Available online at www.sciencedirect.com
ScienceDirect

Energy Reports 8 (2022) 493–500

www.elsevier.com/locate/egyr

2021 8th International Conference on Power and Energy Systems Engineering (CPESE 2021),
10–12 September 2021, Fukuoka, Japan

Analysis of GOA optimized two-stage controller for frequency regulation of grid integrated virtual power plant

Ashtabhuj Kumar Srivastava[a], Abdul Latif[a], Subash Chandra Shaoo[a], Dulal Chandra Das[a], S.M. Suhail Hussain[b], Taha Selim Ustun[b],*

[a] *Department of Electrical Engineering, National Institute of Technology Silchar, Assam, India*
[b] *Fukushima Renewable Energy Institute, AIST (FREA), National Institute of Advanced Industrial Science and Technology, Koriyama, Japan*

Received 26 October 2021; accepted 7 November 2021
Available online 26 November 2021

Abstract

Renewable energy has been employed to reduce greenhouse emissions and global warming. VPP is an example of renewable energy integration technology that enables users to tap into unlimited renewable energy supplies while reducing their reliance on traditional power sources. This research looks at a synchronized control grid integrated VPP with parabolic trough solar collector thermal system (PTSCTS), a wind generator (WG), and an electric vehicle (EV). An active power control strategy on an interconnected microgrid in revised form is attempted taking into consideration the communication delay. The proportional integrator derivative (PID) and two-stage (PI)-(1+PD) controllers are used in the proposed control strategy. Firefly algorithm (FA), butterfly optimization algorithm (BOA), particle swarm optimization (PSO), and recent Grasshopper optimization algorithm (GOA) have been used for optimizing the control parameters of the controllers. The analysis shows that the new GOA algorithm performs better in terms of control strategy than other optimization tools such as FA, BOA, and PSO. The sensitivity analysis of the proposed controller under different conditions has been done, and it has been explored that the proposed Two-stage PI-(1 + PD) controller parameters are very robust in dealing with the parametric variations of the integrated VPP model.

Peer-review under responsibility of the scientific committee of the 2021 8th International Conference on Power and Energy Systems Engineering, CPESE, 2021.

Keywords: Parabolic-Trough Solar Thermal Power System (PTSTPS); Virtual power plant (VPP); PI-(1+PD) controller; Communication time delay; Grasshopper Optimization Algorithm (GOA)

---

1. Introduction

Renewable-energy (RE) based distributed generation (DG) structures are gaining extensive popularity. They represent a desirable choice for minimizing the greenhouse effect and enhance the electric power sector's effectiveness and sustainability. For example, DGs provide flexibility to customers, and simultaneously it also helps minimize

---

* Corresponding author.
E-mail address: selim.ustun@aist.go.jp (T.S. Ustun).

https://doi.org/10.1016/j.egyr.2021.11.117

Peer-review under responsibility of the scientific committee of the 2021 8th International Conference on Power and Energy Systems Engineering, CPESE, 2021.

capital required in the traditional power system. The enhanced deployment of RE sources enhances the activities of the prosumers into networks and provides scope for fighting against global warming and minimizing carbon emissions, saving non-renewable fuels [1]. However, different challenges associated with the RE integration, such as difficulties in stabilizing the system, controlling power flow & protecting coordination, have been uncovered [2]. The virtual power plant (VPP) concept has emerged as plausible solution to solve these problems of RE integration. VPP consisting of several components such as generating units, storage units, controllable loads etc. acts as a single entity. The generating units in VPP may be DG units including renewable and conventional dispatchable power units [3]. Generally, VPP works in the grid-tied mode because isolated mode of operation is not be feasible, hence VPP control strategy may be pondered as that of grid-tied microgrid system [4].

In context to the generating units in a VPP, dispatchable units play a key role. Unlike most of renewable generating units, parabolic-trough solar thermal power system (PTSTPS) [5] is a viable technology with dispatchable power capacity. When solar radiance is not available, such as on a gloomy day or at night, the thermal storage capacity of the PTSTPS can provide electricity for more than six hours. The molten salt as heat transfer fluid has certain advantages over synthetic oil for instance, higher operating temperature (480–550 °C), low cost, and heat energy storage for a long time. PTSTPS is a carbon-free and long-term electricity alternative because of these advantages. Many features of PTSTPS technology have been covered in [6]. Many nations are attempting to enhance this technology, which will make PTSTPS an important choice for VPP use.

