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Improved load frequency control performance by tuning parameters of PID controller and BESS using Bat algorithm

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ABSTRACT

The oscillation of frequency can cause the generator to run out of sync in a power system. Therefore, load frequency control (LFC) is needed to reduce frequency oscillation and prevent out of sync operation. The LFC regulates the governor to balance the turbine speed with changes in the load of existing. In this paper, a proportional integral differential (PID) controller and a battery energy storage system (BESS) are added to an LFC to improve the frequency stability of a power system. The parameters of the PID controller and BESS are optimized using the Bat algorithm (BA) to attain a good coordination. The frequency performance analysis is done by introducing disturbance in the form of changes in load power. The simulation results show that the frequency deviation of the system with the PID controller and BESS, has a faster settling time and smaller overshoot value. The system performs better than those with only the PID controller or the BESS. In conclusion, the BA algorithm can be used to find optimal parameter values of the PID controller and BESS for a synchronized coordination of an LFC.

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1. INTRODUCTION

The dynamics of a power system is influenced by its components such as generators, transmission networks, loads and control modules [1]–[3]. Although the interaction of its components is complex, it must be well understood for a smooth and safe operation [4], [5]. The stability of the electric power system is defined as the ability of an electric power system and its components to maintain synchronization and balance [6], [7].

Load frequency control (LFC) is a module that controls the frequency fluctuations caused by changes in the load. It is be done by controlling the integral gain in the governor. The integral controller normally used in an LFC is usually sufficient to maintain a stable operating frequency, but under drastic load changes, it is inadequate [8]. This happens when the response of the governor is relatively slow compared to the electrical load changes. Therefore, additional tools such as a proportional integral differential (PID) controller and a battery energy storage system (BESS) can be introduced to overcome the fluctuating frequency [9]. In this paper, we show that by adding a PID controller and a BESS to an LFC, the ability of a power system to control frequency fluctuation is improved [10].

Lately, adding a substantial BESS to a power system is a topic of much discussion. Examples of large-scale deployments of BESS include the Mitsubishi 50 MW/300 MWh system at Buzen, Fukuoka Prefecture, Japan and Tesla 100 MW/129 MWh system at Jamestown, South Australia [11], [12]. At present, vistra energy is collaborating with PG and E to construct a bigger BESS with a capacity of 300 MW/1200 MWh in California, USA [13].

A BESS is a flexible but expensive component in an electrical power system [14]. Installing a BESS with an optimal size is important to avoid frequency fluctuation and cost overrun [15]. BESS can be used as a frequency regulator to help preserve system stability. Furthermore, BESS can act as an energy arbitrage, allowing the aim of reduced generation costs to be met [16]. In our work, we use the Bat algorithm (BA) to optimize the PID and BESS parameters to obtain more optimal results.

2. LOAD FREQUENCY CONTROL MODEL

A multi-area electric power system consists of large and small capacity plants interconnected with each other. All of the machines work synchronously to generate power of the same frequency [17], [18]. Frequency oscillation in a multi-area electric power system can cause the generators to go out of sync. For each plant, the LFC functions as a frequency regulator to ensure that the frequency is within the desired range. The LFC also help regulate the exchange of power between areas by setting the output power of the generator. Ultimately, it regulates load sharing when changes in the load are needed, especially for plants operating on low-cost generation. Therefore, LFC is used to regulate frequency as well as load [19]–[21]. Figure 1 shows a schematic of a LFC of a synchronous generator. The overall linear model of the LFC electric power system in two areas can be seen in Figure 2.

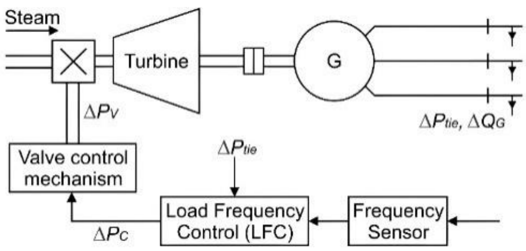


Figure 1. LFC schematic diagram [1]

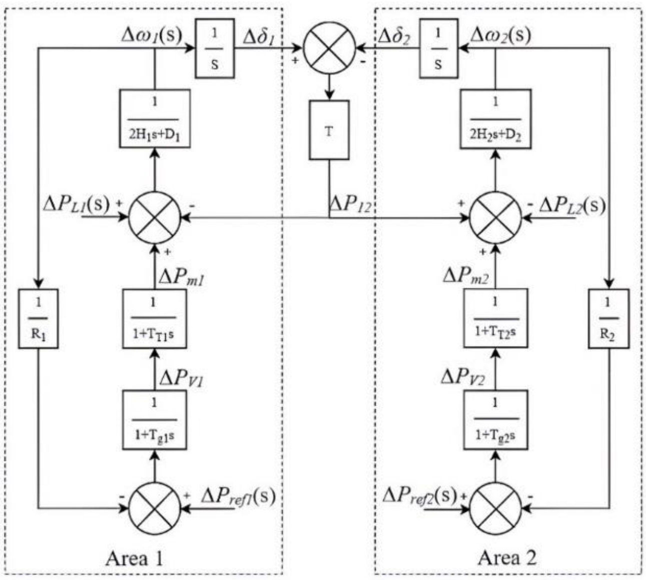


Figure 2. Linear model of two-area electric power system [1]

