthermore, the Australian government has set a target of 23.5% of renewable energy production in 2020 [5], [6].

This growing part of renewable energies in the power mix necessitates to decommission conventional power plants or to put them offline [7]. These decommitted power plants are mostly coal and gas-based and rely on synchronous generators [3], which have a major role to play for power system security. They provide voltage support and short-circuit currents to the grid which help to maintain sufficient system strength [7]. Short-Circuit Ratio (SCR) is usually used as an index to characterise system strength of a power grid [8]. SCR at the Point of Common Coupling (PCC) of a wind farm is defined as the ratio between the short-circuit capacity (also fault VA) at the PCC and the rated capacity of the wind farm [9]–[11]. A minimum value of SCR at the PCC of wind power plants is essential for the operation of protection devices and voltage and dynamic stability. Consequently, it ensures the successful ride through of wind power plants during faults [8], [10], [12].

Most Wind Turbine Generators (WTGs) installed lately are type-III (Doubly-Fed Induction Generator, DFIG) and type-IV (permanent-magnet generator with a full scale power converter) machines [13], [14]. They are connected to the grid through power electronics converters [15]. The current saturation limit of these converters is 1.1-1.2 pu which ultimately limits the fault current contribution from these WTGs [16].

The associate editor coordinating the review of this manuscript and approving it for publication was m Jaya Bharata Reddy.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

Consequently, prolific installation of modern wind power plants is likely to reduce short-circuit currents at the corresponding PCCs.

To counteract the above situation, wind power plants are intentionally being curtailed to allow a certain number of synchronous generators online to maintain adequate system strength [17]–[20]. Note that this strategy is already implemented in SA [8]. However, due to implementation of such a rule, the share of gas-based power plants in the generation mix of South Australia increases. It eventually leads to wind curtailment and causes financial concerns. For instance, wind farm owners encountered a loss of 5.2 million $ during July and August 2017 due to wind power cut [20]. Furthermore, gas power plants are expensive to run and consequently this sets higher electricity price in South Australia compared to other Australian states [3]. In addition, wind farms usually have high capital costs ($/MW) but low operational costs ($/MWh) [21]. Hence, they should run as much as possible to amortise their capital costs. Therefore, constraining some conventional plants online is not a cost-effective solution while long-term economic benefit is taken into consideration. To tackle low system strength challenge, deployment of synchronous condensers can be a promising solution.

Synchronous condensers are synchronous machines with their shaft unloaded [22]. As they are directly linked to the grid, they contribute to fault levels akin to synchronous generators. Moreover, they can regulate their reactive power output, hence controlling voltage levels. Numerous papers have shown that synchronous condensers have the capability to maintain power system security in wind prolific power systems [7], [9], [23]. Therefore, the question of their optimal location naturally arises, which is also highlighted in [9], [24], [25].

A Genetic Algorithm (GA) to determine the optimal installation of synchronous condensers to enhance Danish power system strength at the lowest cost is proposed in both [9] and [24], whereas [25] implements a search algorithm to determine the optimal synchronous condenser ratings to improve the overall system strength. The IEC 60909 standard is used in [9] to calculate SCR, whereas a modified method based on Thévenin theorem is implemented in [24]. Both these methods deploy static fault analysis.

Moreover, the aforementioned studies use objective functions which are either the minimisation of the cost of installation of synchronous condensers to maintain satisfactory SCR [9], [24] or the maximisation of the Weighted Short-Circuit Ratio (WSCR) [25]. However, no insights on the long-term economic profitability of synchronous condenser installation are provided in [9], [24], [25]. Installation of synchronous condensers usually result in high costs (e.g. 30 million US $ [9], [24]). Therefore, a model to quantify the long-term economic benefits of a synchronous condenser installation is needed. Nevertheless, the existing literature does not suggest any detailed technique to install synchronous condensers by simultaneously considering both system strength and economic aspects. To meet this gap, this paper proposes an optimisation algorithm for determining the best locations and ratings of synchronous condensers to enhance system strength at the PCC of wind farms while being the most economically viable. To this end, system strength is calculated based on Time Domain Dynamic Simulation (TDDS). Also, revenue and losses are modelled to investigate the long-term profit of deploying synchronous condensers. The proposed algorithm is applied on the South-East Australian 14 generator model [26] under a foreseeable high wind penetration case.

The paper is organised in five sections. Problem formulations are presented in detail in Section II. Section III describes an overview of the studied power system. Simulation results and analyses are provided in Section IV, and finally the concluding remarks are drawn in Section V.

II. PROBLEM FORMULATION

A. SHORT-CIRCUIT RATIO (SCR) CALCULATION

In this work, system strength is evaluated by the indicator SCR. For SCR calculation, a balanced three-phase fault is applied at the PCC of a wind farm to investigate the most severe condition. SCR at the wind farm PCC is then calculated using (1) and (2) [7], [9], [25].

$$SCC = \sqrt{3}V_n I_f \tag{1}$$

$$SCR = \frac{SCC}{P_{max}} \tag{2}$$

where V_n is the line-to-line pre-fault voltage at the PCC (in kV), I_f is the fault current at the PCC in (kA), SCC is the short-circuit capacity in MVA and P_{max} the rated generation capacity of the wind power plant (in MW).

The work presented in this paper has been carried out on the software PSS®E, which is widely used in the engineering community. While calculating SCR, V_n is determined by load flow analysis using PSS®E. To determine I_f, the fault current is recorded from TDDS. The value of I_f is then taken at the end of the subtransient period of the dynamic analysis [16].

B. OPTIMISATION PROBLEM

The optimisation problem is described by the objective function (3) and the constraint (4). The objective function is the maximisation of the Net Present Value (NPV) of installing synchronous condensers and the constraint is maintaining SCR above the minimum value (e.g. 3 in the Australian power system [7], [13]) at every PCC of wind power plants. The NPV is an economic indicator which is the difference between the present value of cash inflows and the present value of cash outflows over a period of time.

$$\max_{x} NPV(x) \tag{3}$$

$$\text{s.t } SCR(x) \geq SCR_{min} \tag{4}$$

where x is the solution vector of size $N_{PCC} \cdot 1$ and N_{PCC} is the number of PCC under study. The j-th row of x contains the information about the type of synchronous condenser installed at the j-th PCC. The number of synchronous condensers installed is not fixed in advance in the proposed algorithm. $SCR(x)$ is a vector containing at its j-th row the value of SCR at the j-th PCC and SCR_{min} is a vector with the value of the lowest limit of acceptable SCR (considered as 3 in this paper).

