

EFFICIENT ACTIVE POWER ALLOCATION IN MICROGRID-INTEGRATED VIRTUAL POWER PLANTS USING SALP SWARM ALGORITHM

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Abstract

The increasing reliance on renewable energy sources (RES) introduces challenges in power system stability due to the inherent variability and intermittency of these sources. Microgrid-integrated virtual power plants (VPPs) offer a promising solution by aggregating diverse energy resources and controllable loads while working as an entity. This study investigates an optimized control strategy for regulating active power within such a system. The proposed hybrid microgrid comprises Solar Photovoltaics (PV), Wind Turbines, Diesel Generators, and controllable loads such as Hybrid Electric Vehicles (HEVs) and Heat Pumps. Utilising a Proportional-Integral-Derivative (PID) controller, optimised through the Salp Swarm Algorithm (SSA) and Particle Swarm Optimization (PSO), the study demonstrates improved system stability and response to power fluctuations. Comparative analysis confirms the superiority of the SSA-based control mechanism over the PSO-based approach. This work underscores the robustness and efficiency of the proposed strategy in ensuring stable power management in dynamic microgrid environments.

Keywords: Active Power Regulation; Dynamic Power Management; Frequency Stability; Hybrid Microgrid; Renewable Energy; Salp Swarm Algorithm (SSA); Virtual Power Plant (VPP)

Introduction

The reduction of carbon dioxide (CO₂) emissions and the subsequent mitigation of global warming, along with the identification of sustainable energy sources, are among the foremost challenges of our time. Recent data indicates that global CO₂ emissions rose 2.1% in 2017 alone (Greer *et al.*, 2019). Renewable energy sources (RES) such as solar and wind power have considerable potential to

address these concerns due to their sustainability and eco-friendly characteristics. However, the variability and intermittency of these sources, which are heavily influenced by environmental conditions, pose significant challenges to maintaining power system stability (Roy, 2016). Fluctuations in power output can lead to voltage and frequency instability, which complicates their integration into the existing

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power grid. A promising solution to these challenges is the concept of a Virtual Power Plant (VPP) (Yavuz *et al.*, 2019). A VPP integrates a diverse range of energy resources-including renewable energy sources, energy storage systems, and controllable loads-into a single, flexible entity capable of participating in energy markets and providing grid services (Roy *et al.*, 2024). By aggregating multiple small-scale generation units and controllable loads, a VPP can enhance the reliability and predictability of renewable energy output, effectively smoothing out fluctuations and supporting grid stability (Ullah *et al.*, 2019). However, VPPs require sophisticated Information and Communication Technology (ICT) infrastructure to manage and optimise these resources efficiently. This ICT framework is essential for real-time monitoring and control of energy production and consumption, enabling active participation in energy markets and providing ancillary services to the grid.

Despite the potential advantages of VPPs, more specific control strategies still need to be tailored to their unique characteristics. Existing secondary control strategies used in microgrid management (Roy *et al.*, 2023) can be adapted for VPPs. However, they may need to fully address the complexities of integrating diverse energy resources on a larger scale. To explore these issues, this work focuses on a microgrid-integrated VPP where the control strategy involves dynamically adjusting the aggregated power output to maintain system frequency within desired limits. Simulations were conducted to evaluate the VPP's ability to provide frequency support to an interconnected microgrid, demonstrating that such hybrid systems combining both renewable and non-renewable sources are particularly suitable for remote areas where conventional grid electricity is inaccessible or uneconomical.

Designing and implementing hybrid power systems presents various challenges, particularly in voltage and frequency control as well as power quality management (Bajaj and Singh, 2019). Maintaining stable voltage and frequency levels is critical for ensuring effective power dispatch to consumers, making these parameters a priority in the design and operation of Virtual Power Plants (VPPs). A review of existing literature (Ryu and Kim, 2022) highlights the pressing need for enhanced control strategies to regulate frequency within VPPs and sustain overall system stability. For example, some studies (Datta *et al.*, 2020; Chen *et al.*, 2021; Zhao *et al.*, 2021) highlight how VPPs enable flexible loads to contribute to the balance between energy production and consumption over various timeframes, thereby enhancing grid stability. Others (Al-Shetwi *et al.*, 2020; Mishra *et al.*, 2022;

Mohamed *et al.*, 2022) demonstrate how novel distributed coordination algorithms can empower smaller generation units or loads to participate in secondary frequency control, thus contributing to system-wide frequency stabilization. Generally, VPPs rely on advanced optimization tools to manage frequency fluctuations effectively (Fernández-Guillamón *et al.*, 2019; Zhong *et al.*, 2021). The current research focuses on the frequency control of a hybrid microgrid operating in an interconnected mode using a mini VPP. This system comprises various renewable and non-renewable energy sources, such as solar photovoltaic (SPV) systems (Das *et al.*, 2012), wind turbines (WTG) (Das and Pal, 2011), and diesel generators (DIESEL) (Bhatt *et al.*, 2010), along with critical loads and controllable loads, including heat pumps (HP) and plug-in hybrid electric vehicles (PHEVs) (Khezri *et al.*, 2018). The proposed controller uses a PID controller, optimized by SSA and PSO algorithms, to continuously monitor system frequency and adjust the power consumption of controllable loads.

