Impact of Renewable Energy Generation on Frequency: An Economic Case Study

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Abstract: The flow of power on an electrical network has transitioned from a unilateral flow (Traditional System) to a bilateral flow with the inclusion of embedded generation at various voltage levels. The traditional power system has numerous issues notability the production of harmful greenhouse gases such as Carbon (IV) Oxide from burning fossil fuels. The need to minimize and substitute the amount of energy generated from fossil fuels requires the use of alternative energy sources which do not require fossil fuels such as wind turbines, and solar photovoltaic cells which are Renewable Energy Source (RES). This substitution of fossil fuels for RES comes with technical issues such as reactive power and real power imbalances. Real and reactive power imbalances are caused by both frequency and voltage instability on the network respectively. The primary cause of the power system imbalances is the intermittent generation of RES. System Operators (SO) have the daunting task of balancing power systems which have a high penetration of RES. The SO dispatches Battery Energy Storage and thermal storage to bridge the power gap created by RES generation.

Keywords: RES (Renewable Energy Sources), Frequency Control, Cost of Balancing the Grid (COB), ROCOF(Rate of Change of Frequency), ENS(Energy Not Supplied), WT(Wind Turbine), PV(Photovoltaic), SG(Synchronous Generator) and BESS (Battery Energy Storage System)

1 Introduction

Frequency response is a response to shifts in supply and demand brought on by faults, loss of load, and abrupt changes in a generation. All the preceding circumstances fall under the category of disturbance. In the UK the nominal frequency is 50Hz. The success of a frequency response technique is often evaluated using the Rate of Change of Frequency (ROCOF) [1].

Power generation is a nonlinear system because different dynamics influence the frequency. Observing the frequency from a high-level perspective is affected by supply and demand. Power system nonlinearities include the Dead band of governor speed, communications and generating rate limitations. Figure (1) depicts the numerous frequency control approaches utilised in power systems based on techniques such as Controller, Soft Computing Techniques and Mixed (Soft Computing and Controller) [2].

Synchronous Generators can control frequency through inertial response via an electrotechnical coupled rotor which synchronises with the grid frequency. The inertial response allows the generator to respond to grid frequency as required. The substitution of SG for RES is reducing the amount of available inertia for the network to resist disturbance on the network. The inertial response provided from SG can be provided by various technologies such as Battery Energy Storage, Solar, Wind, and Generator in the form of synthetic inertia. Ancillary Services provide

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synthetic inertia which RES cannot provide except if the controllers of the RES are altered to provide ancillary services and participate in Frequency Control.
PV controller can be changed to provide ancillary services in the form of deloading and Load Following Controllers. Whereas Wind Turbine can perform pitch angle and speed control to provide inertial response.

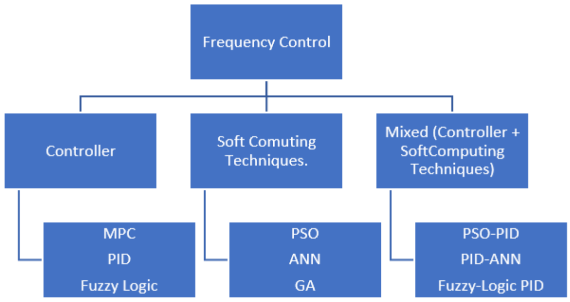

Figure 1. General Frequency Control by Techniques

PV and WT farms usually cannot contribute to system inertia, however, the controllers in both RES can be altered to provide system inertia in the form of Deloading [3].
Several literatures have conducted de-loading studies on PV systems in an attempt to reduce the effect of RES on frequency. Zarina et al. propose an approach to mitigate the frequency transients considering load changes in a microgrid. A similar study was conducted using a droop controller for de-loading the PV farm considering ROCOF and available reserve on the PV farm. However, in both studies, a microgrid was selected to conduct the study rather than a distribution network. [4]. Yan el Tal applied an adaptive de-loading technique with three control loops namely droop controller, active power voltage matching controller and vector control. These controllers give the PV farm the ability to adjust the power output of the PV for frequency regulation. Tavakkoi El tal observed the overshoot, undershoot and setting time for de-loading using vector control [5].