The NPV is given by (5).

$$NPV = \sum_{i=1}^{i=N_{years}} \frac{R_i - C_i}{(1+r)^i} - C_0 \tag{5}$$

where N_{years} is the number of years under study, i.e. the number of years that the synchronous condensers will be in operation, C_i and R_i are the net cash outflows (costs) and the net cash inflows (revenues) during the i-th year respectively. Also, C_0 is the installation cost of synchronous condensers and r is the discount rate, which is set to 7% following [5]. According to [27], the synchronous condenser asset life is assumed to be 30 years, hence N_{years} is assumed to be 30 years at most.

C. COSTS MODELLING

The cost of installing synchronous condensers C_0 is given by (6), which is composed of a fixed price C_f ($/synchronous condenser installed) and of a variable price C_v ($/MVA installed). S and g are functions which respectively indicate the rating and the number of synchronous condensers installed at a wind plant PCC.

Running synchronous condensers over a long time requires periodic maintenance. Yearly maintenance costs C_{main} are given by (7), where C_m is the averaged maintenance cost ($/MVA per year). Moreover, synchronous condensers do consume electricity because of internal losses (P_{loss}). The cost of electricity consumption over years can be significant because of the large ratings of the synchronous condensers and the continuous use of these devices. This yearly cost C_{elec} is given by (8) where C_{MWh} is the yearly averaged cost of electricity ($/MWh) and τ_{SC} is the percentage of time the synchronous condensers are online.

$$C_0(x) = \sum_{j=1}^{j=N_{PCC}} \left(C_f + C_v S(x_j)\right) g(x_j) \tag{6}$$

$$C_{\text{main}}(x) = \sum_{j=1}^{j=N_{PCC}} C_m S(x_j) \tag{7}$$

$$C_{\text{elec}}(x) = 365 \cdot 24 \cdot \tau_{SC} C_{MWh} P_{loss} \cdot \sum_{j=1}^{j=N_{PCC}} S(x_j) \tag{8}$$

The cost of electricity consumption of the synchronous condensers is directly linked to their internal losses P_{loss}. As mentioned in [28], losses in synchronous condensers usually vary from 1.5% to 3% of their rated capacities. In the following, to consider a conservative scenario, P_{loss} is assumed to be 3%.

C_f is set to 1 million US $ [24] and C_v and C_m are assumed to be 30,000 US $/MVA and 800 US $/MVA per year, following [29] published in 2006. These prices are adjusted by considering the average inflation rate of 2.46% in Australia over the past 12 years [30].

D. REVENUES MODELLING

Because of security concerns due to high non-synchronous penetration, wind farms have experienced curtailment in some countries including Ireland, Spain, China and Australia [5], [13], [17]–[20]. Note that a significant portion of the Australian wind farms are situated in SA and Victoria (VIC). The report from the Australian Energy Market Operator (AEMO) [13] predicts that wind curtailment could reach 35% in Victoria and 15% in SA in 2020. In Ireland, depending on the limitation set for the level of non-synchronous generation, wind curtailment can reach 7 to 14% [19] and [18] affirms that wind curtailment has reached 20% in China. In SA, around 6% of wind generation was curtailed over eight weeks in 2017 due to new dispatch constraints imposed by the AEMO in order to maintain a certain level of synchronous generators online [20]. Installing synchronous condensers would enhance SCR which eventually will reduce wind curtailment [5].

Assume that synchronous condenser installation reduces wind curtailment by α_{SA}% in SA and α_{VIC}% in Victoria. The maximum wind curtailment reduction is assumed to be 6% based on [20]. Also, 1% and 3% wind curtailment reductions are analysed to take into account the conservative scenarios. The yearly revenue obtained by installing synchronous condensers in the Australian power network is the additional electricity generated and sold R_{wtg}, given by (9). P_{VIC} and P_{SA} (MW) are the averaged power output of wind farms in Victoria and SA (in reality so far only SA and VIC are likely to experience wind curtailment).

$$R_{\text{wtg}} = 365 \cdot 24 \cdot C_{MWh}(\alpha_{SA} P_{SA} + \alpha_{VIC} P_{VIC}) \tag{9}$$

When wind power is curtailed, this deficit is supplied by coal and gas power plants. Thus, additional fuel price needs to be paid. If wind power is not curtailed, this additional cost is saved. As such, yearly fuel saving R_{fuel} is given by (10) and is included as a revenue in the NPV. C_{gas} is the cost of gas in SA and C_{mix} is the combined cost of gas and coal in VIC.

$$R_{\text{fuel}} = 365 \cdot 24 \cdot (\alpha_{SA} P_{SA} C_{\text{gas}} + \alpha_{VIC} P_{VIC} C_{\text{mix}}) \tag{10}$$

All the data, for instance the cost of fuels, yearly averaged wind power production in South Australia and Victoria etc., are given by the AEMO database for the next 20 years [5]. Consequently, the NPV analysis is performed over a period of 20 years which implies conservative results as the synchronous condensers are expected to run longer than 20 years [27].

Note that in (5) R_i and C_i are respectively the summation of R_{wtg} and R_{fuel} and the summation of C_{elec} and C_{main} for

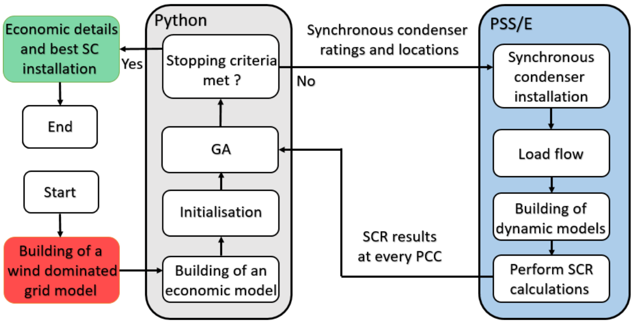


FIGURE 1. Flow graph of the problem formulation.

year i. They are expressed as

$$R_i = R^i_{\mathrm{wtg}} + R^i_{\mathrm{fuel}} \tag{11}$$

and

$$C_i = C^i_{\mathrm{elec}} + C^i_{\mathrm{main}} \tag{12}$$

In this paper, revenues are modelled for the Australian power system. However, this modelling can also be applied to any power system experiencing wind curtailment.