In each area of the system block diagram such as depicted in Figure 2, is represented by a turbine and governor system with effective speed drop (R), equivalent moment of inertia (H), and load constant damping (D). Synchronous torque coefficient (T) represents the tie line. ΔP12 is positive because there is an increase in consumption of power from area 1 to area 2. Then a negative sign on feedback ΔP12 for area 1 and a positive sign for area 2.

2.1. Proportional integral differential controller

PID works by taking an error signal that is processed by summing up the parameters of the PID setting, namely the proportional, integral and differential controllers. In determining these parameters, the function of a plant (system) must be reviewed to arrive at the desired order response performance specifications, then we can specify the value of these parameters. Heuristically, these parameters can be interpreted in terms of time, where P is the current error (in the simulation denoted by Kp), I is the accumulation of past errors (τi), and D is the prediction of future errors taking into account of the error rate when this (τd) [22].

The PID controller application is done by adding in each area on the system. The action of PID control is to set the area control error (ACE) signal so that changes in frequency of each area (Δf) and power between areas (Ptie) return to value 0. The control signal from the PID is entered to the value of load reference in the governor unit (set point load governor). The block diagram for the power system of two-area electric with the PID controller can be seen in Figure 3.

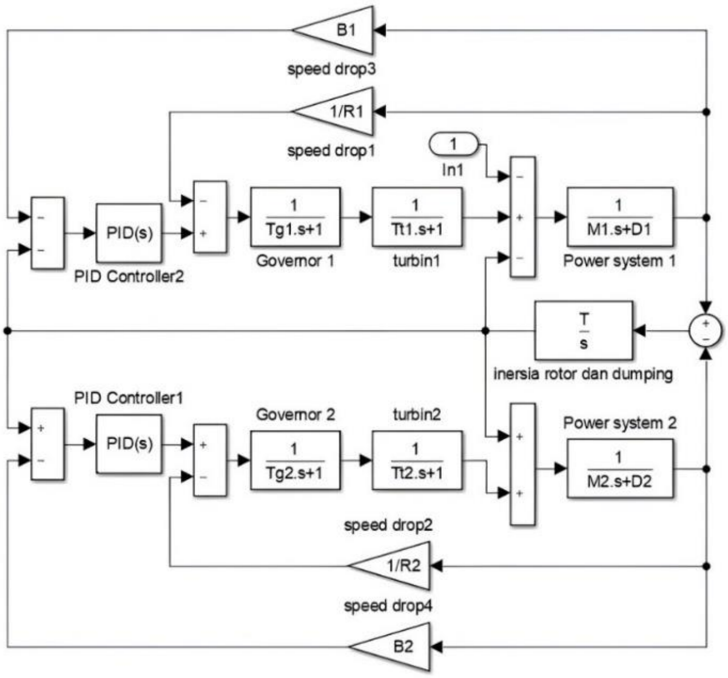


Figure 3. LFC system in two areas with PID controller

2.2. Battery energy storage system

One alternative to increase the reliability of electrical energy supply during the peak load period is the facilities use of energy storage, and currently the best energy storage system is BESS [23]. BESS can be used in various aspects of the power system. The advantages of BESS include increasing the system frequency especially when BESS is used for system frequency control. However, installing a BESS with a size that is too large or incorrect can cause frequency problems to the system and increase costs. For this reason, the BESS optimal size is an important factor for the system [15]. Because the BESS can provide fast active power compensation, it can also be used to improve LFC performance. The LFC problem is basically a sudden disruption of small loads that disrupt the normal operation of the power system. However, the BESS can provide fast energy storage measures to help LFC to suppress system oscillations after a load disturbance [9]. In Figure 4, it can be seen that the basis of the equivalent configuration of BESS contains a battery with several parallel/serial battery cells, a 12-pulse converter connected to transformer of Y/Δ-Y, and a controller scheme. The output voltage equation of the battery can be written as (1):

$$E_{bt} = V_{avg} - R_c\ I_{BESS} = \frac{3\sqrt{6}}{\pi} E_t\ \left(cos\alpha_1\ + cos\alpha_2\ \right) - \frac{6}{\pi} X_{co} I_{BESS} \tag{1}$$