The objectives of this study are twofold:

1. To develop a coordinated control mechanism for generating units within a grid-connected hybrid microgrid. This includes SPV systems, WTGs, diesel generators, critical loads, and controllable loads like HPs and PHEVs aimed at maintaining stable system frequency.
2. To assess the robustness of the proposed control strategy by conducting sensitivity analyses of the controller gains under varying conditions, such as random changes in critical loads, SPV output, and wind turbine generation.

This research highlights the critical role of coordinated control strategies in ensuring the stability and reliability of hybrid microgrids integrated into VPPs. By effectively managing the diverse energy resources within a VPP, it is possible to mitigate the inherent variability of renewable energy sources, maintain grid stability, and contribute to the global effort of reducing CO₂ emissions and combating climate change. The findings highlight the need for customised control strategies and optimised integration of renewable energy to ensure a sustainable and resilient power system.

Literature Review

Recent advancements in Virtual Power Plants (VPPs) and hybrid microgrid systems have highlighted the need for robust solutions to address

challenges related to renewable energy integration and frequency stability. (Makolo *et al.*, 2021) Discussed inertia and frequency control strategies for high-renewable systems, showcasing the value of adaptive techniques to maintain grid stability. However, their reliance on traditional PID controllers limits their effectiveness under large-scale uncertainties. (Gao *et al.*, 2024) A VPP operation strategy was proposed to emphasise market participation through demand response, but a detailed focus on frequency control mechanisms in dynamic environments is needed. Zhong *et al.* (2021) introduced coordinated control techniques to improve short-term dynamics in VPPs, but the potential of advanced metaheuristic algorithms for optimisation is still being explored. (Abdulla *et al.*, 2024) examined grid compliance of PV systems and their impact on power quality management; however, their study needed to address the complexities of hybrid systems involving diverse energy sources and controllable loads. (Yuvaraj *et al.*, 2024) focused on resilience planning for VPPs with integrated energy systems, offering significant insights into infrastructure resilience but neglecting real-time control strategies to handle power fluctuations effectively. While these studies present valuable contributions, they share notable limitations, including a lack of focus on dynamic frequency control in hybrid microgrids, insufficient use of advanced metaheuristic algorithms such as the Salp Swarm Algorithm (SSA), and inadequate integration of controllable loads like hybrid electric vehicles (HEVs) for grid support. This study's proposed SSA-optimized PID controller addresses these gaps by offering enhanced frequency stability and robust power management under dynamic conditions. By incorporating HEVs and heat pumps as controllable loads, the model ensures scalability and adaptability to varying load and generation scenarios, providing a more comprehensive solution. This work contributes significantly by introducing an SSA-based control strategy tailored for hybrid microgrids, effectively overcoming the limitations of existing methods and advancing state-of-the-art VPP optimisation and dynamic power regulation.

Proposed Control Strategy

VPP is a coordinated system combining multiple Distributed Energy Resources (DERs), microgrids, and controllable and critical loads, leveraging sophisticated communication technologies and software for efficient energy management. The primary role of a VPP is to manage, regulate, and supervise energy flow within its network and its

connection to the primary grid. VPPs are divided into two types according to their functions: Technical Virtual Power Plants (TVPPs) and Commercial Virtual Power Plants (CVPPs) (Das, 2017). A TVPP primarily provides technical support to the grid, including frequency regulation, voltage control, and ensuring power quality. In contrast, a CVPP deals with market-related activities, such as trading and optimising the economic benefits of DERs. The central entity responsible for managing these activities within a VPP is the VPP Coordinator, whose primary responsibility is to oversee the active power set points of all DERs and ensure a balance between supply and demand. The VPP Coordinator achieves this by interfacing with the Point of Common Coupling (PCC), which connects the microgrid to the primary grid. The VPP Coordinator calculates the required adjustments to maintain grid stability by monitoring power flows at the PCC.

Two primary control methods for VPPs are proposed: Direct Control and Market-Based Control (Shukla *et al.*, 2021). In the Direct Control method, the VPP Coordinator directly determines the necessary power adjustments for each unit within the microgrid and communicates these changes to all units. This method grants the VPP Coordinator complete control over the DER portfolio, and the overall system efficiency is directly linked to the coordinator's decision-making capabilities. The Market-Based Control method operates differently, as the VPP Coordinator sends price signals to DERs through a VPP market or accepts bids from DERs (He *et al.*, 2021). Here, each DER determines the power adjustments locally to maximise their profit without direct control from the VPP Coordinator. Instead, the coordinator indirectly influences the DERs by adjusting the incentives, making this a decentralised approach. Both control methods require two-way communication, intelligent decision-making, and significant computational resources. However, this study focuses solely on the Direct Control method, which ensures a higher level of centralised control and coordination, optimising grid stability and performance.

