

Contingency Reserve Evaluation for Fast Frequency Response of Multiple Battery Energy Storage Systems in a Large-scale Power Grid

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Abstract—Recently, the fast frequency response (FFR) service by large-scale battery energy storage systems (BESSs) has been successfully proved to arrest the frequency excursion during an unexpected power outage. However, adequate frequency response relies on proper evaluation of the contingency reserve of BESSs. The BESS FFR reserve is commonly managed under fixed contracts, ignoring various response characteristics of different BESSs and their coexisting interactions. This paper proposes a new methodology based on dynamic grid response and various BESS response characteristics to optimise the FFR reserves and prevent the frequency from breaching the under-frequency load shedding (UFLS) thresholds. The superiority of the proposed method is demonstrated to manage three large-scale BESSs operating simultaneously in an Australian power grid under high renewable penetration scenarios. Further, the proposed method can identify remaining battery power and energy reserve to be safely utilised for other grid services (e.g., energy arbitrage). The results can provide valuable insights for integrating FFR into conventional ancillary services and techno-effective management of multiple BESSs.

Index Terms—Fast frequency response (FFR), fast frequency contingency reserve, multiple large-scale battery energy storage system (BESS), synthetic inertia requirement, under-frequency load shedding (UFLS).

I. INTRODUCTION

OVER the last decade, the massive increase in renewable generation calls for new ancillary services to address network stability issues, such as the frequency response under potential generation trips [1]. Fast frequency response (FFR) is a new and rapid service to enhance grid resilience. Large-scale battery energy storage systems (BESS) are popular sources for providing FFR because of their reliability and rapid cost decline [2]. Nevertheless, successful BESS provision relies

on the power and energy reserved, which is vital to ensure network security.

The determination of the BESS contingency reserve relies on two factors: security and economy. From the security viewpoint, grid operators are responsible for the FFR allocation by compiling results from trials [3] and extensive dynamic simulation studies [4]. Authors from [5] identify the FFR reserve at different inertia levels and contingency sizes. However, it is only suitable for a single BESS with a fixed time delay and ramp rate. Thus, the method proposed in [5] cannot be implemented in a grid with multiple BESSs. Researchers in [6] calculate the required reserve for multiple FFR sources. However, this method is based on a static function of the load, generation and FFR ramp rates, which ignores the dynamics of the grid response and interactions of multiple FFR resources. From the economic aspect, available generators and power resources are co-optimised to minimise operating costs and maximise reserve profits, including individual or multiple BESSs [7], [8]. However, the detailed dynamic models and system frequency dynamic response are not considered for the pure economic power reserve and energy calculation, which may not guarantee network security. Besides, [9] proposed a method for evaluating the FFR reserve of multiple resources combining economics and security criteria. Nevertheless, results in [9] are conservative as the reserve allocation is more than needed to avoid the under-frequency load shedding (UFLS) activation. Hence, it lacks an effective method for calculating the power reserve of multiple BESSs to keep the security system.

On the other hand, current practices to manage large-scale BESS for FFR are under fixed agreements with grid operators. For example, the German transmission operator established a mandatory prequalified power reserve provision of BESSs for 15 minutes (e.g., 1 MW/250 kWh) to hold the frequency up until remedial actions take place by grid operators (e.g. automatic generation control) [10]. However, this regulation results in less revenue for stakeholders from an economic perspective. In Australia, the grid-following Hornsdale BESS and the grid-forming Dalrymple ESCRI-SA BESS keep 70% [11] and 100% [12] of their rated power reserve for security services (e.g., FFR and synthetic inertia). Due to the lack of FFR and synthetic inertia markets, these services are unremunerated, while BESS remaining capacity can produce valuable revenues from other ancillary services and arbitrage. Additional large-

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scale BESSs are being installed in the Australian power grid, which leads to a challenge to manage several BESSs since there are dynamic interactions among different frequency support resources (e.g., inertia, governor, and FFR resources). Hence, Australian grid operators are urged to develop an effective method to operate all the current and future large-scale BESSs, especially because of the upcoming FFR market implementation by mid-2023 [13].

To overcome the above challenges, this paper aims to develop an innovative methodology to quantify an adequate power reserve for multiple BESSs, considering their different operating characteristics to avoid the UFLS activation. The main contributions of the presented work are as follows.

1) Synthetic inertia requirement quantification: A semi-theoretical framework is developed for calculating the synthetic inertia requirement for BESS according to the grid response and the UFLS limit. The synthetic inertia is formulated in terms of the FFR power and energy from BESS;

2) FFR reserve estimation for multiple BESSs: A mathematical relationship is proposed for optimally estimating the FFR power reserve of multiple large-scale BESSs with various time-response capabilities (e.g., delays and ramp rates). The calculated power reserve can efficiently prevent any UFLS activation;

3) Methodology validation with an actual large power grid: The effectiveness of the proposed approach is validated under the support of a transmission network service provider. Two dispatch scenarios are tested with different system inertia and renewable penetration levels. Likewise, three large-scale BESSs are included based on the projections to 2030.

The proposed methodology can offer effective management of existing or planned large-scale battery energy storage systems. Research outcomes can assist grid operators in efficiently determining the required FFR resources to secure the dynamic frequency response.

II. PROBLEM FORMULATION

A. Frequency Support from Different Resources

Frequency support is mainly provided by synchronous generators (e.g., system inertia and governor) and FFR from inverter-based energy resources (e.g., BESS). However, the adequate assimilation of FFR into conventional frequency response mechanisms has some difficulties, mainly because of their varied response timescales. As shown in Fig. 1, FFR is not instantaneous as is the system inertial response (SIR) due to its intrinsic time-response limitations (e.g., delays and ramp rates). Consequently, FFR is not directly interchangeable with grid inertia [14]. On the other hand, FFR is faster than governor control. Thus, traditional methods to estimate the governor's headroom may not accurately assess the FFR power reserve.

How much FFR reserve is required, and how it can be correctly harmonised with conventional frequency control ancillary services? These are significant questions for modern power grids, anticipating potential stability threats, such as UFLS activation or a power blackout [15].

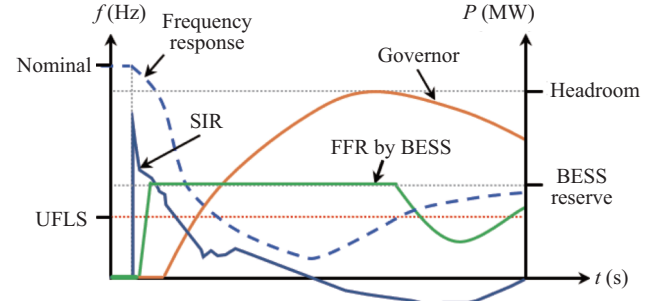


Fig. 1. Frequency response and frequency ancillary services interaction.

