Journal of Operation and Automation in Power Engineering

Vol. XX, No. XX, Dec. 2022, Pages: XXXX (Proofed)

http://joape.uma.ac.ir

Research Paper

Stability Enhancement of Hybrid Wind-Diesel Systems via SVC and PSO-Optimized Voltage and Frequency Control

Wilson-Wilmar Candia-Quispe [1, *], *Iris-Liliana Vásquez-Alburqueque* [2], *Nestor Cuba Carbajal* [3], *Marco Antonio Ananos Bedrinana* [4], *Diana Luján Pérez* [5], *Yersi-Luis Huamán-Romaní* [6], and *Juan-Jesús Garrido-Arismendis* [7]

[1]*Faculty of Engineering, Universidad Tecnologica de los Andes , Andahuaylas, Peru.*
[2]*Academic Department of Philosophy and Art, National University of Trujillo, Trujillo, Peru.*
[3]*Departamento Académico of Turismo y Hotelería, Universidad de San Martin de Porres, Lima, Peru.*
[4]*Faculty of Agricultural Sciences Professional School of Forestry and Environmental Engineering, National Autonomous University of Chota, Chota, Peru.*
[5]*Department of Graduate School, National University of San Cristobal de Huamanga, Ayacucho, Peru.*
[6]*Department of Basic Sciences, National Amazonian University of Madre de Dios, Puerto Maldonado, Peru.*
[7]*Department of Food Industries Engineering, National Frontier University, Sullana, Peru.*

Abstract— *Nowadays, distributed generation (DG) systems with renewable energies are increasingly used to supply a portion of fluctuating electric loads. However, the intermittent nature of these systems leads to variable frequency and voltage, posing challenges for consistent energy supply. This paper addresses the challenges of variable frequency and voltage in DG systems powered by re-newable energy sources. It models a hybrid wind-diesel system in MATLAB to optimize voltage and frequency control using a Particle Swarm Optimization (PSO) algorithm with Sine-Cosine Acceleration Coefficients (SCAC). Simulation results show that the optimized Proportional-Integral (PI) controller reduces frequency deviations to 0.21 Hz under a 1% active power disturbance and minimizes voltage deviations with support from a Static Var Compensator (SVC). The system stabilizes rapidly, achieving a settling time of 0.4 seconds, demonstrating the advantages of the SCAC-PSO approach over traditional methods.*

Keywords—Voltage control, frequency control, proportional-integral, particle swarm algorithm, static var compensator, sine-cosine accel-eration coefficients, active power perturbation.

1. Introduction

1.1. Research motivation

Ensuring stability in distributed generation (DG) systems that utilize renewable energy sources is crucial due to the inherent intermittency of these resources. Reliable support systems are essential, particularly in hybrid systems that combine wind and diesel generation, where maintaining stable voltage and frequency is critical for optimal perfor-mance. Conventional backup solutions, such as diesel generators, provide consistent energy supply during periods of renewable shortfall. Many intelligent optimization and control approaches, such as optimal control [1], fractional-order PID [2], genetic algorithm [3], particle swarm optimization (PSO) [4], bacterial foraging optimization algorithm (BFOA) [5], and fuzzy logic controllers [6], are recommended for voltage and frequency control. Numerous studies have ex-plored methods for voltage and frequency control in wind-diesel hybrid systems, highlighting the effectiveness of Static Var Compensators (SVC) in enhancing overall system stability. This paper builds on existing research by focusing on the integration of SVC and optimized control strategies, specifically utilizing the PSO algorithm with Sine-Cosine Ac-celeration Coefficients (SCAC). Through comprehensive simulations, we demonstrate how these approaches signifi-cantly improve dynamic response and reduce fluctuations, ultimately contributing to a more stable and reliable power system. Research in the field of hybrid power systems has advanced significantly, particularly concerning the integra-tion of renewable energy sources and effective control strategies to enhance system stability.

Received: 02 Jul. 2024
Revised: 05 Jan. 2025
Accepted: 08 Jan. 2025
*Corresponding author:
E-mail: wwcandia@gmail.com (W.W Candia-Quispe)
DOI: 10.22098/joape.2025.15384.2178

1.2. Literature review

Guchhait *et al.* [7] applied a posicast controller along with an SVC to a wind-diesel hybrid power system, achieving im-proved stability and reactive power compensation through parameter optimization using soft computing techniques. Their approach effectively damped oscillations and enhanced system performance under disturbances. We explore the application of the Particle Swarm Optimization (PSO) algorithm with sine-cosine acceleration coefficients for optimal voltage and frequency control, focusing on faster convergence and reduced fluctuations. Younesi *et al.* [8]