E. PROPOSED ALGORITHM

The optimisation problem described in section II.B includes integer variables, constraints and is non-linear because of SCR calculations. GA is often used for mixed-integer non-linear optimisation problems and more globally in many power system problems [31]. In this work, a joint platform consisting of a Genetic Algorithm (GA) and PSS®E is established. The GA is developed in Python by defining mutation, selection and crossover functions. The steps of the proposed algorithm are outlined as follows:

- The GA randomly creates the initial generation and sends it to PSS®E. Note that here generation does not mean power generation. Instead, it indicates biological inception used in GA algorithm.
- Synchronous condensers are installed in the network. Then load flow analysis is performed via PSS®E, and voltages of all PCC buses are recorded. This process is executed using Python scripts.
- System strength calculation is done using TDDS in PSS®E at every PCC of wind power plants.
- PSS®E sends the results to the GA which creates the next generation, and so on until the stopping criteria is fulfilled.

In the proposed algorithm, the optimisation process terminates if the total number of generation exceeds a predefined maximum and/or there are high similarities between subsequent generations. Fig. 1 illustrates the problem formulation, with the red box as input (i.e. a wind dominated power grid model) and the green box as output (i.e. the best synchronous condenser installation and the economic details).

III. OVERVIEW OF THE STUDIED POWER SYSTEM

The studied power system is designed based on the Australian South-East 14-Generator model [26], which closely represents the high voltage transmission network of the Southern and Eastern Australia. This network is significantly augmented with wind power plants based on [3] and [13]. Wind farms (WF) are lumped together when they are geographically close. Wind farms are modelled using standard type III GE WTG model [32]. This model takes into account the current saturation limits of the power electronics converters. A typical low-load case is simulated in this work as the system strength deteriorates when few synchronous generators are committed. Note that low load scenario occurs during night time, hence no photovoltaic is considered. The total power generation is around 14,800 MW, which include 2,833 MW of wind generation.

The power network is composed of five areas and each area represents one state. The installed capacity (MVA) and the generation (MW) of wind power of each area are shown in Table 1. Wind power integration levels are high in South Australia, Victoria and Australian Capital Territory (ACT). Note that a prolific share of the Australian wind farms is located in SA-VIC boarder. Also, the number of synchronous generators has significantly reduced in SA grid. Therefore, the aforementioned portions of the studied system as shown in Fig. 2 are under possible risk of experiencing low SCR in wind plant PCC. The studied system contains thirteen wind farms. Hence thirteen wind farm PCCs are under investigation.

TABLE 1. Summary of wind integration in each area.

Area number	State	Number of WF online	Wind capacity	Wind generation	Percentage of load
1	ACT	1	114	100	37
2	NSW	3	540	450	7.8
3	VIC	4	1465	1225	30
4	QLD	1	12	10	0.3
5	SA	4	1580	1048	73.2

IV. SIMULATION RESULTS AND ANALYSES

A. OPTIMAL LOCATION OF SYNCHRONOUS CONDENSERS

At first, SCR at the wind farm PCC are calculated without any synchronous condensers. Table 2 shows the SCR values that are relatively low. It can be noticed that SCR becomes low only in the wind plant PCC that are located in SA (Area 3) and VIC (Area 5). Area 2 and 4 do not incur low SCR as wind penetration is relatively insignificant, and several synchronous generators are committed in those areas. However, in Area 1, even with high wind penetration, SCR is also high. This is due to the fact that Area 1 has strong interconnection with Area 2 [26]. As found from Table 2, five wind plant PCCs have SCR values less than 3 (VIC 3, SA 1, SA 2, SA 3 and SA 4).

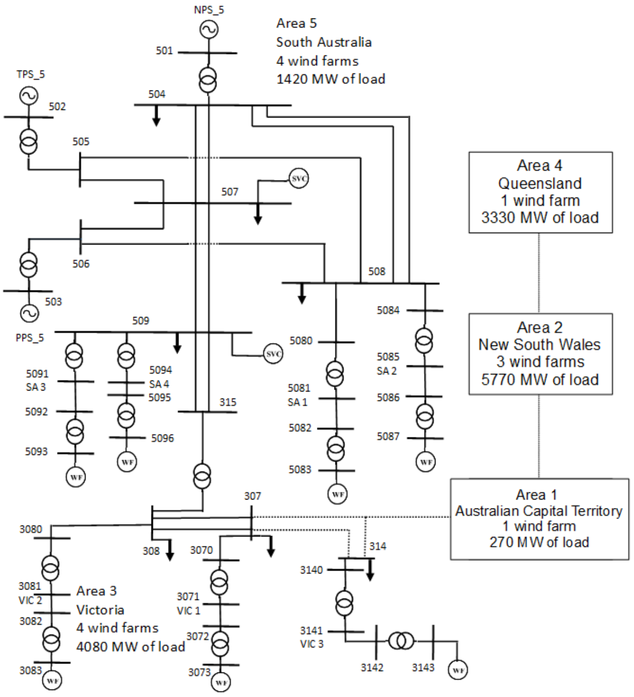


FIGURE 2. Single line diagram of the studied power system [26].

TABLE 2. SCR results with and without synchronous condensers.

PCC	VIC 2	VIC 3	SA 1	SA 2	SA 3	SA 4
Bus	308	314	508	508	509	509
SCR w/o SC	3.21	2.57	2.66	2.83	2.06	2.07
SCR with SC	3.28	3.34	3.75	3.95	4.24	4.25

Therefore, these PCCs are of interest while performing the optimisation.

For the optimisation problem, four different synchronous condensers candidates are considered with different ratings: 100, 166, 250 and 333 MVA. However, two synchronous condensers of same rating can be installed in parallel at the same PCC (for instance, two 100 MVA synchronous condensers to obtain a 200 MVA installation) [22]. Thus, in total, there are nine possibilities for a PCC (no synchronous condenser installed or one of the eight different possible installations). Therefore, the solution vector x is composed of integers from 0 to 8, each number indicating a type of synchronous condenser installation (and 0 means no synchronous condenser installed). Including more synchronous condenser candidates would just increase the computational time. With those nine possibilities, there are already $2.54 \cdot 10^{12}$ possible combinations for the optimisation of the locations and ratings of the synchronous condensers.

The GA is run with a population size of 160 and a maximum number of generation of 40. As the GA is a heuristic method, it is run ten times and the best result is kept. Wind curtailment reduction has been modelled such that if synchronous condensers tackle low SCR problem, wind curtailment is reduced. The sensitivity analysis is performed with percentage of wind curtailment reduction in the ranges based on the suggestions from a technical report provided in [20]. As mentioned before, around 6% of wind power was curtailed in South Australia over two months in 2017 [20]. Accordingly, the upper limit of wind curtailment reduction is assumed to be 6%. As α_{SA} and α_{VIC} are variables of the economic model, different values have been chosen to perform the sensitivity analysis. The results always give the same synchronous condenser installation: a synchronous condenser of 100 MVA at the PCC VIC 3, and SA 1, 2, 3 and 4. The variation of α_{SA} and α_{VIC} and the optimal size and locations of synchronous condensers are shown in Table 3.