B. FFR by Multiple Large-scale BESSs

Large-scale BESSs have been successfully proved as reliable grid service and profitable investment resources [12], [16], [17]. For instance, the Hornsdale Power Reserve (HPR) (the first large-scale BESS in Australia) has successfully supported the South Australian grid by using contracted 70 MW/10 MWh for system contingency reserve and 30 MW/119 MWh for energy arbitrage [11]. The HPR's performance encouraged the installation of another 260 MW of BESS capacity in the Australian power grid, expecting significantly more investment in BESS power capacity by 2030 [18]. However, the FFR reserve is usually fixed under contract, and it is determined individually for each BESS so the dynamic interactions of the frequency support from multiple BESSs have been ignored. Also, as other large-scale BESSs were recently installed in worldwide power grids (see Table I), the need of managing multiple BESS is extended to other countries. Thus, a more flexible and adequate FFR reserve determination method has been proposed in this paper for multiple BESSs with various realistic response characteristics.

TABLE I
LARGE-SCALE BESS WORLDWIDE

Site Name	Year	Capacity (MW/MWh)	Country
Vistra Moss Landing Battery [19]	2021	400/1600	USA
Victoria Big Battery [20]	2021	300/450	Australia
Gateway Energy Storage [21]	2020	250/250	USA
Thurcroft [22]	2020	50/75	UK
Jardelund [23]	2018	48/50	Germany

III. PROPOSED EVALUATION APPROACH

The methodology to quantitatively determine the FFR contingency power reserve from multiple BESSs is developed in this paper to arrest the frequency excursion under a credible generation trip. In addition, the effectiveness and superiority of the proposed approach have been demonstrated by comparing it with the contract based FFR reserve.

The proposed methodology has been divided into three stages: 1) synthetic inertia requirement formulation, 2) battery power reserve optimisation, and 3) power and energy reserve determination. The first stage defines the FFR synthetic inertia requirement to prevent UFLS activation. The optimal battery power reserve of all BESSs that satisfies the synthetic inertia requirement is obtained in the second stage. Then, the power

and energy reserve for FFR and energy participation is determined in the third stage.

A. Augmentation of System Inertia by FFR

System inertia is the total kinetic energy stored in all online synchronous machines. When a large generation trip occurs, system inertia decreases with the frequency and reaches its nadir when the frequency drops to the nadir. The post-contingency frequency dynamics, including the load frequency relief, is defined by the Swing equation as (1) [24]:

$$\frac{df(t)}{dt} = \frac{f_0}{2HS_B} (P_m(t) - P_e(t) - D2\pi(f(t) - f_0)) \quad (1)$$

where $f(t)$ is the frequency following a power disturbance (Hz), f_0 is the nominal grid frequency (Hz; 50 Hz in the Australian power grid), H and S_B are the total constant inertia in seconds and power base in MVA, respectively. D is the load-damping rate (Hz^{-1}), $P_m(t)$ and $P_e(t)$ are the mechanical and electrical power (MW) from the synchronous generators.

Frequency dynamics related to the system inertia dynamics are described in (2).

$$SI(t) = \frac{1}{2} J (2\pi f(t))^2 \quad (2)$$

where $SI(t)$ is the system inertia (MWs) and J is the moment of inertia (kgm^2) of the combined turbine-generator groups.

Note that system inertia is directly proportional to frequency, and it can be locally linear if the tolerance band for a contingency event is less than 1 Hz [25]. Hence, this paper formulates a framework to calculate the synthetic inertia requirement for filling the system inertia gap when a generation trip occurs by providing FFR from BESSs.

Figure 2 depicts the synthetic inertia required from FFR. According to (1)–(2), system inertia with no FFR starts to decrease at t_k due to the contingency, breaches its lower limit of $SI(t_{\text{ufls}})$ at t_{ufls} and reaches its nadir $SI(t_{\text{nad}})$ at t_{nad} . The

difference between the system inertia nadir $SI(t_{\text{nad}})$ and its limit $SI(t_{\text{ufls}})$ is the lack of system inertia SI_{lack} . Therefore, SI_{lack} is set to be the required synthetic inertia SI_{ffr} from FFR.

The time variables shown in Fig. 2 are explained as below:

$$T_{\text{ufls}} = t_{\text{ufls}} - t_k; T_{\text{nad}} = t_{\text{nad}} - t_k \quad (3)$$

$$T_{\text{trig}} = t_{\text{trig}} - t_k; T_{\text{fact}} = t_{\text{fact}} - t_{\text{trig}} \quad (4)$$

where t_k , t_{ufls} , and t_{nad} are the grid response times when the generator k is tripped, the frequency breaches the UFLS limit, and the nadir occurs, respectively. T_{ufls} is the period from the disturbance time to t_{ufls} . T_{nad} is the period from disturbance time to t_{nad} . The time variables associated with the BESS response are: t_{trig} , the time when FFR is triggered, and t_{fact} , the time when the maximum power reserve is activated. Also, T_{trig} is the time delay from the event occurring to the time when FFR is triggered, and T_{fact} is the period from when the FFR is triggered to the time when the FFR is fully activated.

Based on (2), the system inertia at t_k , t_{ufls} , and t_{nad} are shown in (5)–(7).

$$SI(t_k) = \frac{1}{2} J (2\pi f(t_k))^2 \quad (5)$$

$$SI(t_{\text{ufls}}) = \frac{1}{2} J (2\pi f(t_{\text{ufls}}))^2 \quad (6)$$

$$SI(t_{\text{nad}}) = \frac{1}{2} J (2\pi f(t_{\text{nad}}))^2 \quad (7)$$

The lack of system inertia without FFR support, SI_{lack} (MWs) is expressed by (8):

$$SI_{\text{lack}} = SI(t_{\text{ufls}}) - SI(t_{\text{nad}}) \quad (8)$$

The required synthetic inertia to be provided by FFR will be equivalent to the system inertia gap as follows:

$$SI_{\text{ffr}} = SI_{\text{lack}} \quad (9)$$

Then, the synthetic inertia to be provided by BESS FFR will be established as in (10)–(12) based on Fig. 2 and (9). It needs to be noted that the adequate provision of FFR depends on how much power reserve is utilised and how fast it is delivered.

$$\int_{t_k}^{t_{\text{win}}^*} P_{\text{ffr}}(t) dt = SI_{\text{ffr}} \quad (10)$$

$$T_{\text{win}}^* = t_{\text{win}}^* - t_k \quad (11)$$

$$P_{\text{ffr}}(t) \leq P_{\text{ffr}}^* \quad (12)$$

where $P_{\text{ffr}}(t)$ is the instantaneous FFR power, P_{ffr}^* is the optimal battery power reserve, t_{win}^* and T_{win}^* are the optimal time and time window that indicates how fast the FFR should satisfy the synthetic inertia requirement, respectively.

