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Black Widow Optimization for Power System Load Frequency Control: A Comparative Study

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ABSTRACT- This research paper mainly engrossed on developing a suitable novel tuning methodology named Black Widow Optimization (BWO) Algorithm for power system optimization problems. Load Frequency Control (LFC) and Automatic Voltage Regulator (AVR), two of the most important control systems in the power system arena, are employed as test systems to assess the efficiency of the suggested BWO approach. Various analyses, such as transient analysis, are employed to evaluate the efficiency of the suggested BWO approach in LFC and AVR systems. robustness analysis and convergence analysis. The significant performance measures of test system such as output power of each generating unit, maximum peak, settling time, steady state error, rise time and voltage/frequency deviations of the frequency and voltage responses are considered for the comparison purposes. The comparative analysis clearly demonstrates that the proposed novel tuning methodology provides better transient performances subjected to Step Load Perturbations (SLP), Variable Load Perturbations (VLP), and robustness performances under a wide range of load and parameter changes ranging from -50% to +50%. The convergence analysis of BWO algorithm also performed in LFC and AVR test systems and results better convergence characteristics with minimal convergence time as well as least fitness value is obtained with the BWO algorithm.

Keywords: Automatic Voltage Regulator (AVR), Black Widow Optimization Algorithm (BWO), Load Frequency Control (LFC), Integral Controller (I), Proportional Integral Derivative controller (PID), single-area multi- source LFC system.

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1. INTRODUCTION

Recent research works in LFC arena extended towards incorporating renewable energy resources. This will lead to the development of optimal control methodologies in LFC system to rectify the uncertainty problems because renewable energy sources have been included [1–5].

The majority of such intelligent tuning techniques, including Hybrid Bacterial Foraging Particle Swarm Optimisation (BFOA-PSO), produced successful results in multi-source LFC systems, water cycle algorithm, whale optimizer algorithm, Artificial Bee Colony optimisation algorithm (ABC), Bacterial Foraging Optimization Algorithm (BFOA), modified Jaya optimization, constrained population algorithm, Imperialist competitive algorithm, GOA, Grey Wolf Optimization Algorithm, Cuckoo search optimization etc., [6, 7]. In similar way, so many metaheuristic approaches have been developed for tuning the AVR system's controller gain levels for techniques like salp-swarm optimization, [8 9,10].

BFOA, cuckoo search algorithm, chaos-ABC, local unimodal sampling approach, teaching learning based optimal tuning approach, Sine–cosine algorithm and chaotic yellow saddle goatfish algorithm [11].

These optimization algorithms have proved their effectiveness in any of the aspects. Still research works are carried out in these arenas to innovate a novel intelligent control approach, to enhance the system effectiveness further compared to existed controllers for many control approaches and suitable for all type of environmental constraints as well as with improved convergence characteristics. An alternate feasible optimization algorithm named BWO, is suggested in this article for optimal tuning of integral as well as PID's gain values in both LFC and AVR systems. The BWO algorithm was developed recently and proved its excellence in most of the engineering problems [12, 13]. In many ways, involving early convergence and attaining

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optimum fitness values, the BWO method is superior to other optimization algorithms. It can also get results which are competitive and promising. The BWO method performs well throughout the exploitation and exploration phases, obtains rapid convergence, and stays away from local optimization issues. The capability to preserve a balance between development and exploration is another important feature of BWO. To achieve the best overall solution, one can examine a vast area, in other words. Therefore, BWO can be used to solve numerous optimization issues employing a variety of local optimizations. The target of this research is to develop the BWO approach for optimizing integral and PID controller gain values in both LFC and AVR test systems [14]. In every optimization approach, the cost function plays a crucial role. In this paper, one of the most promising ITAE fitness function is chosen due to its fast response and lesser settling time. Moreover, the ITAE error can be used to reduce small errors that remain for long time. This study work [15,16] suggests that ITAE mistakes be minimized in order to prevent power system problems caused by tiny frequency and voltage changes that persist over an extended period of time.