Where α is the ignition angle controlled using a thyristor. By setting the α value, it can play the converter settings so that it only produces active power. The BESS equivalent circuit can be represented as converter connected to a battery with the same value of cosine, as shown in (2). Then, the equivalent circuit of the BESS is as shown in Figure 5. Only the addition of active power is calculated in the LFC. Therefore, the α value is obtained as (3):

$$E_{bt} = \frac{6\sqrt{6}}{\pi} E_t\ \left(cos\alpha_1\ + cos\alpha_2\ \right) - \frac{6}{\pi} X_{co} I_{BESS} \tag{2}$$

$$\alpha_1\ = -\alpha_2\ = \alpha \tag{3}$$

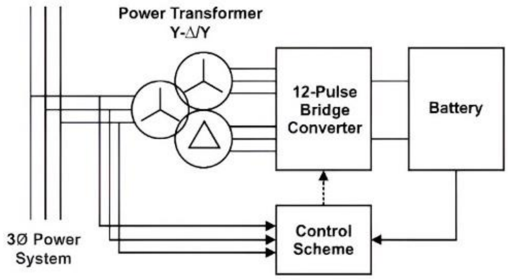


Figure 4. Schematic description of the BESS [10]

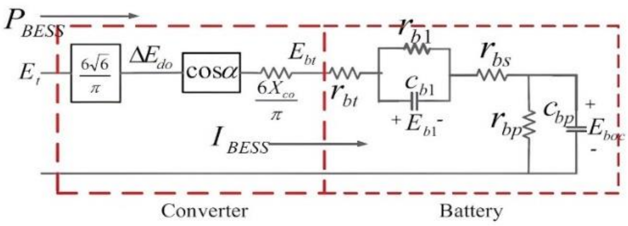


Figure 5. Equivalent circuit of the BESS [10]

Based on the equivalent of the BESS, the direct current (DC) flowing into the battery can be expressed by (4):

$$I_{BESS} = \frac{E_{bt} - E_{boc} - E_{b1}}{r_{bt} + r_{bs}} \tag{4}$$

Then the battery capacitance equation is obtained as (5):

$$E_{b1} = \frac{1}{c_{b1}} \int I_{cb1} dt$$

$$\frac{d}{dt} E_{b1} = \frac{1}{c_{b1}} I_{cb1} \tag{5}$$

If the battery current is deviated, it will also experience a change in value, then (5) will become (6):

$$\frac{d}{dt} \Delta E_{b1} = \frac{1}{c_{b1}} \Delta I_{cb1} \tag{6}$$

The battery capacitance current equation can be written as (7):

$$I_{cb1} = \frac{r_{b1}}{r_{b1}+X_{cb1}} I_{BESS} \tag{7}$$

Likewise, if there is a current deviation, then (7) will become (8):

$$\Delta I_{cb1} = \frac{r_{b1}}{r_{b1}+X_{cb1}} \Delta I_{BESS} \tag{8}$$

Combining (6) and (8) results in (9):

$$\frac{d}{dt}\Delta I_{cb1} = \frac{1}{c_{b1}} \frac{r_{b1}}{(r_{b1} + X_{cb1})} \Delta I_{BESS}$$

$$\frac{d}{dt}\Delta I_{cb1} = \frac{r_{b1}}{(c_{b1}r_{b1}+\frac{1}{\omega})} \Delta I_{BESS} \tag{9}$$

The Laplace transformation of (9) is as in (10):

$$s\Delta I_{cb1} = \frac{r_{b1}}{(c_{b1}r_{b1}+\frac{1}{\omega})} \Delta I_{BESS} \tag{10}$$

Where E_{b1} is the number of capacitance voltages that have undergone deviation, and a new constant is determined, i.e.

$$T_{b1} = c_{b1}r_{b1} \tag{11}$$

Then (10) can be written as (12):

$$E_{b1} = \frac{r_{b1}}{1 \quad +sT_{b1}} (I^{o}_{BESS} + \Delta I_{BESS}) \tag{12}$$

In the same way, the equation for voltage capacitance E_{boc} is as (13):

$$E_{boc} = \frac{r_{bp}}{1 \quad +sT_{bp}} (I^{o}_{BESS} + \Delta I_{BESS}) \tag{13}$$

With

$$T_{bp} = c_{bp}r_{bp} \tag{14}$$

The equation of active and reactive power absorbed by BESS are as (15) and (16) respectively [11]:

$$P_{BESS} = \frac{3\sqrt{6}}{\pi} E_t \ I_{BESS}(cos\alpha_1 \ + cos\alpha_2 \ ) \tag{15}$$

$$Q_{BESS} = \frac{3\sqrt{6}}{\pi} E_t \ I_{BESS}(sin\alpha_1 \ + sin\alpha_2 \ ) \tag{16}$$