TABLE 3. Results of the optimisation algorithm in different cases.

Parameters	Time	NPV after 10 years	NPV after 20 years	SC location
α_{SA}=α_{VIC}=0.01	3h51	5.6 (M$)	45.2 (M$)	A 100 MVA SC at VIC 3 and SA 1 to 4
α_{SA}=α_{VIC}=0.03	3h24	215.7	424.3	Same
α_{SA}=α_{VIC}=0.06	4h02	530.7	992.9	Same

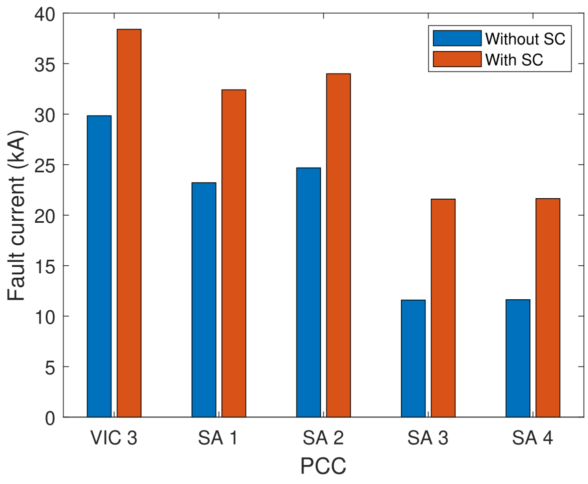


FIGURE 3. Fault current with and without synchronous condensers.

SCR results after the installation of these synchronous condensers can be found in Table 2 for a clearer observation. The SCR values are above 3. It can also be seen that SCR at PCC VIC 2 does not noticeably increase because the nearest synchronous condenser installation is at bus 509. However, this bus is geographically far from VIC 2. The optimisation algorithm based on TDDS requires long computational times (from 3h20 to 4h02 as shown in Table 3, with differences due to the low diversity stopping criteria).

To more precisely analyse the influence of the synchronous condensers, fault current levels with and without a 100 MVA synchronous condenser at PCC VIC 3, SA 1, 2, 3 and 4 are compared in Fig. 3. It is found that the fault current increases from 28.7% to 86.28% due to additional synchronous condensers.

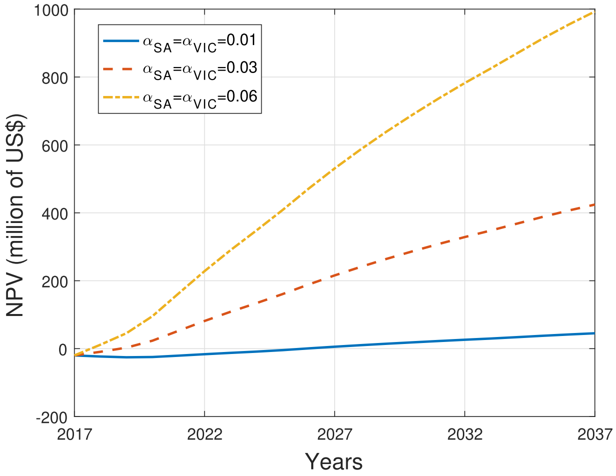


FIGURE 4. Trend of NPV in three different cases.

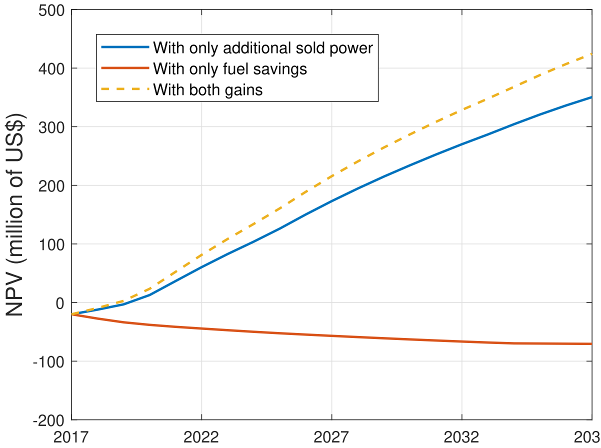


FIGURE 5. Influence of fuel savings and additional sold power on NPV.

B. ECONOMIC ANALYSIS

1) NPV CALCULATION

NPV is calculated using (5). The NPV values after 10 and 20 years are given in Table 3. The values are positive, which implies that installation of synchronous condenser is economically viable. When synchronous condensers are installed, wind curtailment in South Australia and Victoria reduces. Thus, revenue is produced by trading additional wind power and saving the cost of coal and gas. Fig. 4 shows the trend of the NPV for 20 years for the three wind curtailment reduction levels. In first case (α_{SA} and $\alpha_{VIC} = 1\%$), the NPV decreases in the first three years because the averaged wind generation in South Australia and Victoria is not high enough. In other words, revenue due to wind curtailment reduction is less than the maintenance and operational cost of synchronous condensers. From the fourth year, the average wind generation in South Australia and Victoria becomes relatively higher [5]. Consequently, the NPV starts to increase. It can also be found from Fig. 4 that for other two cases (α_{SA} and $\alpha_{VIC} = 3\%$ and 6%), the NPV slowly increases in first three years compared to later years. In addition, as wind curtailment reduction increases, the net economic benefit of installing synchronous condensers becomes larger. The more wind curtailment is avoided, the larger the benefits.

2) THE PREDOMINATING FACTOR AFFECTING THE NPV

In the developed economic model, the revenue comes from additional wind power (due to reduction of wind curtailment level) and fuel savings. In order to find the predominating factor affecting economic benefits, the NPV is re-calculated considering the following cases one at a time.

1) with only fuel savings.
2) with only additionally sold wind power.
3) with additionally sold wind power and fuel savings.

Fig. 5 shows the effects of the above three cases on the NPV. Wind power reduction is assumed as 3% to demonstrate an example. It is found that with only fuel savings, the NPV is negative and does not significantly change over time. However, when only the additionally sold wind power is considered, the NPV shows increasing trend. The NPV becomes even larger when both case (i) and (ii) are simultaneously considered. From this analysis, it is evident that the additionally sold wind power is the most prevailing factor for achieving economic benefits through optimal allocation of synchronous condensers.