In multi-source LFC systems, most of these intelligent tuning methods, including hybrid bacterial foraging particle swarm optimization (BFOA-PSO), were successful. Accordingly, three significant investigations like transient analysis, robustness analysis and convergence study were performed in this research workStep Load Perturbation (SLP) was used in transient analysis, and potential multi-source output responses were examined. LFC system and AVR system were analyzed [17].

2. DESCRIPTIONS OF MULTI-SOURCE LFC SYSTEM

2.1 Wind Energy System (WES) Integrated Single-Area Multi-Source LFC System-Test System-1

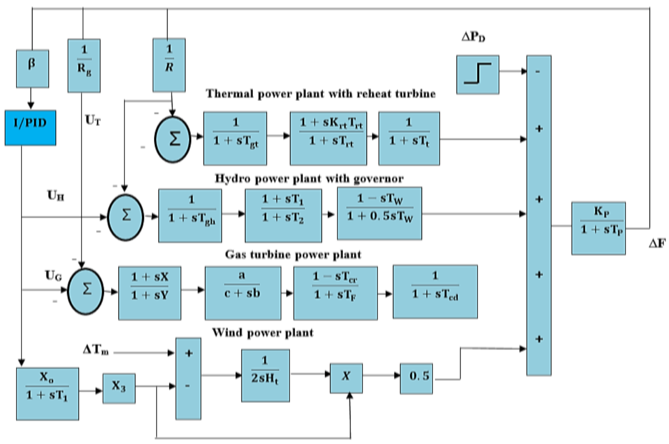

Figure 1: Linearized model of hybrid LFC system with wind energy source

The mathematical model of proposed hybrid LFC arrangement is given in *figure 1*. The linearized design of test system is developed by incorporating both conventional and renewable energy resources such as thermal, hydro, gas and wind energy resources.

Figure 1 displays the notional specifications and configurations of conventional and renewable power generation systems, which are drawn from existing research [18, 19] papers and are provided in the Appendix.

2.2 Transient Response Analysis of the Multi-Source LFC System without Controller

To examine the transient behaviour of the suggested multi-source LFC structure without employing a controller, an SLP of 10% is applied to test system 1. MATLAB is used to simulate the output frequency deviation behaviour and output of each power supply, and the resulting graphs are displayed in *figure 2*.

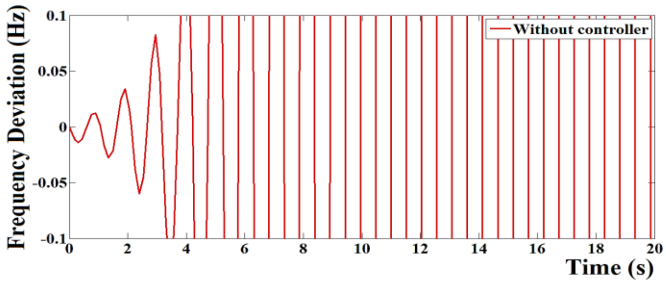

Figure 2: Frequency deviation behaviour of hybrid LFC system without controller

2.3 Automatic Voltage Regulator System-Test System 2

The linearized structure of AVR unit proposed in this research article is illustrated in *figure 3*. Amplification benefit is shown using the word KA, while exciter benefit and time steady are indicated using KE, and TE, respectively. In the same manner that sensor benefit and time steady are denoted by KR and TR, generator benefit and time steady are denoted by KG and TG, respectively. This research thesis takes into consideration the typical values of nominal parameter configurations that are found in the majority of past research works, and these values are provided in Appendix [20-24].

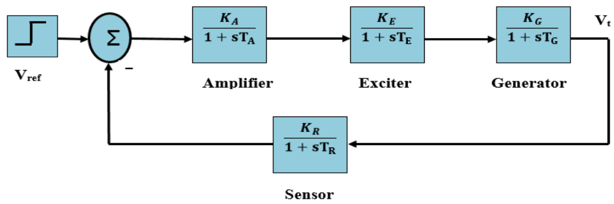

Figure 3: Linearized mathematical model of AVR system

2.4 Transient performance analysis of AVR system without controller

To study the AVR device's short-term performance without a controller, the Straight-Line Program (SLP) of one p. u is practical [25-28]. The output voltage deviation responses are simulated using MATLAB and corresponding plots are depicted in *figure 4*.