Then (15) and (16) when substituted with (2) become (17) and (18) respectively:

$$P_{BESS} = \frac{6\sqrt{6}}{\pi} E_t \ I_{BESS}(cos\alpha \ \ ) \tag{17}$$

$$Q_{BESS} = 0 \tag{18}$$

Then the power deviation equation BESS is obtained as per (19):

$$\Delta P_{BESS} = I_{BESS}\Delta E_d \tag{19}$$

The use of the BESS in LFC is to reach a damping signal (ΔE_d). By giving feedback in the form Δf to give a damping effect, the ΔE_d value is obtained as (20) [17]:

$$\Delta E_d = \frac{K_{bess}}{1 + sT_{bess}} \Delta f \tag{20}$$

The LFC system with the PID controller is then added with a BESS. The output response of the system with the addition of both the PID controller and BESS is expected to be better than the two systems working individually. The PID controller is installed in each area, while the BESS is still only installed in area 1 where there will be a change in the load. Based on (1) to (20), a block diagram is obtained as shown in Figure 6. The initial settings of both (PID controller and BESS) were taken from previous studies [8], [9] as seen in Figure 7. Furthermore, Table 1 shows the PID controller and BESS parameters used in this paper. This study used four parameters K_p, K_i, K_d and K_{bes}.

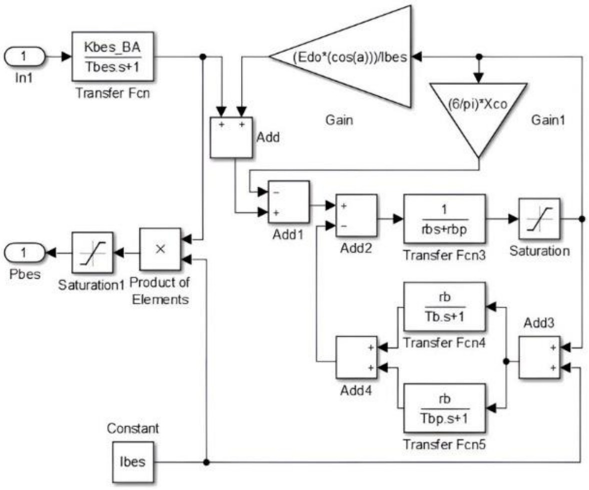


Figure 6. BESS block diagram [17]

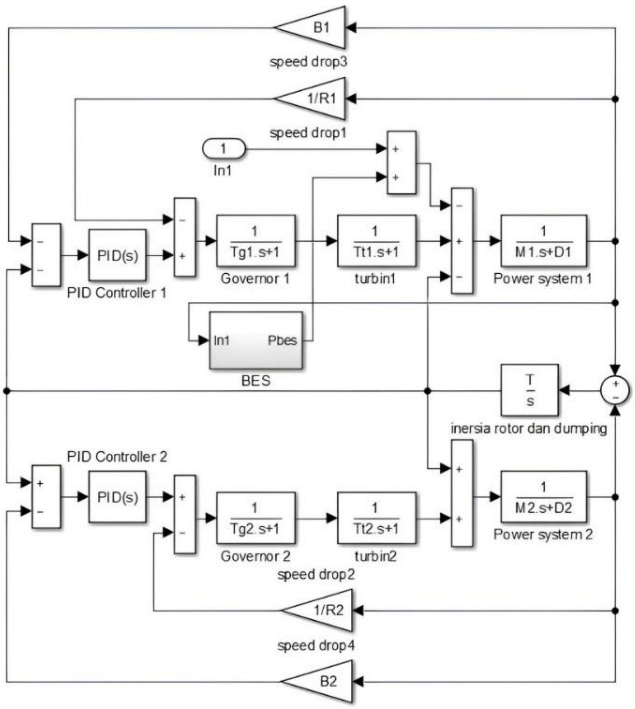


Figure 7. LFC system in two areas with PID controller and BESS

Table 1. PID and BESS parameters in both areas

Parameter	Value
K_p	1
K_i	2
K_d	1.2
K_{bes}	100

2.3. Proportional integral differential controller and battery energy storage system tuning using BA

In the search for optimal values using the BA, the parameters to be optimized are determined first. In this paper, there are four parameters that will be optimized, namely, Kbess, Kp, Ki, and Kd. Their values are assumed to be dimensions in the BA. The BA will optimize these dimensions up to the specified iteration [24]. The best combination is the combination that produces a system with the smallest oscillation overshoot and the fastest settling time [25]. The combination of the values of Kbess, Kp, Ki, and Kd will attain the best combination. In BA, the objective function is an evaluation function of each population. The objective function used in this work is CDI. If the sum produces the smallest value, then the response is considered the best with the fastest settling time and the smallest overshoot. The CDI equation is as (21):

$$CDI = \sum_{i=1}^{n}(1-\xi_i) \tag{21}$$

The smaller the CDI value means the damping (ξ) value is getting bigger, and this in turn means that the system has a higher attenuation to oscillation. Where oscillation attenuation is getting higher, this shows that the Eigen value of the system has a very small imaginary value. Calculation of the Eigen value and damping value of the system is done automatically using the Matlab program. The full BA parameters used in this optimization method are shown in Table 2. The PID controller and BESS parameter optimization simulation results using BA [26] on the two-area system are shown in Table 3, and the convergence graph obtained is shown in Figure 8.