VPP principles fix problems such as increasing the presence of distributed energy resource (DER) in power systems through the utilization of internet of energy. VPP is more focused on DER technology's software accumulation and can be enforced under existing regulatory frameworks. A VPP will collect data from such small generating stations, collect all single power requirements and deliver it to the power grid as a single entity in terms of power market access and controllability, identical to a considerable traditional power generating unit. Stable auxiliary services are the essential part of the VPP process, and power quality is expected to be adequate to distribute power to customers. While the integration of DGs and storage units by VPPs is likely to play an important role in future energy systems, designing control strategies for efficient working is a difficult job. It happens when dispersed energy supplies are installed in an electrical grid with disorganized manner. It may result in a number of issues, including increased network power losses, inefficient safety mechanism activity, an undesirable voltage profile, and an unbalance between real energy supply and demand.

Recent VPP literature [7–11] emphasizes the need for frequency regulation in electrical network with higher participation of REs. A VPP could meet this demand with a reliable and effective energy management system (EMS) [12]. VPPs based on combined heat and power (CHP), VPPs' elements and designing, VPP with demand response (DR), and VPP intervention in the power market have been discussed in [2]. The frequency regulation procedure of DR is proposed in [7] for a multi-territory power framework. Genetic algorithm is used in this control strategy with the inclusion of automatic generation control parameters as well as the DR control parameters, which improves the performance of the control system. In [8], fine-tuning of PID-based load frequency control (LFC) for independent hybrid microgrid system (HμGS) has been routed to improve the dynamic response. A social-spider optimizer (SSO) has been applied to create PID controllers' ideal settings in different scenarios such as load variations, varieties in wind speed, and solar irradiance. The transmission of cyber signals, which impose substantial communication delays, necessitates a public communication network. As a result, during the design of the VPP model, such communication delays cannot be avoided. Therefore, in VPP model an appropriate communication delay need to set before the adjusting action started to regulate the power imbalance which is not yet been explored.

In the meantime, work has focused on optimization approaches and control methods for microgrid/interconnected systems. So many optimization methods have been investigated, including the firefly algorithm (FA) [13], particle swarm optimization (PSO) [14], and butterfly optimization algorithm (BOA) [15]. The grasshopper optimization algorithm (GOA) [16] has been recently stated to have greater features in solving many engineering problems. Application of GOA worth investigating in obtaining optimum control parameters to address frequency regulation problem of the VPP system which is not yet is been utilized.

Based on the above discussion, the current study investigates the likelihood that the access control strategy on interconnected microgrids [17] can be utilized to coordinate VPP in the presence of DERs. The detailed contribution of the paper are discussed as follows:

(1) To develop and model a grid tied VPP integrating PTSTPS, WG, EV for frequency control operation in MATLAB simulation platform.

(2) To design and access the control strategy on an interconnected microgrid, taking into consideration of communication delay in frequency response VPP model.
(3) To verify the optimality of proposed two-stage PI-(1 + PD) controller and optimization technique by comparing the system dynamic responses and objective function.
(4) To validate the robustness of the optimal PI-(1 + PD) controller using sensitivity analysis by subjecting the nominal system through different system parametric variations.

The progression of the paper can be portrayed as: after introduction, Section 2 presents the modeling of the RE-based examined VPP and the idea of objective function formulation. Section 3 shows the simulation consequences of the proposed control strategy and analyzed the dynamic responses. Finally, it sums up the fundamental ends in Section 4.

2. DERs modeling in VPP and objective problem formulation

The schematic structure of the proposed grid integrated virtual power plant is represented in Fig. 1. Different types of DER, such as PTSTPS [18], EV [19], and WG [18], are classified as area 1, while non-reheat turbines [19] are classified as area 2. Table 1 shows the terminologies with numeric values of model parameter which are used in this work.

