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Optimization of Unit Commitment Problems Integrated PV Generation Plants Based on Particle Swarm Optimization Algorithm

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ABSTRACT

The increasing integration of renewable energy sources, particularly photovoltaic (PV) systems, poses significant challenges in the Unit Commitment (UC) problem due to their intermittent and inertial nature. This condition can cause frequency instability during system disturbances, necessitating the development of new strategies to maintain reliable power system operation. This study proposes an enhanced UC optimization framework by integrating conventional thermal generating units, PV plants, and energy storage systems (ESS) that act as virtual inertia providers. To solve the optimization problem while considering various technical constraints—such as ramping limits, minimum on/off times, rotating reserve requirements, and nadir frequency thresholds—a modified Particle Swarm Optimization (PSO) algorithm is employed. The model is tested on a generating system consisting of nine thermal units, one PV plant, and one ESS. Simulation results show that the proposed method is capable of maintaining the system frequency above the nadir threshold of 49.5 Hz during disturbances while minimizing the total operating cost. Specifically, the optimal configurations without nadir constraints and with ESS integration achieve convergence in only four iterations with a computational time of 1.9 seconds. These findings demonstrate the effectiveness of integrating ESS as virtual inertia and the efficiency of a modified PSO algorithm in handling UC in systems with high renewable energy penetration. This framework offers a promising approach to improving cost efficiency and frequency stability in future renewable energy-based power systems.

Keywords: Particle Swarm Optimization; PSO; Unit Commitment; Frequency Nadir; Photovoltaic.

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I. INTRODUCTION

As time passes, the increase in population and economic growth continues, and the need for domestic electrical energy also increases from year to year [1]. To ensure a reliable electricity supply and increase the reliability of the electric power system, electricity supply does not only depend on non-thermal power plants but also involves thermal plants that help conserve fossil fuels, which are essential for maximizing the fulfilment of the electrical energy load [2]. Technically, not all plants are operated simultaneously to serve all existing electricity load needs. This cause can be influenced by various factors, including maintenance, characteristics, generating capacity, and generation costs, among others [3]. Therefore, in this study, a simulation of scheduling plant operations was conducted to optimize resource utilization. The increasing demand for electrical power results in a substantial amount of electrical power entering the plant. The load conditions that the plant must supply are always changing, so the transmission of electrical energy must follow the energy generated by the plant and the amount of load that must be supplied to obtain the most economical generation cost [4].

The electricity load, which is constantly changing and will continue to increase from year to year, requires power plants using non-renewable fuels to adjust their energy production by incorporating renewable energy sources, the cost of generation remains economical [5]. The amount of electrical energy produced should be as close as possible to the amount of load that must be supplied. The operation of the electric power system in the generation area involves adjusting the output power, as well as switching on and off the generating units to balance the load. To overcome the large electricity load, the government constructed power plants with a high-power capacity. In its operation, careful arrangements are needed, both in terms of load, power, and fuel management. The goal is to strike a balance between the plant's power supply and the power needs that must be met.

The primary principle of UC is to minimize the overall cost of generation while ensuring the system still meets the load requirements, thereby maintaining the safety and stability of the system. Analysis of the effect of frequency on the optimization of

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UC problems has been described, with some involving the influence of renewable energy sources or load fluctuations [6][7][8][9][10]. UC is an optimization problem in an electric power system to determine the combination of generating units operated at each time interval to minimize total operating costs, including fuel costs, start-up, and shut-down, while meeting technical constraints such as generation capacity, minimum up/down time, and system reliability [11][12]. The UC problem has been implemented in wind power generation with an AI algorithm [13]. This is due to the intermittent and uncertain nature of renewable generation, which requires more accurate load and power predictions. Previous research has primarily focused on conventional and renewable energy generation that already possesses an inertia value. The Particle Swarm Optimization algorithm has been proven capable of solving optimization problems in MPPT and economic generation scheduling systems [14][15][16][17].

Renewable energy analysis plays a significant role in meeting current energy needs [18] Wind power generation, a renewable energy source, possesses the same inertial properties as conventional power generation [19] Inertia in energy sources significantly impacts frequency performance; when inertia decreases, the electrical frequency also decreases, affecting the system's generator performance[20]. Batteries are an alternative to accommodate inertia requirements [21]. Therefore, the UC problem faces its greatest challenge when PV generation, which lacks inertia, becomes more prevalent. PV generation penetration will reduce the total system inertia, resulting in a decrease in system frequency.