Table 2. Data of BA's parameters

BA parameters	Value
Size of population	40
Noise	0.15
Pulse ratio	0.45
Alpha=Gamma	0.7
Maximum frequency	100
Minimum frequency	0
Number of iterations	50

Table 3. Results of PID controller and BESS parameter optimization using BA in two areas

Controller parameters	Parameters' value
K_P	5.4049
K_I	2.4232
K_D	4.0804
K_{BESS}	104.687

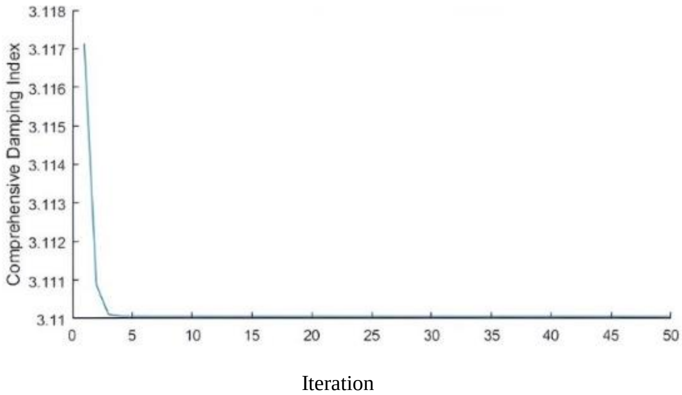


Figure 8. BA convergence graph for two areas system parameter optimization

From the convergence graph, the simulation is done within 50 iterations and the objective function reaches the best value at the 5th iteration. The best objective function shows that the BA has found the best location (the best solution). The best location shows that the PID controller and BESS parameters coordination is optimal.

3. RESULTS AND DISCUSSION

The results of the simulations for the uncontrolled LFC system, LFC system with PID, LFC system with BESS, the system of LFC with PID+BESS, and LFC system with PID+BESS tuned using BA are compared. The response that was observed was in the form of Δf and Ptie each area when there was a change load in area 1. The results of the response shows that the use of the PID controller and BESS optimization method using the BA improves the overshoot and settling time of the system.

Simulation is conducted by testing the system frequency response when given a disturbance in the form of changes in load of 0.02 per unit (pu) and 0.05 pu. The BESS capacity installed is 0.04 pu. In this simulation, the result of the system output response is said to return to the steady state condition if the frequency deviation is 2-5% of the overshoot peak. When the system is given a step input noise of 0.02 pu, the system will respond as shown in Figures 9(a)-(c). A comparison of the overshoot values for each scenario is presented in Table 4.

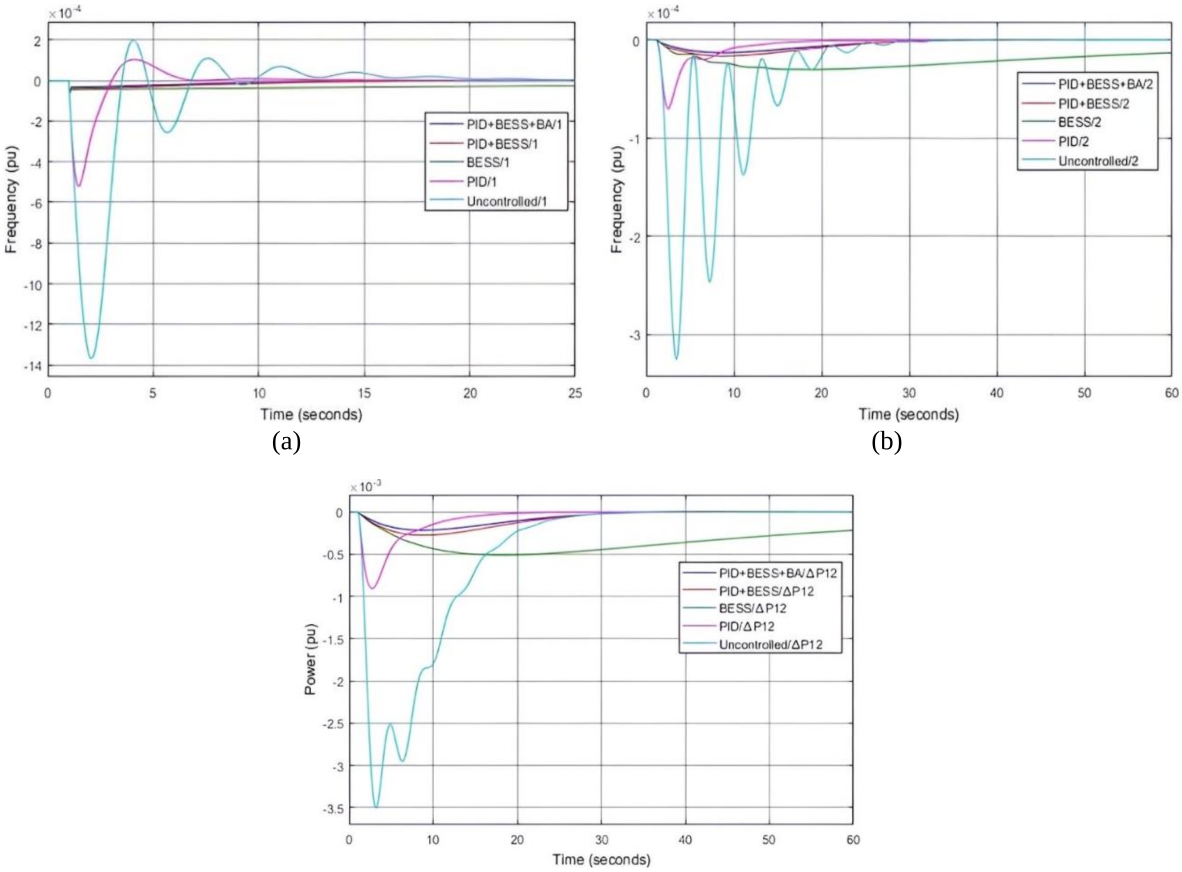
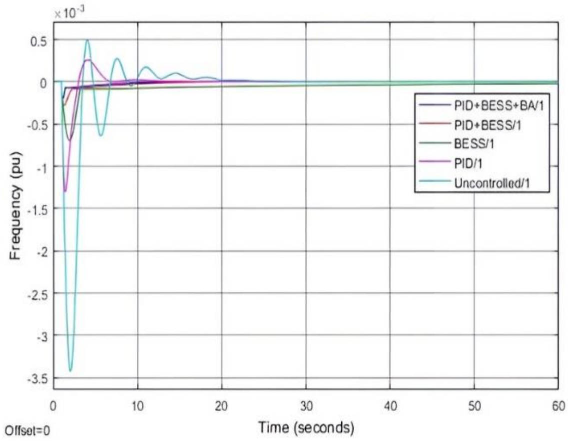


