Coordinated Optimal Power Dispatch Incorporating the Scheduling of Distributed Energy Resources Under the Virtual Power Plant Concept

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ABSTRACT

In this paper, a method is proposed for coordinated optimal power dispatch (OPD) incorporating the scheduling of distributed energy resources (DERs) (COPD-IDS). The proposed COPD-IDS aims to minimize the total daily operating cost of a power system by considering the optimal scheduling of DERs. In the problem formulation, the DERs are considered dispatchable limited energy units and treated as a virtual power plant (VPP). The OPD is solved for total hourly cost minimization, using quadratic programming (QP) as a subproblem in COPD-IDS. Meanwhile, the total daily operating cost minimization incorporating the scheduling of DERs is solved by particle swarm optimization (PSO) and compared to a genetic algorithm (GA). The proposed COPD-IDS is tested on the modified IEEE 30-bus system under a practical load and the daily profiles of DERs. The simulation results show that the proposed method can minimize the total daily operational cost of the electricity system with the dispatchable condition of DERs using the VPP concept.

Keywords: Distributed energy resources, Optimal power dispatch, Particle swarm optimization, Quadratic programming, Virtual power plant

1. INTRODUCTION

The electricity supply industry has been steadily transformed into a more complex structure with distributed energy resources (DERs), vehicle to grid (V2G), energy storage systems (ESSs), and demand responses (DRs). Many of the former electricity consumers have either shifted or planning to shift, their roles to prosumers, requiring the system operators (SOs) and distribution network operators (DNOs) to change their strategies and policies to achieve the best performance [1–2]. Among the many energy policy concepts, a virtual power plant (VPP) is one of the most interesting business models for enhancing the efficiency and reliability of system operation [3–5].

The concept of VPP is illustrated in Fig. 1. By aggregating the DERs in the grid using information technology and advanced metering infrastructure, the non-firm DERs can be dispatched as the power plant but the power inputs are dispersed over the system.

As a result, many studies have proposed VPPs for optimal power system operation, over the past decade. For example, the authors in [6] proposed the optimal scheduling of VPPs using the robust optimization method in the day-ahead electricity markets, where electricity prices are highly uncertain. The proposed method aims to maximize social welfare in the day-ahead market with an offer and bid-based energy trading mechanism. Similarly, a model for evaluating the physical characteristics of the VPP with uncertainties was developed in [7] for day-ahead unit commitment. Meanwhile, day-ahead self-scheduling for a virtual power plant trading in both energy and reserve electricity markets has been proposed in [8]. The method for optimal management of renewable energy sources by VPP has been introduced by [9] to minimize the total operating cost, considering the cost of energy loss during a 24 h time interval. From the players' perspective, the optimal strategies for participating in the power market are interesting. The bidding strategy in the VPP day-ahead and real-time markets, as a price taker, was proposed in [10]. In [11], a VPP bidding strategy for participating in energy and spinning reserve markets was introduced.

However, there are several VPP business models, depending on national energy policies. In addition, VPPs are usually aggregated by renewable energy, which has daily limits, and DR, by shifting the loads. Hence, ESS is the key tool in the management of DERs. It can shift the power during high potential and light load to the high loading period, enabling the DERs to be partially dispatchable or schedulable, as limited distributed energy units (LDERs). The ESS investment is also a crucial issue for both utilities and VPP players. Therefore, the study of cost-effectiveness is essential for encouraging and regulating the players in the system to participate in VPP business under superlative conditions.

