Grid-connected advanced energy storage scheme for frequency regulation

Iram Akhtar¹ · Sheeraz Kirmani¹

Received: 20 March 2020 / Accepted: 24 August 2020 / Published online: 23 September 2020
© Springer Nature Switzerland AG 2020

Abstract

Secure and economic operation of the modern power system is facing major challenges these days. Grid-connected Energy Storage System (ESS) can provide various ancillary services to electrical networks for its smooth functioning and helps in the evolution of the smart grid. The main limitation of the wide implementation of ESS in the power system is the high cost, low life, low energy density, etc. However, improved battery technology is changing the scenario rapidly. Also, any mismatch in power demand and supply causes fluctuation in frequency. Therefore, this paper presents a way for reducing the frequency fluctuation using an Advanced Energy Storage System with utility inductors. To compensate for the mismatch of supply and demand, a new system is proposed so that the nominal frequency of the power system is maintained. Due to the very high penetration of energy systems, there is a need for frequency regulation, hence different control strategies are employed to overcome this problem. In case of extreme power supply, the ESS acts as a load and gets itself charged whereas during the power deficit the ESS supplies power to maintain balance in demand and supply, and hence it mitigates the frequency fluctuation. The simulation model contains an ESS connected to a grid with a varying commercial or residential load profile. Simulation results illustrate the effectiveness of grid-connected ESS in minimizing frequency variation.

Keywords Energy storage system · Frequency regulation · Load frequency control · Power flow analysis · Fourth keyword

1 Introduction

The electric power grid is of vital significance in the present scenario. Electric power is an empowering innovation which helps in regular assignments and advanced procedures. It gives a perfect, sheltered, and flexible power supply for a large variety of applications. The power electronics devices are connected to the different sources when they are interfaced with the utility grid and they create stability issues also because of the high penetration of these devices. The energy storage system provides a quick frequency response and they have been recognized. While the growth of the storage system has made this system

feasible to be connected to the grid with desired performance, economics issues, codes are giving the walls for a high level of application and investment.

The quality of electric power depends on the balance between supply and demand and this balance must be maintained [1]. This frequency variation is very dangerous to the different parts of the power system. Energy storage systems give power to the different loads when there is a shortage of power supply from the grid so that the stability of the power system is maintained due to its fast response.

If the frequency severely deviates from the standard frequency, then many of the instruments connected to

✉ Iram Akhtar, iram1208@gmail.com; akhtariram12@gmail.com | ¹Department of Electrical Engineering, Faculty of Engineering and Technology, Jamia Millia Islamia, New Delhi, India.

the power system can be damaged. The high speed of the turbine due to an increase in frequency will result in its destruction. With the rapid advancement of battery technology, it has gained the capability of fast controlling the active and reactive power even at the high switching frequency.

Whereas the over fluxing of the CT and PT due to frequency fluctuation causes maloperation of the protection relays, it will trip out the generators, lines, and transformer which may cause large scale blackouts. A thermal power plant consists of various fans like PA, LD, and ID fans. The fluctuation of frequency will result in variation of its speed of these fans and hence affect the performance of the power plants. Even many electrical devices that we use in our daily life are designed to operate at a particular frequency and can get damaged due to high or low frequency. The fluctuation of frequency indicates the imbalance between demand and supply. The VRFB (vanadium redox flow battery) based BESS can regulate frequency effectively due to its rapid response along with a reduction in peak demand [1]. Nevertheless, there are limited studies on the topic discussed. With the increase in the integration of stochastic renewable energy sources with the grid, the regulation of frequency becomes a difficult task. The best way of frequency regulation is to use a hybrid of ESS and generator. It has several advantages as the generators have to supply steady power which reduces wear and tear on it and increases its life. During the fast fluctuation of frequency, the ESS comes into play for frequency regulation whereas the generator follows the general trend of the frequency fluctuation and also helps to reduce the power required by the ESS to control it. On the other hand, ESS has various features that make it suitable for frequency regulations. Frequency regulation is done by changing its output power in a short period. ESS can balance the rapidly varying power demand and improve the performance of the LFC [2]. The regulation of power and frequency is called load frequency control (LFC). The power balance achieved by rapidly following the change in demand by the supply helps in frequency regulation. Traditionally, the generator performs the frequency regulation on a power system but it has various disadvantages as it causes wear and tear of the generators and reduces its efficiency [3]. The energy storage systems for frequency control application needs some analytical tools with conventional coal-based power plants. In the case of a coal-based power plant, the load-duration curve is very important for getting the use of traditions. Still, this curve does not provide the ramp rate information. When an energy storage system is used then ramp rate and energy duration curves are very important.