Microgrid System Components and Modelling

As the global demand for clean energy continues to rise exponentially, solar photovoltaic (PV) technology (Das *et al.*, 2012) has naturally emerged as a key player in meeting this growing need. In the future, Solar PV is anticipated to be among the most reliable renewable energy sources for delivering clean and sustainable power. Within this hybrid

microgrid system, the first-order transfer function of solar PV (Das *et al.*, 2012) is used to fulfill the system's energy demand.

$$G_{PV} = \frac{K_{PV}}{1+sT_{PV}} \quad (1)$$

Wind energy is another form of clean energy source from which we can extract power with the help of a wind turbine (Das and Pal, 2011); the characteristic of the wind turbine is explained in the form of the first order transfer function (2) (Das and Pal, 2011) which has taken in the hybrid microgrid system.

$$G_{WTG}(s) = \frac{K_{WTG}}{1+sT_{WTG}} \quad (2)$$

The plug-in hybrid electric vehicle is one of the most promising technologies for tackling the problem regarding CO-2 emission during transportation, and it also supports microgrids during frequency variation. During idle periods, a PHEV is connected to the microgrid to manage active and reactive power from the vehicle and its internal capacitor to the grid. The use of PHEV for frequency regulation is explored in (Khezri *et al.*, 2018), with its transfer function provided in equation (3).

$$G_{PHEV} = \frac{K_{PHEV}}{1+sT_{PHEV}} \quad (3)$$

Another controllable load within the system is the heat pump, which serves as a source of hot water for residential use and provides frequency support in the microgrid (Khezri *et al.*, 2018). The heat pump uses a compressor to circulate heat mixed with a refrigerant. The mixture is then routed to a location where the surrounding environment absorbs the heat. The refrigerant evaporates at low pressure as it flows through the heat exchanger coils (Das, 2017). The heat pump's performance is described by the transfer function in equation (4) (Khezri *et al.*, 2018).

$$G_{HP}(s) = \frac{K_{HP}}{1+sT_{HP}} \quad (4)$$

To ensure a continuous power supply in the event that one or more generating units in the hybrid microgrid are unavailable (Bhatt *et al.*, 2010), A diesel generator serves as a backup unit, with a synchronous generator connected to a diesel engine to generate electrical power. The diesel generator is a controllable unit within the system. Its behaviour is characterised by the transfer function provided in equation (5) (Bhatt *et al.*, 2010).

$$G_{DIESEL} = \frac{sK_{DIESEL} + K_{DIESEL}}{s^2(1/40) + s} \quad (5)$$

Where, K_{PV} , K_{HTG} , K_{PHEV} , and K_{DIESEL} are the gains of the PV, WTG, PHEV, HP, and DIESEL respectively. Meanwhile, T_{PV} , T_{WTG} , T_{PHEV} , and T_{HP} are the time constants of PV, WTG, PHEV, and HP. The parameter values are collected from relevant papers (Bhatt *et al.*, 2010; Das and Pal, 2011; Das *et al.*, 2012; Khezri *et al.*, 2018) and given in Table 1.

Table 1. System Parameters

Generating Units	Gains	Time Constants (s)
Solar PV	$K_{PV} = 1$	$T_{PV} = 1.8$
WTG	$K_{WTG} = 1$	$T_{WTG} = 1.5$
PHEV	$K_{PHEV} = 1$	$T_{PHEV} = 0.15$
HP	$K_{HP} = -1$	$T_{HP} = 0.1$
DIESEL	-	$T_{DIESEL} = 16.5$
Damping Constant	$D = 0.012$ p.u MW sec/Hz	
Inertia Constant	$M = 0.2$ p. u. MW/Hz	
Load Machine	$K_p = 120$	$T_p = 20$
Turbine	-	$T_T = 0.3$
Governor	-	$T_G = 0.08$
Droop constant	$R = 2.4$ Hz/p.u. MW	
Frequency bias coefficient	$B_1 = B_2 = 0.429$	
Synchronizing coefficient	$T_{12} = 0.08$	

To ensure system stability, active power generation must match active power consumption. The difference between power generation and load demand (ΔP_e) is expressed in equation (6).

$$\Delta P_e = P_{GEN} - P_{Load} \quad (6)$$

Where P_{GEN} is the active power generation and P_{Load} active power demand. This variation in power leads to a change in frequency (Δf), which is given by (7)

$$\Delta f = \frac{\Delta P_e}{K_{sys}} \quad (7)$$

Where K_{sys} is the power system constant (Shukla *et al.*, 2021). In real-time situations, a time lag has been observed between changes in system frequency and power mismatch. The transfer function of the power system, shown in Figure 1, can be expressed as equation (8), as stated below (He *et al.*, 2021).

$$G_{SIS}(s) = \frac{\Delta f}{\Delta P_e} = \frac{1}{K_{SIS}(sT_{SIS} + 1)} = \frac{1}{Ms + D} \quad (8)$$

Where T_{sys} is the power time constant, M is the inertia constant, and D is the damping factor (He *et al.*, 2021).

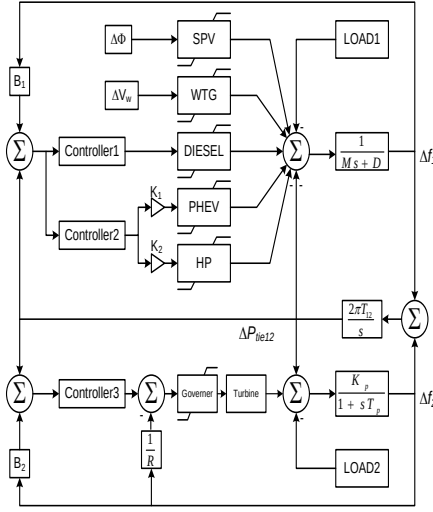


Figure 1. Symmetric diagram of an interconnected microgrid with the primary grid system

The microgrid is connected through the non-reheat turbine, which is flexible and efficient. It has three main parts represented by the transfer function (Shami *et al.*, 2022).