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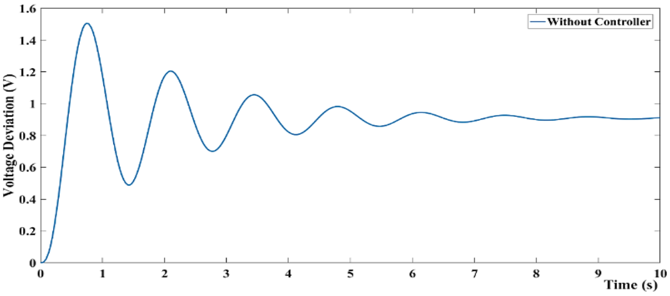

Figure 4: Output performance of hybrid LFC system without integral controller

Table 1: Transient response analysis of AVR without controller

Measuring Indices	AVR without controller
Steady State Error (V)	0.0881
Settling time (s)	7.0189
Maximum Peak (V)	1.5055
Rise Time (s)	0.2620

These charts demonstrate quite well that the AVR's output performance is more oscillatory in the absence of a controller [29-31]. For clear analysis the transient measuring indices are measured from the graph using 'stepinfo' comment in MATLAB and scheduled in *table 1*. In this article, the fundamental measurements are error at steady state condition (SSE), settle time (ST), maximum peak value (MP), and rise time (RT). This table clearly illustrates an optimal controller should be provided to retain the stability of the system as well as reducing voltage error.

3. BLACK WIDOW OPTIMIZATION ALGORITHM

The BWO is the newly developed novel intelligent optimization technique, that copies the behaviour of the black widow spiders [13]. Due to its simple coding and faster convergence, it can be suited for any type of optimization problems. This approach is developed through concerning the pairing of the black widow spiders.

The algorithmic steps of BWO tuned LFC multi source system are as follows:

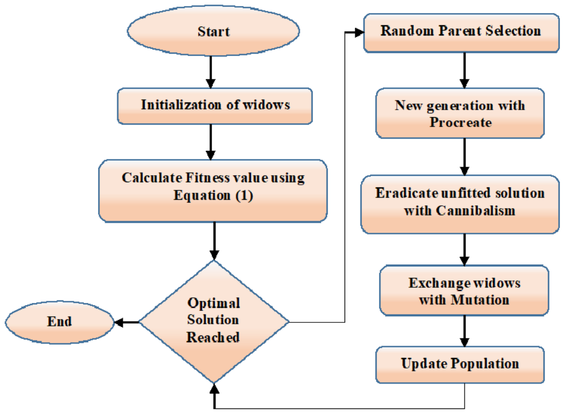

Figure 5: Flow Chart of BWO Algorithm

The flowchart representation of BWO algorithm is illustrated in *figure 5*. The global optimal solution is obtained in BWO algorithm by one of the main algorithmic steps named cannibalism in which the least fitted solutions are eradicated. Compared to other optimization approaches the BWO converges very faster and can be applicable to both minimization and maximization function.

4. RESULTS AND DISCUSSION

4.1 Transient response analysis of hybrid LFC system tuned with BWO algorithm

To analyze the transient performance response of hybrid LFC series tuned with BWO algorithm using the SLP of 10% results in the following controller gain values for the LFC system with integrated controller and PID controller: KI2=0.7958, KP=0.12264, KI=0.8578, and KD= 0.21131 are the tuned PID gain parameters. The LFC system's frequency deviation response is then taken into account with these tuned controllers. By comparing the frequency deviation response of the BWO-tuned LFC controller, BWO-tuned LFC integral controller, and PID controller with the reported LQR-based integral tuning methodology, the accuracy of the BWO algorithm is evaluated.