The generator is best suited for the bulk power supply but not for providing frequency regulations. Additionally,

it provides various benefits like load balance, spinning reserve, area frequency control, transmission line stabilization, and power factor control, etc. [4]. The frequency regulation can also be achieved in the wind energy system by using the battery storage [5] and the battery energy storage can be optimized for controlling the frequency [6]. The statcom integration with energy storage can give better results [7] and this can be achieved in the power system [8, 9]. Further, renewable energy sources are generated large frequency deviations when these sources are connected to the utility grid. The frequency deviation caused by renewable energy sources is unavoidable problems in regulation and control of frequency [10, 11], whereas the frequency deviation contains different parts [12]. Besides, the demand-side sources are taking more consideration in frequency deviation problems [13], and these are defined by the efficiency and flexibility, many models are developed to satisfy the frequency deviation which keeping the power constraints [14]. Also, the energy storage system promotes as a good alternative in giving the frequency deviation issues because of its quick response [15–20]. The energy storage system is a promising alternative in the different types of loads i.e. industrial, commercial, and residential [21–23]. Renewable energy sources are also used to reduce carbon emission and ultimately reduces greenhouse gasses emission from the environment. But, due to the very high penetration of energy systems, there is a need for frequency regulation, hence different control strategies are employed to overcome this problem [24]. The energy storage systems are also needed to compensate for the different characteristics of renewable-based energy systems. The energy storage systems are used for controlling the frequency of the system [25].

To compensate for the mismatch of generation-load, an advanced energy storage system is proposed in the paper so that the nominal frequency of the power system is maintained. The fast ramping merit of the energy storage system is a feat to give regulation of the frequency. During the extra power supply, the energy storage system actions as a load and gets itself charged whereas during the power shortage the energy storage system supplies power to keep the balance in demand and supply, and hence it lessens the frequency fluctuation.

On the other hand, if the power generated from the system than the demand then system frequency decreases. So, in modern power systems, if the system frequency increases then the system output is reduced, so to maintain the frequency proper control strategy is required [26–29].

This technique reduces the burden on the coal-based plant by dividing the frequency control signal between the energy storage system and coal-based plant. The coal-based system is restricted in its capacity to give the

frequency control due to the limitation of the power ramp rate. Therefore, this advanced energy storage system is suited to high-frequency operation. The main aim of this system is to lessen the maintenance and fuel necessities of the coal-based plant and to join the different generation resources that could enhance the frequency control necessities.

Therefore, this paper provides an assessment to perform the frequency regulation with and without an energy storage system connected to the power system in the MATLAB/Simulink platform. The fast response of the energy storage system with the change in load makes it a better option for frequency regulation of the system.

In the present paper, the system modeling is described with a typical energy storage system in Sect. 2. Results and discussion are provided in Sect. 3. Finally, the concluding comments are given in Sect. 4.

2 System modelling

Figure 1 shows the major components of a typical ESS. It uses an IGBT (insulated-gate bipolar transistor) in the Power Conversion System (PCS) which interconnects the battery and the power system utility. It is a 4 quadrant PCS which converts the utility AC into battery DC and vice versa. When the system frequency is high the battery gets charged and mitigates the frequency fluctuation whereas during low-frequency battery supplies power to the load and maintain the frequency. The LC filter reduces the high-frequency harmonics which is generated from Pulse Width Modulation (PWM) technique used in BESS. First of all, a Simulink model is made so that the frequency variation can be shown and the problem could be identified. The model consists of a generator of rating 800MVA, 11 kV which represents a utility grid. The 11 kV voltage is step down by a transformer to 400 V. A transmission line connects the utility grid to the distribution grid. The distribution grid is connected with three parallel loads. The three parallel loads can be varied to observe the frequency variation at different loads. This represents a power system without ESS connected. The

battery energy system comprises cooling and control systems, converter, filters, and battery strings. By using the significant control technique, this system can give a quick change of power in different directions, so the advanced energy storage system is capable of enhancing the load frequency control performance.