3) EFFECT OF SYNCHRONOUS CONDENSER DISPATCH STRATEGY ON THE NPV

Table 4 shows the detailed cost of a 100 MVA synchronous condenser. The total cost of installing the synchronous condenser is 4,000,000 US$ (in the first year). The maintenance and operational costs are 95,200 US$ and 2,300,000 US$ per year in average. All these costs have been calculated using (6), (7) and (8). Over a 20 year period, the operational costs represent 88.6% of the total costs whereas the installation costs and the maintenance costs are respectively 7.7% and 3.7%. Therefore, to minimise the overall cost, synchronous condensers can only be run when the system strength is low. They can be put offline when sufficient synchronous generators are committed, hence reducing operational costs.

TABLE 4. Detailed costs for a 100 MVA synchronous condenser.

Costs for a 100 MVA SC	C_0	C_{main}	C_{elec}
Average per year (US $)	4,000,000 once	95,200	2,300,000
In total over 20 years (%)	7.7	3.7	88.6

To study the influence of such a synchronous condenser operating strategy on total revenues, the NPV is calculated for two cases, $\alpha_{SA} = \alpha_{VIC} = 0.03$ and $\alpha_{SA} = \alpha_{VIC} = 0.06$. The percentage of time synchronous condensers are online (i.e. τ_{SC} in (8)) are considered as 100% and 70%. Fig. 6 illustrates the NPV curves. It can be seen that the differences between NPV for two different τ_{SC} is small. For instance, when $\alpha_{SA} = \alpha_{VIC} = 0.06$, the NPV increases by 3.6% when

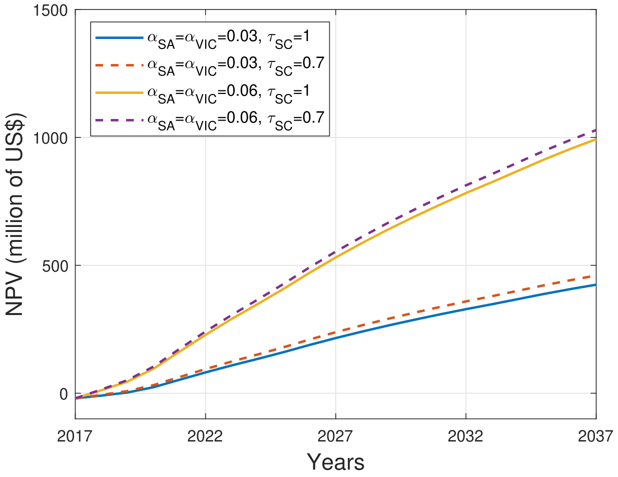


FIGURE 6. Influence of operation strategy on NPV.

τ_{SC} changes to 70% from 100%. Therefore, the operation strategy of synchronous condensers has a small impact on the total NPV.

4) VALUE PROPOSITION OF SYNCHRONOUS CONDENSERS

Installation of synchronous condensers at the weakest parts of the grid enhances system strength by increasing SCR at the PCC of wind power plants, which is shown in Table 2. In Australia, wind power was curtailed in the past to keep additional synchronous generators online to maintain system strength at a desired level [20]. When synchronous condensers are utilized, they ensure acceptable system strength. Therefore, additional synchronous generators, which intend to maintain adequate system strength, can be replaced from dispatch. As a result, the share of wind power in generation mix increases. In other words, deliberate wind curtailment is eventually reduced when synchronous condensers are deployed.

It is evident that installation of synchronous condensers increases the dispatch of wind generation. Therefore, producing power from wind plants instead of conventional synchronous generators causes fuel savings that ultimately brings economic benefits. These revenues are comprehensively modelled in section II.D. The value proposition of synchronous condensers is given by NPV, which is modelled in section II.B. Also, net profit of year i is calculated using (13) as follows.

$$\text{Net profit}^{i} = R^{i}_{\text{wtg}} + R^{i}_{\text{fuel}} - (C^{i}_{\text{elec}} + C^{i}_{\text{main}}) \qquad (13)$$

Meanings of different symbols are already provided in section II. D.

Table 5 outlines the value proposition of synchronous condensers by showing NPV values and net profits in four years interval. For the analyses, 3% wind curtailment reduction is assumed. It is found that both NPV and net profit exhibit increasing trends. It indicates that optimal allocation of synchronous condensers brings techno-economic benefits for network operators by reducing wind curtailment through the improvement of system strength.

TABLE 5. Value proposition of synchronous condensers.

Year	4	8	12	16	20
Net profit (M US$)	38.1	45.6	53.4	56.9	67.3
NPV (M US$)	52.5	160.7	264.5	347.9	424.3

TABLE 6. Influence of the synchronous condenser losses on the NPV results.

P_{loss}	1.5%	3%	4.5%
NPV after 10 years (M US$)	253.9	215.7	177.5
NPV after 20 years (M US$)	484	424.3	364.6

5) SENSITIVITY ANALYSIS OF THE INTERNAL LOSSES OF A SYNCHRONOUS CONDENSER

As stated in Section II. C, the cost of electricity consumption, which is the most important cost as shown in Table 4, is directly proportional to the internal losses P_{loss}. A sensitivity analysis with regards to this parameter is carried out, with a wind curtailment reduction of 3%. The NPV results are shown in Table 6 with different P_{loss}. The NPV results are still positive even with 4.5% of internal losses. This shows that reduction of wind curtailment would result in economic benefits even with internal losses more than 3%.

C. OPTIMISATION INCLUDING RETROFITTED SYNCHRONOUS CONDENSERS

In the last few years, some large synchronous generators in South Australia incurred planned retirement to facilitate increased wind penetration. These generators however provided necessary ancillary supports for voltage and frequency management. In absence of these generators, the overall strength of the South Australian grid further deteriorates. Therefore, an alternative idea of retrofitting the retired synchronous generators as synchronous condensers is explored in [7] and [8]. A comprehensive analysis is done to find the savings in cost when retrofitted synchronous condensers are used instead of newly installed synchronous condensers. To this end, synchronous condensers with ratings of 100, 166, 250 and 333 MVA are considered. Table 7 shows the savings in costs (compared to new installation) for deploying the above retrofitted synchronous condensers.

It is worth clarifying that these retrofitted synchronous condensers may not be located very close to wind power plants. Thus, the impact of such condensers on the SCR at the PCC of wind power plants needs to be investigated. To this end, two different retrofitted synchronous condensers with ratings 333 MVA and 666 MVA are assumed to be connected in bus 501 (refer to Fig. 2) as those synchronous generators are the only one to be retired in the power grid under study [26]. Then, SCR values are calculated. As shown

TABLE 7. Cost savings by using retrofitted synchronous condensers instead of new installation.