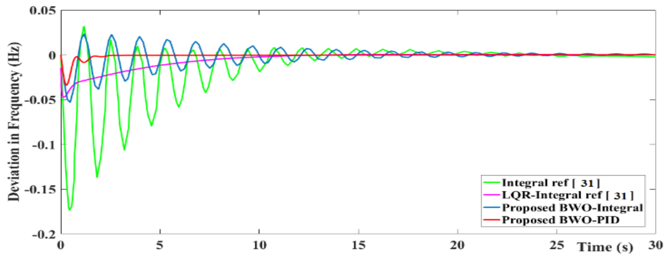

Figure 6: Comparative transient responses of hybrid LFC system

The comparative plots are illustrated in *figure 6*. This figure certainly reveals that, the LFC system performance with BWO-PID controller exemplify better output power for all conventional and renewable energy system with, lesser oscillations, less transcend, and less settle time error in contrast to other techniques.

4.2 Transient analysis of AVR System tuned with BWO algorithm

The *figure 7* obviously describes that, the suggested BWO tuned PID controller extemporize the response of the AVR module with less SSE, SE, MP compared to the uncontrolled system and GOA tuned PID controller stated in earlier reference.

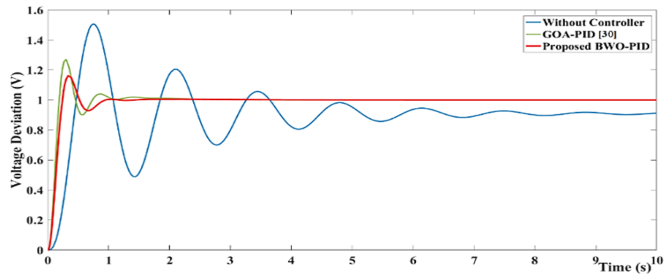

Figure 7: Comparative transient responses of AVR system

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4.3 Robustness investigation of hybrid LFC System with fixed load perturbations

To assess the system's robustness, wide fluctuations in SLP are applied to the LFC system in the range of -50% to +50% in 25% step variations.