developed an adaptive control strategy using reinforcement learning (RL) to address voltage and frequency oscillations in a microgrid with wind power integration. Their approach applies Q-learning, a model-free RL method, to improve system stability by adaptively controlling voltage and frequency. The method outperforms traditional and fuzzy PID controllers, espe-cially in nonlinear scenarios. While both approaches aim to stabilize power systems, our emphasis is on the integration of SVC for enhanced voltage and frequency stability, targeting hybrid systems with different configurations. Sadeghi *et al.* [9] optimized voltage and frequency control in a distributed generation system using (BWO) algorithm, enhancing system stability through optimized gains in the Static Var Compensator (SVC) and synchronous generator. While both studies utilize SVC for reactive power compensation, our approach emphasizes faster convergence and reduced fluctua-tions, offering a distinct optimization dynamic compared to BWO. Labed *et al.* [10] applied adaptive acceleration coeffi-cients in PSO algorithms, specifically APG-PSO and NDAC-PSO, to optimize power flow, reduce fuel costs, and improve power system efficiency with SVC devices in a transmission network. Their work focused on the IEEE 30-bus system, showcasing practical improvements in power flow optimization. Sharma *et al.* [11] studied multi-source power genera-tion in a wind-diesel hybrid system using an optimal output feedback controller. Demirrorin and Zineljil investigated automatic production control in a wind-diesel hybrid system and used the GA method to obtain optimal integral effi-ciencies and bias factors. Bahat *et al.* [12] investigated the problem of voltage and frequency control in a four-zone power system. Hybrid particle swarm optimization has been utilized to receive the optimal efficiency of the PI controller. The writers didn't take into account significant physical con-strains including governor dead band (GDB) as well as genera-tion rate constraint (GRC) in the system model that has an effect on power system performance. Elgerd [13] suggested the two-degree (TDF) internal model control (IMC) approach to adjust PI-type decentralized volt-age controllers and frequency for wind-diesel hybrid sys-tems. Liu *et al.* [14] sugegsted optimal load frequency control in refurbished power systems with various market structures. Ali *et al.* [15] demonstrated the notion of a restructured power system and the DISCO (DPM) participation matrix. In [16] optimal designs of hybrid wind turbine and diesel generator systems with reactive power supply strategy have been carried out. In [17] the measurement of a mi-cro-hydro-photovoltaic hybrid system based on seasonal changes of both solar and water sources was presented. In another study [12], the hybrid system of wind turbine and diesel generator has been evaluated with the aim of control-ling reactive power. To achieve this aim, a mathematical model has been used. The wind turbine-diesel generator hybrid system has been evaluated and STATCOM has been used to adjust and control the voltage and frequency. The purpose of this re-search is to manage reactive load demand [11]. In a research that has been presented by 45 centuries, different mathematical models for modeling synchronous generators connected to diesel generators have been investigated [18].

1.3. Novelty and main contribution of paper

In this study, we propose a novel approach to enhance voltage and frequency control within hybrid wind-diesel power systems. By integrating Static Var Compensators (SVCs) with a Particle Swarm Optimization (PSO) algorithm refined with sine-cosine acceleration coefficients, we aim to provide a more adaptive and responsive control solution than pre-vious methods. While much of the existing literature focuses on theoretical modeling for synchronous generators, our research places a stronger emphasis on practical implementation and system behavior. Specifically, we develop a de-tailed framework for evaluating performance by modeling and linearizing the governing equations for the hybrid die-sel-wind system. This approach allows us to account for dynamic fluctuations more effectively, aiming to minimize the Integral Squared Error (ISE) and increase the rate at which voltage and frequency deviations are dampened. We further implement a computer program based on the PSO algorithm to optimize these control parameters, ensuring more robust and reliable system stability under varied operating conditions. This contribution represents a significant advance in hybrid system control, providing a comprehensive method for maintaining stable voltage and frequency amidst the challenges posed by renewable intermittency and load fluctuations.

1.4. Paper organization

The remainder of the paper is structured as follows: Section 2 presents the SVC modeling in the hy-brid wind-diesel system, along with the system model for voltage and frequency control. Section 3 presents the simulation outcomes and evaluates the effectiveness of the optimized PI controller and SVC integration and finally, the article summary is given in section 4.

2. MATERIALS AND METHODS

In this section, the methodology for modeling the wind-diesel hybrid system and the Particle Swarm Optimization (PSO) algorithm with sine-cosine acceleration coefficients is described, along with the integration of a Static Var Com-pensator (SVC) to enhance voltage and frequency control.

2.1. PSO algorithm for voltage and frequency control

In this study, the Particle Swarm Optimization (PSO) algorithm is employed for voltage and frequency control in the wind-diesel hybrid system, optimizing the SVC for enhanced stability. As detailed by Jain *et al.* [19], PSO is a widely used nature-inspired technique due to its simplicity and flexibility. The algorithm iteratively adjusts a swarm of parti-cles to minimize an objective function, which, in this case, is designed to reduce voltage and frequency deviations. Key optimization parameters, such as the objective function, lower and upper limits (search space), fitness function, maximum number of iterations, and number of particles, are defined according to the relationships provided in Jain's work. This ensures a comprehensive approach to tuning the SVC for optimal control performance. In line with the PSO framework, the objective function minimizes voltage and frequency deviations, while the search space is bounded by lower and upper limits of control parameters. The fitness function measures system stability and performance, ensuring robust voltage and frequency regulation. The number of iterations and particles is chosen to bal-ance solution accuracy and computational efficiency, following established guidelines from Jain *et al.* [19].

The application of PSO in this study showed that it can effectively enhance voltage and frequency regulation within the wind-diesel hybrid system. By optimizing the control parameters of the SVC, PSO helped to mitigate the fluctuations caused by varying wind power and load conditions. The results demonstrated that the system achieved more stable performance, with voltage and frequency maintained within acceptable ranges. While the improvement in control was significant, further refinement of the method could still lead to more robust and adaptable solutions.

2.2. SVC modeling in hybrid wind-diesel systems

An SVC is a type of reactive power compensation device that helps stabilize power systems by dynamically adjusting reactive power in response to fluctuations. By regulating voltage levels and improving system stability, the SVC ensures that voltage remains within acceptable limits, even in the presence of varying load demands and fluctuating renewable energy sources like wind. In this study, the SVC plays a key role in addressing the inherent variability of wind power. Wind turbines, which use squirrel-cage generators, and diesel generators with synchronous generators are employed as power sources, as shown in Fig. 1. Under normal wind conditions, active and reactive power can be controlled effec-tively. However, when wind speed or load changes, maintaining consistent voltage and frequency becomes difficult. This is where the SVC steps in to stabilize the system, particularly during periods of wind variability. To prevent severe voltage fluctuations, SVCs are used as in Fig. 2 to compensate for severe fluctuations with this strategy. On the synchronous generator, the excitation system is connected with a smaller time constant than the governor to control the voltage and frequency properly [13]. In [14], the advantageous impact of the excitation ring for effective fre-quency control is presented. Nonetheless, the study has been carried out for the single machine infinite bus power sys-tem (SMIB), and 4 large synchronous generators were taken into consideration to provide infinite bus power by the long transmission line. In that study, the impact of the frequency control loop and the voltage control loop on each other is thoroughly analyzed for the pneumatic-diesel isolation system.