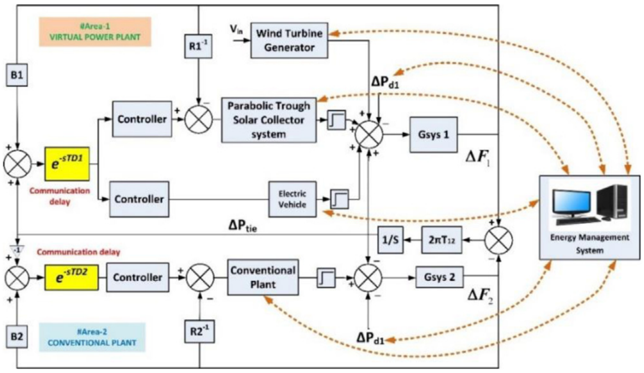


Fig. 1. Schematic of the proposed VPP system.

Table 1. List of nomenclature and value.

Terminology		Value
R1, R2	Speed regulation quantity of area-1 and 2	2.4 Hz/p.u MW
B1, B2	Biasing constant of area-1 and 2	0.429, 0.424
Gsys1, Gsys2	System characteristics	1, 120
M1, M2	Moment of inertia of the area-1 and 2	0.2 s, 0.166 s
D1, D2	Damping constant of the area-1 and 2	0.012, 0.008 (p.u MW/Hz)
Tc1, Tc2	Time delay of area-1 & area-2.	1.2 s, 1 s
T_{12}	Tie-line coefficient of area-1 & 2	0.07

2.1. Information and Communication Technology (ICT)

VPP and ICT's heart is energy management system (EMS) that deals with the activity of other VPP parts such as power flow coming from the generating units, flexible loads, and storage by communication technologies in bidirectional ways. EMS is featured by sending signals that manage the generation & demand pattern for every generating unit, consumption unit. EMS controls the system ideally, depending on the energy demand, weather situation, and storage capacity. Two types of communication technologies are used in VPP, one is wired, and the other is wireless. Wired communication technologies are Power Line Communication, Twisted Pair, and Optical Fiber. Wireless communication technologies are Satellite Communication, Cellular Communication, ZigBee, Wireless Local Area Network (WLAN), and Wireless Mesh e Z-Wave. In any kind of communication technology there exists some delay for receiving and transmitting the data over an ICT network, called communication delay. Communication delays cannot be ignored because they may cause instability in the microgrid and VPP [20].

In the VPP model, the communication time delay (Tc) is made up of two components. The power profile data of each VPP portion is gathered and guided towards the energy management system during the first part of the communication time delay (EMS). When the EMS issues a generation control instruction, the second part of the communication time delay occurs. The VPP components begin to respond to the generation dispatch instruction. The communication time delay has significant impacts on the VPP operation's stability & reliability. The transfer function model of communication delay e^{-sT_c} using PedeIst order approximation (7) [21] is represented in the following form: where T_c is delay margin.

$$e^{-sT_c} = \{-0.5\, sT_c + 1\}/\{-0.5\, sT_c + 1\} \tag{1}$$

2.2. Power and frequency deviation

The grid operator must keep the operating frequency within the allowable frequency bandwidth as demand and supply requirements change to satisfy customers' high-quality power needs. The frequency can be regulated by achieving the desired active power balance between supply and consumption. As a result, the system transfer function model can be expressed mathematically as (2) [18]. The parameters are defined in Table 1.

$$G_{SYS} = \frac{\Delta F}{\Delta P_e} = \left(\frac{1}{K_{SYS} + (1 + sT_{SYS})}\right) = \frac{1}{Ms + D} \tag{2}$$

2.3. Objective problem formation (J)

The control strategy employed for VPP aims to maintain a generation and demand balance regardless of random power generation by RE sources. VPP, in combination with ICT and an effective control technique, restricts the power mismatch in this way. The objective function to be minimized here is an integral squared error (ISE) of the frequency deviation of the VPP model and the tie-line power, as expressed below:

$$Minimize;\ J_{ISE} = \int_0^{t_{sim}} \left[(\Delta F_1)^2 + (\Delta P_{tie})^2 + (\Delta F_2)^2\right].dt \tag{3}$$

Since power systems are fundamentally non-linear, fine-tuning the controller's parameters is a difficult job. As a result, simultaneous tuning of controller parameters is a popular topic in research. The PID and Two-stage PI-(1 + PD) controller's gains are optimized using common optimization tools such as PSO, FA, BOA, and, more recently developed, GOA to analyze the proposed system responses in the presence of communication time delay attacks. The values of the considered parameters of optimization techniques are depicted in Appendix.