This research makes a new contribution to the optimization of Unit Commitment (UC) by considering the penetration of PV generation, which lacks natural inertia properties, and the use of batteries as a virtual source of inertia to maintain the stability of the electric power system's frequency. In contrast to previous research, which has mostly focused on conventional power generation units or renewable energy sources with natural inertia, such as wind farms, this study explicitly integrates inertia-less PV generation, thereby posing a new challenge to frequency stability. To address this problem, batteries are modelled as virtual inertia providers, playing a crucial role in compensating for the decline in system inertia resulting from PV penetration. In solving complex and nonlinear UC problems, the Particle Swarm Optimisation (PSO) algorithm has been employed, which has been proven to be reliable and efficient in addressing various optimization problems, including the scheduling of power plants and renewable energy systems. With this approach, the research not only contributes to reducing operating costs and improving system reliability but also provides adaptive solutions to changes in system dynamics resulting from the large-scale integration of renewable energy sources without inertia.

II. METHOD

A. PSO Method

The workflow (Fig.1) for the PSO algorithm used in this study to solve the unit commitment problem.

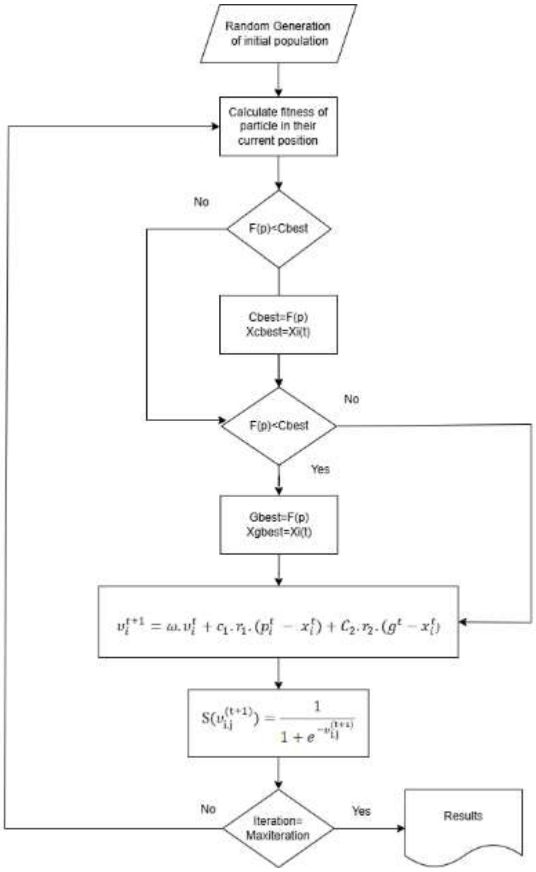

Fig.1. Flowchart Particle Swarm Optimization

The process begins with the random generation of the initial population, where each particle represents a candidate solution in the form of the ON/OFF status of the generating unit over a time horizon. Furthermore, the fitness value of each particle is calculated based on the total operating cost of the electric power system. If the fitness value of a particle is better than the previous personal best (Pbest) value, then Pbest is updated with that value. Similarly, if the best fitness value of all particles is better than the previous global best (Gbest), then Gbest is updated.

After the Pbest and Gbest value updates, the particle velocity was calculated using a conventional PSO equation involving the components of inertia, individual (cognitive), and social attraction. Then, the velocity is converted to probability using the sigmoid function, and the particle's position is updated based on a sampling method that corresponds to the probability, which reflects the characteristics of the PSO binary. This process is repeated until the termination criteria are met, i.e., the maximum number of iterations has been reached. The final solution obtained is the particle with the best fitness value (Gbest), which represents the optimal combination of generating units during the planning period.

B. Objective Function

The objective function for Equation (1) of this study is to minimize the variable production cost, which includes the initial cost and fuel cost for generation over a given period in the Day Ahead UC (DAUC) problem. The objective function of the Unit Commitment (UC) issue aims to minimize the total operating costs of the power generation system over the time horizon T. Where $\boldsymbol{Ci}$ is unit *fuel cost i* (in cost/MWh), the $\boldsymbol{Pi,t}$ variable is the power generated by the unit *i* at time *t,* and $\boldsymbol{SUi}$*,* $\boldsymbol{SDi}$ is start-up and shut-down unit *costs i*.

$$min \sum_{t=24}^{T} \left(\sum_{i=1}^{N}[Ci.Pi,t + SUi.u_{i,t}^{on} + SDi.u_{i,t}^{off}]\right); \tag{1}$$

$$u_{i,t}^{on} = \text{Other}\begin{cases} 1\,, & If\ the\ unit\ turns\ on\ at\ t\ and\ \ turns\ off\ at\ t-1 \\ 0\,, & else \end{cases}$$

$$\boldsymbol{u_{i,t}^{off}} = \text{Other}\begin{cases} \boldsymbol{1}\,, & \boldsymbol{If\ the\ unit\ turns\ off\ at\ t\ and\ \ turns\ on\ at\ t-1} \\ \boldsymbol{0}\,, & \boldsymbol{else} \end{cases}$$