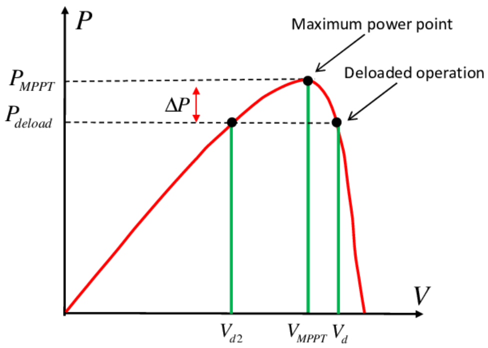

Figure 2. Pitch Angle Control of Wind Turbine [5]

Pitch Angle control is similar to governor control for SG. The pitch control limits the active power of the WT to a nominal power sustainable to balance network frequency. The limited active power from the WT can be injected into the network as the frequency drops thus giving the wind turbine more mechanical power from the wind flow and vice versa [6].

Speed Control is an alternative method for WT to contribute to frequency control. The WT selects a rotational speed from the maximum active power delivered from the WT based on the power speed curve to absorb active power from the grid or inject active power to the grid dependent on a low or high frequency event respectively. The stored kinetic energy is transferred to the grid for low frequency events.

In [7] a speed control scheme approach is utilized on double fed induction wind farm of 5MW for frequency control. The speed control scheme operated the 5MW WT farm according to the deloading power speed curve in the article for optimum power extraction thus improving network frequency.

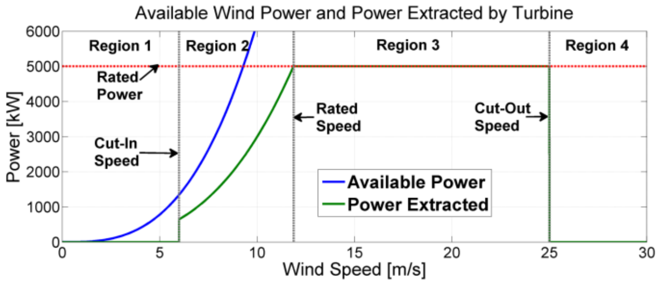

Figure 3. Speed Control of WT for Frequency Control [8].

The combination of Controllers and Soft Computing Techniques allows for the tuning of controllers for optimal performance in the case of PID, MPC and Fuzzy logic controllers.

The PID controller can be adopted by many algorithms such as PSO, ANN, and GA. However, all-natural algorithms tune the controller differently. The adoption of a Bacterial Foraging Particle Swarm Optimization (BFPSO) for PID tuning is done by the authors in [8]. The response of the BFPSO is very dynamic and better in curtailing frequency events than the ordinary PID controller. However, this study does not consider the presence of RES technologies [9]

The symbiotic Optimization Search (SOS) algorithm is utilized to tune the PID for frequency control. The algorithm was employed on a three-area power system. The algorithm improved the transient response and improved stability margins for the power system.

The study in [10] considers the net power exchange between power, frequency, and ramp rates for the generators. However, does not model the intermittent nature of RES as such the author has not emulated all DER on a typical [11]

In [12] an adaptive Model Predictive control is designed to control frequency in a multi-area network consisting of both synchronous and inverter-based generation-based. The author provides constraints for the network in the form of SOC, demand and supply. However, does not have constraints on cost and voltage.

The author provides a novel robust distributed MPC for curtailing frequency events caused by the uncertainty of RES. The author does not include an optimization function for the minimization of frequency however considers the uncertainty modelling of RES. Subsequently, the RES is modelled as only variables. The RES should be able to switch between DER and Frequency curtailment technologies [13]. This research proposes a Cost-Effective Control Strategy for operating the network based on a coordinated approach to DER dispatch, the strategy considers the stochastic nature of RES, Cost of Balancing, ROCOP and ROCOF; see Table (1) for the compassion of literature with the proposed study. The objectives of this study are:

- Develop a control strategy which can effectively reduce ROCOF caused by RES.
- Consider constraints in the study such as COB and ENS
- Compare the Pros and Cons of various control schemes on COB

Table 1 Comparison of Literature with Current Study

Literature	Cost of Balancing Grid	Frequency Constraints	RES	DSR	RES for Grid Services
9		X	X	-	-
10		x	x		
11		X	X	X	
12		X	X		
13		X	X	X	
Proposed Study	X	X	X	X	X

In this paper, the Load Frequency Model and Power System Modelling and Impact of Low-Inertia are discussed in Section II. The Mathematical Formulation for Cost of Energy not Supplied, ROCOP, and ROCOF. Section III the LFC model of control schemes Section IV will provide a detailed discussion and Conclusion.