SC rating (MVA)	100	166	250	333
Saving with retrofitted SC (% per year)	7.47	6.78	6.42	6.24

TABLE 8. Comparison of SCR with retrofitted synchronous condensers.

PCC	VIC 3	SA 1	SA 2	SA 3	SA 4
Without retrofitting	2.57	2.66	2.83	2.06	2.07
333 MVA retrofitted	2.57	2.81	3.03	2.06	2.07
666 MVA retrofitted	2.57	2.86	3.1	2.06	2.07

in Table 8, SCR values at PCCs VIC 3, SA 3 and SA 4 are not influenced by the retrofitted synchronous condenser as they are geographically far from bus 501. In contrast, SCR at PCCs SA 1 and SA 2 increase. Also, at PCC SA 2, the SCR values are more than 3 for both retrofitting cases.

It is found that other four PCCs - VIC 3, SA 1, SA 3 and SA 4 still face low SCR problem. Therefore, the proposed optimisation model is executed. It suggests the installation of 100 MVA synchronous condensers at these PCCs. Therefore, four additional synchronous condensers need to be installed when the retrofitting of 333 MVA and 666 MVA synchronous condensers are considered. Note that when no retrofitting is taken into account, five new synchronous condensers are required to be installed to tackle low SCR problem at the wind plant PCCs.

To analyse whether retrofitting is economically profitable, the NPV and Internal Rate of Return (IRR) are determined. IRR is defined as the maximum value of the discount rate for which the NPV remains positive and is given by (14). It is an indicator to estimate the profitability of an investment. Higher IRR means, a project is more profitable.

$$IRR = r \text{ such as } \sum_{i=1}^{i=N_{years}} \frac{R_i - C_i}{(1+r)^i} - C_0 = 0 \tag{14}$$

Table 9 presents the NPV and IRR values after 20 years for each case. Wind curtailment reduction level is assumed to be 3%.

It can be noticed that for both retrofitting cases, NPV and IRR values are less than that of without any retrofitting. This is due to the fact that retrofitted synchronous condensers have large rated capacities. As such, they have higher operational and maintenance costs. Also, their ratings and locations cannot be independently chosen (since an existing synchronous generator is converted to run as a synchronous condenser after retirement). Therefore, the retrofitted synchronous condensers do not offer financial benefits when only the improvement of SCR at wind plant PCCs is considered.

However, retrofitted synchronous condensers have other advantages including improvement of system strength at other network buses and providing inertia support. Fig. 7 compares fault currents at some high voltage buses of Area 5 (refer to Fig. 2) with and without a 666 MVA synchronous condenser.

TABLE 9. Comparison of NPV and IRR values with retrofitted synchronous condensers.

Case	NPV (M$)	IRR (%)
Without retrofitting	424.3	90.5
333 MVA retrofitted	368.6	83.5
666 MVA retrofitted	284.3	56.5

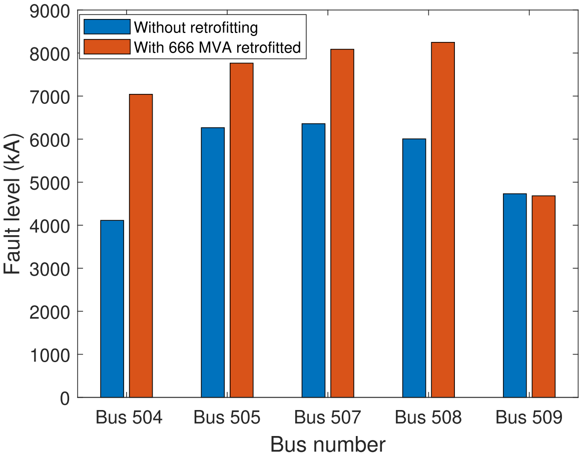


FIGURE 7. Comparison of fault currents with and without a retrofitted synchronous condenser.

It is found that fault currents significantly increase due to the deployment of the 666 MVA machine. Thus, the retrofitted synchronous condenser at bus 501 enhances system strength at several high-voltage buses at the same time. Furthermore, this large capacity synchronous condenser provides reasonable amount of additional inertia. It helps to slow down rate of change of frequency following load-generation imbalance. Therefore, retrofitted synchronous condensers can be useful to increase the overall system strength and inertia even if they do not offer a cost-effective solution while enhancing SCR at wind plant PCCs.

D. SUMMARY OF THE ASSUMPTIONS IN NPV MODELLING

The assumptions used in the NPV modelling are summarised as follows.

- The main assumptions in the NPV modelling lie in the cost of electricity consumption of synchronous condensers and their revenues associated with additionally sold wind power, and subsequent savings of fuel cost. Installation, operation and maintenance costs of synchronous condensers are taken from existing literature [24], [28], [29].
- The internal losses of a synchronous condenser vary from 1.5% to 3% of its rated capacity [28]. Those losses are related to the cost of electricity consumption of a synchronous condenser. To consider a conservative scenario

in this paper, the internal losses of a synchronous condenser are assumed to be 3% in the NPV modelling. In addition, a sensitivity analysis is carried out to demonstrate the impact of internal losses on NPV. It is found that the NPV is still positive even with internal losses greater than 3% (Table 6).

- The dispatch strategy of synchronous condensers is prudently assumed in the NPV modelling. To minimise the overall cost, synchronous condensers can be operated only when the system strength is low. They can be put offline when adequate number of synchronous generators are committed. To this end, NPV analyses are performed by considering two cases. In the first case, synchronous condensers are assumed to be operated for 100% time in a year, whereas in the second case, the yearly operating time is presumed to be 70%. These assumptions are made to represent two different network scenarios. In the first case, it is assumed that sufficiently high wind generation is available throughout a year. Consequently, the number of committed synchronous generators is fewer. As a result, synchronous condensers need to be operated for 100% time to ensure satisfactory system strength in the PCC of wind power plants. In the second case, it is presumed that the grid encounters low system strength problem for 70% time in year due to substantial wind power penetration. To mitigate this challenge, synchronous condensers run for 70% time in a year. The results presented in Fig. 6 show that the operating strategy of synchronous condensers has an implication on the NPV.
- In the NPV modelling, various levels of wind curtailment reductions are assumed. NPV analyses are carried out with three levels of wind curtailment reduction such as 1%, 3% and 6%. These levels are presumed based on a technical report [20]. The report shows that around 6% of wind generation was curtailed over eight weeks in South Australia in 2017 due to new dispatch constraints imposed by the AEMO. If this wind curtailment can be avoided, it necessarily provides savings in fuel cost. Note that 1% and 3% wind curtailment reductions are also analysed to show some conservative cases. It is found that even in a very conservative scenario (i.e. only 1% wind curtailment reduction), the NPV remains positive in 20 years period (Fig. 4).