C. Production Costs

The total operational cost of the power generation system in the unit commitment planning period is calculated using Equation (2). Where C_i is unit fuel cost to – i(in [\$/MWh] or [Rp/MWh]), the $P_{i,t}$ variable for the power generated by the unit *i* at time t, and SU_i, SD_i is a start-up and shut-down unit *costs i.*

$$Total\ Cost\ = \sum_{t=1}^{T}\sum_{i=1}^{N}(C_i.P_{i,t} + SU_i.u_{i,t}^{on} + SD_i.u_{i,t}^{off}); \tag{2}$$

$$u_{i,t}^{on} = \text{Other}\begin{cases} 1\,, & If\ the\ unit\ turns\ on\ at\ t\ and\ \ turns\ off\ at\ t-1 \\ 0\,, & else \end{cases}$$

$$\boldsymbol{u_{i,t}^{off}} = \text{Other}\begin{cases} \boldsymbol{1}\,, & \boldsymbol{If\ the\ unit\ turns\ off\ at\ t\ and\ \ turns\ on\ at\ t-1} \\ \boldsymbol{0}\,, & \boldsymbol{else} \end{cases}$$

The start-up cost, which is the cost incurred when the generating unit changes from OFF to ON, is calculated using Equation (3). Where, the $SC_{i,t}$ variable is the start-up cost for the unit to – i at time *t*, the SU_i variable is the start-up cost of the first unit, and the $U_{i,t}$ variable is an ON/OFF (1/0) status of the unit to – *i* at time *t*.

$$SC_{i,t} = SU_i.(U_{i,t} - U_{i,t-1})\ Jika\ U_{i,t} = 1\ danU_{i,t} = 0 \tag{3}$$

The shut-down fee is charged when the unit changes from ON to OFF during 24 hours, calculated using Equation (4). Where, the $SDC_{i,t}$ variable is the shut-down cost for units to *-i* at time *t*, and the SD_i variabel is unit shut-down fee to *-i*.

$$SDC_{i,t} = SD_i\,.(U_{i,t-1} - U_{i,t})\ jika\ U_{i,t} = 1\ dan\ U_{i,t} = 0 \tag{4}$$

D. Unit Limitations

1). Power Generation Limitations: Each generator unit can only generate power within a certain range, depending on the ON/OFF condition of the unit. This is explained in Equation (5). Where, the P_i^{min}, P_i^{max} variable is minimum and maximum power limits of the I-I unit, and $U_{i,t}$ is ON/OFF status of the unit *(1 if on, 0 if off)*$U_{i,t}\{0,1\}$. If the unit is OFF, then the output is limited according to the characteristics of the unit.$P_{i,t} = 0$.

$$P_i^{min}.U_{i,t} \leq\ P_{i,t} \leq\ P_i^{max}.U_{i,t} \tag{5}$$

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2). Ramp Speed Limit: The ramp rate limits the intermittent power change for each active unit so that there are no sudden spikes that endanger the stability of the system or damage the equipment using Equation (6). Where the RR_i^{down} variable is ramp down rate, the RR_i^{up} variable is the ramp-up rate (maximum increase), which is only valid when the unit is switched on simultaneously.

$$-RR_i^{down} .\leq \; P_{i,t} - P_{i-t} \leq \; RR_i^{UP} \tag{6}$$

E. System Limitations

1). System Power Balance: This Equation states that at any time *t*, the total amount of power generated by all sources (conventional plants, PV, and ESS) should be equal to the total load $P_{load,t}$ demand, explained in Equation (7). Where, the $P_{i,t}$ variable is power from the third unit at *time t,* the $P_{ESS,t}$ variable is power from the storage system (positive = discharge, negative = charge), the $P_{PV,t}$ variable is output power from PV (solar panel), and the $P_{load,t}$ variable is system load at *time t.*

$$\textstyle\sum_{i=1}^{N} P_{i,t} + P_{pv,t} + P_{ess,t} = P_{load,t} \tag{7}$$

2). Spinning Reserve System: In Equations (8) and (9) the total available spinning reserve of all active generating units at any given time must be greater than or equal to the system's rotational reserve requirement at each hour *t*. This rotary reserve is crucial for maintaining the reliability of the electric power system in the event of sudden disruptions, such as power plant outages or load spikes. Where the $[P_{Gmax}(k) - P_G(k,t)]U(k,t)$ variable indicates the spare capacity of unit k if the unit is in operation. These equations ensure that the accumulated reserves of all units in operation are sufficient to meet the system's backup demands.