The optimisation results of multiple battery energy storage reserves and the time window are detailed in Section III-B.

B. Optimal Battery Contingency Reserve Determination

T_{win} tuning by gradient descent with momentum: The gradient descent with momentum is based on [26], and it optimises the time window T_{win} by using the derived formulation in (13) based on (8)–(12) and Fig. 2.

$$P_{\text{ffr}} = \frac{SI_{\text{ffr}}}{T_{\text{win}} - \left(\frac{T_{\text{fact}}}{2} + T_{\text{trig}}\right)} \quad (13)$$

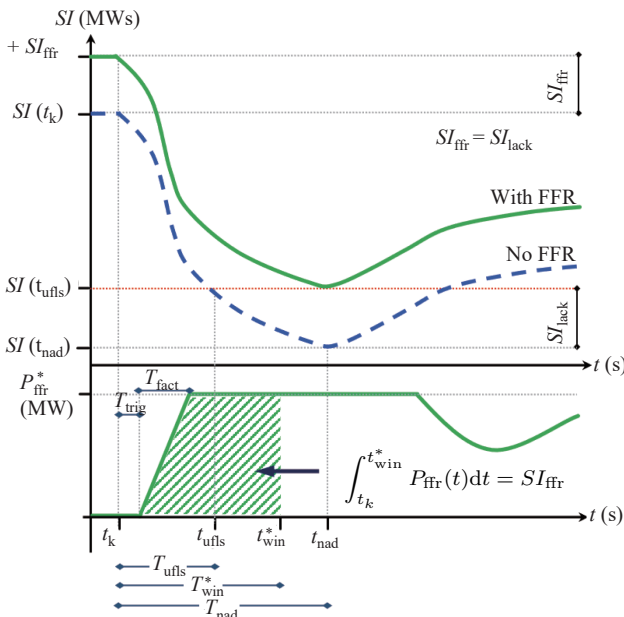


Fig. 2. Illustration of synthetic inertia required from FFR.

Furthermore, the time window can be obtained by minimising the synthetic inertia requirement error using the objective function in (14), and the post-contingency frequency dynamics derived in (15) based on (1). Further, system inertia dynamics and gradient descent with momentum equations are in (16)–(19):

Objective function for T_{win} :

$$J_{T_{win}} = \min \left[(SI(t_{nad})_i - SI(t_{ufls}))^2 \right] \quad (14)$$

$$\frac{df(t)_i}{dt} = \frac{f_0}{2HS_B} (P_m(t)_i - P_e(t)_i - D2\pi(f(t)_i - f_0)) \quad (15)$$

$$SI(t_{nad})_i = \min \left(\frac{1}{2} J(2\pi f(t)_i)^2 \right) \quad (16)$$

$$P_{ffr_res}(T_{win,i}) = \frac{SI_{ffr}}{T_{win,i} - \left(\frac{T_{fact}}{2} + T_{trig} \right)} \quad (17)$$

$$\Delta T_{win,i} = \alpha \Delta T_{win,i-1} - \eta \nabla f(t)_i (\Delta T_{win,i}) \quad (18)$$

$$T_{win,i} = T_{win}^{(i-1)} + \Delta T_{win,i} \quad (19)$$

where α is the momentum $\in [0, 1]$, η is the learning rate $\in [0, 1]$, and i is the iteration number.

The constraint for the optimal solution T_{win}^* is in (20):

$$T_{ufls} < T_{win}^* < T_{nad} \quad (20)$$

Multi-BESS power reserve optimisation by Genetic Algorithm (GA): The multi-storage power reserve calculation is based on [27], and it includes n BESSs with various rated power values and time-response capabilities (e.g., delays and ramp rates). The two objective functions are formed in (21) and (22) for the synthetic inertia procurement and the overall power reserve optimisation, respectively.

Objective function 1 – Synthetic inertia procurement:

$$J_1 = \min \left[\left(\sum_{j=1}^n P_{ffr,j}^* \left(T_{win}^* - \frac{T_{fact,j}}{2} - T_{trig,j} \right) \right) - SI_{ffr} \right]^2 \quad (21)$$

Objective function 2 – Battery power reserve optimisation:

$$J_2 = \min \left[\sum_{j=1}^n P_{ffr,j}^* \right] \quad (22)$$

Constraints of power reserves are set according to the battery rated power (P_{bess_rated}) as follows:

$$ub = [P_{bess_rated_1}, \dots, P_{bess_rated_j}, \dots, P_{bess_rated_n}] \gamma_{ub} \quad (23)$$

$$lb = [P_{bess_rated_1}, \dots, P_{bess_rated_j}, \dots, P_{bess_rated_n}] \gamma_{lb} \quad (24)$$

where ub and lb are the upper and lower boundaries of the battery power reserve solutions, respectively. While γ_{ub} and γ_{lb} are the upper and lower percentage of the power capacity allowed for security services to the full rated BESS power.

C. Flowchart of the Proposed Methodology

The proposed approach can be implemented in different grids with various inertia levels and renewable penetrations. The detailed steps are shown in Fig. 3. Stage 1 assesses the synthetic inertia requirement according to the grid response. Stage 2 tunes the time window and optimises the battery power reserve of multiple BESSs. Finally, Stage 3 computes the power obtained by the method, and the energy of FFR BESSs under the 15-min criterion (e.g., 1 MW/250 kWh; [10]). Then, the remaining BESS capacity is securely identified for other grid services.