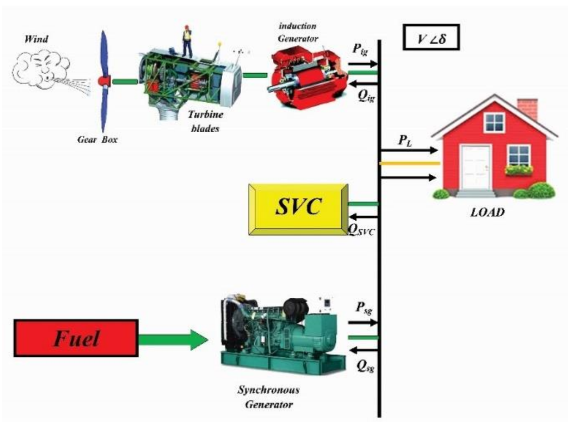

Fig. 1. Wind and diesel generator HYBRID system studied.

As can be seen in Fig. 2, two sources of wind turbine and diesel generator are used to generate electrical energy and it is done by a voltage and frequency control feedback. Fig. 1 illustrates the hybrid wind and diesel generator system studied, where both energy sources work together to supply electrical power. To maintain stable voltage and frequency under varying load conditions, Fig. 2 shows the detailed block diagram of the isolated wind-diesel power system, with a focus on the control mechanisms. In particular, the system integrates a Static Var Compensator (SVC) to manage voltage fluctuations caused by wind speed variations. The relationship between the two figures lies in how the system in Fig. 1 relies on the control framework and reactive power compensation strategies presented in Fig. 2 to ensure smooth and stable operation, especially under conditions of wind variability and load changes.

2.3. Problem formulation

Changes in reactive power cause changes in frequency. The reactive power generated by the synchronous generator can be seen in Eq. (1) [20]:

$$Q_{SG} = \frac{E_q' \cos\delta - V^2}{X_d'} \tag{1}$$

For small perturbations, Eq. (1) can be written as follows [21]:

$$\Delta Q_{SG} = \left(\frac{V\cos\delta}{X_d'}\right)\Delta E_q' + \left(\frac{E_q'\cos\delta - 2V}{X_d'}\right)\Delta V - \left(\frac{E_q' V \sin\delta}{X_d'}\right)\Delta\delta$$

Where $\Delta E_q'$ is the internal emf deviation of the armature proportional to the change in the direct axis field flux under

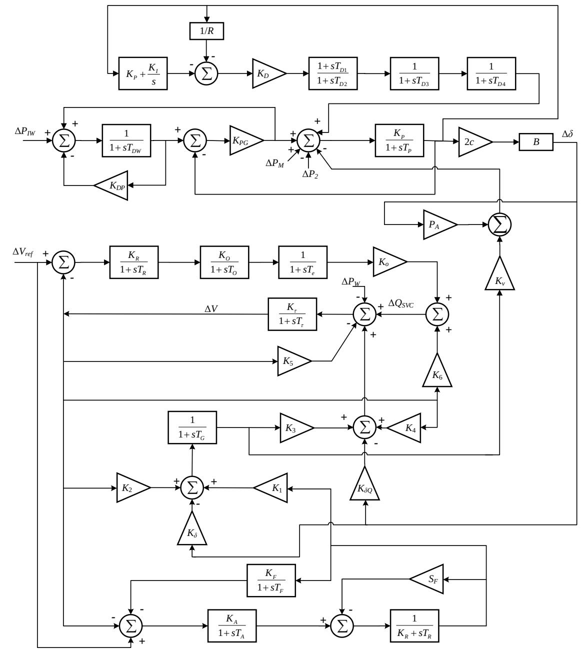

Fig. 2. Isolated wind-diesel power system block diagram.

transient conditions, ΔV is the deviation of the terminal voltage, and $\Delta\delta$ is the deviation of the power angle of the syn-chronous generator. Laplace conversion of both sides for Eq. (2) results in:

$$\Delta Q_{SG}(s) = K_1 \Delta E_q'(s) + K_2 \Delta V(s) - K_\delta \Delta\delta \tag{2}$$

$$K_1 = \frac{V\cos\delta}{X_d'} \tag{3}$$

$$K_2 = \frac{E_q'\cos\delta - 2V}{X_d'} \tag{4}$$

$$K_\delta = \frac{E_q' V \sin\delta}{X_d'} \tag{5}$$

The internal emf of the armature for the synchronous machine of the cylindrical rotor is given in Eq. (7) and its change with small perturbation is expressed as [22]:

$$E_q = \frac{X_d}{X_d'} E_q' - \frac{X_d}{X_d' X_d'} V\cos\delta \tag{6}$$

$$\Delta E_q = \frac{X_d}{X_d'}\Delta E_q' = \left(\frac{X_d - X_d'}{X_d'}\right)\cos\delta\Delta V + \left(\frac{X_d - X_d'}{X_d'}\right) V\sin\delta\Delta\delta \tag{7}$$

The change in emf internal emitter is proportional to the change in the direct axis field flux under steady-state conditions. For a cylindrical rotor synchronous machine, the dispersion flux equation for small perturbation is as follows:

$$\frac{d}{dt}(\Delta E_q') = \frac{\Delta E_{fd} - \Delta E_q}{T_{do}'} \tag{8}$$

T_{do}' is the transient temporal open circuit of the direct center. Therefore:

$$\Delta E_q'(s) = \frac{1}{1+sT_G}\left[K_1 \Delta E_{fd}(s) + K_2 \Delta V(s) - K_\delta \Delta\delta(s)\right] \tag{9}$$

whereby:

$$T_G = \frac{X_d' T_{do}'}{X_d} \tag{10}$$

$$K_1 = \frac{X_d'}{X_d} \tag{11}$$

$$k_6 = \left(\frac{X_d - X_d'}{X_d}\right) \cos\delta \tag{12}$$

$$k_\delta = \left(\frac{X_d - X_d'}{X_d}\right) V \sin\delta \tag{13}$$

Fig. 3 shows the flowchart of the particle swarm algorithm and the sine-cosine acceleration coefficients.