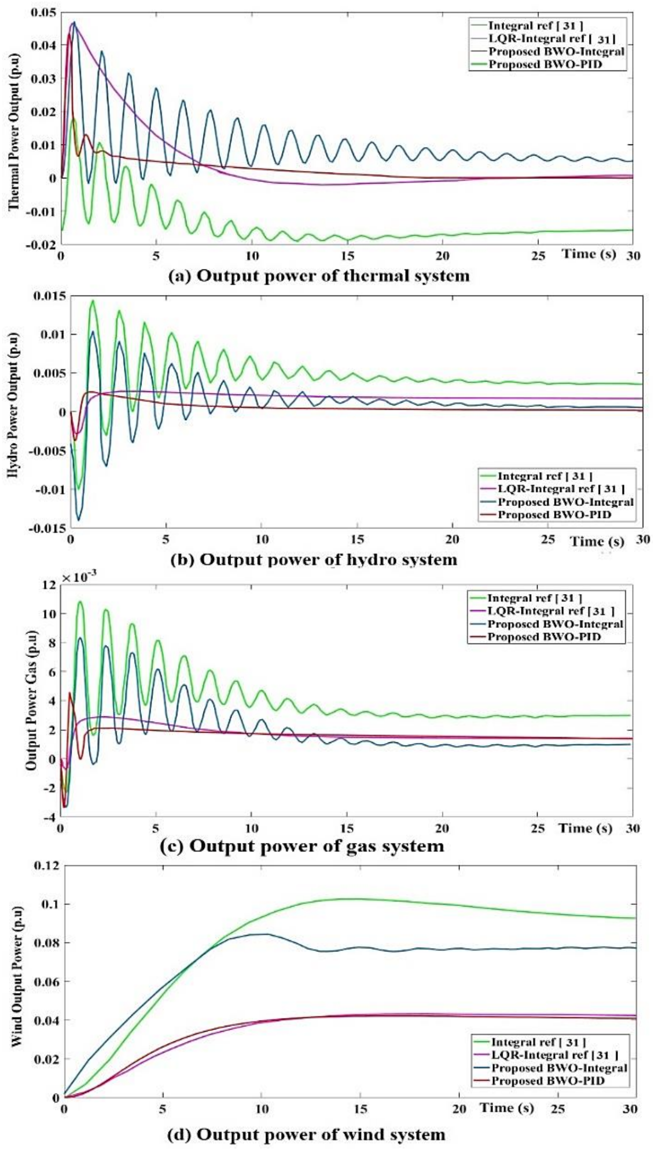

Figure 8: Output power of individual power source in multi-source LFC system with controller

Hence, from *figure 8*, the superiority of proposed BWO-PID controller is evidently proved in multi-source LFC test system integrated with wind energy resources. The robustness can be calculated using following steps:

Parameters of linearized single- area multi source LFC test system [31]

LFC system parameters: R1 = 10, R2=R3 =2.4, β= 0.425, Tp= 20 s, Kp =120.

Thermal series parameters: TSG = 0.07 s, Tt = 0.4 s, Krt = 10.5/3, Trt = 11 s.

Hydro series parameters: Tw = 2 s, Tgh = 0.3 s, T1 = 6 s, T2 = 27.85 s.

Gas series parameters: M = 0.7, N= 1, a= 1.04, b= 1.1, Tcd = 1.2 s, Tcr = 1.3 s, Tf = 1.23s

Wind series parameters: ωs = 1.3 p.u, ωopt=1 p.u, Ht=5.42 s, Lm=3.7 p.u, Lr / Ls=3.06/4.09 (p.u), Rr/Rs=0.017 (p.u), X0=62.5 (p.u), Twt=(Lr + Lm2/Ls) / (ωs/Rr)= 2.304 s

4.4 Robustness investigation of hybrid LFC System with variable load perturbations

The output performances of the suggested BWO tuned PID controller of the test system-1 under these wide range of load variations are simulated using MATLAB and depicted in *figure 9*. To increase the visibility the peak and ultimate settling period is depicted in the same image and is magnified. *Figure 9* obviously describes that, under the wide range of load variations, the proposed BWO tuned PID controller for LFC system provides a stable response with minimum range of deviations in time domain specifications.