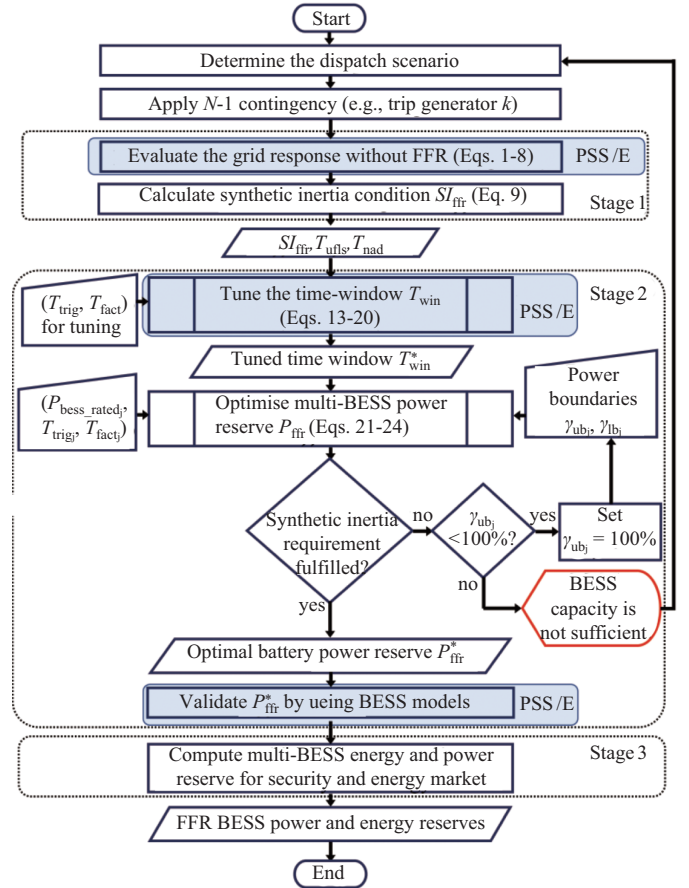


Fig. 3. Flowchart of the proposed approach.

In this paper, the case study with 34% penetration will consider a default upper bound of 70% of the BESS rated power. In comparison, an upper bound of 100% will be required for a higher renewable penetration case. The decision tree of Stage 2 contains the determination of the upper bound. This method not only estimates the FFR power reserve of multiple BESSs, but also recognises if the battery capacity is not sufficient to deploy the synthetic inertia condition as highlighted by the red element of Fig. 3.

IV. CASE STUDY AND RESULTS DISCUSSION

A. Power Network for Case Study

The Australian Government is committed to the world's emission reduction policies in the Australian National Electricity Market (NEM). To this end, the Australian Electricity

Market Operator (AEMO) biennially develops and updates a roadmap for the eastern and south-eastern seaboard's power system over the next two decades by establishing a whole of system plan for an efficient transformation to a renewables-based energy system. This roadmap, known as the Integrated System Plan (ISP), also considers state-based renewable energy targets. For instance, the Queensland state power grid meets the 50% renewable energy target by 2030 [18].

The case study of the Australian Queensland state power grid is one of four sub-networks of the NEM characterised as a long and non-meshed transmission network. The analysis assumes that Queensland is operating in an islanded state. The Queensland grid is divided into the North, Central, and South regions, including 275 kV and 132 kV transmission lines. A simplified representation of the network is shown in Fig. 4. The detailed grid data is in the format of PSS®E [28] and contains around 1200 buses, 28 synchronous generators, 2 pumped storage units, and more than 40 renewable power plants (e.g. existing and future wind and solar PV plants as informed by the ISP).

The assumed operating standards for the Queensland islanded power system (as shown in Table II) are used as constraints for the multi-BESS power reserve optimisation.

TABLE II
QUEENSLAND NETWORK OPERATING STANDARD [29]

Item	Value
Nominal frequency	50 Hz
UFLS threshold	49 Hz
Secure inertia	16,000 MWs
Credible generation contingency	750 MW

For this study, three large-scale BESSs of 100 MW [30], 150 MW [31], and 50 MW [32] are considered connected to the Queensland network in coming years. These are shown by green circles in Fig. 4. For validation purposes, the generic battery storage model with droop control reported in [33] is used. Also, the battery time-response capabilities are assumed fast enough to be classified as a FFR source in the NEM. Due to the present lack of Australian grid standards for FFR reserves, assumptions for BESS contracted power and energy are considered based on local trials and international practices. Hence, it is assumed that 1) power contracted: 70% of the BESS rated power capacity based on the Hornsdale BESS experience [11], and 2) energy contracted: the BESS power contracted during 15 min, also known as the 15-min criterion [10]. Table III contains the assumed BESS characteristics, where BESS 1 has the fastest response, and BESS 2 has the slowest.

TABLE III
BESS FEATURES FOR CASE STUDY

BESS	Planned capacity		Time-response features		Contracted FFR reserve	
	Power (MW)	Energy (MWh)	T_{trig} (s)	T_{fact} (s)	Power (MW)	Energy (MWh)
1	100	150	0.05	0.8	70	17.5
2	150	400	0.1	2.0	105	26.3
3	50	200	0.1	1.5	35	8.8

An FFR market in the NEM will be established in Q3 2023. This will provide a market mechanism for the power and energy reserved for FFR to be remunerated [13].

The proposed method in this paper will manage the BESSs in Table III for minimising the FFR reserve, allowing the remaining BESS capacity for energy arbitrage.

Two cases are created, each with 5,400 MW-load grid dispatch but with different grid inertia and renewable penetration levels as depicted (refer to Table IV). Note that the Queensland-New South Wales Interconnection (QNI) is disabled to operate the Queensland grid under more critical scenarios for frequency stability studies.

TABLE IV
CASE SETTINGS OF THE QUEENSLAND GRID

Grid Parameters	Case I	Case II
Grid Load (MW)	5,400	5,400
Pre-contingency Inertia (MWs)	31,980	20,100
Post-contingency Inertia (MWs)	29,900	18,020
Credible Generation Trip (MW)	750	750
Governor Headroom (MW)	2,900	2,400
Instantaneous Renewable Penetration	34%	70%

Based on the flowchart in Fig. 3, the following case studies are developed during three stages to achieve the FFR effective reserves of several BESSs for the Queensland network under a 750 MW generation trip.

B. Case I: 34% Renewable Penetration

The first case study demonstrates the proposed methodology is capable of managing the three BESSs to keep the frequency above the UFLS threshold in a power grid with 34% of renewable penetration and 29.9 GWs of system inertia.

Stage 1: The benchmark evaluation through a single dynamic simulation is shown in Fig. 5. Frequency and system inertia dynamics are included in Fig. 5(a), and the grid power response comprising the power loss, system inertial response, and mechanical power deviation in Fig. 5(b).

As shown in Fig. 5, the first 3 seconds are in steady state considering $f = 50$ Hz, and post-contingency $SI = 29.9$ GWs. When the generation trip occurs ($t_k = 3$ s), frequency and system inertia start to decrease, breaching the lower limit (dotted red line) and reaching their nadir values. Frequency control mechanisms by synchronous generators arrest the frequency by a sudden injection of active power (P_{sir}) followed by the governor response (ΔP_m). It should be noted that the governor reaches up to 1,100 MW of active power injection, but this is not fast enough to keep the frequency operating above its lower UFLS threshold. Therefore, the lack of system inertia obtained by (8) is the required synthetic inertia of $SI_{\text{ffr}} = 357$ MWs, where FFR should meet within T_{win}^* .