$$\textstyle\sum_{k=1}^{N}[P_{Gmax}(k) - P_G(k,t)]U(k,t) \geq S_{req}(t)\,, 1 \leq t \leq 24 \tag{8}$$

$$\textstyle\sum_{k=1,k\neq i}^{N}[P_{Gmax}(k)U(k,t) - P_G(k,t)] \; \geq P_G(i,t), 1 \leq t \leq 24\,, 1 \leq i \leq N \tag{9}$$

F. Time-Dependent Limitations

This constraint ensures that the unit is not turned on or off too frequently, which can lead to premature wear and tear and energy waste.

1). Minimum Up Time: In Equation (10), if the unit is on, then it must be on at *UTi time*

$$\textstyle\sum_{T\,=\,t}^{t+DTi-1} U_{i,T} \geq UT_i(startup) \tag{10}$$

2). Minimum Down Time: In Equation (11), if the unit is turned off, then the unit must remain dead for the minimum time *of Dti.* Where, the UT_i variable is Minimum on-up time (Hours), and DT_i for the minimum outage time (Hours).

$$\textstyle\sum_{T=t}^{t\,+\,DTi\,-\,1}(1 \; - \; U_{i,t}) \geq DT_i(shutdown) \tag{11}$$

The limit of active power in the energy storage system (ESS) at time t, which regulates the amount of power that can be absorbed (charged) by the ESS or discharged to the system, is given by this Equation in Equation (12).

$$-P_{ess}^{max} \leq P_{ess,t} \leq P_{ess}^{max} \tag{12}$$

This serves to ensure that there will be adequate inertia in the system to avoid frequency instability, including Equation (13) for the limitations

$$H_{\mathrm{sys}}(t) = \textstyle\sum_{k=1}^{N} U(k,t)\, H(k) \frac{S_B(k)}{S_B}\,, 1 \leq t \leq 2 \tag{13}$$

G. Nadir and Rocof Frequencies

1). RoCof (Rate of Change of Frequency): In Equation (14) RoCoF is caused by the power imbalance and is directly related to the total inertial constant [22].

$$RoCoF = -\frac{\Delta P}{2H_{total}} \tag{14}$$

2). Nadir Frequency: In Equation (15) is used by European system operators as a minimum frequency guide (e.g. 49 Hz) and how nadirs are affected by RoCoF and primary responses [23]. Where, the F_0 variable is system nominal frequency 50 Hz, the ΔP variable is power imbalance (MW) power load, and the H_{sys} variable is total inertia constant, and the Δ_t variable is iime interval of decline (seconds), often taken Δt=1 second as an initial estimate

$$F_{nadir} = F_0 + \frac{-\Delta P}{2H_{sys}} \,.\, \Delta_t \tag{15}$$

Equation (16), it can be known that the Equation for the lowest frequency nadir frequency constraint is reached by the electric power system when there is a major disturbance, if (for example, 49.0 Hz), then the system violates the frequency stability limit.$F_{nadir} < F_{min}$.

$$F_{nadir} \geq F_{min} = 49.0\ Hz \tag{16}$$

III. RESULT AND DISCUSSION

A. Data System

To conduct the unit commitment simulation, this study utilizes technical data from nine power generation units. The parameters of the system, including inertia, and the frequency constraints of these units are detailed in Table I. Technical data from 9 generating units (PG 1 to PG 9) used in the study of commitment units are shown, considering system inertia parameters and frequency constraints.

The PG1 to PG3 are large units with a maximum capacity of between 250–300 MW, an *Hsys* value of 3.75 seconds, and a pseudo-power of up to 500 MVA, indicating their primary role in maintaining system stability. PG4 to PG6 are intermediate units with a capacity of 150–200 MW and an Hsγs of about 1,125 seconds. Meanwhile, PG7 to PG9 are small units with a maximum power of 100–150 MW and a relatively lower *Hsys*, which is 1,313 seconds for PG7 and PG8, and only 0.366 seconds for PG9, reflecting a smaller inertia contribution to the system.