2. System Dynamics of A Power System

This section provides a description of the system dynamics of a frequency response model for a single power system with an aggregated generator, as outlined in reference [5]. This model serves as the case study for the present investigation. The interconnection between a generator, load, and rate of change of frequency (ROCOF) can be mathematically represented by Equations (1)-(3) and visually illustrated in Figure (4).
The mathematical relationship between the generator-load in terms of frequency deviation is represented in the following equation (4):

$$s\Delta f = \left(\frac{1}{M}\right)\Delta P_d - \left(\frac{1}{M}\right)\Delta P_1 - \left(\frac{D}{M}\right)\Delta f \quad (1)$$

The dynamics of the turbine can be expressed as:

$$s\Delta P_d = \left(\frac{1}{T_t}\right).\Delta P_g - \left(\frac{1}{M}\right).\Delta P_d \quad (2)$$

The dynamic of the governor can be expressed as:

$$s\Delta P_g = \frac{1}{T_g}.\Delta P_c - \left(\frac{1}{R.T_g}\right)\Delta f - \left(\frac{1}{T_g}\right).\Delta P_g \quad (3)$$

Where s is the differential operator, y is system output, D damping coefficient, R is speed droop characteristics, $.\Delta P_g$ is the governor output change, $.\Delta P_m$ the mechanical power change, $.\Delta f$ is the frequency deviation, $.\Delta P_1$ is the load change, $.\Delta P_c$ is the supplementary control action.

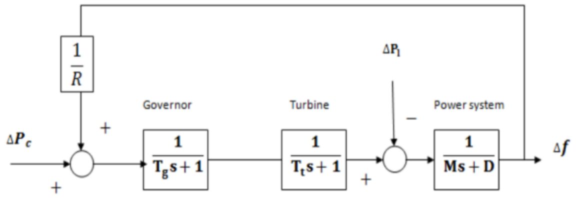

Figure 4. Schematic of General LFC Model for Frequency Analysis [14]

The power imbalance is caused by the difference in demand and supply. A sudden increase in net demand will cause the frequency to drop and vice versa a sudden decrease in demand will cause the frequency to rise. This can be shown in Equation (4) where the relationship between ROCOF and ROCOP is mathematically derived [14-16]:

$$\frac{\partial f}{\partial t} = \left(\frac{\Delta P}{2H}\right) . f_0 \quad (4)$$

Where H is the inertia constant of the network, ΔP is the ROCOP and f_0 is nominal network frequency.

The formula for the ROCOP is articulated in Equation in (5) :

$$\Delta P = PA_{SG} + PA_{Gen} + PA_{batt\_Charge} - PA_{batt_{Discharge}} + PA_{Wind} + PA_{Solar} \quad (5)$$

Where ΔP , PA_{SG}, PA_{Gen}, PA_{Batt_CH}, PA_{Batt_DH}, PA_{Wind}, *and* PA_{Solar} *is ROCOP for the power system, Active power from the SG, Generator, Battery Charge, Battery Discharge, Wind and Solar.*

In [17], a power system study gives the relation of power systems with low system inertia. Inertia refers to the inherent capacity of a power system to withstand and impede alterations or modifications. Figure (5) and Table (2) show how power systems with various inertia constants react to changes in frequency. The power system requires more active power to maintain stability with a low inertia constant, however, with a higher inertia constant, the power system requires much less active power.

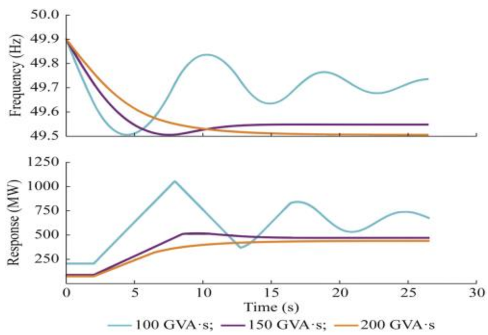

Figure 5. System Responds to various inertia constants [16]

Table 2 System Responds to various inertia constants [16]

System Inertia (GVA.s)	Response Requirements (MW)	
	500MW	600MW
100	590	1285
150	365	575
200	365	365