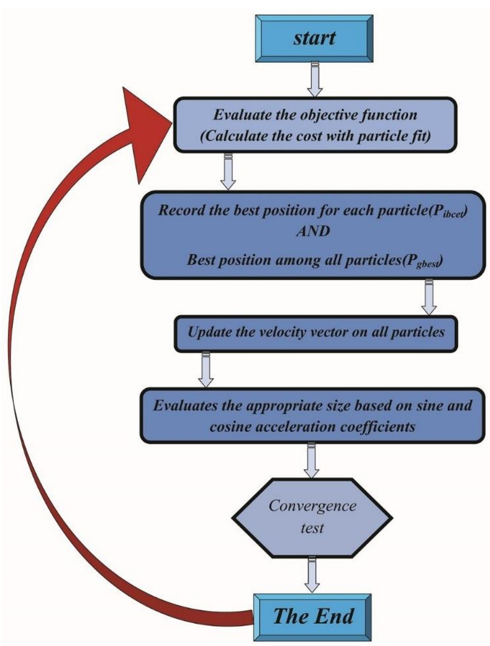

Fig. 3. Flowchart of particle swarm algorithm and sine-cosine acceleration coefficients.

To show the dynamic performance of the hybrid system under wind and voltage changes in the MATLAB software en-vironment, a computer simulation will be performed and the results will be compared with the results of the reference article.

3. RESULTS AND DISCUSSION

The PSO-tuned SVC, addressing significant challenges posed by load fluctuations and variable wind speeds. To imple-ment the PSO algorithm with cosine-sine coefficients to adjust the gain of the PI controller, the mentioned controller pa-rameters are optimized using MATLAB software [23–26]. Eq. (14) represents the load disturbances affecting the hybrid power system, such as demand changes and load fluctuations. These disturbances impact voltage and frequency stability, which the PSO-tuned SVC is designed to mitigate. While voltage input is critical, the primary focus here is on how these disturbances influence overall system stability and control. The corresponding load disturbances, are as fol-lows:

$$\Delta P_{D1} = 0.02 \quad \Delta P_{D2} = 0.01 \tag{14}$$

Table 1. Optimized frequency and voltage loop PI controller coefficients.

Diesel-wind system \ Parameter	P	I
Diesel-wind system	3.1032	2.6359

Table 1 provides the optimized parameter values for the PI controller in the diesel-wind system, specifically tuned for effective frequency and voltage control. The optimized parameters for the PI controller show improvements in response time and stability in both the diesel and wind generation sources, demonstrating the controller's effective configuration for hybrid systems.

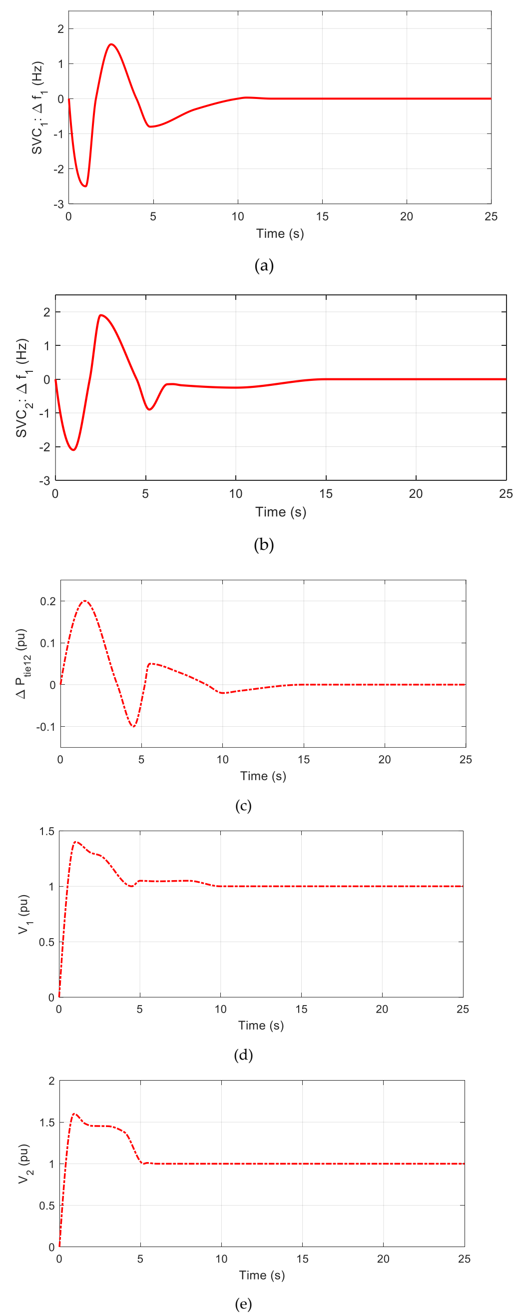

Fig. 4. Simulation results of combined frequency and voltage loop system a) F1 b) F2 c) F3, d) V1 e) V2.