Stage 2: The optimal time window, $T_{\text{win}}^* = 3.8 \in [T_{\text{ufls}}, T_{\text{nad}}]$, is found within five dynamic-simulation iterations based on the gradient descent optimisation method as detailed in Fig. 6. Hence, all BESSs should be managed to provide at least 357 MWs within $T_{\text{win}}^* = 3.8$ s to avoid the UFLS activation.

As shown in Figs. 7–8, the energy provision within T_{win}^* is achieved ($J_1 \approx 0$ in Fig. 7) at the minimum total power reserve of 113 MW ($J_2 = 113$ in Fig. 7) based on GA. This

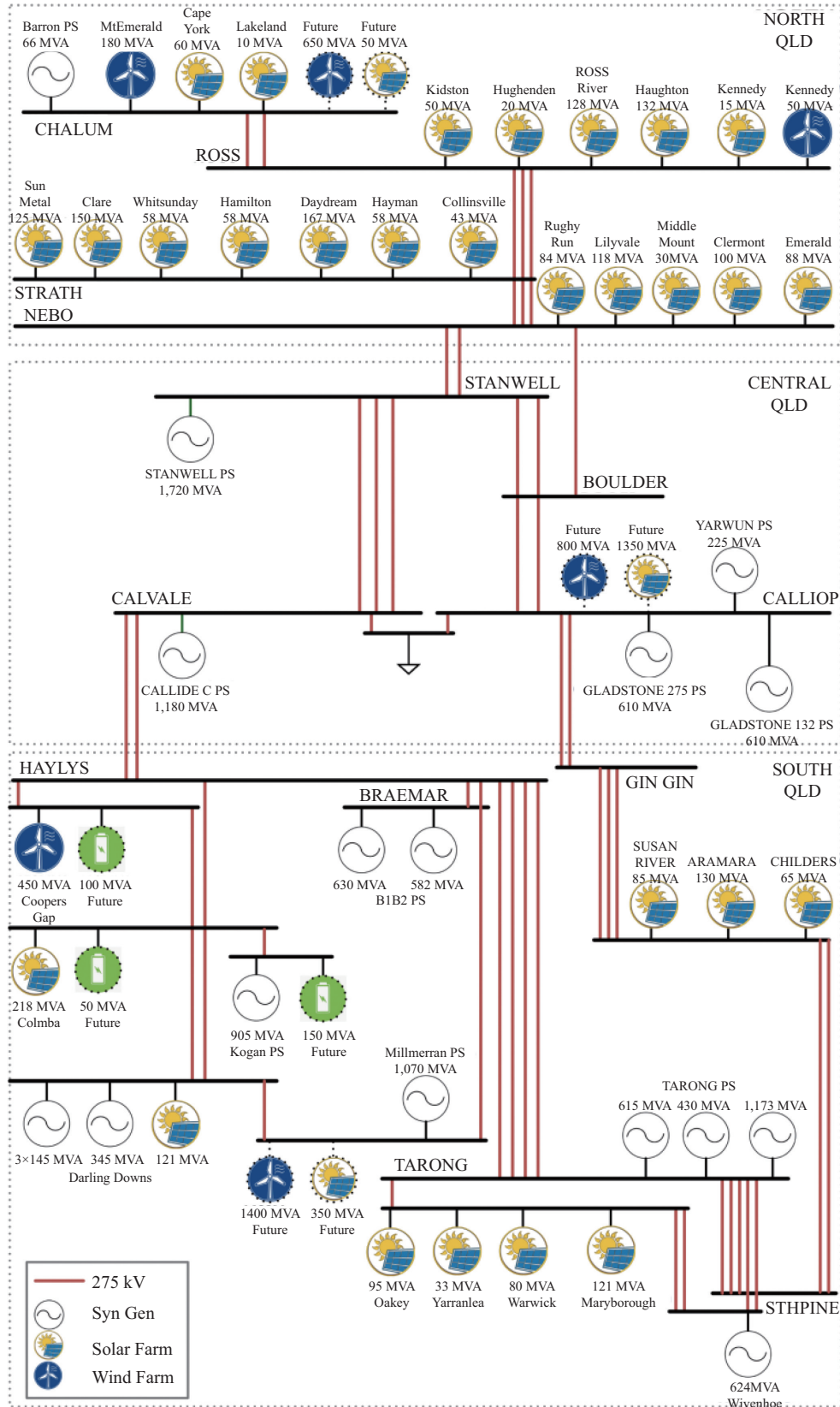


Fig. 4. Simplified diagram of the Queensland Power System [18].

is attained by restraining the BESS solutions by $\gamma_{ub} = 70\%$ in GA. The estimated contingency power reserve for the three BESSs is shown in Fig. 8 and Table V. Notice the BESS with

a faster response should deploy a larger power reserve for accomplishing the overall minimum FFR reserve.

The dynamic power response comparison between the ob-

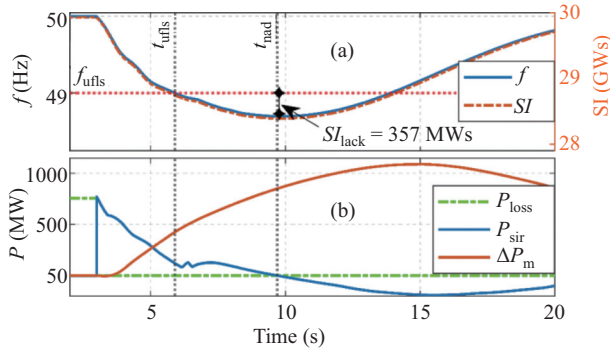
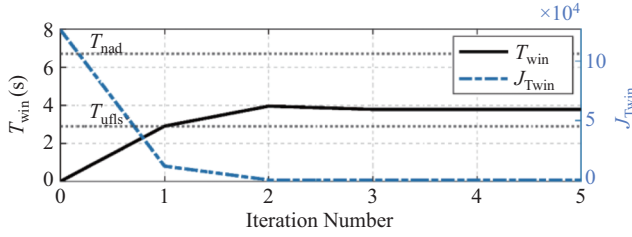


Fig. 5. Benchmark's grid response under a 750 MW generation trip of Case I.

Fig. 6. Optimal T_{win} by gradient descent with momentum for Case I.

tained optimal and contracted FFR power reserves are shown in Fig. 9.