E. DISCUSSION

The proposed optimisation model helps to reduce wind curtailment levels. Additionally sold wind power and fuel savings are considered in the developed model. However, there are other factors that can be taken into account in the future research. These include penalty due to failure to meet renewable energy targets (caused by wind curtailment), climate change issue by reducing CO_2 emissions and change of network topology etc. Furthermore, a market for inertia services could also be introduced. It will offer additional revenues for synchronous condensers by sourcing inertia support (along with fault current).

Energy storage can be deployed to improve system strength and subsequently reduce wind curtailment. In the literature, such a solution is provided using pumped storage and compressed air energy storage [33]. Note that a Battery Energy Storage System (BESS) is mainly utilized for power smoothing and offering emulated inertia. A BESS is connected to the grid through power electronics converters, which ultimately limit its fault contribution. However, with necessary controllers, a BESS might be able to generate sufficient fault current that eventually would improve the system strength. The development of strategies to enhance system strength and reduce wind curtailment with BESS will be explored in our future work.

V. CONCLUSION

In this paper, an optimisation algorithm has been proposed to determine the ratings of synchronous condensers to install at the best locations in a wind dominated power grid. The objective has been to enhance the system strength at the point of common coupling of the wind plants while being the most economically viable. Detailed analysis has been carried out to simultaneously determine technical and financial aspects of installing synchronous condensers.

The proposed optimisation algorithm has recommended the installation of 100 MVA synchronous condensers at five locations in South Australia and Victoria to reduce the wind curtailment level and eventually generate revenue by selling surplus energy and saving fuel cost. It has been shown via net present value curve that significant economic benefit is achievable by adopting the proposed approach. Furthermore, the net present value curve has demonstrated increasing benefits over 20 year period for various wind curtailment reduction levels. In addition, selling wind power has been found to be the predominating factor to obtain economic benefits. It has also been confirmed that the operation strategy of synchronous condensers, that is the percentage of time they are online, has an impact on the total net present value.

Through the proposed algorithm, it has been shown that retired synchronous generators can be retrofitted to be used as synchronous condensers to improve short-circuit ratio values at the point of common couplings of a certain wind plant. However, four new synchronous generators have yet been recommended to install to ensure sufficient system strength in the Australian power system. Based on the net present value and internal rate of return analysis, it has been found that retrofitted synchronous condensers do not offer a cost-effective solution when only the short-circuit ratio enhancement at wind plants' point of common couplings are considered. Nonetheless, such retrofitting has additional advantages in terms of improving the fault level at high voltage buses and providing inertia supports. Finally, it is worth mentioning that the proposed algorithm can be applied to any other power system with high wind penetration to improve its network resilience.

REFERENCES

[1] E. Hossain, J. Hossain, and F. Un-Noor, "Utility grid: Present challenges and their potential solutions," *IEEE Access*, vol. 6, pp. 60294–60317, 2018.

[2] A. S. Dagoumas and N. E. Koltsaklis, "Review of models for integrating renewable energy in the generation expansion planning," *Appl. Energy*, vol. 242, pp. 1573–1587, May 2019.

[3] AEMO. (2019). *Generation Information Page*. [Online]. Available: https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Generation-information

[4] R. Yan, T. K. Saha, N. Modi, N.-A. Masood, and M. Mosadeghy, "The combined effects of high penetration of wind and PV on power system frequency response," *Appl. Energy*, vol. 145, pp. 320–330, May 2015.

[5] *National Transmission Network Development Plan*, Austral. Energy Market Operator, Melbourne, VIC, Australia, 2016.

[6] M. N. I. Sarkar, L. G. Meegahapola, and M. Datta, "Reactive power management in renewable rich power grids: A review of grid-codes, renewable generators, support devices, control strategies and optimization algorithms," *IEEE Access*, vol. 6, pp. 41458–41489, 2018.

[7] N.-A. Masood, R. Yan, T. K. Saha, and S. Bartlett, "Post-retirement utilisation of synchronous generators to enhance security performances in a wind dominated power system," *IET Gener., Transmiss. Distrib.*, vol. 10, no. 13, pp. 3314–3321, Oct. 2016.

[8] AEMO. (2017). *South Australia System Strength Assessment, 2017*. [Online]. Available: https://www.aemo.com.au/-/media/Files/Media_Centre/2017/South_Australia_System_Strength_Assessment.pdf

[9] E. Marrazi, G. Yang, and P. Weinreich-Jensen, "Allocation of synchronous condensers for restoration of system short-circuit power," *J. Mod. Power Syst. Clean Energy*, vol. 6, no. 1, pp. 17–26, Dec. 2018.

[10] J. W. Feltes and B. S. Fernandes, "Wind turbine generator dynamic performance with weak transmission grids," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2012, pp. 1–7.

[11] D. Wu, G. Li, M. Javadi, A. M. Malyscheff, M. Hong, and J. N. Jiang, "Assessing impact of renewable energy integration on system strength using site-dependent short circuit ratio," *IEEE Trans. Sustain. Energy*, vol. 9, no. 3, pp. 1072–1080, Jul. 2018.

[12] D. J. Burke and M. J. O'Malley, "Factors influencing wind energy curtailment," *IEEE Trans. Sustain. Energy*, vol. 2, no. 2, pp. 185–193, Apr. 2011.

[13] *Integrating Renewable Energy–Wind Integration Studies Report*, Austral. Energy Market Operator, Melbourne, VIC, Australia, 2013.

[14] Nahid-Al-Masood, R. Yan, and T. K. Saha, "A new tool to estimate maximum wind power penetration level: In perspective of frequency response adequacy," *Appl. Energy*, vol. 154, pp. 209–220, Sep. 2015.

[15] W. Jin and Y. Lu, "Stability analysis and oscillation mechanism of the DFIG-based wind power system," *IEEE Access*, vol. 7, pp. 88937–88948, 2019.

[16] R. A. Walling, E. Gursoy, and B. English, "Current contributions from type 3 and type 4 wind turbine generators during faults," in *Proc. PES T&D*, May 2012, pp. 1–6.