Another Simulink model is built which find the solution of the problem identified in the previous model i.e. the frequency fluctuation problem is mitigated by an ESS. The next simulation model is very similar to the earlier one. The only difference is, an ESS is connected at the low voltage side of the utility transformer. The initial SOC of the battery is 80% with charge and discharge capacity of 25 MW. The DC output of the ESS is connected to the ac of the utility grid through a universal bridge. There is an inverter controller which controls the power output from the dc to the ac side and vice-versa. This is a powerful system with ESS connected.

The mathematical modeling of different component of the system is presented as.

2.1 Synchronous generator system

Synchronous generator (SG) supplies the discrepancy power to the load to maintain a balanced condition of supply and demand. The generator may be a diesel-driven generator or turbine-driven generator. It consists of a speed governor and turbine system which can be represented by its transfer function as [30, 31]

$$G_G(s) = \frac{\Delta P_v(s)}{\Delta P_g(s)} = \frac{K_g}{1 + ST_g} \quad (1)$$

$$G_T(s) = \frac{\Delta P_m(s)}{\Delta P_v(s)} = \frac{K_T}{1 + ST_T} \quad (2)$$

where T_g and T_T are the time constant of governor and turbine respectively. The default value of K_g and K_T is equal to 1. The speed regulation of the governor is around 5% from zero to full load.

Fig. 1 Schematic diagram of ESS

2.2 Energy storage system

Energy storage systems supply power to the load when there is a shortage of power supply from the grid and effectively maintain the stability of the power system because of its fast response. With the rapid advancement of battery technology, it has gained the capability of fast controlling the active and reactive power even at the high switching frequency. But the main application is still to maintain the supply–demand balance, voltage regulation, and harmonics cancellation. It can also be used to damp out the power system swing which improves both the transient and dynamic stability of the power system. The transfer function of the Energy Storage System is given by [32],

$$G_{ESS}(s) = \frac{\Delta P_{ESS}}{\Delta \omega} = \frac{K_{ESS}}{1 + sTESS} \quad (3)$$

where K_{ESS} is the gain and $TESS$ is the time constant

2.3 Power deviation and system frequency variation

For the mitigation of the frequency deviation and stable operation of the power system, the power generation must be equal to the load requirement.

The total power generated in this model is the algebraic sum of the power generated by the generator (P_{SG}) and the energy storage system (P_{ESS}) [33],

$$P_T = P_{SG} \pm P_{ESS} \quad (4)$$

The difference between the power generation (P_T) and the load demand (P_D) is given by

$$\Delta P_e = P_T - P_D \quad (5)$$

Since the frequency variation in a power system is proportional to the difference between the demand and supply power (ΔP_e).

$$\Delta \omega = \frac{\Delta P_e}{K_{SYS}} \quad (6)$$

where K_{SYS} is constant. A time delay exists between frequency and power variation. So, the transfer function of system frequency deviation per unit power deviation can be represented as

$$G_{SYS}(S) = \frac{\Delta \omega}{\Delta P_e} = \frac{1}{K_{SYS}(1 + sT_{SYS})} = \frac{1}{D + Ms} \quad (7)$$

where M and D are the inertia constant and damping constant of the power system, respectively.

The advanced energy storage system is very effective for decreasing the peak deviations of frequency by giving quick power compensation. If extra frequency happens, this system may absorb the power during this period and supply the power to the utility grid for low-frequency periods. Therefore, in case of within frequency changes, the power absorbed and supplied is zero. The energy level of this system varies with the addition of different elements.

3 Results and analysis

After the model was simulated with and without ESS connected to the power system, results for frequency variation was compiled. The ESS successfully mitigate the frequency fluctuation under the load variation. For analyzing the frequency fluctuation with a change in load, firstly, frequency fluctuation is created by changing the load connected to the power system. Later in the same power system, an ESS is connected along with an inverter and a controller which provides a net power output from the ESS to the power system and vice versa. The frequency variation is mitigated due to the ESS connected to the power system. Three different cases of the load variation have been analyzed in this work. The load variation is represented in tabular form and a graph is shown which compares the frequency fluctuation with and without ESS connected to the power system.