TABLE I
SYSTEM DATA

Unit	K ( )pu	T (seconds)	H_{sys} (seconds)	P_{Gmax} (MW)	P_{Gmin} (MW)	S (MVA)	Generator (Type)
PG1	8.4	2.3	3.75	300	100	500	Coal
PG2	8.4	2.3	3.75	300	100	500	Coal
PG3	8.4	2.4	3.75	250	80	500	Gas
PG4	8.4	2.7	1.125	200	60	150	Diesel
PG5	2.4	2.8	1.125	200	60	150	Diesel
PG6	2.4	2.8	1.125	150	40	150	Geothermal
PG7	2.8	3	1.313	150	40	175	Geothermal
PG8	2.8	3	1.313	100	20	175	Peaker
PG9	1.7	2.6	0,366	100	20	100	Peaker

The economic and operational parameters of the 9 power generation units used in the unit commitment modelling are presented in Table II. The economic and operational parameters of the 9 power generation units are modelled in the commitment unit. Large units, such as PG1 and PG2, have high start-up and shut-down costs of $500 and $250, respectively, as well as fuel costs of $20/MW. This is natural because large units tend to require more energy and time to make the on-off transition.

In addition, they have a ramp rate of 50 MW/h up and 40 MW/h down, as well as a minimum on-and-off time of 3 hours, signalling limited operational flexibility. Conversely, in small units such as PG8 and PG9, there are low start-up and shut-down costs ($100 and $50), fuel costs of only $5/MW, and higher ramp rates (55 MW/h up and 80 MW/h down), reflecting high flexibility.

TABLE II
SYSTEM DATA

Unit	SUc ($)	SDc ($)	FC $\frac{\$}{MW}$	URR $\frac{MW}{h}$	DRR $\frac{MW}{h}$	MUT (h)	MDT (h)	Generator (Type)
PG1	500	250	300	50	40	3	3	Coal
PG2	500	250	300	50	40	3	3	Coal
PG3	400	200	250	50	50	2	2	Gas
PG4	300	150	200	55	50	2	2	Diesel
PG5	300	150	200	55	50	2	2	Diesel
PG6	200	100	150	55	60	1	1	Geothermal
PG7	200	100	150	55	60	1	1	Geothermal
PG8	100	50	100	55	80	1	1	Peaker
PG9	100	50	100	55	80	1	1	Peaker

Additionally, the minimum on/off time of only 1 hour makes it highly responsive to changes in load or system needs. The technical specifications of the Energy Storage System (ESS) or batteries used in this simulation are presented in Table III. This data shows that the ESS system used is quite efficient and has a large capacity, but with a strict restriction on filling and discharging rates, with a maximum of 20% per time interval. This data is crucial in Unit Commitment simulations, enabling the optimal utilization of the battery without exceeding technical limits, and can help support the system when the plant is unable to meet demand or when the system's frequency begins to decrease.

TABLE III
BATTERY SPECIFICATION

Unit	effDischarge (%)	effCharge (%)	Discharging Maximum (%)	Charging Maximum (%)	Initial Condition Soc (%)	Capacity (MW)
10	95	95	20	20	0	100

B. *Optimal UC results (scenario 1 without ESS and nadir frequency)*

This section presents the results of unit commitment optimization for scenario 1, which assumes a condition without considering the energy storage system (ESS) and without utilizing a nadir frequency constraint. The operational schedule of the 24-hour power plant is presented in Table IV. The results of unit commitment optimization indicate that generating units are operated economically, following load needs and technical limitations. Unit 3 is most often active due to its low operating costs, followed by Units 6 and 9, which have moderate capacity. Units 1 and 2 only operate at certain hours, especially during high loads, such as 14–18 hours (Unit 1) and 11, 12, 14, 19, and 24 hours (Unit 2). The 10 o'clock indicates the minimum generation combination, while the 2 o'clock display shows the highest activity, signalling the peak load. On the other hand, operations from 1 to 4 hours show minimal activity due to a low load in the early morning.

TABLE IV
SCENARIO 1 WITHOUT ESS AND NADIR FREQUENCY

Hour/Unit	1	2	3	4	5	6	7	8	9
1	29	0	0	60	0	0	0	0	0
2	0	0	250	0	0	0	0	0	80
3	0	180	80	0	0	0	40	20	0
4	0	130	80	0	0	0	40	20	0
5	0	0	180	0	0	40	0	20	0
6	0	0	250	0	0	40	0	20	0
7	0	120	80	0	60	40	0	0	20
8	140	0	80	0	0	40	40	0	20
9	110	0	80	0	60	40	40	0	20
10	0	0	0	0	0	150	0	0	100
11	0	250	80	0	0	0	40	20	0
12	0	300	0	0	0	40	40	20	20
13	0	0	80	60	0	0	0	0	20
14	280	220	80	60	60	0	0	0	20
15	180	0	80	60	60	0	40	0	20
16	300	0	0	0	100	0	40	20	0
17	260	100	0	60	0	40	0	0	0
18	280	100	0	0	0	40	40	0	0
19	0	300	0	60	0	40	0	20	20
20	140	100	80	0	60	0	0	20	20
21	300	0	0	0	60	0	40	0	0
22	0	0	220	60	0	40	40	0	20
23	0	0	250	0	0	40	80	0	0
24	0	280	0	0	60	0	0	0	20

Fig. 2 of this graph indicates that although most of the system's time is within the sTable limits, there are two critical hours (around the 15th and 17th hours) where the nadir frequency falls below the safe threshold of 49.5 Hz, indicating the need for improved dispatch strategies or the addition of inertia/ESS to maintain system stability.