3. Simulation results and analysis

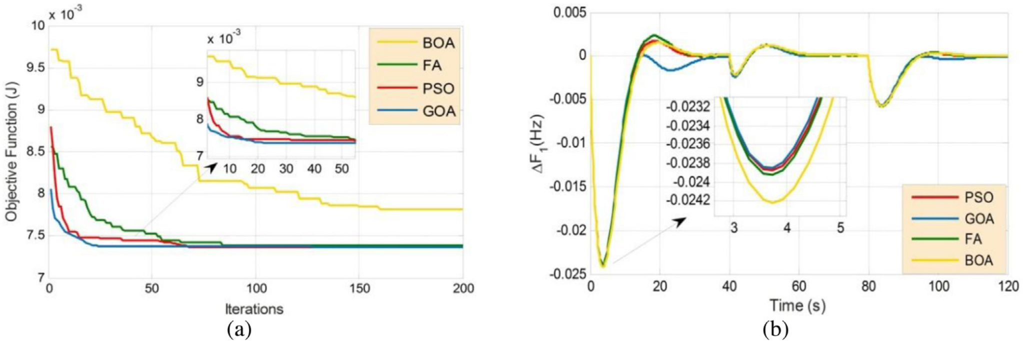
The current VPP system model, shown in Fig. 1, is simulated in the MATLAB platform to analyze system performance changes under various operating conditions, discussed in the following subsections.

3.1. Case 1: Performance comparison of the VPP model with PSO, FA, BOA and GOA optimized controller

In this case study, the VPP model is employed with PID controller and the optimum control parameters are obtained using meta-heuristic algorithms viz FA, PSO, BOA, and the recently developed GOA. The operating conditions as mentioned in Table 2 is applied for assessing the performance of the model. The convergence curve for FA, PSO, BOA, and GOA optimized PID controller are illustrated in Fig. 2(a). The plot of convergence curves indicates that the performance of GOA in minimizing the objective function and hence providing the optimum controller parameters is superior over FA, BOA, and PSO. Further, frequency deviation in area-1 ΔF_1 is presented in Fig. 2(b) also confirm the superiority of GOA. In view of this, other case studies are carried out considering GOA.

Table 2. Simulation conditions for different cases.

Cases	System components	Simulation time (s)	Operating condition
Case-1: Performance comparison of the model with PSO, FA, BOA and GOA optimized controller.	PTSTPS, WG, SG, EV and load	120	PWG $= 0.01$ p.u. at $0 < t < 40$ s $= 0.02$ p.u. at $t > 40$ s Pd1 $= 0.05$ p.u. at $0 < t < 40$ s $= 0.06$ p.u. at $40 < t < 80$ s $= 0.07$ p.u. at $t > 80$ s Area-1 Tc1=1.2 s; Area-2 Tc2 = 1 s
Case-2: Performance comparison of PID and (PI)-(1+PD) controller on the model.			
Case-3 Sensitivity analysis of the model with change in Load, Wind gain, and Biasing constant.			Load change of ±5%, ±10%, ±15% of nominal value for $0 \le t \le 40$. Different $K_{\mathrm{WG}} = 0.9, 0.7, 0.5, 0.3, 0.1$ B1 change by ±10%, ±20%, ±30% of the nominal value.

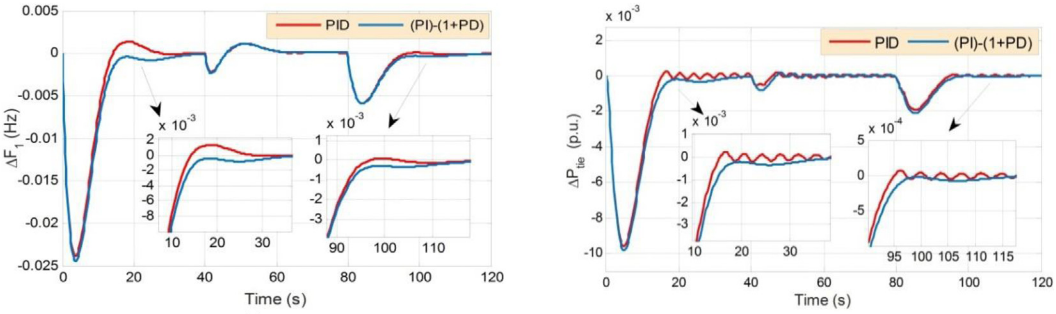


(a) (b)

Fig. 2. (a) Convergence curves of FA, PSO, BOA, and GOA (b) ΔF_1 under FA, PSO, BOA, and GOA.