Figure 9. System responses to 0.02 pu load changes (a) area 1, (b) area 2, and (c) tie line

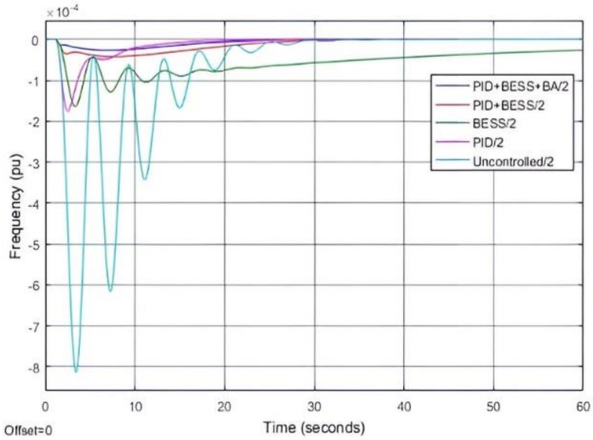
Table 4. Comparison of overshoot values in each scenario

	LFC	LFC with PID	LFC with BESS	LFC with PID+BESS	LFC with PID+BESS using BA
Δf_1(Hz)	0.0686	0.0261	0.0031	0.0030	0.0029
	100%	38.03%	4.49%	4.44%	4.22%
Δf_2 (Hz)	0.0163	0.0035	0.0015	0.0008	0.0006
	100%	21.53%	9.25%	5.00%	3.93%
ΔP_{12} (pu)	0.0035	0.0009	0. 0005	0. 0003	0.0002
	100%	25.83%	14.53%	7.87%	6.18%

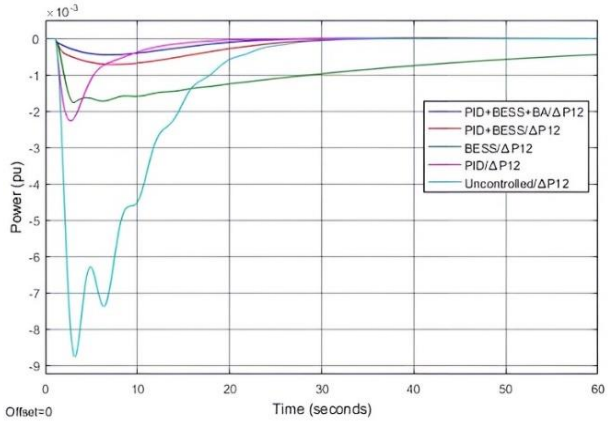
When the system is given a disturbance of 0.05 pu input, the system will respond as per Figures 10(a)-(c). With a step input disturbance of 0.05 pu, which is a disturbance with ΔP12 greater than the BESS capacity, the system with BESS can still provide a smaller overshoot value. The comparison of overshoot values for each scenario is presented in Table 5. The PID controller and BESS optimized with BA produces the best overshoot and settling time. This result proves that BA is able to produce optimal parameter values for the PID controller and BESS.