(a) Governor with dynamics (9)

$$G_G(s) = \frac{1}{1+sT_G} \quad (9)$$

(b) Turbine with dynamics (10)

$$G_T(s) = \frac{1}{1+sT_T} \quad (10)$$

(c) Load and machine with dynamics (11)

$$G_P(s) = \frac{K_P}{1+sT_P} \quad (11)$$

The objective function (12) is minimized by taking the integral of the squared error (ISE) of the frequency deviation in the hybrid microgrid, the tie-line power, and the frequency deviation of the primary grid.

$$J = \int_0^\infty ((\Delta f_1)^2 + (\Delta p_{tz})^2 + (\Delta f_2)^2) dt \quad (12)$$

It is subject to

$$K_p^{\min} \leq K_p \leq K_p^{\max} \quad (13)$$

$$K_l^{\min} \leq K_l \leq K_l^{\max} \quad (14)$$

$$K_D^{\min} \leq K_D \leq K_D^{\max} \quad (15)$$

Where K_p , K_l and K_D (13-15) are the parameters of the PID controller. By using the old and tested optimization technique PSO (Gad, 2022) and recent SSA, the PID controller's gain is optimized.

Salp Swarm Algorithm

Salps are barrel-shaped planktonic tunicates that often form large groups, known as salp chains, in the deep sea to enhance their movement through rapid, synchronised changes and efficient foraging (Barik and Das, 2018; Salgotra *et al.*, 2022). This collective behaviour of salp chains has been mathematically modelled as the Salp Swarm Algorithm (SSA) by S. Mirjalili (Salgotra *et al.*, 2022), which divides the salps into two groups. The salps leading the chain guide the swarm while the followers trail behind, moving in sequence around the food source based on the leader's direction. The SSA algorithm's detailed procedures are illustrated in the flowchart in Figure 2, which includes a swarm of salps with N search agents, d dimensions, and specified upper and lower bounds (lb and ub).

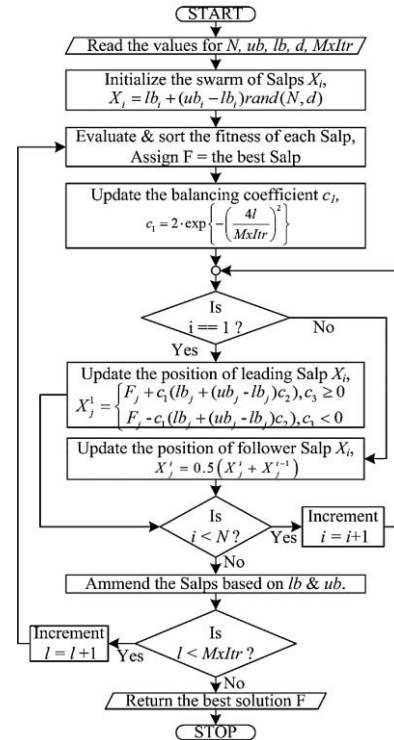


Figure 2. Flowchart for SSA

SSA was introduced to study the optimal load frequency responses in isolated microgrids by tuning PID controllers, which outperformed PSO, as reported by (Barik and Das, 2018). The algorithm optimises the proposed model by tuning the PID

controller gains within specified upper and lower limits. Table 2 lists the key parameters for both Particle Swarm Optimization (PSO) and Salp Swarm Algorithm (SSA). The PID controller gains, optimised for effective frequency control of the proposed VPP using both PSO and SSA, are shown in Table 3.

Table 2. Parameters of SSA and PSO

SSA Parameters	Value	PSO Parameters	Value
Maximum Iteration	100	Maximum Iteration	100
Population size	25	Population size	25
C2	rand	w, wd	0.9, 0.99
C3	rand	C1, C2	1.5, 2

Table 3. Comparative PID controller's Gain

Controller Gains	SSA	PSO
K_{p1}	9.9	4.3
K_{i1}	0.0001	0.001
K_{d1}	29	31.99
K_{p2}	38.96	32
K_{i2}	37.2	32
K_{d2}	0.009	7.08
K_{p3}	27.33	27.8
K_{i3}	1.85	10.06
K_{d3}	23.39	28.16
K_1	0.96	0.99
K_2	0.002	0.01

Results and Discussion

Case - 1

The proposed system, featuring an interconnected hybrid microgrid as illustrated in Figure 1, is modelled and simulated on the MATLAB platform to analyse responses to variations in critical loadings, as depicted in Figure 3.

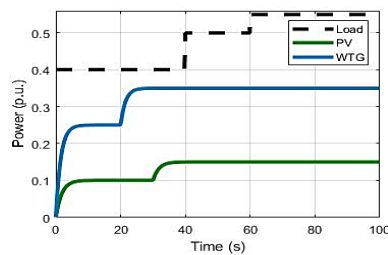


Figure 3. PSPV, PWTG, and Critical Load

As depicted in Figure 3, the initial critical load demand is 0.4 p.u. at 0s, increasing to 0.5 p.u. by 40s, and further rising to 0.55 p.u. at 60s, which remains constant until 100s. The SPV unit produces 0.1 p.u. of power for the first 30s, which then increases to 0.15 p.u. from 30s to 100s. The WTG unit generates 0.25 p.u. during the initial 20s, rising to 0.35 p.u. from 20s to 100s.