3.2. Case 2: Dynamic performance study of the model using PID and (PI)-(1 + PD) control strategy

This study is devoted to comparative performance of the PID and (PI)-(1 + PD) controller in arresting frequency fluctuation following disturbances as mentioned in Table 1. The dynamic performance analysis in terms of frequency variations of area 1 and tie-line power are presented in Fig. 3(a) and (b). The parameters of the PID and PI-(1 + PD) controller were optimized using GOA. The responses of PID controlled system and the two-stage (PI)-(1 + PD) controlled system are very close to each other. However, performance of two-stage (PI)-(1 + PD) controller is little better in terms of peak overshoot and oscillations.

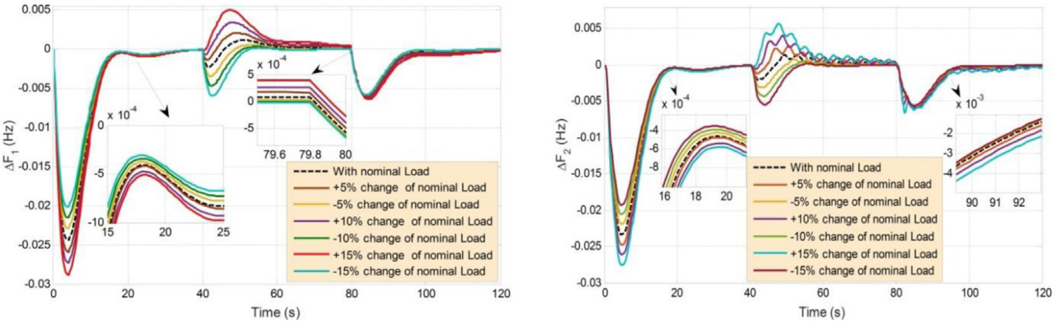


(a) (b)

Fig. 3. (a) ΔF_1 for PID and (PI)-(1 + PD), (b) ΔP_{tie} for PID and (PI)-(1 + PD).

3.3. Case 3: Sensitivity analysis of Two-stage PI-(1 + PD) controller with change in Load, Wind gain, and Biasing constant of area-1 (B1)

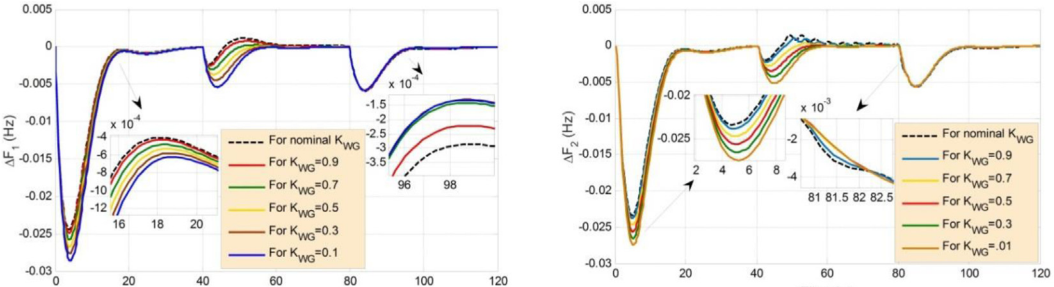
In order to establish the sturdiness of the proposed control mechanism employed with GOA tuned Two-stage PI-(1 + PD) controller, sensitivity analyzes have been carried out. The control parameters obtained in Case 1 are used to assess the robustness of the Two-stage PI-(1 + PD) controller following significant changes in the loading conditions, wind power variations and biasing constant of area 1. At the beginning load variations such as ±5%, ±10% and ±15% of the base value have been attempted and responses in terms of frequency deviations (of area 1 and 2) are presented in Fig. 4(a) and (b). Results obtained in this study indicate that changes in load as large as ±15% do not cause much change in the frequency deviation and tie-line power as compared to base case condition.



(a) (b)

Fig. 4. (a) ΔF1 with change in nominal load (b) ΔF2 with change in nominal load.