As it can be seen, the optimal reserves are less than the contracted reserves. Hence, power reserves of (a) 30 MW, (b) 141 MW and (c) 16 MW can be safely utilised for other ancillary services or arbitrage.

Figure 10(a) shows the frequency dynamic response with FFR and the benchmark without FFR. The corresponding total FFR active power is shown in Fig. 10(b). First, frequency is kept within specified frequency operating standards when

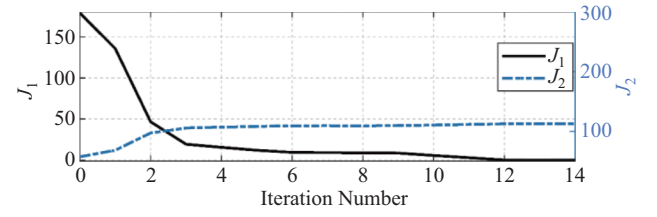


Fig. 7. Cost functions of the optimal multiple BESSs for FFR by GA for Case I.

TABLE V
OPTIMAL MULTI-BESS CONTINGENCY RESERVE FOR CASE I

BESS	FFR BESS power contracted (MW)	FFR optimal power with upper bound $\gamma_{ub} = 70\%$	
		Optimal power P_{ffr}^* (MW)	Synthetic inertia SI_{ffr} (MWs)
1	70	70	235
2	105	9	24
3	35	34	100
Total	210	113	359

using FFR from multiple BESSs, where the contracted reserve is overestimated. Second, the overall optimal reserve achieves better battery management when targeting synthetic inertia procurement within T_{win}^* , which is sufficient to arrest the frequency drop. These results demonstrate the developed methodology effectively assimilates FFR into the system inertia and enhances system security by the management of multiple BESSs.

Stage 3: The attained power and energy reserves of each BESS for FFR and the energy market are shown in Table VI. Note the overall optimal BESS capacity (113 MW/19.8 MWh) to remain on standby is less than the contracted one (210 MW/52.6 MWh). As a result, the impact on other revenue streams is minimized when using the proposed method, which

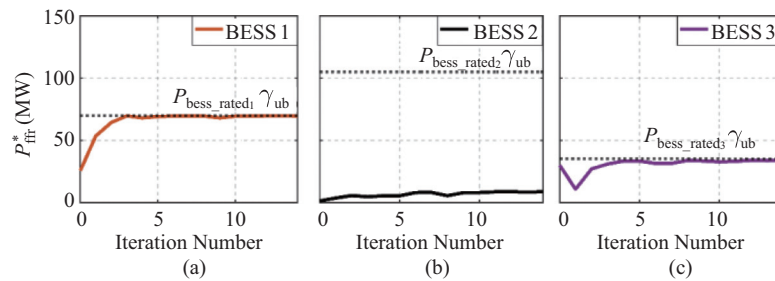
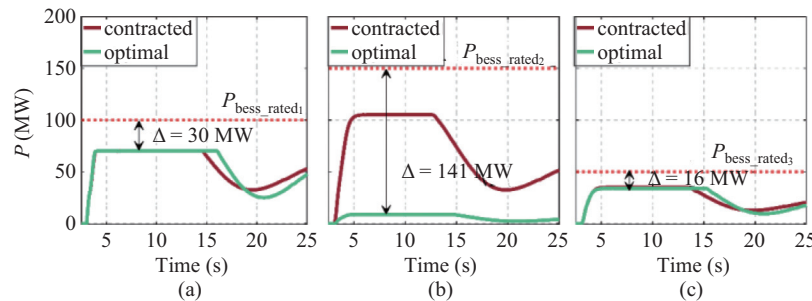
Fig. 8. BESS power reserve solutions with $\gamma_{ub} = 70\%$ by GA for Case I.

Fig. 9. FFR comparison: (a) BESS 1, (b) BESS 2, and (c) BESS 3 for Case I.

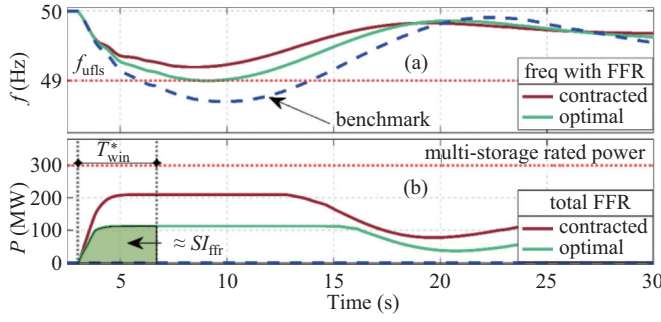


Fig. 10. Grid response (a) frequency, and (b) overall FFR BESS of Case I.

is more profitable for stakeholders. Further, this is also represented in Fig. 11 for FFR and Fig. 12 for arbitrage, where (a) is the power and (b) is the energy reserved. It is seen in Fig. 11 that with the proposed methodology, less power and energy reserves are needed for ensuring grid security. This avails greater energy availability for arbitrage trading, as shown in Fig. 12.

C. Case II: 70% Renewable Penetration

To demonstrate the proposed method can be employed in power grids with higher renewable penetration levels, 70% of renewable penetration with system inertia reduced by 10 GWs in the Queensland power grid is simulated in Case II.

Stage 1: The dynamic response without FFR is shown in Fig. 13, where (a) describes the frequency and system inertia after the generation trip and (b) shows the power dynamic changes of synchronous machines (i.e., power loss P_{loss} , system inertial response P_{sir} , and mechanical power deviation ΔP_m).

As it can be seen, the generation loss of 750 MW leads to frequency and system inertia violating their corresponding lower limits despite the SIR and governor deployment. Thus, FFR action is required for the grid to remain within the specified frequency operating standard. For Case II, the system

TABLE VI
MULTI-BESS RESERVE FOR FFR AND ARBITRAGE OF CASE I

BESS	FFR				Energy Arbitrage			
	Contracted		Optimal		Contracted		Optimal	
	Power (MW)	Energy (MWh)	Power (MW)	Energy (MWh)	Power (MW)	Energy (MWh)	Power (MW)	Energy (MWh)
1	70	17.5	70	17.5	30	132.5	30	132.5
2	105	26.3	9	2.3	45	373.8	141	397.8
3	35	8.8	34	8.5	15	191.3	16	191.5
Total	210	52.6	113	19.8	90	697.6	187	721.8

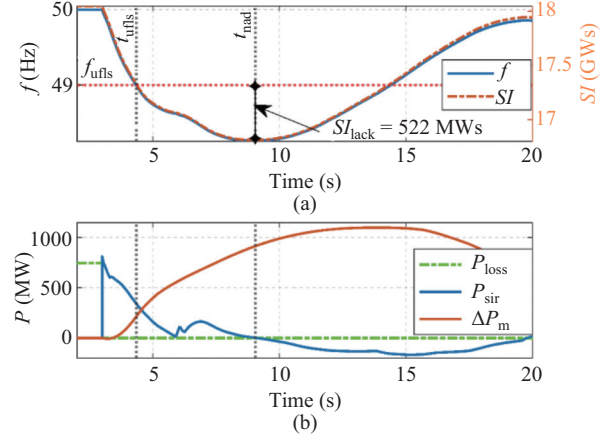


Fig. 13. Benchmark's grid response under a 750 MW generation trip of Case II.

inertia shortage is $SI_{lack} = 522$ MWs, which leads to a higher synthetic inertia requirement than Case I.