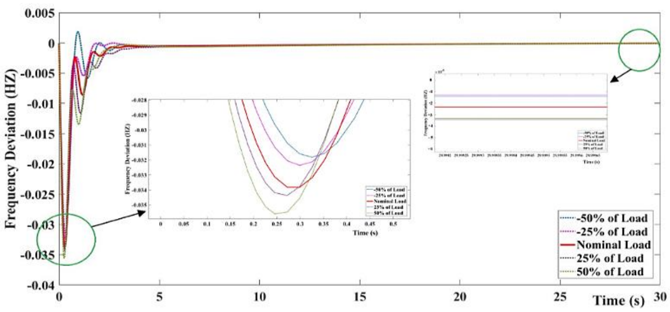

Figure 9: Robustness of LFC series subject to fixed load disturbances

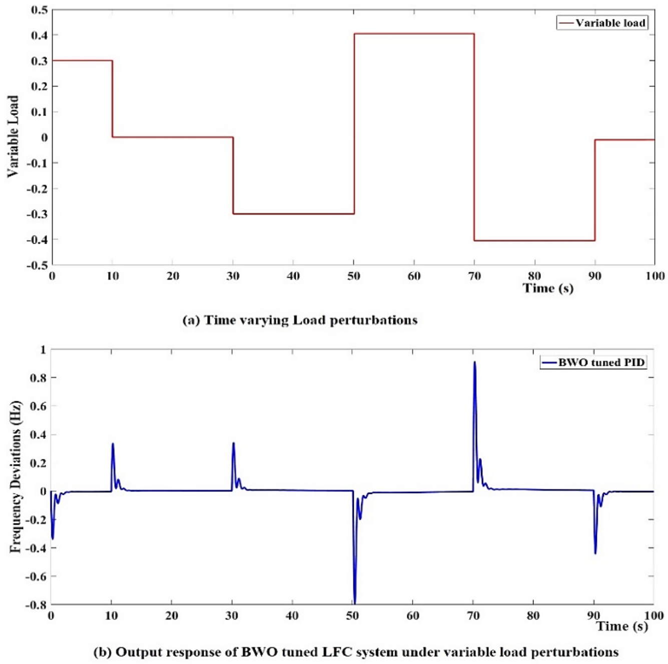

Figure 10: Robustness of LFC series subject to fluctuating load disturbance

To analyze the flexibility of the BWO tuned LFC test system subjected to practical environments the dynamic load testing is used to further evaluate the system's resiliency as shown in figure 10a. Corresponding frequency deviation response is depicted in figure 10b. The figure demonstrates that the suggested BWO-tuned PID controller for the proposed multi-source test system can early maintain stability with minimal frequency deviation when subjected to a fluctuating load disturbance.

5. CONCLUSION

An off-line tuning of PID for single-area hybrid LFC system with conventional and renewable energy resources and an AVR system with an effective novel metaheuristic approach named BWO is suggested in this paper. The multi-source LFC test system chosen for analysis consists, thermal, hydro, gas and wind energy resources. Initially, the output frequency deviation responses and the output power of individual energy sources of the LFC system are analysed without any controller and these results clearly reveals that the performances of the system without controller becomes unstable. Similarly, it was observed that, the AVR system without controller has high steady state error values. Hence, BWO-tuned integral and BWO-tuned PID controllers have been developed to further explore the performance of LFC and AVR test systems with three analyses, including transient, robustness, and convergence analyses. In order to reduce frequency error, ITAE is suggested as an appropriate fitness function in this approach of optimal adjustment. The simulation results of transient analyses in both LFC and AVR test systems clearly reveals that the BWO tuned PID controller produces better output response with improved system stability. Comparing to earlier documented results, minimum value of final state error, settle time, rise time and maximum peak is obtained while analyzing the output transient responses of both LFCs and AVRs. The performance of LFC and AVR systems in robustness analysis illustrates that the proposed BWO tuned LFC and AVR systems are maintaining stability under static and dynamic load perturbations that ensures the suitability of the suggested algorithm in practical environments. Similarly, the convergence analysis results of the BWO algorithm on the LFC and AVR test systems clearly demonstrated that the BWO algorithm converges very quickly with minimal computation time and lowest goodness-of-fit value. The positional values of randomly generated particles in the solution space over consecutive iterations are also analyzed in the convergence analysis, and proved that, the solutions produced in BWO tuned LFC and AVR systems are, global optimal solutions.

Conflicts of Interest: This paper has no conflict of interest for publishing.

Contributions of the Author: The following are the authors' confirmed contributions to the paper: research design and conceptualization: A. Jasmine Gnanamalar, K. Balachander; data gathering: V. Thiyagarajan; investigation and analysis of results: K. Prabhakaran, A. Jasmine Gnanamalar; draft manuscript preparation: K. Balachander, V. Thiyagarajan. The final draft of the paper was approved by all authors after they had evaluated the results.

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REFERENCES

[1] Gnanamalar, A.J., Bhavani, R., Arulini, A.S. et al. CNN–SVM Based Fault Detection, Classification and Location of Multi-terminal VSC–HVDC System. J. Electr. Eng. Technol. 18, 3335–3347 (2023). https://doi.org/10.1007/s42835-023-01391-5

[2] Gnana Malar, A.J., Sellamuthu, S., Ganga, M. et al. Power System Planning and Cost Forecasting Using Hybrid Particle Swarm-Harris Hawks Optimizations. J. Electr. Eng. Technol. (2023). https://doi.org/10.1007/s42835-023-01610-z

[3] Isha, G., Jagatheeswari, P. & Jasmine Gnana Malar, A. Elitist Harris Hawks Optimized Voltage Stability Enhancement in Radial Distribution System. J. Electr. Eng. Technol. 18, 2683–2693 (2023). https://doi.org/10.1007/s42835-023-01375-5