The aim of this study is to achieve optimal frequency control of the hybrid isolated power system. The functions of sine and cosine acceleration coefficients (SCAC) criteria were tested, each with

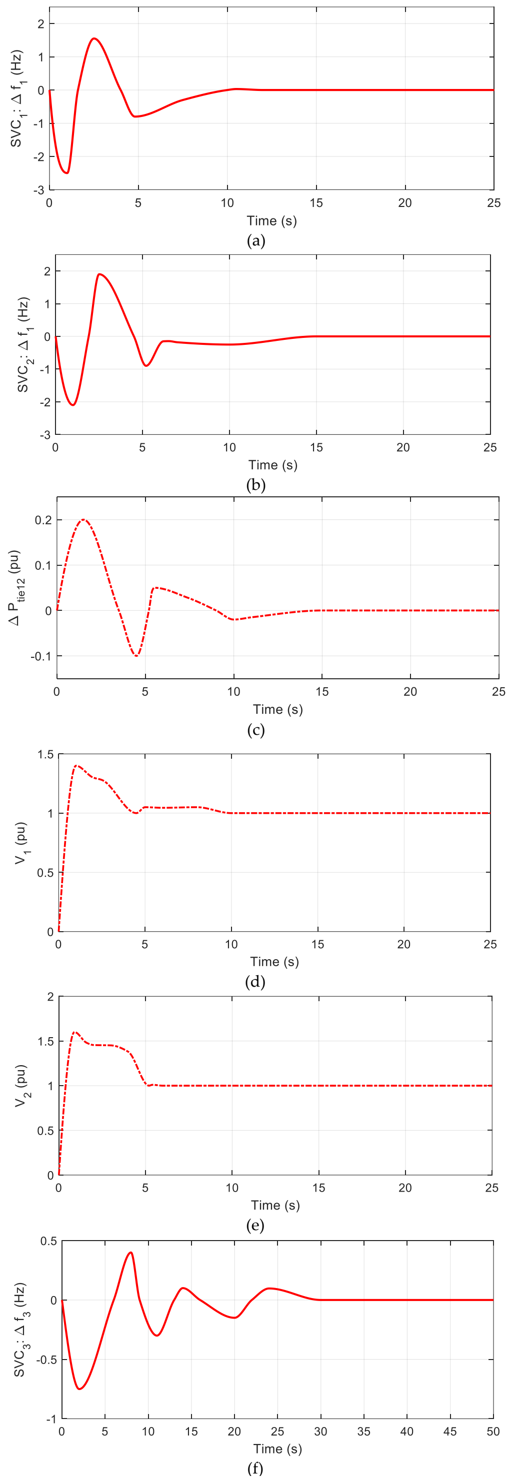

Fig. 5. Simultaneous voltage and frequency control works to transient responses.

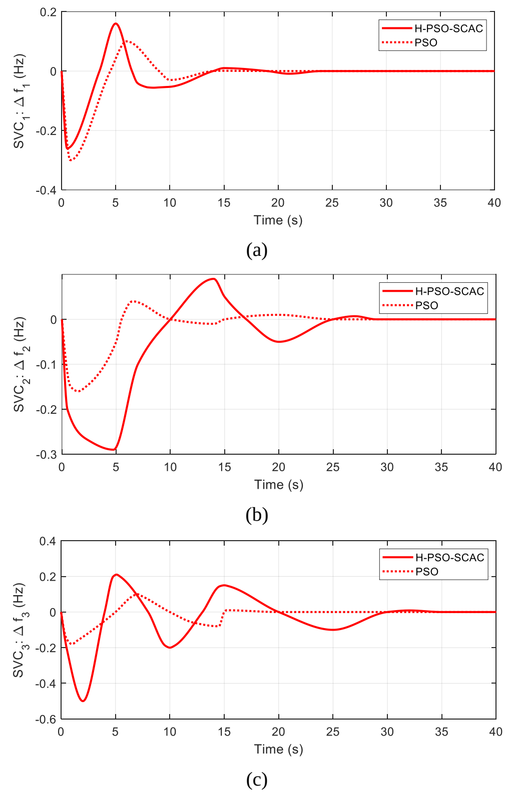

Fig. 6. Comparison of the results of optimization of H-PSO-SCAC algorithm with particle swarm algorithm.

dimensions of 10, 30, and 50. For each opti-mization function, 20 test voltages are performed and the average optimal values and standard deviations are presented [27]. In this study, all experimental experiments with a population size of 40 and a maximum number of cycles for all functions were set to 1000. PSO control parameters can be obtained from reference [28–30]. Moreover, the application of various criteria for varied conventional standard functions is presented [31, 32]. Having said that, all of the test functions hold a zero optimum overall solution. Consequently, for numerical functions, the cycles' maximum number is regarded as stopping criteria. The Integral of Squared Error (ISE) is used as the objective function as follows:

$$f = \int_{time} e^2 dt \tag{15}$$

- F1, F2, and F3 show the frequency responses across different stages.
- V1 and V2 depict the voltage stability levels during these changes.

The results in Fig. 4 confirm that the optimized PI controller effectively reduces deviations in frequency and enhances the stability of the system, even in the face of variable load demands. By minimizing the objective function through PI control, frequency deviation errors are notably reduced in the steady state, while the diesel generator can increase its output power to compensate for fluctuations. Since the wind speed remains constant in this setup, the SCIG (squirrel cage induction generator) contributes limited active power, relying on the diesel unit to manage frequency fluctuations. The optimized PI controller thus plays a key role in maintaining frequency stability and preventing excessive deviations in the system, ultimately contributing to overall system robustness.

3.1. Integrated frequency and voltage control system

In the integrated frequency and voltage control system, the control of these two variables is considered simultaneously.

That changes in the active power of the synchronous generator relative to the frequency control can be seen in Eqs. (16) and (17).

$$\Delta P_{m,SG} + \Delta P_{m,IG} + \Delta P_e = \Delta P_L \tag{16}$$

Table 2. Simulation results of the proposed method.