Stage 2: The optimal time window is obtained within five dynamic simulation iterations, as shown in Fig. 14. Consistently, time window provision is between the UFLS and nadir periods as $T_{win}^* = 3.0$ s $\in [T_{ufls}, T_{nadir}]$. This means that not only the synthetic inertia requirement is higher for Case II, but its deployment should be earlier than Case I.

Results of the FFR power reserve optimisation are in

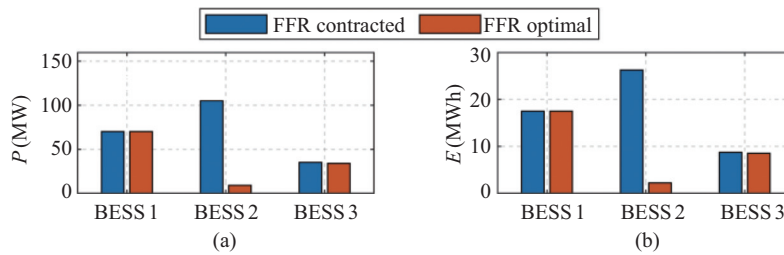


Fig. 11. FFR reserves for Case I: (a) Power, and (b) Energy.

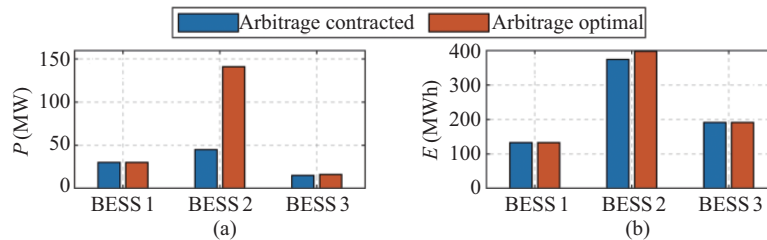


Fig. 12. Arbitrage reserves for Case I: (a) Power, and (b) Energy.

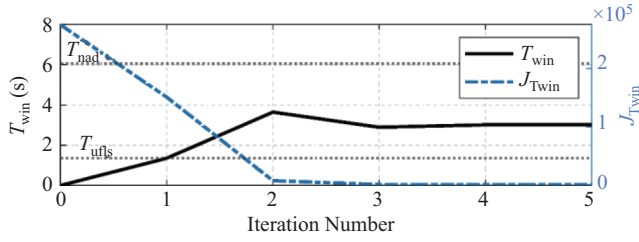
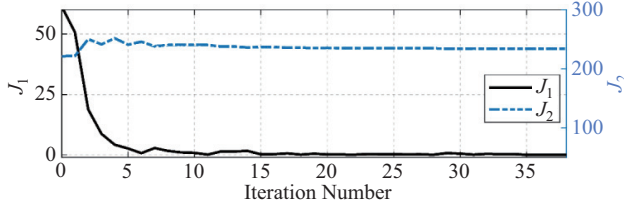
Fig. 14. Optimal T_{win} by gradient descent with momentum for Case II.

Fig. 15. Cost functions of the optimal multiple BESSs for FFR by GA for Case II.

Figs. 15–16 and Table VII. It should be mentioned that the synthetic inertia condition is not attained when using 70% of the BESSs rated power, leading to a lack of system inertia of 69 MWs ($J_1 = 69$). Then, the contracted FFR is not enough to prevent the UFLS activation for Case II. Hence, the upper bound limit γ_{ub} is set as 100% for GA (as explained in Fig. 3), which allows achieving the synthetic inertia requirement ($J_1 \approx 0$ in Fig. 15). Thus, the minimum total battery reserve from three BESS is 235 MW ($J_2 \approx 235$ in Fig. 15).

The FFR support from each BESS is detailed in Table VII. As it can be seen, the BESS with a slower frequency response will provide less power reserve. Consequently, only BESS 2 can safely participate in energy arbitrage as detailed in Fig. 16.

TABLE VII
OPTIMAL MULTI-BESS CONTINGENCY RESERVE FOR CASE II

BESS	FFR BESS power contracted (MW)	FFR optimal power with upper bound $\gamma_{ub} = 100\%$	
		Optimal power P_{ffr}^* (MW)	Synthetic inertia SI_{ffr} (MWs)
1	70	100	255
2	105	85	161
3	35	50	108
Total	210	235	524

If it was the case that $J_1 > 0$ even when using $\gamma_{ub} = 100\%$, the installed BESS capacity in the grid would not be sufficient to fulfil the synthetic inertia requirement. As a result, the UFLS limit would be violated unless grid operators take further actions and do not entirely rely on BESSs. This is indicated by the red element of the method's flowchart in Fig. 3.

Figure 17 shows the dynamic power response from each BESS based on the proposed method and the contracted power reserve. As shown in Fig. 17(b), 65 MW can be securely used for arbitrage.

The system frequency dynamic response and total BESS power support are described in Fig. 18. It is observed from Fig. 18(a) that the UFLS limit is breached when using only the contracted BESS reserve while the grid frequency complies with the specified standards with effective power reserves with the proposed approach. Thus, the FFR addition to the system inertia prevents the UFLS limit violation even in the higher renewable penetration case.