[4] Babu N. R.; Saikia, L. C. Automatic generation control of a solar thermal and dish-stirling solar thermal system integrated multi-area system incorporating accurate HVDC link model using crow search algorithm optimised FOPI Minus FODF controller. IET Renewable Power Gener., 2019, Vol. 13, No. 12, pp. 2221-2231. https://doi.org/10.1049/iet-rpg.2018.6089

[5] Y. Li, B. Xiong, Y. Su, J. Tang, and Z. Leng, "Particle swarm optimization-based power and temperature control scheme for grid-connected DFIG-based dish-Stirling solar-thermal system," Energies., 2019, Vol. 12, No. 7, pp. 1300. https://doi.org/10.3390/en12071300

[6] Tasnin W.; Saikia, L. C. Deregulated AGC of multi-area system incorporating dish-Stirling solar thermal and geothermal power plants using fractional order cascade controller. Int. J. of Electr. Power & Energy Syst., 2014, Vol. 101, pp. 60-74. https://doi.org/10.1016/j.ijepes.2018.03.015

[7] Shazly, J.; Hafez, A.; El Shenawy, E.; Eteiba, M. Simulation, design and thermal analysis of a solar Stirling engine using MATLAB. Energy convers. manage., 2014, Vol. 79, pp. 626-639, https://doi.org/10.1016/j.enconman.2014.01.001

[8] Lee D.J.; Wang, L.; Small-signal stability analysis of an autonomous hybrid renewable energy power generation/energy storage system part I: Time-domain simulations. IEEE Trans. energy convers., 2008, Vol. 23, No. 1, pp. 311-320, https://doi.org/10.1109/tec.2007.914309

[9] Saadat, H. Power system analysis. McGraw-Hill, 1999, https://doi.org/10.1007/978-1-349-07397-9_6

[10] Kundur, P.; Balu, N. J.; Lauby, M. G.; Power system stability and control. Mc Graw-hill New York. 1994, https://doi.org/10.1201/9781420009248.sec2

[11] Pradhan C.; Bhende, C. N.; Online load frequency control in wind integrated power systems using modified Jaya optimization. Eng. Appl. Artif. Intell., 2019, Vol. 77, pp. 212-228, https://doi.org/10.1016/j.engappai.2018.10.003

[12] Hasanien H. M.; El-Fergany, A. A. Salp swarm algorithm-based optimal load frequency control of hybrid renewable power systems with communication delay and excitation cross-coupling effect. Electr. Power Syst. Res., 2019, Vol. 176, pp. 105938, https://doi.org/10.1016/j.epsr.2019.105938

[13] Lu, K.; Zhou, W.; Zeng, G.; Zheng, Y. Constrained population extremal optimization-based robust load frequency control of multi-area interconnected power system. Int. J. Elect. Power Energy Syst., 2019, Vol. 105, pp. 249-271, https://doi.org/10.1016/j.ijepes.2018.08.043

[14] Chandrakala K. V.; Balamurugan, S. Simulated annealing based optimal frequency and terminal voltage control of multi-source multi area system. Int. J. Electr Power & Energy Syst., 2016, Vol. 78, pp. 823-829, https://doi.org/10.1016/j.ijepes.2015.12.026

[15] Goud, B. S.; Varma, P. S.; Rao, B. L.; Reddy, M. S. K.; Pandian, A.; Reddy, C. R. Cuckoo search optimization based MPPT for integrated DFIG-wind energy system. in 2020 International Conference on Decision Aid Sciences and Application (DASA), 2020; pp. 636-639, https://doi.org/10.1109/dasa51403.2020.9317072

[16] Arya, Y. Automatic generation control of two-area electrical power systems via optimal fuzzy classical controller. J. Franklin Inst., 2018, Vol. 355, No. 5, pp. 2662-2688. https://doi.org/10.1016/j.jfranklin.2018.02.004