Parameter	Setting time (sec)	Peak over shoot
ΔF_1	1	0.6
ΔF_2	2	0.15
ΔF_3	3	0.4
V_1	4	0.65
V_2	4.5	0.15
V_3	5	0.4

Table 3. Comparative performance of optimization algorithms on frequency and voltage control in hybrid wind-diesel system.

Algorithm	Peak overshoot (ΔF)	Setting time (Sec) (ΔF)	Peak overshoot (V)	Setting time (Sec) (V)
PSO-SCAC	0.15	2	0.15	4.5
GWO	0.18	2.5	0.17	5
SSA	0.2	3	0.22	5.2
WOA	0.16	2.3	0.18	4.8

$$\Delta P_e = P_s \Delta\delta + K_{E,v} \Delta E'_q \tag{17}$$

In Eq. (15) DP, the amount of changes in the power generated by SCIG is intended to compensate for the power of the resources, as well as the DP changes in the power generation of wind turbines and DP are changes in the power genera-tion of synchronous diesel generators. DP is the changes of the load. In Fig. 5, we can see how frequency and voltage control works. According to the form, the correct function of this scenario can be seen concerning power changes. Con-sidering that the reaction of diesel generators to produce electrical power is very high, it prevents the reduction of fre-quency well, and given that the electric power generation by the wind turbine is not continuous, it cannot prevent fre-quency fluctuations well, but for a long time it is a good solution for the production of reactive power as well as fre-quency control.

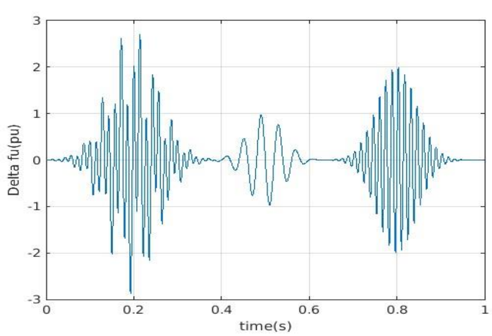

Fig. 7. Transient responses of frequency deviation and power generated by considering the coordinated control of frequency and voltage control loops against the random change of SVC type 3 load.

When a step-type disturbance is applied to active power, terminal voltage initially deviates from its set point. This devi-ation is effectively mitigated by reactive power support from the synchronous generator and the SVC. Fig. 5 shows the transient responses.

SVC Type 3 demonstrates the best performance in maintaining voltage stability, as it rapidly compensates for voltage deviations and eliminates any residual voltage error. This capability is achieved through its integrated control with the PI controller, allowing it to respond more effectively to sudden changes.

SVC Types 1 and 2 show a slower response in voltage compensation, with a small, persistent deviation remaining after stabilization. Although they eventually stabilize the voltage, the recovery time is longer than that of SVC Type 3, which could lead to undesirable voltage fluctuations if the load continues to vary. This coordinated PI and SVC control reduces voltage fluctuations and improves system resilience, keeping voltage and frequency within acceptable limits even as load conditions fluctuate.

Where f is the objective function and e is the error between the system frequency and the reference frequency.

3.2. Test system with frequency control loop

In this scenario, only frequency control is considered without simultaneous voltage regulation, while active power gen-eration is assumed to increase at a rate of 0.1% per second starting from t=0t = 0t=0. A significant advantage of the PI controller is its capability to be optimized for effective frequency regulation, thus providing stability in the system's re-sponse. The transient responses, including frequency deviation and active power outputs from both the wind and diesel units, were analyzed under a 1% active power load perturbation. This perturbation results in a frequency decrease of approximately 0.21 Hz, demonstrating the system's sensitivity to load changes. Fig. 4 illustrates these dynamic re-sponses within the combined frequency and voltage loop system. Here:

3.3. Investigation of reactive power latency in simultaneous control mode of voltage and frequency

Reactive power is one of the cases that causes discrepancies in voltage production, making its control essential for volt-age stability in the hybrid wind-diesel system. Fig. 6 compares the performance of SVC configurations, with SVC Types 2 and 3 showing superior speed in reducing voltage latency and preventing severe fluctuations under load dis-turbances. Notably, Type 3 provides the least latency, nearly eliminating voltage deviation when integrated with the control system. Fig. 5 further illustrates that increased reactive power from the synchronous generator helps mitigate latency, sustaining voltage stability. Comparing Figs. 5 and 6, higher terminal voltage fluctuations are associated with greater reactive power requirements, emphasizing the critical role of SVC Types 2 and 3 in responding to these variations effectively. The synchronous generator's steady reactive power support further reduces response time.

The H-PSO-SCAC algorithm, using sine-cosine acceleration coefficients, optimally tunes control parameters, with Fig. 6 showing that it outperforms the standard PSO by achieving faster convergence and greater stability. This analysis un-derscores the effectiveness of SVC Types 2 and 3 in ensuring transient voltage stability essential for consistent voltage and frequency control amidst fluctuating load and generation conditions.

As shown in Eq. (12), the test system changes randomly:

$$\Delta f_l = 0.003\sin(4.36t) + 0.005\sin(5.3t) - 0.01\sin(6t) \tag{18}$$

Fig. 7 depicts the dynamic responses of frequency deviation and power generation following a disturbance from an active load, showcasing the effectiveness of the coordinated control strategy for frequency and voltage loops. The system quickly stabilizes frequency deviation after disturbance, demonstrating robust control performance. Coordinate control effectively reduces oscillations, highlighting the synergy between frequency and voltage control strategies. Additionally, the figure emphasizes the importance of swift recovery to maintain a consistent power supply and protect electrical equipment.

Overall, the results confirm the proposed method's ability to enhance the resilience of wind diesel hybrid systems in dynamic scenarios.