3. Methodology

The cost of balancing the network has predominantly been done with SG, however, the BESS technology is an emergency for network balancing and providing synthetic inertia. There is a direct relationship between the increase in RES and the increase in COB. Equation (7) is for balancing the traditional network which consists of a simple generation, load and reserve service (backup diesel generator) with low penetration from RES. Equation (8) is for the High RES which consists of wind, solar, and BESS for fast frequency response.
The integration of power is energy, thus the energy from the RES can be estimated as ENS. See Equation (8) for the mathematical expression of Energy not Supplied during Frequency control from RES.

$$E_{Ens} = \int P_{Wind\_Ens} + \int P_{Solar\_ENS} \qquad (6)$$

The DERs for balancing the grid can be split up into two categories such as controllable and uncontrollable resources. However, with modifications, DERs such as WT and PV can be used to curtail specifically high-frequency response. Table (2) highlights the type of frequency response required from various DERs.

$$COB_{Traditional\_Grid} = C_t^{Gen}.\int_{t1}^{0} P_{SG} \qquad (7)$$

$$COB_{High\_RES\_Grid} = C_t^{SG}.\int P_{SG} + C_t^{Reserve} + C_t^{Battery}.P_{Battery} + C_t^{Wind}.\int P_{Wind\_ENS} + C_t^{Solar}.\int P_{Solar\_ENS} \qquad (8)$$

Where C_t^{Gen}, $C_t^{Reserve}$, $C_t^{Battery}$, C_t^{wind}, and C_t^{Solar} is Cost of balancing the grid (£/MWh) with reserve generators, battery, wind and solar respectively.
Where P_t^{SG}, P_t^{Gen}, $P_t^{Battery}$, P_t^{Wind} and P_t^{Solar} is the active power used for frequency control during the operation of the SG, Generator, Battery, Solar farms and Wind turbines..

LF (Low- Frequency) events range is between 49.5Hz-50Hz while an HF (Half Frequency) event is >50Hz-50.5Hz. The LF and HF frequency events require different responses for DER.

The response from the DER for LF and HF events is injecting or absorbing active power into the network. RES such as WT and PV can only be utilized in High-frequency events such as frequencies greater than 50Hz -50.5Hz.

Table 3 DER respond to frequency events.

Frequency Event	DER	DER Response	Frequency Range
LF	Battery and SG	Inject active power	>50Hz
HF	Wind, Solar, Battery and SG	Absorb active power	<50Hz
HF and LF	Battery and SG	Inject and Absorb Active Power	-

3.1 Frequency Characteristics

Frequency deviation occurs as a consequence of the disparity between the electrical load demand and the mechanical power supply. Figure 6 illustrates the frequency of the electricity system following a frequency incident. The frequency of the power system has experienced a decline due to a rapid surge in electrical load.
The rate of change of frequency (ROCOF) in an electrical power system is influenced by the level of inertia present in the system. This relationship is particularly evident in networks with a high penetration of renewable energy sources (RES) and low levels of system inertia. Based on the initial rate of change, the frequency eventually reaches a minimum value, denoted as ω nadir, after a certain amount of time, denoted as t n, from the beginning of the frequency event. The highest rate of change of frequency (ROCOF) is represented as ω˙ max in Figure 6. During the early few seconds, the inertial reaction solely contributes to the maintenance of power balance. Subsequently, governors commence taking action within the system in order to establish frequency stability and minimise steady-state error. The recovery/settling time is the duration required for the frequency to return to its steady-state value.

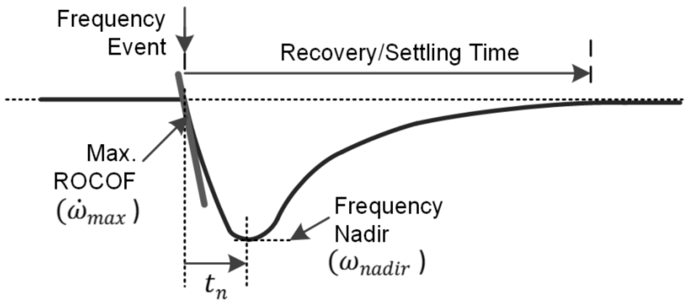

Figure 6 Frequency Nadir

3.2 System Model

The system model for this case study is adapted from a Load Frequency Model for an isolated power system. LFC models are typically utilized in literature to capture frequency dynamics. The LFC Model is modified to include RES and DERs such as PV, Wind and BESS. The PV and WT data are derived from Homer Energy Model for a Microgrid which is in Lagos Nigeria. The BESS is controlled using a Droop-Control to provide HF and LF responses based on frequency magnitude. See table for LFC parameters and BESS Droop Characteristics. The LFC model is shown in Table (4).