Fig.2. Frequency of the Nadir System Method 1

The results of the unit commitment optimization process for scenario 1, including the best cost computation time achieved in each iteration, are summarised in Table V. The results of the optimization process indicate that the best cost value has decreased significantly by the third iteration. In the first two iterations, the PSO algorithm generated the same optimal cost, which was IDR 5,891,340.62, indicating the stability of the temporary solution. However, in the third iteration, the algorithm managed to find a more optimal solution by lowering the cost to Rp 5,288,550.00, and this value remained until the fourth iteration. This indicates that the algorithm has converged to the optimal solution in four iterations.

TABLE V
Cost of Scenario 1 Result

Iteration	Computation Time (Seconds)	Cost (Rs)
1	1,5	IDR 5,891,340.62
2	1	IDR 5,891,340.62
3	1,5	IDR 5,288,550,00
4	1	IDR 5,288,550,00

C. *Optimal UC results (scenario 2 without ESS and with nadir frequency)*

The optimal unit commitment results for scenario 2, i.e., conditions without an energy storage system (ESS) but considering the nadir frequency constraint, are presented in Table VI. This schedule displays the power output of nine generating units over a 24-hour period. The power output schedule of nine generating units over 24 hours, considering the frequency constraint and PV integration. Units 1 and 2 alternately supply large amounts of power, especially when an inertial contribution is required, such as at 4–8 and 13–14 hours (Unit 1). Units 3 and 4 are used flexibly to meet the main load at various times. Units 6 and 7 are only active occasionally, presumably for frequency recovery. Unit 9, assumed to be PV, is active during daylight hours, making a small but significant contribution. The presence of PV leads to the need for inertial compensation by other units. The dominance of Unit 1 at certain hours shows its role in maintaining system stability when PV is inactive.

TABLE VI
Scenario 2 without ESS and with frequency constraint

Hour/Unit	1	2	3	4	5	6	7	8	9
1	0	300	0	0	0	0	0	0	50
2	0	0	250	80	0	0	0	0	0
3	0	0	0	200	0	0	120	0	0
4	300	0	0	0	0	0	0	0	0
5	300	0	0	0	0	0	0	0	0
6	300	0	0	0	0	0	0	0	0
7	300	0	0	0	0	0	0	0	20
8	300	0	0	0	0	0	0	0	0
9	0	0	0	200	0	150	0	0	0
10	0	0	0	200	0	0	0	100	60
11	0	0	0	200	0	150	40	0	0
12	0	0	250	170	0	0	0	0	0
13	300	0	140	0	0	0	0	0	0
14	300	140	0	0	0	0	0	0	0
15	0	0	250	0	190	0	0	0	0
16	0	300	160	0	0	0	0	0	0
17	0	300	160	0	0	0	0	0	0
18	0	300	160	0	0	0	40	0	0
19	0	300	140	0	0	0	0	0	0
20	0	0	250	0	0	0	150	0	20
21	0	300	100	0	0	0	0	0	0
22	0	0	0	0	200	0	0	0	0
23	300	0	0	70	0	0	0	0	0
24	0	300	0	0	0	60	0	0	0

Fig.3 shows the system's nadir frequency profile over 24 hours. This graph illustrates the lowest post-interruption frequencies per hour, with the horizontal axis representing time (1–24 hours) and the vertical axis representing the nadir frequency (Hz). There was an increase in frequency at approximately 50.1 Hz, followed by a spike to nearly 50.4 Hz at 17–18 hours, indicating an excess of power (supply exceeding demand). In general, the system can keep the frequency within safe limits, but the 5th and 17th to 18th hours require special attention. The unit commitment setting is effective, but it can still be refined to reduce over-frequency spikes. Table VII presents a summary of the results from the optimization iteration for Scenario 2, including the best computation time and operational costs achieved.