Table 2 shows the results of the voltage stimulation of the wind-diesel system using the PSO algorithm and its optimi-zation or cosine sinusoidal acceleration coefficients. Peak overshoot, indicates the maximum deviation from the desired setpoint during a transient response. Lower values (0.15 to 0.65) suggest better stability. Setting time (sec), represents the time taken for the output to stabilize within a specified range after a disturbance. Shorter times (1 to 5 seconds) indicate a more responsive system. In parameters, frequency deviations (ΔF) and voltage levels (V) reflect the system's performance under varying operational conditions.

3.4. Comparative analysis of optimization algorithms

To further validate the efficacy of the PSO algorithm with sine-cosine acceleration coefficients (SCAC) in stabilizing voltage and frequency control, comparative simulations were run using three recent optimization algorithms: the Grey Wolf Optimizer (GWO), Salp Swarm Algorithm (SSA), and Whale Optimization Algorithm (WOA). These algorithms were selected for their adaptability to power system applications and unique approaches to balancing exploration and exploitation in complex control environments. Each algorithm was configured with equivalent population sizes and iteration limits for a fair comparison, and all simulations were conducted in MATLAB. The PSO-SCAC approach, GWO, SSA, and WOA were used to tune the PI controller in the hybrid wind-diesel system. In Table 3, the comparative perfor-mance of Peak Overshoot and Setting Time for both frequency (ΔF) and voltage (V) control is presented, demonstrating each algorithm's response to similar load disturbances. Lower overshoot and faster setting times indicate improved stability and re-sponsiveness across the various optimization approaches.

The results demonstrate that while PSO-SCAC achieves the lowest peak overshoot and setting time, GWO and WOA also perform effectively in maintaining system stability. The SSA algorithm shows comparatively higher overshoot and longer settling times, highlighting the strengths of PSO-SCAC in achieving precise control under varying conditions. These findings confirm the robustness of the PSO-SCAC method, underscoring its superior convergence speed and re-duced fluctuation control relative to recent optimization methods.

4. Conclusion

This study presents a robust voltage and frequency control strategy for a hybrid wind-diesel power system, leveraging a Particle Swarm Optimization (PSO)-tuned Static VAR Compensator (SVC) to maintain stability under variable load conditions and wind speeds. The optimization employs Sine-Cosine Acceleration Coefficients (SCAC), allowing for adaptive tuning of the PI controller to respond quickly and effectively to dynamic changes in load and generation. Sim-ulation results highlight the system's ability to minimize voltage and frequency deviations, particularly with SVC Types 2 and 3, which provide the fastest response times and effectively minimize voltage latency. By adjusting reactive power in real-time, the SVC addresses voltage discrepancies induced by load perturbations, while the PI controller en-hances frequency stability even as active power generation varies. The coordinated frequency-voltage control loop demonstrates improved convergence, maintaining voltage and frequency within acceptable bounds across different op-erating conditions. This approach significantly reduces peak overshoot and settling times, thereby minimizing system oscillations and achieving a more resilient performance. These findings underscore the applicability of the PSO-optimized SVC control strategy for real-world hybrid systems, where rapid adaptation and robust control are es-sential for integrating renewable energy sources reliably. This solution holds promise for enhanced stability, reduced fluctuations, and a streamlined path to steady-state operation, demonstrating its effectiveness in meeting the complex demands of hybrid power systems.

Funding: This research received no external funding.

Data availability statement: All data used to support the findings of this study are included in the article.

Conflicts of interest: The authors declare no conflict of interest.

References

[1] A. R. Jordehi, "Particle swarm optimisation (pso) for allocation of facts devices in electric transmission systems: A review," *Renewable Sustainable Energy Rev.*, vol. 52, pp. 1260–1267, 2015.

[2] A. R. Jordehi, "Time varying acceleration coefficients particle swarm optimisation (tvacpso): A new optimisation algorithm for estimating parameters of pv cells and modules," *Energy Convers. Manage.*, vol. 129, pp. 262–274, 2016.

[3] A. R. Jordehi, "A review on constraint handling strategies in particle swarm optimisation," *Neural Comput. Appl.*, vol. 26, pp. 1265–1275, 2015.

[4] A. Rezaee Jordehi and J. Jasni, "Parameter selection in particle swarm optimisation: a survey," *J. Exp. Theor. Artif. Intell.*, vol. 25, no. 4, pp. 527–542, 2013.

[5] A. R. Jordehi, "Enhanced leader pso (elpso): a new pso variant for solving global optimisation problems," *Appl. Soft Comput.*, vol. 26, pp. 401–417, 2015.

[6] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proc. ICNN'95-Int. Conf. Neural Networks*, vol. 4, pp. 1942–1948, ieee, 1995.

[7] P. K. Guchhait, A. Banerjee, and V. Mukherjee, "Application of posicast controller with svc in wind-diesel hybrid power system model," *SN Appl. Sci.*, vol. 3, pp. 1–16, 2021.

[8] B. Sadeghi, N. Shafaghatian, R. Alayi, M. El Haj Assad, F. Zishan, and H. Hosseinzadeh, "Optimization of synchronized frequency and voltage control for a distributed generation system using the black widow optimization algorithm," *Clean Energy*, vol. 6, no. 1, pp. 105–118, 2022.

[9] A. Younesi, H. Shayeghi, and P. Siano, "Assessing the use of reinforcement learning for integrated voltage/frequency control in ac microgrids," *Energies*, vol. 13, no. 5, p. 1250, 2020.

[10] M. A. Labed, M. Benidir, H. Sekhane, and M. Zellagui, "Solving the optimal power flow problem in transmission power system with svc using the adaptive acceleration coefficients pso algorithms," in *2024 2nd Int. Conf. Electr. Eng. Autom. Control*, pp. 1–5, IEEE, 2024.