(a)



(b)



(c)

Figure 10. System response to load changes of 0.05 pu (a) area 1, (b) area 2, and (c) tie line

Table 5. Comparison of overshoot values in each scenario

	LFC	LFC with PID	LFC with BESS	LFC with PID+BESS	LFC with PID+BESS using BA
Δf_1 (Hz)	0.1713	0.0652	0.0348	0.0139	0.0086
	100%	38.04%	20.3%	8.1%	5.019%
Δf_2 (Hz)	0.0407	0.0088	0.0082	0.0021	0.0016
	100%	21.58%	20.18%	5.1776%	3.9299%
ΔP_{12} (pu)	0.4382	0. 1132	0. 0881	0. 0355	0.0271
	100%	25.83%	20.1%	8.098%	6.184%

4. CONCLUSION

In this paper, PID and BESS are added to an LFC of a power system to improve its frequency stability. The parameters of the PID and BESS are optimized using a BA algorithm. The frequency performance analysis is done by introducing disturbance in the form of changes in load power. The simulation results show that the frequency deviation of the system with the PID controller and BESS, has a smaller overshoot value and faster settling time. The system performs better than those with only the PID controller or the BESS. In conclusion, the BA algorithm can be used to find optimal parameter values of the PID controller and BESS for a synchronized coordination of an LFC.

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REFERENCES

[1] A. Delavari and I. Kamwa, "Sparse and Resilient Hierarchical Direct Load Control for Primary Frequency Response Improvement and Inter-Area Oscillations Damping," *IEEE Transactions on Power Systems*, vol. 33, no. 5, pp. 5309–5318, Sep. 2018, doi: 10.1109/tpwrs.2018.2795462.

[2] Suyanto, Soedibyo, and A. A. Firdaus, "Design and simulation of Neural Network Predictive Controller pitch-angle in permanent magnetic synchronous generator wind turbine variable pitch system," in *2014 The 1st International Conference on Information Technology, Computer, and Electrical Engineering*, IEEE, Nov. 2014, doi: 10.1109/icitacee.2014.7065769.

[3] A. A. Firdaus, R. T. Yunardi, E. I. Agustin, S. D. N. Nahdliyah, and T. A. Nugroho, "An improved control for MPPT based on FL-PSo to minimize oscillation in photovoltaic system," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 11, no. 2, p. 1082, Jun. 2020, doi: 10.11591/ijpeds.v11.i2.pp1082-1087.

[4] C. R. Balamurugan, "Three Area Power System Load Frequency Control Using Fuzzy Logic Controller," *International Journal of Applied Power Engineering (IJAPE)*, vol. 7, no. 1, p. 18, Apr. 2018, doi: 10.11591/ijape.v7.i1.pp18-26.

[5] F. Liu, Y. Li, Y. Cao, J. She, and M. Wu, "A Two-Layer Active Disturbance Rejection Controller Design for Load Frequency Control of Interconnected Power System," *IEEE Transactions on Power Systems*, vol. 31, no. 4, pp. 3320–3321, Jul. 2016, doi: 10.1109/tpwrs.2015.2480005.

[6] E. Alves, G. B-Diaz, D. Brandao, and E. Tedeschi, "Sufficient Conditions for Robust Frequency Stability of AC Power Systems," *IEEE Transactions on Power Systems*, vol. 36, no. 3, pp. 2684–2692, May 2021, doi: 10.1109/tpwrs.2020.3039832.

[7] M. Mounica, C. Prasad, D. J. V. Prasad, and M. Aruna Bharathi, "Load Frequency Control of an Isolated Power System in Presence of Controllable Energy Storage Devices," *Majlesi Journal of Electrical Engineering*, vol. 12, no. 2, pp. 29–38, Jun. 2018.

[8] C. Osinski, G. V. Leandro, and G. H. da C. Oliveira, "Fuzzy PID Controller Design for LFC in Electric Power Systems," *IEEE Latin America Transactions*, vol. 17, no. 01, pp. 147–154, Jan. 2019, doi: 10.1109/tla.2019.8826706.

[9] S. Arunsawatwong and P. Kalvibool, "Design of load frequency control for power systems with BESS and generation rate constraint subject to persistent load disturbances," in *2016 IEEE Region 10 Conference (TENCON)*, IEEE, Nov. 2016, doi: 10.1109/tencon.2016.7848622.

[10] P. Prajapati and A. Parmar, "Multi-area Load Frequency Control by various conventional controller using Battery Energy Storage System," in *2016 International Conference on Energy Efficient Technologies for Sustainability (ICEETS)*, IEEE, Apr. 2016, doi: 10.1109/iceets.2016.7583800.

[11] P. Brown, "Mitsubishi Installs 50MW Energy Storage System to Japanese Power Company," *Industrial & Medical Technology*, Mar. 2016, Accessed: May 27, 2022. [Online]. Available: https://electronics360.globalspec.com/article/6402/mitsubishi-installs-50mw-energy-storage-system-to-japanese-power-company.