During the initial 20s, the critical load demand exceeds the combined power output of the SPV and WTG units, requiring additional power from the PHEV and DIESEL units, as shown in Figure 5. Here, PPHEV represents the power supplied (or absorbed if negative) by the PHEV, PHP indicates the power absorbed by the heat pump, and DIESEL denotes the output power from the diesel units.

Figure 4 shows the variation of the cost function (J) between PSO and SSA in the total iteration. The conversion curve indicates that the SSA has a better conversion rate than PSO. Considering all the case results, the SSA performs better than the PSO.

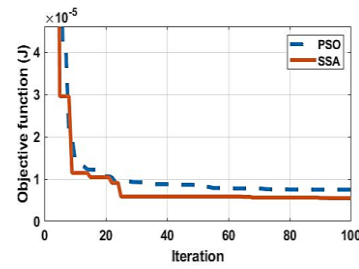


Figure 4. Objective function Vs iterations

Figure 5 shows the variation of power absorbed and delivered in PHEV, HP, and DIESEL during the entire period. Initially, for the first 20 seconds, the load demand exceeds the power generation, so the PHEV supports the system by supplying power back. After 20 seconds, when the combined power from the SPV and WTG exceeds the demand, the PHEV draws power from the system to recharge its battery.

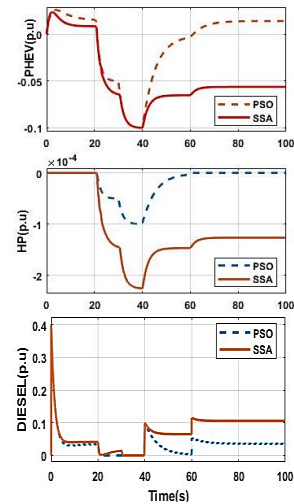


Figure 5. Comparison Of PHEV, PHP, And DIESEL Power Absorbed and Delivered

The HP demand is more for the initial 20s and didn't take power from the system after the 20s.

When generation is more than the demand, it takes power from the system and supports balancing the frequency deviation. DIESEL also supplies the power to the system for initially 20s because the generation is not enough to fulfill the demand. Then, after the supply is sufficient to mitigate the load, DIESEL is in the rest period. At the 40s, once again, demand is more than the supply, so DIESEL starts to give power back to the system to maintain balance; at 60s, the required demand once increases, so it increases the capacity up to 0.1 p.u. and gives power to the system.

The frequency response of the proposed hybrid microgrid using PSO and SSA is illustrated in Figure 6, which shows the superiority of SSA over the PSO algorithm. At starting both give the same response, and SSA settles fast. In the 20s, when WTG increases the generation at that time the overshoot in SSA is less compared to the PSO; in the 30s, when PV generation is increased at that time once again, SSA has less overshoot compared to the PSO. At the 40s when demand is increasing at that time too SSA has less undershoot than PSO and in SSA frequency settle fast compare to PSO. So, the result shows that SSA is superior to the PSO.

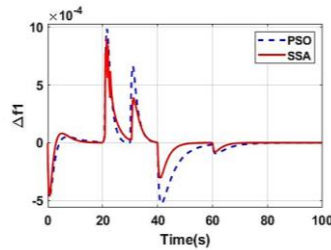


Figure 6. Frequency deviation for microgrid

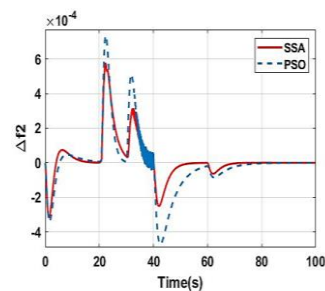


Figure 7. The frequency deviation of the primary grid

The frequency response of the primary grid using PSO and SSA is depicted in Figure 7. The frequency deviation curve for the primary grid demonstrates that the SSA algorithm consistently performs better than the PSO algorithm during all instances of system changes. This highlights the superiority of the SSA approach over PSO. Despite

disturbances in critical load and variations in generation, the PID controller ensures that the frequency of the interconnected hybrid microgrid remains within acceptable limits. The frequency deviation plots for both the hybrid microgrid and the primary grid are presented in Figures. 7 and 8, respectively, indicate that the PID controllers optimized using SSA delivers superior performance to those optimized with PSO.

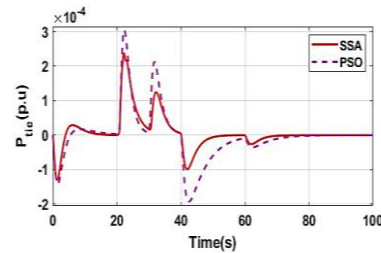


Figure 8. Tie-line power-sharing between the microgrid and primary grid

The response of tie-line power sharing between the microgrid and primary grid in the proposed mini VPP using PSO and SSA is illustrated in Figure 8, which shows the superiority of SSA over PSO.