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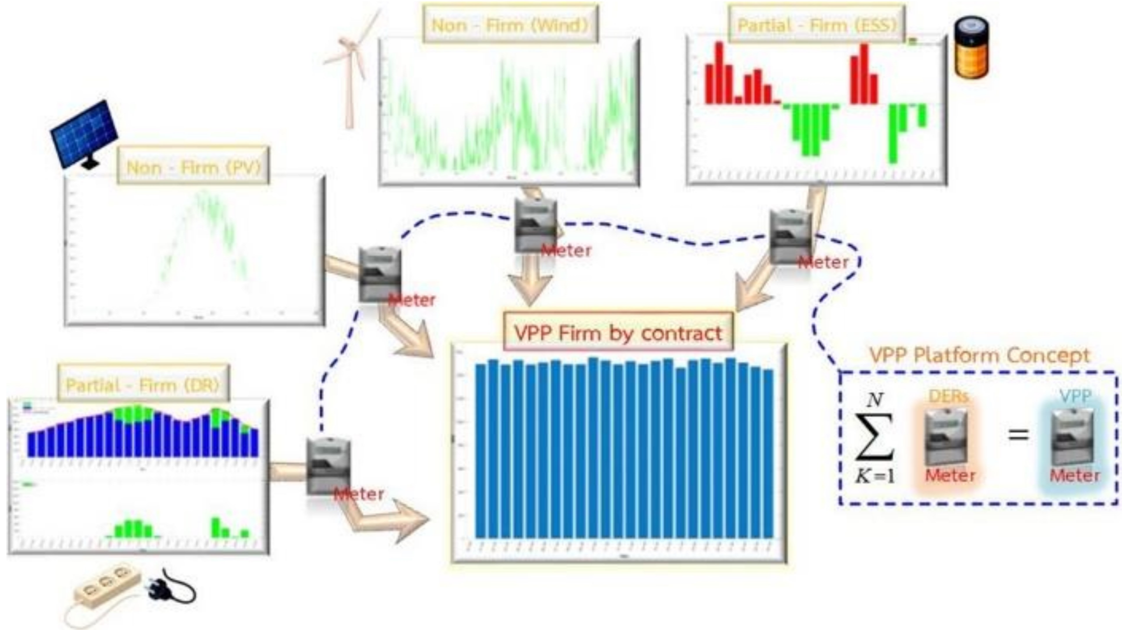