[12] G. Parkinson, "Tesla big battery goes the full discharge–100MW–for first time," *RenewEconomy*, Dec. 14, 2017. Accessed: May 27, 2022. [Online]. Available: https://reneweconomy.com.au/tesla-big-battery-goes-full-discharge-100mw-first-time-37826/.

[13] S. Patel, "Vistra Energizes Massive 1.2-GWh Battery System at California Gas Plant," *POWER Magazine*, Jan. 14, 2021. Accessed: May 27, 2022. [Online]. Available: https://www.powermag.com/vistra-energizes-massive-1-2-gwh-battery-system-at-california-gas-plant/.

[14] A. Stock and P. Stock, "Powerful Potential: Battery Storage for Renewable Energy and Electric Cars," *Climate Council*, 2015. Accessed: May 27, 2022. [Online]. Available: https://www.climatecouncil.org.au/resources/batterystoragereport2015/.

[15] T. Kerdphol, K. Fuji, Y. Mitani, M. Watanabe, and Y. Qudaih, "Optimization of a battery energy storage system using particle swarm optimization for stand-alone microgrids," *International Journal of Electrical Power &amp\mathsemicolon Energy Systems*, vol. 81, pp. 32–39, Oct. 2016, doi: 10.1016/j.ijepes.2016.02.006.

[16] F. N. Tsany, A. A. Widayat, D. R. Aryani, F. H. Jufri, and I. M. Ardita, "Power system stability improvement using Battery Energy Storage System (BESS) in isolated grid," *IOP Conference Series: Earth and Environmental Science*, vol. 599, no. 1, p. 012025, Nov. 2020, doi: 10.1088/1755-1315/599/1/012025.

[17] S. Kalyani, S. Nagalakshmi, and R. Marisha, "Load frequency control using battery energy storage system in interconnected power system," in *2012 Third International Conference on Computing, Communication and Networking Technologies (ICCCNT'12)*, IEEE, Jul. 2012, doi: 10.1109/icccnt.2012.6396052.

[18] P. A. Gbadega and A. K. Saha, "Load Frequency Control of a Two-Area Power System With a Stand-Alone Microgrid Based on Adaptive Model Predictive Control," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 6, pp. 7253–7263, Dec. 2021, doi: 10.1109/jestpe.2020.3012659.

[19] E. Sahin, "Design of an Optimized Fractional High Order Differential Feedback Controller for Load Frequency Control of a Multi-Area Multi-Source Power System with Nonlinearity," *IEEE Access*, vol. 8, pp. 12327–12342, 2020, doi: 10.1109/access.2020.2966261.

[20] T. Tao, S. Roy, and S. Baldi, "Stable Adaptation in Multi-Area Load Frequency Control Under Dynamically-Changing Topologies," *IEEE Transactions on Power Systems*, vol. 36, no. 4, pp. 2946–2956, Jul. 2021, doi: 10.1109/tpwrs.2020.3044436.

[21] P. S. Devi and R. V. Santhi, "Introducing LQR-fuzzy for a dynamic multi area LFC-DR model," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 9, no. 2, p. 861, Apr. 2019, doi: 10.11591/ijece.v9i2.pp861-874.

[22] M. A. Ghany and M. A. Shamseldin, "Parallel distribution compensation PID based on Takagi-Sugeno fuzzy model applied on egyptian load frequency control," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 5, p. 5274, Oct. 2020, doi: 10.11591/ijece.v10i5.pp5274-5287.

[23] A. Oshnoei, M. Kheradmandi, and S. M. Muyeen, "Robust Control Scheme for Distributed Battery Energy Storage Systems in Load Frequency Control," *IEEE Transactions on Power Systems*, vol. 35, no. 6, pp. 4781–4791, Nov. 2020, doi: 10.1109/tpwrs.2020.2997950.

[24] C. Thammarat, K. Lurang, D. Puangdownreong, S. Hlangnamthip, A. Nawikavatan, and S. Suwannarongsri, "Application of Bat-Inspired Algorithm to Optimal PIDA Controller Design for Liquid-Level System," in *2018 International Electrical Engineering Congress (IEECON)*, IEEE, Mar. 2018, doi: 10.1109/ieecon.2018.8712168.

[25] A. A. Firdaus, R. T. Yunardi, E. I. Agustin, T. E. Putri, and D. O. Anggriawan, "Short-term photovoltaics power forecasting using Jordan recurrent neural network in Surabaya," *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 18, no. 2, p. 1089, Apr. 2020, doi: 10.12928/telkomnika.v18i2.14816.

[26] M. Ali *et al.*, "The comparison of dual axis photovoltaic tracking system using artificial intelligence techniques," *IAES International Journal of Artificial Intelligence (IJAI)*, vol. 10, no. 4, p. 901, Dec. 2021, doi: 10.11591/ijai.v10.i4.pp901-909.

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