Stage 3: The obtained power and energy reserves for FFR and energy market are contained in Table VIII, and Figs. 19–20. For this 70% renewable energy penetration case, the total calculated BESS capacity for FFR (235 MW/58.8 MWh) is

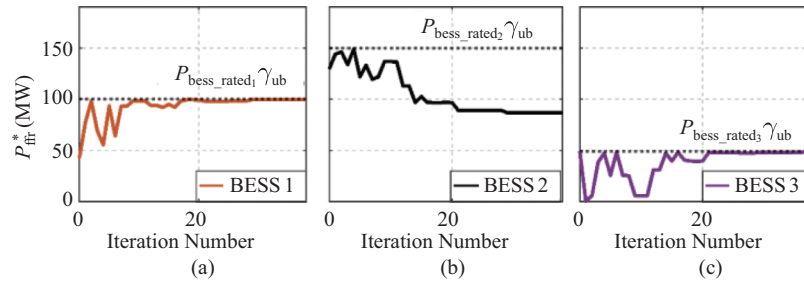
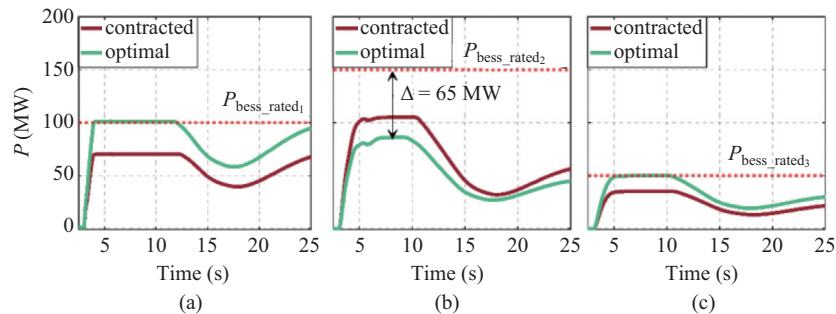
Fig. 16. BESS power reserve solutions with $\gamma_{ub} = 100\%$ by GA for Case II.

Fig. 17. FFR comparison: (a) BESS 1, (b) BESS 2, and (c) BESS 3 for Case II.

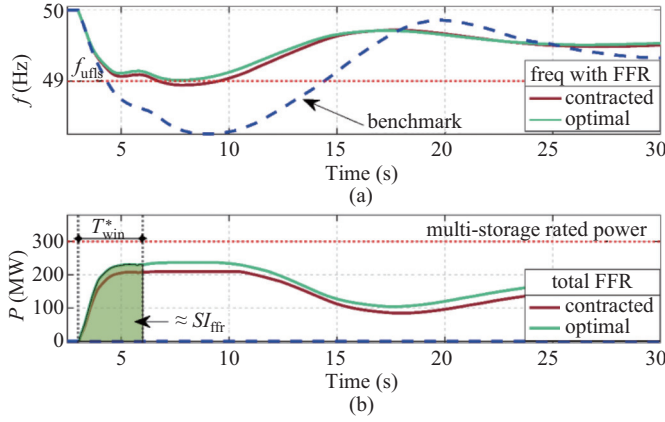


Fig. 18. Grid response (a) frequency, and (b) overall FFR BESS for Case II.

TABLE VIII
MULTI-BESS RESERVE FOR FFR AND ARBITRAGE OF CASE II

BESS	FFR				Energy Arbitrage			
	Contracted		Optimal		Contracted		Optimal	
	Power (MW)	Energy (MWh)	Power (MW)	Energy (MWh)	Power (MW)	Energy (MWh)	Power (MW)	Energy (MWh)
1	70	17.5	100	25	30	132.5	0	125
2	105	26.3	85	21.3	45	373.8	65	397.8
3	35	8.8	50	12.5	15	191.3	0	187.5
Total	210	52.6	235	58.8	90	697.6	65	691.5

larger than the contracted one (210 MW/52.6 MWh).

This is further observed in Fig. 19, where the optimal and secure MW/MWh expenditure for the FFR service is greater than the agreed one. As a result, the residual BESS reserve that can be safely traded for arbitrage is less than the contracted capacity, as observed in Fig. 20, which may reduce the stakeholder's revenue. However, the proposed method guarantees a safer FFR reserve allocation than the fixed contract for a more critical dispatch case.

Overall, the effectiveness of the developed methodology

is proved to incorporate FFR into the existing frequency response systems (e.g., inertia and governor). The quantitative evaluation of power reserves of multiple large-scale BESSs is achieved for their coordinated FFR support. This research contributes to improving resilience in grid dominated by converter-interfaced renewable sources.

V. CONCLUSION

This paper proposes an innovative methodology to estimate contingency reserves of multiple battery storage systems for fast frequency response. The theoretical framework is developed to determine the required synthetic inertia from FFR based on the UFLS limit and grid response under a credible generation trip. The optimisation of multiple BESSs contingency reserve for FFR is formulated to satisfy the synthetic inertia condition. The proposed methodology has been tested using an actual large-scale Australian power grid with two renewable penetration scenarios. The case study results demonstrate the superiority of the developed methodology over a typical fixed contract approach by quantitatively determining an effective power reserve. Further, the proposed method can accurately decide the optimal power reserve for each BESS considering their different operating characteristics (e.g., capacities, ramp rates, and response time delays). Moreover, the case study results show the optimal power reserve is not evenly distributed for each BESS. The BESS with a faster response will need to keep more power reserve than the slower response BESS if the required FFR service is to be minimised across the participating BESSs. In future work, the power reserve considering other FFR resources (e.g., wind and solar PV farm) will be investigated.

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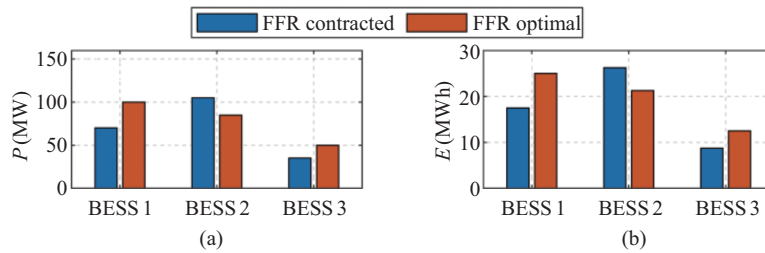


Fig. 19. FFR reserves for Case II: (a) Power, and (b) Energy.

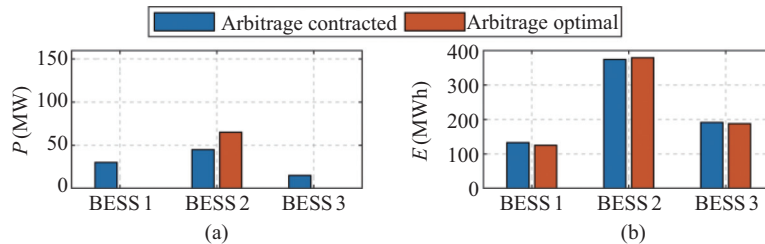


Fig. 20. Arbitrage reserves for Case II: (a) Power, and (b) Energy.

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analysis.



renewable energy integration and big data technology applications in power grid.



plants, power systems and power quality.



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