Table 4 System Model

Turbine Time Constant	0.5	sec
Governor Time Constant	0.2	sec
Governor Inertia constant	5	sec
Governor Speed Regulation	0.05	sec
PV Size	50	kW
Wind Size	50	kW
BESS Size	50	kW
Cost of WT for COB	100	£/kWh
Cost of PV for COB	100	£/kWh

3.3 Case Studies: Control Strategies

This study gives three case studies to compare the effect of control of RES and BESS for grid stability and COBIn this study all DERs will be used for grid balancing.
This case study is based on Table (3) for an isolated low inertia system. See the table for the droop control flowchart for the BESS is shown in Fig (7).

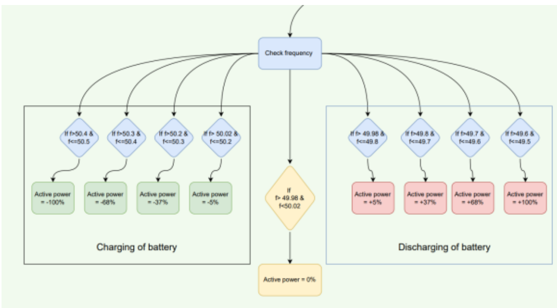

Figure 7. BESS charge discharge profile

3.3.1 Case One: BESS Droop Control for Frequency Control

The system is tested with a load drop change at 0.8 Seconds, In this case study only the BESS is utilized for frequency control as such the ROCOF is affected by the penetration rapid change of load on the network. The Frequency drops to 49.75 at 0.8 seconds. However, recovers relatively quickly to 50.01Hz at time 10seconds seconds.

The introduction of PV and WT causes the network frequency to oscillate between 49.75 Hz and 50.2 Hz. The BESS absorbs and dispatches active power to balance grid frequency based on droop control and frequency magnitude.

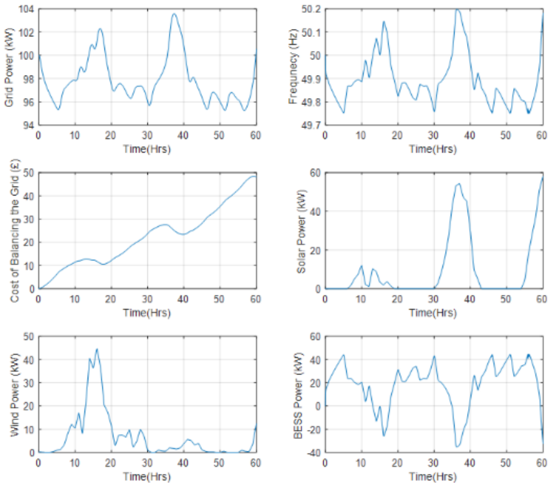

Figure 8. BESS Droop Control for Frequency Control

3.3.2 Case Two: BESS Droop Control + RES Control

The system is tested with a load drop change at 0.8 Seconds. In this case study the RES are utilized for frequency control with BESS droop. The RES control strategy is shown in Figure (9). The ROCOF is not affected by the high penetration of RES. The frequency oscillates between 50.014 and 49.995. The RES reduce output when the frequency goes above the control threshold detailed in Fig (9). The network frequency experiences a sudden loss of generation at 0.8 Seconds, the BESS responds to minimize ROCOF. Additionally the excess power from the

RES is curtailed from the BESS, however, due to the low magnitude of the ROCOF change the BESS is not utilised.

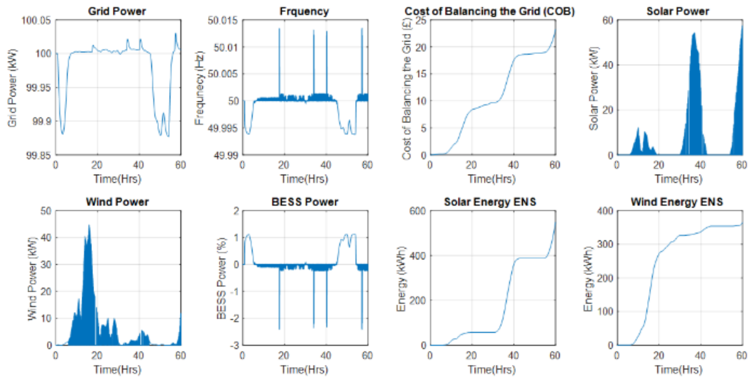

Figure 9. RES+BESS Droop Control

Table 5. Comparison of LFC Topology

Control Scheme Configuration	Frequency Nadir	ENS (kWh)	COB (£/kWh)
RES+ Battery (Hybrid)	49.95	1100	25
BESS	49.75	X	42