Case - 2

In this case, the power co-ordinations considered to study the proposed system responses are shown in Figure 9. In this part, solar PV power generation and critical load demand are taken as variables to see the effect on the system with the same wind turbine generation as illustrated in case 1.

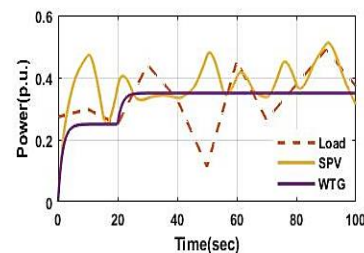


Figure 9. PSPV, PWTG, and Critical Load for case 2

For this case, the convergence comparison of the optimized cost function (J_{min}) with PSO and SSA is illustrated in Figure 10, for 100 iterations, which indicates the SSA has a better convergence rate as compared to PSO. The tuned PID controller gains for optimal frequency control of the proposed system with optimization parameters of Table 2, using both PSO and SSA, are listed in Table 4

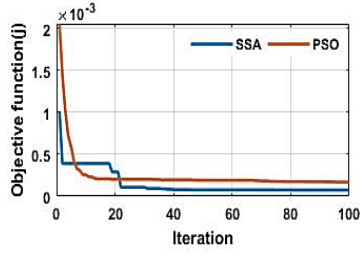


Figure 10. Objective function Vs iterations for case 2

Table 4. PID controller's gain for case 2

Controller Gains	SSA	PSO
Kp1	0.423	28.34
Ki1	0.00029	0.0025
Kd1	21.69	27.025
Kp2	31.43	31.64
Ki2	31.34	31.96
Kd2	0.0022	0.0919
Kp3	0.22	14.40
Ki3	23.58	23.03
Kd3	24.32	13.744
K1	.966	0.99
K2	0.00014	0.00015

The frequency responses of the primary grid using PSO and SSA are illustrated in Figure 11, which shows that the reactions in the case of SSA are better than PSO at all times when changes occur frequently in the system. In this case, we can see that frequency deviation is much more comparable to the previous case because we have taken demand and generation as both variables to see the worst effect of variable generation and variable demand on the

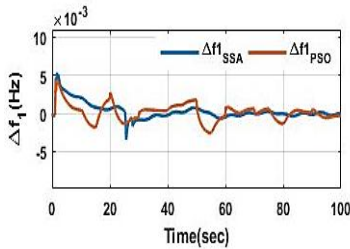


Figure 11. Frequency deviation of a microgrid for case 2

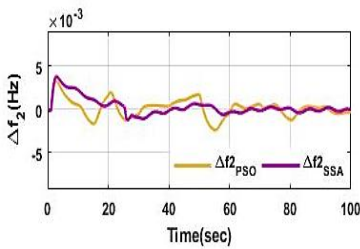


Figure 12. Frequency deviation of the primary grid for case 2

system. The performance of the PID controller with SSA is better than that of PSO. In the case of PSO, there is more deviation, like more undershoot and overshoot, but in the case of SSA, frequency settles with less deviation, i.e. less undershoot and less overshoot, and settling of disturbance is fast compared to PSO. Similarly, the frequency variation in the primary grid is also better when compared to PSP, as shown in Figure 12. i.e., there is less effectiveness in the primary grid power system due to power generation variation and load demand variation, which is the case for SSA over PSO. Figure 13 shows the power-sharing of the tie line between the microgrid and the primary grid, which indicates that SSA is superior to the PSO in handling the tie line power between the primary grid and microgrid.

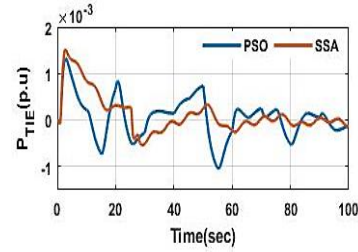


Figure 13. Tie line Power for case 2

Figures 14, 15, and 16 show the power variation response of the electric vehicle, diesel generator, and heat pump during the full-time period of operations, respectively. In the case of PSO electric vehicle power deviation, it is more than SSA and in the heat pump.

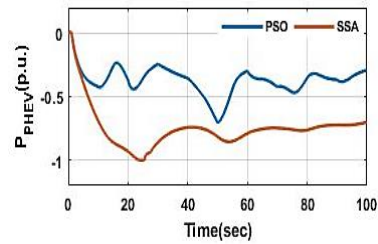


Figure 14. PPHEV of a microgrid for case 2

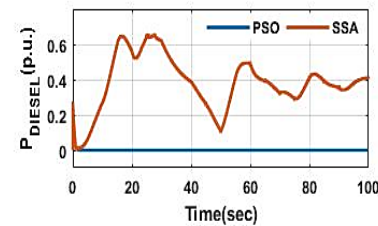


Figure 15. PDIESEL of a microgrid for case 2

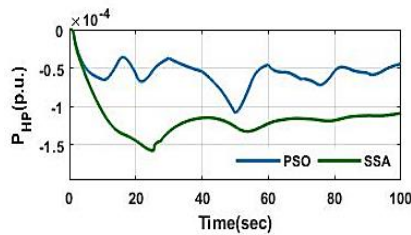


Figure 16. PHP of a microgrid for case 2

From the above case, we can conclude that an interconnected microgrid, which comprises solar PV, WTG, diesel generator, critical load, and controllable loads such as heat pumps and hybrid electric vehicles, is stable during any disturbance. In all cases, a PID-based controller is employed with PSO and SSA. For the optimal result of controller SSA and PSO, it is found that in the proposed technique in this interconnected mode, the SSA-based controller performs better compared to the PSO-based controller. To check the effectiveness of the system, different cases are applied to evaluate the system's robustness.