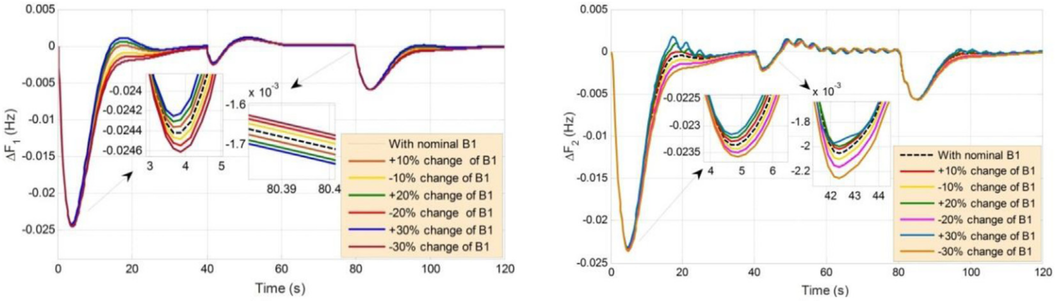
Secondly, wind power variations incorporating gains values such as 0.1, 0.3, 0.5, 0.7, 0.9 times base values have been attempted and responses in terms of frequency deviations of area 1 and 2 compared with that of the corresponding values obtained using base values. Results are presented in Fig. 5(a) and (b) respectively. In this case also, there are no significant changes observed in the system dynamic due to changes in wind power variations. Finally, variations of biasing constant of area 1 by ±10%, ±20% and ±30% of the base values have been attempted. Variations in frequency fluctuations of area 1 and 2 of the VPP model due to these significant biasing variations are compared with the base values as shown in Fig. 6(a), (b) and (c). Results show that deviation in the system dynamic due to variations in the biasing constant in area 1 is insignificant.



(a) (b)

Fig. 5. (a) ΔF_1 with change in Wind gain (b) ΔF_2 with change in Wind gain.

The sturdiness in terms of performance indicators such as peak overshoot and settling time as observed in Figs. 4–6 indicate that following disturbance conditions, the system performance would not differ much from nominal conditions. Finally, it can be concluded that the tuned PI-(1 + PD) control parameters are very robust in dealing with uncertainties occurring in the integrated VPP model.



(a)

(b)

Fig. 6. (a) ΔF_1 with change in nominal B1 (b) ΔF_2 with change in nominal B1.

4. Conclusion

This work investigates a potential control strategy for VPP in incorporation with communication delays in containing grid frequency. The proposed VPP structure consists of PTSTPS, WG, and EV in grid integrated mode. The MATLAB Simulation software is used to build the proposed VPP model and maiden attempt has been made to analyze and estimate system dynamics of the VPP model employed with Two-stage PI-(1 + PD) controller. GOA, a recently developed metaheuristic algorithm is applied to obtain the optimum parameters of PI-(1 + PD) controller employed with VPP model. The analysis shows that the GOA algorithm performs better in acquiring optimum values control parameters for the proposed control strategy as compared to other optimization algorithms such as FA, BOA, and PSO. Further, performance of the proposed GOA optimized PI-(1 + PD) controller is observed superior to PID counterpart. A thorough sensitivity analysis of GOA tuned PI-(1 + PD) controller revealed that the optimal control parameters obtained under base condition are quite robust and hence performance of the VPP model remains stable following changes in loading conditions, biasing constant of area 1 and wind power respectively. Therefore, it can be concluded that the proposed PI-(1 + PD) controller can be used for maintaining stable dynamic operation of the VPP.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

BOA: Population size = 50, Max iterations = 200, P = 0.8, Power exponent = 0.1, Sensor modality = 0.01.

FA: No of fireflies = 50, Max iterations 200, Attractiveness = 0.20, Randomness 0.25, Absorption coefficient = 1.

PSO: Population size = 50, Max iterations = 200, Wmax = 1 & Wmin = 0.99, C1 = 1.5, C2 = 2.

GOA: Population size = 50, $C_{\text{Max}} = 1$; $C_{\text{Min}} = 0.00004$, Max iterations = 200, f = 0.5; L = 1.5.