***Fig. 1**: VPP operating concept.*

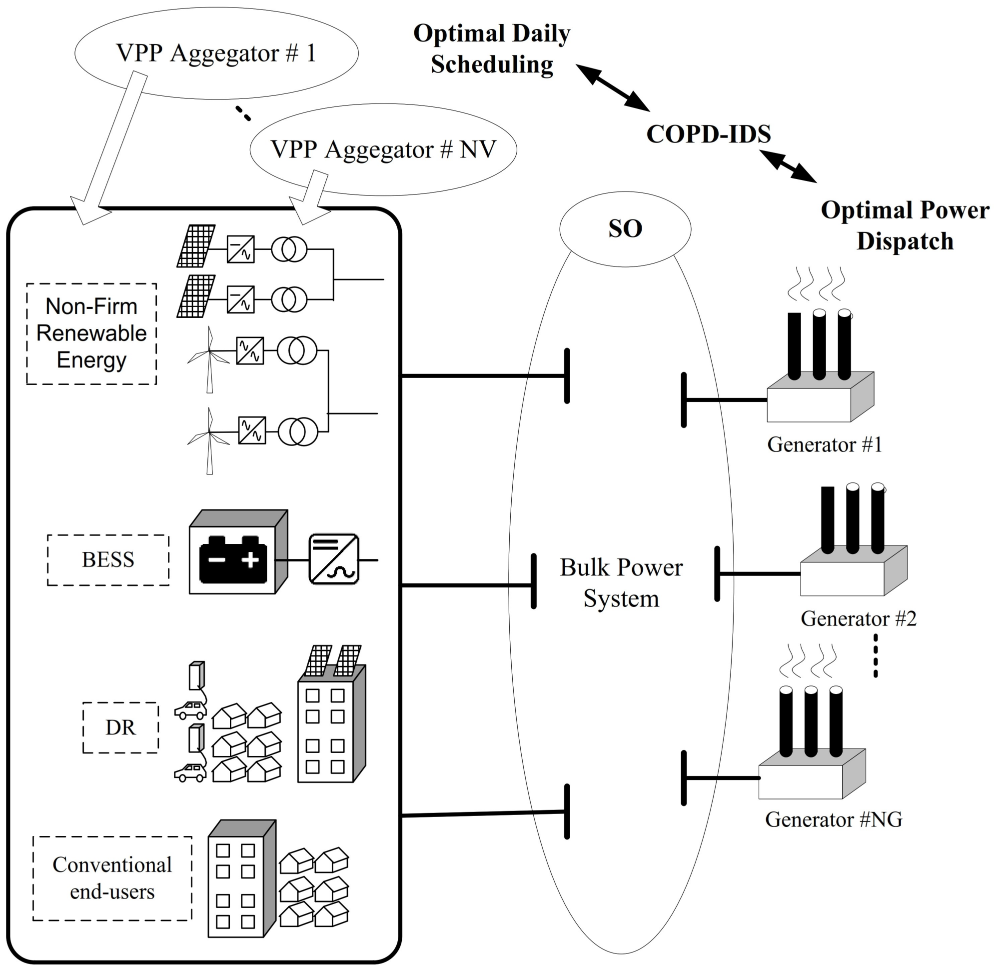

***Fig. 2**: Computational concept of COPD-IDS.*

This paper proposes a method for coordinated optimal power dispatch incorporating the scheduling of DERs (COPD-IDS) when they are dispatchable by the system operator under the VPP concept. The proposed COPD-IDS has been tested with the modified IEEE 30-bus system using practical load and DER daily profiles. Quadratic programming (QP) is used to solve the problem of optimal power dispatch from generators, while particle swarm optimization (PSO) [12] is used for optimal scheduling of DERs and compared to the genetic algorithm (GA) [13]. The cost saving from the dispatchability of DERS is also discussed.

The remainder of this paper is organized as follows. Section 2 addresses the problem formulation of optimal power dispatch considering the DERs as limited energy units. The COPD-IDS under the VPP concept using PSO is illustrated in Section 3. The simulation results for the proposed method with the modified IEEE 30-bus system are presented and discussed in Section 4. Finally, Section 5 provides the conclusion.

2. PROBLEM FORMULATION

In the problem formulation for optimal day-ahead dispatch of distributed limited energy resources (DLERs), the objective function is to find the minimum daily operating cost by utilizing all the DLERs as,

$$\text{Minimize } TDC = \sum_{h=1}^{24} F^h(\mathbf{PG^h}, \mathbf{VPP^h}) + PNF \quad (1)$$

Subject to

$$\sum_{i=1}^{NG} P_{Gi}^h - \sum_{i=1}^{NV} VPP_i^h = \sum_{i=1}^{NB} P_{Li}^h + P_{Loss}, \text{for } h = 1, ..., 24 \quad (2)$$

$$\mathbf{PG^h} = [\mathbf{P_{G1}^h}, ..., \mathbf{P_{GNG}^h}], \text{for } \mathbf{h} = \mathbf{1}, ..., \mathbf{24} \quad (3)$$

$$\mathbf{VPP^h} = [\mathbf{VPP_1^h}, ..., \mathbf{VPP_{NV}^h}], \text{for } \mathbf{h} = \mathbf{1}, ..., \mathbf{24} \quad (4)$$

By treating the VPP as DLERs, the constraint for total daily energy production is,

$$VPPE_i = \sum_{h=1}^{24} VPP_i^h, \text{for } i = 1, ..., NV \quad (5)$$

where

TDC is the total system daily cost,
F^h is the hourly system fuel cost at hour h,
P_{Gi}^h is the real power generation of the generator at bus i at hour h,
VPP_i^h is the real power generation of the VPP at bus i at hour h,
P_{Li}^h s the real power load at bus i at hour h,
P_{Loss} is the real power loss in the system,
NG is the number of generators,
NV is the number of VPPs,
NB is the number of buses,
PNF is the penalty factor applied for constraint violation(s), and
$VPPE$ is the total daily energy production of the VPP at bus i.