Conclusions

The proposed study verifies the optimal frequency stability of a mini VPP using SSA-tuned PID controllers. The responses of the proposed VPP model are found satisfactory under variations in renewable sources and load demands conditions. Sensitivity analysis confirms the robustness of the system controller's gains against random variations in critical load, solar PV, and wind turbine generation. SSA outperforms PSO regarding convergence rate, frequency stability, and control accuracy. The proposed model of the mini VPP can be scaled for larger interconnected hybrid microgrids, ensuring efficient power management and system stability under dynamic conditions.

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References

- Abdulla, H., Sleptchenko, A., and Nayfeh, A. (2024). Photovoltaic systems operation and maintenance: A review and future directions. *Renewable and Sustainable Energy Reviews*, 195:114342. <https://doi.org/10.1016/j.rser.2024.114342>
- Al-Shetwi, A.Q., Hannan, M.A., Jern, K.P., Alkahtani, A.A., and PG Abas, A.E. (2020). Power quality assessment of grid-connected PV system in compliance with the recent integration requirements. *Electronics*, 9(2):366. <https://doi.org/10.3390/electronics9020366>
- Bajaj, M., and Singh, A.K. (2019). Grid integrated renewable DG systems: A review of power quality challenges and state-of-the-art mitigation techniques. *International Journal of Energy Research*, 44(1):26-69. <https://doi.org/10.1002/er.4847>
- Barik, A.K., and Das, D.C. (2018). Active power management of isolated renewable microgrid generating power from rooftop solar arrays, sewage waters, and solid urban wastes of a smart city using Salp swarm algorithm. In *2018 Technologies for Smart-City Energy Security and Power (ICSESP)* (pp. 1-6). IEEE. <https://doi.org/10.1109/ICSESP.2018.8376744>
- Bhatt, P., Roy, R., and Ghoshal, S.P. (2010). GA/particle swarm intelligence based optimisation of two specific varieties of controller devices applied to two-area multi-units automatic generation control. *International Journal of Electrical Power & Energy Systems*, 32(4):299-310. <https://doi.org/10.1016/j.ijepes.2009.09.004>
- Chen, W., Qiu, J., Zhao, J., Chai, Q., and Dond, Z.Y. (2021). Bargaining game-based profit allocation of virtual power plant in frequency regulation market considering battery cycle life. *IEEE Transactions on Smart Grid*, 12(4):2913-2928. <https://doi.org/10.1109/TSG.2021.3053000>
- Das, D.C. (2017). Demand response strategy for frequency control of a parabolic dish solar thermal diesel-based microgrid. In *2017 International Conference on Intelligent Sustainable Systems (ICISS)* (pp. 295-301). IEEE. <https://doi.org/10.1109/ISS1.2017.8389418>
- Das, D.C., and Pal, S. (2011). Genetic algorithm-based PI controller for frequency control of an autonomous hybrid generation system. *International Multiconference of Engineers and Computer Scientists 2011 (IMECS 2011)*, 1:953-958. http://www.iaeng.org/publication/IMECS2011/IMECS2011_pp953-958.pdf
- Das, D.C., Roy, A.K., and Sinha, N. (2012). GA-based frequency controller for solar thermal-diesel-wind hybrid energy generation/energy storage system. *International Journal of Electrical Power & Energy Systems*, 43(1):262-279. <https://doi.org/10.1016/j.ijepes.2012.05.025>
- Datta, U., Kalam, A., and Shi, J. (2020). Battery energy storage system control for mitigating PV penetration impact on primary frequency control and state-of-charge recovery. *IEEE Transactions on Sustainable Energy*, 11(2):746-757. <https://doi.org/10.1109/TSTE.2019.2904722>
- Fernández-Guillamón, A., Gómez-Lázaro, E., Muljadi, E., and Molina-García, Á. (2019). Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time. *Renewable and Sustainable Energy Reviews*, 115:109369. <https://doi.org/10.1016/j.rser.2019.109369>