Based on Table 7, the optimisation results indicate a gradual decrease in operational costs, from Rp 9,200,000.00 in the first iteration to Rp **7,200,000.00** in the fifth iteration. After that, the cost stabilizes until the sixth iteration, indicating that the algorithm has converged to the optimal solution.

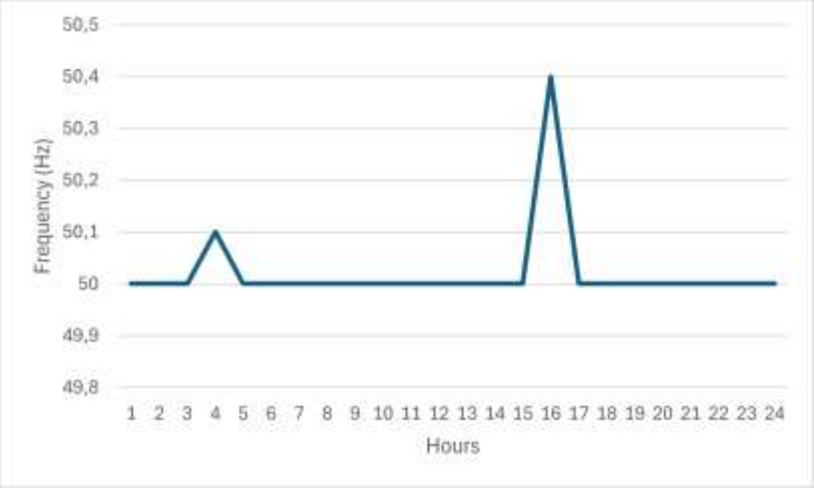

Fig.3. Frequency of the Nadir System Method 2

TABLE VII
SCENARIO ITERATION RESULTS 2

Iteration	Computation Time (Seconds)	Cost (Rs)
1	0,25	IDR 9,200,000,00
2	0,25	IDR 8,800,000,00
3	0,25	IDR 7,200,000,00
4	0,25	IDR 7,200,000,00

D. *Optimal UC results (scenario 3 with ESS and without nadir frequency)*

Table VIII presents the schedule of unit commitment results from the optimization for 24 hours, covering 9 generation units in scenario 3, specifically conditions with energy storage system (ESS) integration and without nadir frequency constraints. The schedule of commitment units for the optimization results over 24 hours for nine power generation units is displayed. Each row displays the hourly power output, and each column represents a single generating unit. The composition of the operating unit varies according to load demands, unit characteristics, and system limitations, such as minimum up/down times, ramp rates, and nadir frequencies. Units 1, 3, and 5 often operate as base loads or intermediates, while units 2 and 4 are only active when the load is high, serving as peakers. Simultaneous activation of several units at 1, 13, and 17 hours indicates a surge in power demand. This schedule reflects optimal strategies that consider the efficiency, flexibility, and security of the system, including the integration of renewable energy and energy storage if used.

TABLE VIII
SCENARIO 3 WITH ESS AND WITHOUT NADIR FREQUENCY

Hour/Unit	1	2	3	4	5	6	7	8	9
1	130	0	80	0	60	40	0	20	20
2	110	0	80	60	0	0	40	20	20
3	260	0	0	0	0	0	40	20	0
4	0	270	0	0	0	40	0	0	0
5	0	0	0	200	0	40	60	0	0
6	0	0	190	0	60	0	40	20	0
7	0	0	140	60	60	0	40	20	0
8	0	0	0	180	60	40	40	0	0
9	130	0	80	0	60	40	0	20	20
10	0	0	0	200	60	40	40	0	20
11	0	210	0	0	60	40	40	20	20
12	0	220	80	0	60	40	0	0	20
13	240	100	0	60	0	0	0	20	20
14	300	0	80	60	0	0	0	0	0
15	100	100	80	0	60	40	40	0	20
16	240	0	80	0	60	0	40	20	0
17	300	0	0	0	0	0	140	0	20
18	0	0	250	0	90	40	40	20	20
19	0	0	0	200	0	0	150	0	0
20	0	0	250	0	0	0	150	0	0
21	0	0	250	0	0	130	0	20	0
22	0	0	200	60	60	40	0	20	0
23	170	0	80	0	60	0	40	20	0
24	140	100	80	0	0	0	40	0	0

Fig. 4. Nadir Frequency Method System 3

Fig. 4 The nadir frequency profile of the electric power system for 24 hours. In general, the value of the nadir frequency is above the minimum permissible limit, which is 49.5 Hz, as indicated by the red dotted line on the graph. This indicates that at most hours, the system has an adequate reserve of inertia to respond to interference and maintain frequency stability. However, there was a significant decrease in nadir frequency around the 19th hour, when the value approached the minimum threshold. This decrease indicates that at that hour, the system is experiencing a lack of inertia, likely caused by the inoperability of the generating unit with a large inertial contribution. This condition makes the system more vulnerable to interference, so special attention is required in unit commitment planning to maintain the overall system reliability.