[17] Sahoo, S.; Dash, S. S.; Jena, N. K.; Sahu, B. K.; Patel, N. C.; Bayindir, R. SHO designed fuzzy logic-based controller for AGC study with capacitor energy storage. in 2019 8th International Conference on Renewable Energy Research and Applications (ICRERA), 2019; pp. 845-850, https://doi.org/10.1109/icrera47325.2019.8996533

[18] Moazzami, M.; Ghanbari, M.; Shahinzadeh, H.; Moradi, J.; Gharehpetian, G. B. Application of multi-objective grey wolf algorithm on energy management of microgrids with techno-economic and environmental considerations. in 2018 3rd Conference on Swarm Intelligence and Evolutionary Computation (CSIEC), 2018; pp. 1-9, https://doi.org/10.1109/csiec.2018.8405408

[19] Malar, A.J.G., Kumar, C.A. and Saravanan, A.G., 2020. Iot based sustainable wind green energy for smart cites using fuzzy logic based fractional order darwinian particle swarm optimization. Measurement, 166, p.108208.

[20] Deepa, P., Rajakumar, S., Shermila, P.J., Devi, E.A., Prince, M.E. and Malar, A.J.G., New Hybrid Cuk-Landsman High Gain Dc-Dc Converter Modelling and Analysis. power, 7, p.8.

[21] Sivasankari, B., Shunmugathammal, M., Appathurai, A., & Kavitha, M. (2022). High-Throughput and Power-Efficient Convolutional Neural Network Using One-Pass Processing Elements. Journal of Circuits, Systems and Computers, 31(13), 2250226.https://doi.org/10.1142/S0218126622502267

[22] Z. Bingul and O. Karahan, "A novel performance criterion approach to optimum design of PID controller using cuckoo search algorithm for AVR system," Journal of the Franklin Institute, vol. 355, no. 13, pp. 5534-5559, 2018.

[23] D.-L. Zhang, T. Ying-Gan, and G. Xin-Ping, "Optimum design of fractional order PID controller for an AVR system using an improved artificial bee colony algorithm," Acta Automatica Sinica, vol. 40, no. 5, pp. 973-979, 2014.

[24] A. M. Mosaad, M. A. Attia, and A. Y. Abdelaziz, "Comparative performance analysis of AVR controllers using modern optimization techniques," Electric Power Components and Systems, vol. 46, no. 19-20, pp. 2117-2130, 2018.

[25] J. Bhookya and R. K. Jatoth, "Optimal FOPID/PID controller parameters tuning for the AVR system based on sine–cosine-algorithm," Evolutionary Intelligence, vol. 12, no. 4, pp. 725-733, 2019.

[26] V. Hayyolalam and A. A. P. Kazem, "Black widow optimization algorithm: a novel meta-heuristic approach for solving engineering optimization problems," Engineering Applications of Artificial Intelligence, vol. 87, p. 103249, 2020.

[27] T. H. Mohamed, J. Morel, H. Bevrani, and T. Hiyama, "Model predictive based load frequency control_design concerning wind turbines," International Journal of Electrical Power & Energy Systems, vol. 43, no. 1, pp. 859-867, 2012.

[28] B. Hekimoğlu and S. Ekinci, "Grasshopper optimization algorithm for automatic voltage regulator system," in 2018 5th international conference on electrical and electronic engineering (ICEEE), 2018, pp. 152-156: IEEE.

[29] S. Anbarasi and S. Muralidharan, "Hybrid BFPSO approach for effective tuning of PID controller for load frequency control application in an interconnected power system," Journal of Electrical Engineering and Technology, vol. 12, no. 3, pp. 1027-1037, 2017.

[30] V. Veerasamy et al., "Automatic load frequency control of a multi-area dynamic interconnected power system using a hybrid PSO-GSA-tuned PID controller," Sustainability, vol. 11, no. 24, p. 6908, 2019.

[31] R. Mandal, K. Chatterjee, and B. K. Patil, "Load frequency control of a single area hybrid power system by using integral and LQR based integral controllers," in 2018 20th National Power Systems Conference (NPSC), 2018, pp. 1-6: IEEE.