- Gad, A.G. (2022). Particle swarm optimization algorithm and its applications: A systematic review. *Archives of Computational Methods in Engineering*, 29(5):2531-2561. <https://doi.org/10.1007/s11831-021-09694-4>
- Gao, H., Jin, T., Feng, C., Li, C., Chen, Q., and Kang, C. (2024). Review of virtual power plant operations: Resource coordination and multidimensional interaction. *Applied Energy*, 357:122284. <https://doi.org/10.1016/j.apenergy.2023.122284>
- Greer, K., Zeller, D., Woroniak, J., Coulter, A., Winchester, M., Deng Palomares, M.L., and Pauly, D. (2019). Global trends in carbon dioxide (CO₂) emissions from fuel combustion in marine fisheries from 1950 to 2016. *Marine Policy*, 107:103382. <https://doi.org/10.1016/j.marpol.2018.12.001>
- He, W., Tao, L., Han, L., Sun, Y., Campana, P.E., and Yan, J. (2021). Optimal analysis of a hybrid renewable power system for a remote island. *Renewable Energy*, 179:96-104. <https://doi.org/10.1016/j.renene.2021.07.034>
- Khezri, R., Oshnoei, A., Tarafdar Hagh, M., and Muyeen, S. (2018). Coordination of Heat Pumps, Electric Vehicles and AGC for Efficient LFC in a Smart Hybrid Power System via SCA-Based Optimized FOPID Controllers. *Energies*, 11(2):420. <https://doi.org/10.3390/en11020420>
- Makolo, P., Zamora, R., and Lie, T.-T. (2021). The role of inertia for grid flexibility under high penetration of variable renewables: A review of challenges and solutions. *Renewable and Sustainable Energy Reviews*, 147:111223. <https://doi.org/10.1016/j.rser.2021.111223>
- Mishra, S., Bordin, C., Wu, Q., and Manninen, H. (2022). Resilient expansion planning of virtual power plant with an integrated energy system considering reliability criteria of lines and towers. *International Journal of Energy Research*, 46(10):13726-13751. <https://doi.org/10.1002/er.8093>
- Mohamed, M.M., El Zoghby, H.M., Sharaf, S.M., and Mosa, M.A. (2022). Optimal virtual synchronous generator control of battery/supercapacitor hybrid energy storage system for frequency response enhancement of photovoltaic/diesel microgrid. *Journal of Energy Storage*, 51:104317. <https://doi.org/10.1016/j.est.2022.104317>
- Roy, S. (2016). Implementation of model to analyse the performance of microturbine as in microgrid comparison with fuel cell. *International Journal of Energy Optimization and Engineering*, 5(3):19-42. <https://doi.org/10.4018/IJEOE.2016070102>
- Roy, S., Das, D.C., and Sinha, N. (2024). Optimizing smart city virtual power plants with V2G integration for improved grid resilience. In 2024 IEEE International Conference on Interdisciplinary Approaches in Technology and Management for Social Innovation (IATMSI) (pp. 1-6). IEEE. <https://doi.org/10.1109/IATMSI60426.2024.10502468>
- Roy, S., Das, D.C., Sinha, N., and Shukla, R.D. (2023). A systematic review of islanding detection approaches in microgrids. In 2023 IEEE Silchar Subsection Conference (SILCON) (pp. 1-6). IEEE. <https://doi.org/10.1109/SILCON59133.2023.10405116>
- Ryu, J., and Kim, J. (2022). Virtual power plant operation strategy under uncertainty with demand response resources in electricity markets. *IEEE Access*, 10:62763-62771. <https://doi.org/10.1109/ACCESS.2022.3181163>
- Salgotra, R., Singh, U., Singh, S., Singh, G., and Mittal, N. (2021). Self-adaptive salp swarm algorithm for engineering optimization problems. *Applied Mathematical Modelling*, 89(1):188-207. <https://doi.org/10.1016/j.apm.2020.08.014>
- Shami, T.M., El-Saleh, A.A., Alswaiti, M., Al-Tashi, Q., Summakieh, M.A., and Mirjalili, S. (2022). Particle swarm optimization: A comprehensive survey. *IEEE Access*, 10:10031-10061. <https://doi.org/10.1109/ACCESS.2022.3142859>
- Shukla, R.D., Singh, N., and Roy, S. (2021). Power electronics for solar photovoltaic system: Configuration, topologies, and control. In *Handbook of Renewable Energy Technology & Systems* (pp. 235-263). World Scientific. https://doi.org/10.1142/9781786349033_0009
- Ullah, Z., Mokryani, G., Campean, F., and Hu, Y.F. (2019). Comprehensive review of VPPs planning, operation and scheduling considering the uncertainties related to renewable energy sources. *IET Energy Systems Integration*, 1(2):147-157. <https://doi.org/10.1049/iet-esi.2018.0041>
- Yavuz, L., Önen, A., Muyeen, S.M., and Kamwa, I. (2019). Transformation of microgrid to virtual power plant - A comprehensive review. *IET Generation, Transmission & Distribution*, 13(7):1994-2005. <https://doi.org/10.1049/iet-gtd.2018.5649>
- Yuvaraj, T., Krishnamoorthy, R., Arun, S., Thanikanti, S. B., & Nwulu, N. (2024). Optimizing virtual power plant allocation for enhanced resilience in smart microgrids under severe fault conditions using the hunting prey optimization algorithm. *Energy Reports*, 11:6094-6108. <https://doi.org/10.1016/j.egy.2024.05.043>
- Zhao, H., Wang, B., Pan, Z., Sun, H., Guo, Q., & Xue, Y. (2021). Aggregating additional flexibility from quick-start devices for multi-energy virtual power plants. *IEEE Transactions on Sustainable Energy*, 12(1):646-658. <https://doi.org/10.1109/TSTE.2020.3014959>
- Zhong, W., Chen, J., Liu, M., Murad, M.A.A., and Milano, F. (2021). Coordinated control of virtual power plants to improve power system short-term dynamics. *Energies*, 14(4):1182. <https://doi.org/10.3390/en14041182>