3.1 Case 1

Three loads are connected in parallel and each one is connected or disconnected to/from the power system at a certain time interval as shown in Table 1. The ratings of the three-load are

1. 1000 kW at 0.85 lag
2. 500 kW at 0.92 lag
3. 300 kW at 0.98 lag

Table 1 Load connection at different time interval–Case 1

Time (s)	Load no. (MW)	Frequency variation without ESS (HZ)	Frequency variation with ESS (HZ)
0.1	3	49.66–50.23	49.67–50.20
0.2	2		
0.3	2+3		
0.4	1		
0.5	1+3		
0.6	1+2		
0.7	1+2+3		

In this case, different loads are connected to the power system with a different interval of time, and the frequency variations are noted for each interval. At $t=0.1$ s, 300 kW load is connected, At $t=0.2$ s, 500 kW load is connected, At $t=0.3$ s, 800 kW load is connected, At $t=0.4$ s, 1000 kW load is connected, At $t=0.5$ s, 1300 kW load is connected, At $t=0.6$ s, 1500 kW load is connected and At $t=0.6$ s, 1800 kW load is connected. The frequency variation is 49.66–50.23 Hz without the energy storage system and frequency variation is 49.67–50.20 Hz with the energy storage system, so, the frequency variation is improved using the advanced energy storage system.

3.2 Case 2

Now three equal loads are connected in parallel and each load rated at 1000 kW at 0.85 lagging power factor. These loads are disconnected one by one at a regular interval of 0.1 s as shown in Table 2. In case 2, different loads are connected to the power system at different intervals of time. At $t=0.1$ s, 300 kW load is connected, At $t=0.2$ s, 500 kW load is connected, At $t=0.3$ s, 1000 kW load is connected, The frequency variation is 49.84–50.22 Hz without the energy storage system and frequency variation is 49.86–50.06 Hz with the energy storage system, so, the frequency variation is enhanced using this system.

3.3 Case 3

In this case, three equal loads are taken, each rated at 1000 kW at 0.85 lagging power factor and these are connected one by one at a regular interval of 0.1 s as shown in Table 3.

Table 2 Load connection at different time interval–Case 2

Time (s)	Load (number of loads connected)	Frequency variation without ESS (HZ)	Frequency variation with ess (hz)
0.1	3	49.84–50.22	49.86–50.06
0.2	2		
0.3	1		

In case 3, when the different loads are coupled to the system with a different time interval then the frequency variations are known for each interval. At $t=0.1$ s, 1000 kW load is connected to the system, At $t=0.2$ s, 500 kW load is connected to the system, At $t=0.3$ s, 300 kW load is connected to the system. Consequently, the frequency variation is 50.10–49.68 Hz without the energy storage system and frequency variation is 50.05–49.75 Hz with the energy storage system, therefore, the frequency variation is better with the advanced energy storage system. Since ESS has desired characteristics it is mentioned to investigate the possibility of introducing new market services and creating incentives.

The frequency fluctuation is reduced using the Advanced Energy Storage System with utility inductors. The energy storage system acts as a load and gets itself charged while during the power insufficiency the energy storage system supplies power to maintain balance in demand and supply and hence it eases the frequency fluctuation. The obtained results are compared with previously published paper [29]. In the previous work, the energy storage system contains only battery without the extra components and provides in alone power system for taking the more effectiveness of battery. The frequency deviation is 49.95 to 50.05 Hz [34] and from the proposed system, the frequency deviations are 49.67–50.20, 49.86–50.06, and 50.05–49.75 with Case 1, 2 and 3 respectively. So the proposed system is well suited for frequency deviation reduction in the power system as shown in Table 4. Table 5 shows the comparison of the proposed method with the previous methods [25]. Results are compared with old controllers like Model predictive controller

Table 3 Load connection at different time interval–Case 3

Time (s)	Load (number of loads connected)	Frequency variation without ESS (HZ)	Frequency variation with ESS (HZ)
0.1	1	50.10–49.68	50.05–49.75
0.2	2		
0.3	3		

Table 4 Comparison of results with previously published work

Methods	Frequency variation with proposed ESS (HZ)
Earlier battery energy storage method [34]	49.95–50.05
Proposed advanced energy storage method with Case-1	49.67–50.20
Proposed advanced energy storage method with Case-2	49.86–50.06
Proposed advanced energy storage method with Case-3	50.05–49.75

Table 5 Comparison with different controllers

Methods	Min ESS capacity [kWh] [25]	Ratio max ESS power/min ESS capacity [24, 25]	Energy throughput [MWh] [24, 25]
MPC	43	56	0.21
PI	44	56	0.33
Proposed Method	45	58	0.35

and PI controller. The capacity of ESS is more with the proposed controller as compared with MPC and PI controllers. Whereas the ratio of maximum ESS power to the minimum ESS capacity as also high with the proposed controller as compared with MPC and PI controllers. Further, the energy level is also high with the proposed controller as compared with MPC and PI controllers. MPC controller has complicated structure and PI controller needs more time to reach the steady-state value therefore the proposed controller gives the best results as compared with MPC and PI controllers as shown in Table 5. The proposed ESS model can further be changed by taking the efficiency of the system and selecting the realistic values of the different components in the system. With the use of technical data and economic indicators of the proposed system, Net Present Value can be known to check the economic viability of the complete investment.