[17] M. Martin Almenta, D. J. Morrow, R. J. Best, B. Fox, and A. M. Foley, "An analysis of wind curtailment and constraint at a nodal level," *IEEE Trans. Sustain. Energy*, vol. 8, no. 2, pp. 488–495, Apr. 2017.

[18] X. Chen, M. B. McElroy, and C. Kang, "Integrated energy systems for higher wind penetration in China: Formulation, implementation, and impacts," *IEEE Trans. Power Syst.*, vol. 33, no. 2, pp. 1309–1319, Mar. 2018.

[19] E. V. Mc Garrigle, J. P. Deane, and P. G. Leahy, "How much wind energy will be curtailed on the 2020 irish power system?" *Renew. Energy*, vol. 55, pp. 544–553, Jul. 2013.

[20] WattClarity, Global Roam. (2017). *How Much Wind-Powered Electricity Production has Been Curtailed in South Australia?* [Online]. Available: http://www.wattclarity.com.au/2017/09/

[21] J. Li, Y. Fu, Z. Xing, X. Zhang, Z. Zhang, and X. Fan, "Coordination scheduling model of multi-type flexible load for increasing wind power utilization," *IEEE Access*, vol. 7, pp. 105840–105850, 2019.

[22] (2017). *Synchronous Condenser Systems. GE*. [Online]. Available: http://www.gegridsolutions.com/powerd/catalog/synch_cond.html

[23] AEMO. (2013). *100 Per Cent Renewables Study—Modelling outcomes*. [Online]. Available: https://www.environment.gov.au/system/files/resources/d67797b7-d563-427f-84eb-c3bb69e34073/files/100-percent-renewables-study-modelling-outcomes-report.pdf

[24] J. Jia, G. Yang, A. H. Nielsen, E. Muljadi, P. Weinreich-Jensen, and V. Gevorgian, "Synchronous condenser allocation for improving system short circuit ratio," in *Proc. 5th Int. Conf. Electric Power Energy Convers. Syst. (EPECS)*, Apr. 2018, pp. 1–5.

[25] Y. Zhang, S.-H.-F. Huang, J. Schmall, J. Conto, J. Billo, and E. Rehman, "Evaluating system strength for large-scale wind plant integration," in *Proc. IEEE PES Gen. Meeting | Conf. Exposit.*, Jul. 2014, pp. 1–5.

[26] M. Gibbard and D. Vowles, "IEEE task force on benchmark systems for stability controls: Simplified 14-generator model of the South East Australian power system," Univ. Adelaide, Adelaide, SA, Australia, Tech. Rep., Jun. 2014.

[27] ElectraNet. (2017). *Synchronous Condenser Asset Life Review*. [Online]. Available: https://www.aer.gov.au

[28] M. Nambiar and Z. Konstantinovic, "Impact of using synchronous condensers for power system stability and improvement of short-circuit power in mining projects," *Mining Eng.*, vol. 67, pp. 38–44, Jan. 2015.

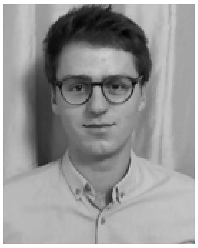
[29] F. Li, J. D. Kueck, D. T. Rizy, and T. King, "A preliminary analysis of the economics of using distributed energy as a source of reactive power supply," Oak Ridge Nat. Lab., Oak Ridge, TN, USA, Tech. Rep. ORNL/TM-2006/014, Apr. 2006.

[30] RateInflation. (2018). *Australian Inflation Rate History*. [Online]. Available: https://www.rateinflation.com/inflation-rate/australia-historical-inflation-rate?start-year=2006&end-year=2018

[31] K. Nara, "Genetic algorithm for power systems planning," in *Proc. Int. Conf. Adv. Power Syst. Control, Operation Manage. (APSCOM)*, vol. 1, 1997, pp. 60–65.

[32] K. Clark, N. W. Miller, and J. J. Sanchez-Gasca, "Modeling of GE wind turbine-generators for grid studies," *GE Energy*, vol. 4, pp. 0885–8950, Apr. 2010.

[33] P. Denholm, "Energy storage to reduce renewable energy curtailment," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2012, pp. 1–4.



LUCAS RICHARD (Student Member, IEEE) received the B.Sc. degree in engineering from École Normale Supérieure Paris-Saclay, Gif-sur-Yvette, France, in 2016. He is currently pursuing the M.Sc. degree in electrotechnics and electronics with the University Paris-Saclay, France. From 2017 to 2018, he worked as a Research Intern with The University of Queensland, Brisbane, QLD, Australia. His research interests include grid integration of renewable energy and power electronics.

NAHID-AL-MASOOD (Senior Member, IEEE) received the B.Sc. and M.Sc. degrees in electrical and electronic engineering (EEE) from the Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh, in 2008 and 2010, respectively, and the Ph.D. degree in power and energy systems from The University of Queensland, Brisbane, QLD, Australia, in 2017. He is currently working as an Associate Professor with the Department of Electrical and Electronic Engineering, BUET. His research interests include power system modeling and analysis, and grid integration of renewable energy.

TAPAN KUMAR SAHA (Fellow, IEEE) received the B.Sc. degree in electrical and electronic engineering from the Bangladesh University of Engineering and Technology, Dhaka, in 1982, the M.Tech. degree in electrical engineering from IIT Delhi, in 1985, and the Ph.D. degree from The University of Queensland, Brisbane, QLD, Australia, in 1994. He is currently a Professor of electrical engineering with the School of Information Technology and Electrical Engineering, The University of Queensland (UQ). He is also the Director of the Australasian Transformer Innovation Centre and the Leader of UQ Solar. His research interests include condition monitoring of electrical assets, power systems, and renewable energy integration to the grid. He is a Fellow and a Chartered Professional Engineer of the Institution of Engineers, Australia.

WAYES TUSHAR (Senior Member, IEEE) received the B.Sc. degree in electrical and electronic engineering from the Bangladesh University of Engineering and Technology, in 2007, and the Ph.D. degree in engineering from The Australian National University, in 2013. He is currently working as an Advance Queensland Research Fellow with the School of Information Technology and Electrical Engineering, The University of Queensland. His research interests include energy and storage management, renewable energy, smart grid, design thinking, and game theory.

HUAJIE GU (Student Member, IEEE) received the B.Eng. degree in automatic control from Nanjing Technical University, Nanjing, China, in 2011, the M.Eng. degree in control theory and control engineering from Tongji University, Shanghai, China, in 2014, and the Ph.D. degree in electrical engineering from The University of Queensland, Brisbane, QLD, Australia, in 2019. His research interests include electricity market and power system stability and control.

• • •