[11] P. Sharma, T. Bhatti, and K. Ramakrishna, "Performance of statcom in an isolated wind–diesel hybrid power system," *Int. J. Green Energy*, vol. 8, no. 2, pp. 163–172, 2011.

[12] R. Bansal, T. Bhatti, and D. Kothari, "Automatic reactive power control of isolated wind-diesel hybrid power systems for variable wind speed/slip," *Electr. Power Compon. Syst.*, vol. 32, no. 9, pp. 901–912, 2004.

[13] O. I. Elgerd and H. Happ, "Electric energy systems theory: an introduction," *IEEE Trans. Syst. Man Cybern.*, no. 2, pp. 296–297, 1972.

[14] A. Chatterjee, S. Ghoshal, and V. Mukherjee, "Transient performance improvement of grid connected hydro system using distributed generation and capacitive energy storage unit," *Int. J. Electr. Power Energy Syst.*, vol. 43, no. 1, pp. 210–221, 2012.

[15] M. Ebrahim and M. Moustafa Hassan, "Control of single area power system based on evolutionary computation techniques";," 01 2015.

[16] T. K. Saha and D. Kastha, "Design optimization and dynamic performance analysis of a stand-alone hybrid wind–diesel electrical power generation system," *IEEE Trans. Energy Convers.*, vol. 25, no. 4, pp. 1209–1217, 2010.

[17] J. Kenfack, F. P. Neirac, T. T. Tatietse, D. Mayer, M. Fogue, and A. Lejeune, "Microhydro-pv-hybrid system: Sizing a small hydro-pv-hybrid system for rural electrification in developing countries," *Renewable Energy*, vol. 34, no. 10, pp. 2259–2263, 2009.

[18] P. Sharma, W. Sulkowski, and B. Hoff, "Dynamic stability study of an isolated wind-diesel hybrid power system

with wind power generation using ig, pmig and pmsg: A comparison," *Int. J. Electr. Power Energy Syst.*, vol. 53, pp. 857–866, 2013.

[19] M. Jain, V. Saihjpal, N. Singh, and S. B. Singh, "An overview of variants and advancements of pso algorithm," *Appl. Sci.*, vol. 12, no. 17, p. 8392, 2022.

[20] X.-S. Yang and S. Deb, "Cuckoo search via lévy flights," in *2009 World Congr. Nat.Biol. Inspired Comput.*, pp. 210–214, Ieee, 2009.

[21] S. A. Mousavi, M. Mehrpooya, and M. Delpisheh, "Development and life cycle assessment of a novel solar-based cogeneration configuration comprised of diffusion-absorption refrigeration and organic rankine cycle in remote areas," *Proc. Saf. Environ. Prot.*, vol. 159, pp. 1019–1038, 2022.

[22] A. Ebrahimi, B. Ghorbani, M. Delpisheh, and M. H. Ahmadi, "A comprehensive evaluation of a novel integrated system consisting of hydrogen boil-off gas reliquifying process and polymer exchange membrane fuel cell using exergoeconomic and markov analyses," *Energy Rep.*, vol. 8, pp. 1283–1297, 2022.

[23] T. Parikhani, M. Delpisheh, M. A. Haghghi, S. G. Holagh, and H. Athari, "Performance enhancement and multi-objective optimization of a double-flash binary geothermal power plant," *Energy Nexus*, vol. 2, p. 100012, 2021.

[24] H. Athari, F. Kiasatmanesh, M. A. Haghghi, F. Teymourzadeh, H. Yagoublou, and M. Delpisheh, "Investigation of an auxiliary option to meet local energy demand via an innovative small-scale geothermal-driven system; a seasonal analysis," *J. Build. Eng.*, vol. 50, p. 103902, 2022.

[25] M. Hekmatshoar, M. Deymi-Dashtebayaz, M. Gholizadeh, D. Dadpour, and M. Delpisheh, "Thermoeconomic analysis and optimization of a geothermal-driven multi-generation system producing power, freshwater, and hydrogen," *Energy*, vol. 247, p. 123434, 2022.

[26] E. Assareh, M. Delpisheh, S. M. Alirahmi, S. Tafi, and M. Carvalho, "Thermodynamic-economic optimization of a solar-powered combined energy system with desalination for electricity and freshwater production," *Smart Energy*, vol. 5, p. 100062, 2022.

[27] E. Jadidi, M. H. Khoshgoftar Manesh, M. Delpisheh, and V. C. Onishi, "Advanced exergy, exergoeconomic, and exergoenvironmental analyses of integrated solar-assisted gasification cycle for producing power and steam from heavy refinery fuels," *Energies*, vol. 14, no. 24, p. 8409, 2021.

[28] X.-S. Yang and S. Deb, "Engineering optimisation by cuckoo search," *Int. J. Math. Modell. Numer. Optim.*, vol. 1, no. 4, pp. 330–343, 2010.

[29] W. Tan, M. Hassan, M. Majid, and H. Rahman, "Allocation and sizing of dg using cuckoo search algorithm," in *2012 IEEE Int. Conf. power Energy*, pp. 133–138, IEEE, 2012.

[30] E. Assareh, M. Delpisheh, E. Farhadi, W. Peng, and H. Moghadasi, "Optimization of geothermal-and solar-driven clean electricity and hydrogen production multi-generation systems to address the energy nexus," *Energy Nexus*, vol. 5, p. 100043, 2022.

[31] A. Abdelaziz and E. S. Ali, "Cuckoo search algorithm based load frequency controller design for nonlinear interconnected power system," *Int. J. Electr. Power Energy Syst.*, vol. 73, pp. 632–643, 2015.

[32] P. Mehta, P. Bhatt, and V. Pandya, "Optimized coordinated control of frequency and voltage for distributed generating system using cuckoo search algorithm," *Ain Shams Eng. J.*, vol. 9, no. 4, pp. 1855–1864, 2018.