4 Conclusion

To recompense the mismatch of generation-load, an advanced energy storage system is proposed in the paper so that the nominal frequency of the power system is sustained. Whereas, the fast ramping merit of the energy storage system is a feat to give regulation of the frequency. The importance of ESS in controlling the frequency fluctuation in a power system has been also described. The proposed ESS model can further be improved by considering the efficiency of the converter system and choosing the realistic values of the electrical components. If for the entire day the simulation is performed, control strategy can be modified with a second component, by taking care of discharging/recharging the battery via a mechanism based on the market. The effects for grid and ESS of this new component can be analyzed. By the use of technological data and economic indicators of ESS, Net Present Value can be found to check the economic viability of the whole investment. A model of a power system connected to ESS is developed to study its response to the frequency fluctuation. Simulation results indicate that generators along with ESS give better frequency control. Three different cases are considered

with the different connection of loads at a different time interval. This gives a better picture of frequency mitigation by ESS.

This paper presents a technique for reducing the frequency fluctuation using the Advanced Energy Storage System with utility inductors. The proposed ESS acts as a load and gets itself charged as well as can supply power to maintain balance in demand and supply. A comparison of frequency variation with and without ESS connected to the power system are also considered for analysis purpose. Whereas, in the previous work, the energy storage system comprises only battery without the advanced technology and provides in alone power system for taking the more efficiency of the battery. This problem is overcome by the proposed technique with utility inductors. It can be observed from the obtained results that when the loads are varied, it causes variation in the frequency and the use of advanced ESS can mitigate the frequency variation effectively due to its fast response.

Since ESS possess desired characteristics it is recommended to investigate the possibility of introducing new market services, creating incentives, redefine requirements to enable the introduction of battery systems for power system applications

Besides, the developed ESS control models can be also used to model other types of batteries. This is possible by changing the control parameters: SOC limits, efficiency, response time, etc. This can be helpful to study the effects on the power system while using ESS based on various types of batteries technology.

Further, it is recommended to research in the future on alternate techniques that can provide services on lines similar to ESS, such as frequency regulation and inertial response. For example wind turbines, HVDC links, flywheels, synchronous condensers, super and ultra-capacitors, and even services such as vehicle to grid applications and demand response.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Alexandre L, Stamatios C (2016) Smart grid energy storage controller for frequency regulation and peak shaving, using Vanadium redox flow battery. In: Proceedings of the Elsevier journal of power and energy systems
2. Shailendra S, Singh SK, Saurabh C, Singh YP (2014) Frequency Regulation of an Isolated Hybrid Power System with Battery