4. Conclusions

The control schemes are based on the participation of RES for ancillary services to improve ROCOP. This study compares two control configurations for improving grid frequency based on ROCOP, ROCOF, ENS, Frequency Nadir and COB. The schemes compare three controllers and various technologies and the effect of ROCOP and ROCOF. See Table for the comparison of technology topologies for frequency control. The use of RES and BESS had a higher frequency of 49.95 Hz compared to the BESS topology. However, BESS has approximately 38% COB than the RES and BESS topology. The difference in COB is because the RES can be controlled which minimizes the ROCOP.

References

1. Shenfeng X, Sheng Z, Tianxing X, Zuelli Z. The Relationship between Electricity Consumption and Economic Growth in China. Phys Procedia. 2012;24:56–62.
2. Ambrose J. UK to be left with five coal power stations after latest closure. The Guardian. 2019 June 13. Available from: https://www.theguardian.com/environment/2019/jun/13/mid-built-by-winter-was-greenest-ever-for-uk-energy-use [Accessed 24th July 2019].
3. Drago K. Drax Electric Insights. 2019. Available from: https://electricinsights.co.uk/#/dashboard?_k=lyn9ha [Accessed 24th July 2019].
4. Johnson D, Papageorgiou D, Malliaragda T, Detjen I, Rhodes M, Webber E. Evaluating rotational inertia as a component of grid reliability with high penetrations of variable renewable energy. Energy. 2019;180:258-271.
5. N. Grid. Frequency response services | National Grid ESO. 2019. Available from: https://www.nationalgrideso.com/balancing-services/frequency-response-services [Accessed 24th July 2019].
6. Vieira W, Freitas H, Huang W, Xu X, Morelato A. Formulas for predicting the dynamic performance of ROCOF relays for embedded generation applications. IEE Proc - Gener Transm Distrib. 2006;153(4):399.
7. Ulibig T, Borsche T, Andersson G. Impact of Low Rotational Inertia on Power System Stability and Operation. IFAC Proc Vol. 2014;47(3):7290-7297.
8. Anbarasi S, Muralidharan S. Hybrid BFP50 approach for effective tuning of PID controller for Load Frequency Control Application in an interconnected power system. J Electr Eng Technol. 2017;12:1027–1037.
9. Guha D, Roy PK, Banerjee S. Symbiotic organism search algorithm applied to load frequency control of multi-area Power System. Energy Syst. 2017;9:439–468.
10. Shah JS, Suleyman ST, Ibrahim K, Zakirussain F. Gravitational Search Algorithm (GSA) based PID Controller Design for Two Area Multi-Source Power System Load Frequency Control. J Control Sci. 2018;31:139–153.
11. Bhongade S. Automatic generation control of two-area ST-Thermal power system using jaya algorithm. Int J Smart Grid. 2018;2:99–110.
12. Kong F, Li J, Yang D. Multi-Area load frequency control of hydro-thermal-wind power based on improved grey wolf optimization algorithm. Elektron Ir Elektrotechnika. 2020;26:32–39.
13. National Grid. System operability framework. 2016. Available from: http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/System-Operability-Framework/ [Accessed 15th February 2017].
14. Tamrakar U, Hansen TM, Tonkoski R. Adaptive frequency control of low inertia microgrids. In: Proceedings of the 2019 IEEE 28th International Symposium on Industrial Electronics (ISIE); 2019; p. [pagination].
15. Guha D, Roy PK, Banerjee S. Symbiotic organism search algorithm applied to load frequency control of multi-area Power System. Energy Syst. 2017;9:439–468.
16. Shah JS, Suleyman ST, Ibrahim K, Zakirussain F. Gravitational Search Algorithm (GSA) based PID Controller Design for Two Area Multi-Source Power System Load Frequency Control. J Control Sci. 2018;31:139–153.
17. Bhongade S. Automatic generation control of two-area ST-Thermal power system using jaya algorithm. Int J Smart Grid. 2018;2:99–110.