References

[1] Hussain SMS, Nadeem F, Aftab MA, Ali I, Ustun TS. The emerging energy internet: Architecture, benefits, challenges, and future prospects. Electronics 2019;8(9):1037.
[2] Ghavidel S, Li L, Aghaei J, Yu T, Zhu J. A review on the virtual power plant: Components and operation systems. In: 2016 IEEE international conference on power system technology (POWERCON). 2016.
[3] Nadeem F, Aftab MA, Hussain SMS, Ali I, Tiwari PK, Goswami AK, Ustun TS. Virtual power plant management in smart grids with XMPP based IEC 61850 communication. Energies 2019;12(12):2398.
[4] Ustun TS, Ozansoy C, Zayegh A. Recent developments in microgrids and example cases around the world—A review. Renew Sustain Energy Rev 2011;15(8):4030–41.
[5] Zarza E, Valenzuela L, Leon J. Solar thermal power plants with parabolic-trough collectors. ESA, Co-sponsored by Ministerio de Ciencia y Tecnologia, Ciemat, USEF, CDTI, EADS Space Transportation, DLR; 2004.

[6] Kopp Joseph E. Two-tank indirect thermal storage designs for solar parabolic trough power plants. In: UNLV Theses, Dissertations, Professional papers, and capstones. 2009.

[7] Yu-Qing Bao, Yang Li, Beibei Wang, Minqiang Hu, Peipei Chen. Demand response for frequency control of multi-area power system. J Mod Power Syst Clean Energy 2017;5.

[8] Fergany Attia A, El-Hameed Mohammed A. Efficient frequency controllers for autonomous two-area hybrid microgrid system using social-spider optimiser. IET Gener Transm Distrib 2017;11.

[9] Rotger-Griful Sergi. Virtual power plant for residential demand response. In: Technical report electronics and computer engineering. 2015.

[10] Liu Yun, Xin Huanhai, Wang Zhen, Gan Deqiang. Control of virtual power plant in microgrids: a coordinated approach based on photovoltaic systems and controllable loads. IET Gener Transm Distrib 2015;9.

[11] Dominguez Xavier, Pozo Marcelo, Gallardo Carlos, Ortega Leonardo. Active power control of a virtual power plant. In: 2016 IEEE ecuador technical chapters meeting (ETCM).

[12] Obaid ZA, Cipcigan LM, Abrahim L, Muhssin MT. Frequency control of future power systems: reviewing and evaluating challenges and new control methods. J Mod Power Syst 2018;7(9):17.

[13] Hussain I, Das DC, Sinha N, Latif A, Hussain SMS, Ustun TS. Performance assessment of an islanded hybrid power system with different storage combinations using an FPA-tuned two-degree-of-freedom (2DOF) controller. Energies 13(21):5610.

[14] Kennedy J, Eberhart RC. Particle swarm optimization. In: IEEE international conference on neural networks. 1995, p. 1942–8.

[15] Dey PP, Das DC, Latif A, Hussain SMS, Ustun TS. Active power Management of Virtual Power Plant under penetration of central receiver solar thermal-wind using butterfly optimization technique. Sustainability 2020;12(17):69–79.

[16] Latif A, Das DC, Hussain SMS, Ustun TS. Double stage controller optimization for load frequency stabilization in hybrid wind-ocean wave energy based maritime microgrid system. Appl Energy 2021;282:116–71.

[17] Wang X, et al. Load frequency control in multiple microgrids based on model predictive control with communication delay. In: 6th international conference on renewable power generation (RPG). 2017, p. 1–6.

[18] Ranjan S, Das DC, Behera S, Sinha N. Parabolic trough solar–thermal–wind–diesel isolated hybrid power system: active power/frequency control analysis. IET Renew Power Gener 2018;12(16):1893–903.

[19] Khezri R, Oshnoei A, Hagh MT, Muyeen SM. Coordination of heat pumps, electric vehicles and AGC for efficient LFC in a smart hybrid power system via SCA-based optimized FOPID controllers. Energies 2018;11:420.

[20] Jesintha Mary T, Parthasarathy R. Delay dependent stability analysis of microgrid with constant and time-varying communication delays. Electr Power Compon Syst 2016;44.

[21] Wu H, Ni H, Heydt GT. The impact of time delay on robust control design in power systems. In: IEEE power engineering society winter meeting, Vol. 2. Tempe, AZ USA; 2002, p. 1–6.