- Energy Storage System. In: Proceedings of the IEEE journal of power and energy systems towards Sustainable Energy
3. Xiaokang X, Martin B, Donna GO, Chen H (2016) Application and modeling of battery energy storage in power systems. *Proc CSEE J Power Energy Syst* 2(3):82–90
 4. Olivia L, James LK (2010) Energy Storage for Use in Load Frequency Control. In: Proceedings of the IEEE conference on innovative technologies for an efficient and reliable electric supply
 5. He G, Chen Q, Kang C, Xia Q, Poolla K (2016) Cooperation of wind power and battery storage to provide frequency regulation in power markets. *IEEE Trans Power Syst* 32(5):3559–3568
 6. Oudalov A, Chartouni D, Ohler C (2011) Optimizing a battery energy storage system for primary frequency control. *IEEE Trans Power Syst* 22(3):1259–1266
 7. Yang Z, Shen C, Zhang L, Crow ML, Atcitty S (2012) Integration of a statcom and battery energy storage. *IEEE Trans Power Syst* 16(2):254–260
 8. Egido A, Fernandez-Bernal F, Centeno P, Rouco L (2013) Maximum frequency deviation calculation in small isolated power systems. *IEEE Trans Power Syst* 24(4):1731–1738
 9. O'Sullivan J, Rogers A, Flynn D, Smith P, Mullane A, O'Malley M (2014) Studying the maximum instantaneous non-synchronous generation in an island system—frequency stability challenges in Ireland. *IEEE Trans Power Syst* 29(6):2943–2951
 10. Palensky P, Dietrich D (2011) Demand side management: demand response, intelligent energy systems, and smart loads. *IEEE Trans Ind Inform* 7:381–388
 11. Nguyen N, Mitra J (2016) An analysis of the effects and dependency of wind power penetration on system frequency regulation. *IEEE Trans Sustain Energy* 7:354–363
 12. Zhao C (2014) Design and stability of load-side primary frequency control in power systems. *IEEE Trans Autom Control* 59:1177–1189
 13. Mallada E, Zhao C, Low S (2017) Optimal load-side control for frequency regulation in smart grids. *IEEE Trans Autom Control* 62:6294–6309
 14. Delavari A, Kamwa I (2018) Improved optimal decentralized load modulation for power system primary frequency regulation. *IEEE Trans Power Syst* 33:1013–1025
 15. Shi Y, Xu B, Wang D, Zhang B (2018) Using battery storage for peak shaving and frequency regulation: joint optimization for super linear gains. *IEEE Trans Power Syst* 33:2882–2894
 16. Zhang YJA, Zhao C, Tang W, Low SH (2018) Profit-maximizing planning and control of battery energy storage systems for primary frequency control. *IEEE Trans Smart Grid* 9:712–723
 17. Xu B, Shi Y, Kirschen DS, Zhang B (2018) Optimal Battery Participation in Frequency Regulation Markets. *IEEE Trans Power Syst* 33:6715–6725
 18. Cheng Y, Tabrizi M, Sahni M, Povedano A, Nichols D (2014) Dynamic Available AGC based approach for enhancing utility scale energy storage performance. *IEEE Trans Smart Grid* 5:1070–1078
 19. Tan Z, Tan Q, Yang S, Ju L, De G (2018) A robust scheduling optimization model for an integrated energy system with P2G based on improved CVaR. *Energies* 11:3437
 20. Stein K, Tun M, Matsuura M, Rocheleau R (2018) Characterization of a fast battery energy storage system for primary frequency response. *Energies* 11:3358
 21. The Electricity Storage Network (2014) Development of electricity storage in the national interest
 22. Renewable Energy Association (2015) Energy storage in the UK—AN Overview
 23. Bird and Bird (2014) The role of energy storage in the UK electricity system
 24. Benini M, Canevese S, Cirio D, Gatti A (2016) Battery energy storage systems for the provision of primary and secondary frequency regulation in Italy. In: IEEE 16th international conference on environment and electrical engineering (EEEIC), pp 1–6
 25. Sockeel N et al (2020) Virtual inertia emulator-based model predictive control for grid frequency regulation considering high penetration of inverter-based energy storage system. *IEEE Transactions on Sustainable Energy*
 26. Yoon M et al (2019) Utilization of energy storage system for frequency regulation in large-scale transmission system. *Energies* 12(20):3898
 27. Cho S-M, Jin-Su K, Jae-Chul K (2019) Optimal operation parameter estimation of energy storage for frequency regulation. *Energies* 12(9):1782
 28. Copp D et al (2019) Energy storage systems in emerging electricity markets: frequency regulation and resiliency. No. SAND2019-0311C. Sandia National Lab. (SNL-NM), Albuquerque, NM (United States)
 29. Turk A et al (2019) Primary frequency regulation supported by battery storage systems in power system dominated by renewable energy sources. *J Eng* 18:4986–4990
 30. Kundur P (1994) Power system stability and control. McGraw-Hill, New York
 31. Saadat H (1999) Power system analysis. McGraw-Hill, New York
 32. Ray PK, Mohanty SR, Kishor N (2010) Small-signal analysis of autonomous hybrid distributed generation systems in presence of ultracapacitor and tie-line operation. *J Electr Eng* 61(4):205–214
 33. Lee DJ, Wang L (2008) Small-signal stability analysis of an autonomous hybrid renewable energy power generation/energy storage system part i: time-domain simulations. *IEEE Trans Energy Convers* 23(1):311–320
 34. Rajesh V, Kumar CHH (2012) Frequency control in an isolated power system by using optimizing a BESS technology, IJSE

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.