Table IX summarises the results of operational costs and computational time achieved during the optimisation process for Scenario 3. Operational costs decreased significantly from IDR 7,298,980.00 in the first iteration to IDR 5,986,278.12 in the second iteration, and remained stable until the fourth iteration. This shows that the algorithm achieves rapid convergence towards the optimal solution.

TABLE IX
COST OF OUTCOME SCENARIO 3

Iteration	Computation Time (Seconds)	Cost (Rs)
1	2,3	IDR 7,298,980,00
2	1,9	IDR 5,986,278,12
3	2,3	IDR 5,986,278,12
4	1,9	IDR 5,986,278,12

E. *Iteration results of scenarios 1,2, and 3.*

This section presents a comparative analysis of the optimization results of the three scenarios discussed earlier. Table X summarizes the key differences in iteration, computation time, and best achieved cost. A comparison of the three Unit Commitment scenarios. Scenarios without ESS and nadir frequency constraints resulted in the lowest cost (Rp 5,288,550.00) with 4 iterations and 7 seconds of computation. When the nadir frequency is considered without ESS, the cost increases significantly to Rp 7,200,000.00, despite the faster computation.

Meanwhile, the use of ESS without a frequency constraint resulted in a medium cost (Rp 5,986,278.12) with the same time and iteration as the first scenario. This indicates that ESS contributes to cost efficiency; however, frequency caps increase the total system cost. Nevertheless, with this nadir frequency capping, frequencies become safer and more reliable.

TABLE X
ITERATION RESULTS OF SCENARIOS 1, 2, AND 3

No.	Scenario	Number of Iterations	Computation Time (Seconds)	Best Cost (Rs)
1.	No ess and no rare frequencies	4	5	IDR 5,288,550,00
2.	No ess and using rare frequencies	8	1	IDR 7,200,000,00
3.	With ess without nadir frequency	4	8,4	IDR 5,986,278,12

F. *Differences in the simulation results of scenario 1, scenario 2, and scenario 3.*

To provide a clearer picture of the impact of each scenario, Table XI presents a detailed comparison of the differences in characteristics and performance of the three methods tested. A comparison of the three tested methods revealed distinct characteristics and performance in terms of frequency stability, operational efficiency, and resource utilization for generation. In Method 1, where neither the Energy Storage System (ESS) nor the nadir frequency constraint is used, the system focuses solely on operating cost savings. Method 2, which integrates the nadir frequency constraint but still does not use ESS, yields more stable results in terms of system frequency.

The nadir frequency was successfully maintained above the safe limit of 49.5 Hz, despite over-frequency at certain hours due to power surplus. Meanwhile, Method 3 relies on ESS to support system operations without directly considering the nadir frequency. ESS is actively utilized, especially when power demand is high, thereby reducing the need for activation of high-cost conventional power generation units.

TABLE XI
DIFFERENCES IN SIMULATION RESULTS OF SCENARIO 1, SCENARIO 2, AND SCENARIO 3.

Aspects	Method 1 (No ESS and No Nadir Frequency)	Method 2 (No ESS, Using Nadir Frequency)	Method 3 (with ESS and without nadir frequency)
Frequency Stability	Not considered	Maintained 49.5 Hz despite over-frequency	Not considered
Use of High Inertial Units	Randomization based on economics	High inertial units (PG1, PG2) are often active at critical hours	Less dominant, substituted for ESS
Operating Efficiency	Economic cost focus	The system meets the stability requirements of the system	Cost optimization with ESS support
Use of ESS	None	None	Used actively, helps when the load is high
Response to Peak Load	Multiple units are active simultaneously	Large units are dominant, adapted to the needs of inertia	ESS and some small units are all active

IV. CONCLUSION

The study evaluates three operational scenarios: scenario one prioritizes economic efficiency without considering system stability, leading to low costs but potentially poor frequency response during disruptions; scenario two incorporates nadir frequency constraints, maintaining frequency stability above 49.5 Hz by operating high-inertia units, albeit with increased operating and start-up costs; and scenario three employs energy storage systems (ESS) without explicit nadir frequency constraints, representing the best balance between efficiency and reliability by reducing reliance on expensive conventional generators and indirectly maintaining system stability. Additionally, the PSO algorithm achieved the minimum cost at 4 iterations within 1.9 seconds, demonstrating its effectiveness and computational efficiency in optimizing operational costs.

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