The hourly system fuel cost at each hour (F^h) is obtained through the optimal power dispatch of the generators incorporating the specified amount of real power generation of the VPP at hour h (VPP_i^h), which are co-ordinately solved by PSO, as illustrated in the following section, and compared to the GA.

3. COPD-IDS UNDER THE VPP CONCEPT USING PSO

In the proposed COPD-IDS, the real power generated for the VPPs in each hour are treated as particles of PSO according to Eqs. (6) and (7).

$$\mathbf{VPP^{(m)}} = [\mathbf{VPP_1^{(m)}}\mathbf{VPP_2^{(m)}}...\mathbf{VPP_{NV}^{(m)}}] \quad (6)$$

$$\mathbf{VPP_i^{(m)}} = [\mathbf{VPP_i^{1(m)}}\mathbf{VPP_i^{2(m)}}...\mathbf{VPP_i^{24(m)}}] \quad (7)$$

To treat the VPPs as LDERs, Eq. (5) is rearranged as,

$$VPP_i^{24(m)} = VPPE_i - \sum_{h=1}^{23} VPP_i^{h(m)}, \text{for } i = 1, ...NV \quad (8)$$

$$PNF = \begin{cases} 0, & \text{if } VPP_i^{24(m)} \geq 0 \\ \text{large number}, & \text{if } VPP_i^{24(m)} < 0 \end{cases}, \quad \text{for } i = 1, ..., NV. \quad (9)$$

where

$\mathbf{VPP^{(m)}}$ is the matrix representing the set of hourly real power generation of the VPP in iteration m,
$\mathbf{VPP_i^{(m)}}$ is the matrix representing the hourly real power generation of the VP P at bus i in iteration m,
$VPP_i^{24(m)}$ is the matrix representing the real power generation of the VPP at bus i at hour 24 in iteration m

Therefore, Eqs. (8) and (9) guarantee that the daily energy generation of each VPP will not exceed its total daily energy limit. The particle that violates the daily energy generation constraint results in the high PNF being added to the objective function in Eq. (1). The computational concept of the proposed COPD-IDS is shown in Fig. 2.

The optimal power dispatch of each hour incorporating VPP scheduling is performed by QP for iteration m. Consequently, the minimum daily operating cost solution among all particles, in iteration m, is selected as $\mathbf{gbest^{(m)}}$ and the minimum daily operating cost solution for particle k, in iteration m, as $\mathbf{pbest^{(m)k}}$. Afterward, the velocities and particles are updated by,

$$\mathbf{v^{(m)k}} = \mathbf{w} \cdot \mathbf{v^{(m-1)k}} + \mathbf{C_1} \cdot \mathbf{rand_1} \cdot (\mathbf{pbest^{(m)k}} - \mathbf{VPP^{(m)k}}) + C_2 \cdot \mathbf{rand_2} \cdot (\mathbf{gbest^{(m)}} - \mathbf{VPP^{(m)k}}), \quad (10)$$

$$\mathbf{VPP^{(m+1)k}} = \mathbf{VPP^{(m)k}} + \mathbf{v^{(m)k}} \quad (11)$$

where

C_1, C_2 are acceleration constants,
$rand_1, rand_2$ are random numbers between 0 and 1,
w is the weight variable.

The computational procedure is illustrated as follows:

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Step 1: Read system data, $VPPE_i$ and load profile, set $m = 1$, set ITM as the maximum number of iterations.
Step 2: Set $k = 1$, set NP as the total number of particles.
Step 3: Initialize the VPP scheduling ($\mathbf{VPP^{(m)}}$) for particle k.
Step 4: Set hour $h = 1$
Step 5: If $VPP_i^{24(m)} \geq 0$, for some $i = 1, \ldots, NV$, set PNF = large number, otherwise, set $PNF = 0$.
Step 6: Initialized power flow for hour h of particle k.
Step 7: Solve optimal power generation dispatch for hour h of particle k, using **QP**.
Step 8: Solve power flow using optimal power generation dispatch from **Step 5** for hour h of particle k.
Step 9: If $h \neq 24$, $h = h + 1$ and go to **Step 5**, otherwise, go to **Step 10**.
Step 10: Compute total daily cost (TDC) of particle k.
Step 11: If $k \neq NP$, $k = k + 1$ go to **Step 3**, otherwise, go to **Step12**.
Step 12: Obtain $\mathbf{gbest^{(m)}}$, $\mathbf{pbest^{(m)k}}$, $\mathbf{v^{(m)k}}$, and update all particles $\mathbf{VPP^{(m)k}}$
Step 13: If m ≠ ITM, m = m+1 go to **Step 2**, otherwise, go to **Step 14**.
Step 14: Obtain $\mathbf{gbest^{(ITM)}}$ as the optimal scheduling of the VPP and TDC.
Step 15: Print result, **Stop**.

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4. SIMULATION RESULTS

The IEEE 30bus system [14] was used to test the proposed method, with the VPP modification added at buses 2, 5, 7, 8, and 21. The network diagram is shown in Fig. 3. The load profile of Thailand and the solar profile are used to represent the non-firm condition of VPPs, as shown in Figs. 4 and 5.

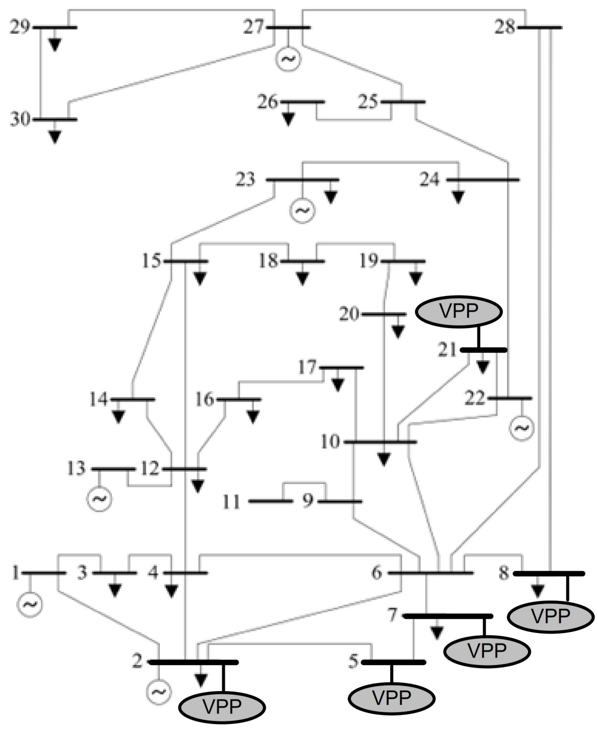

***Fig. 3**: Modified IEEE 30-bus system.*

Assuming the cost of DERs is constant due to non-firm agreements, the SO will purchase this energy without any conditions. The computation for the base case of DERs with non-firm conditions, the OPD results for each hour, and the total daily operating cost are shown in Table 3. The total daily operating cost of this case is 13,997.43 $/day. The net load profile (PLOAD-VPP) of the base case is shown in Fig. 6.

With the proposed COPD-IDS, the daily operating cost can be reduced as indicated by the convergence plot in Fig. 7. The COPD-IDS results addressed in Table 4 show that the total daily operating cost can be reduced to 13925.33 $/day. The difference in operating cost between the base case and COPD-IDS can be used to encourage or subsidize the non-firm small power produced to change their behavior to firm conditions. Fig. 8 addresses the load profile with COPD-IDS. It is noticeable that the load shape is flatter than the base case and the peak load reduced. Therefore, the investment cost for both generation and transmission can be reduced by firming the small power generated using the VPP concept.

The GA is also used to solve the proposed COPD-IDS problem formulation for comparison with the PSO. The convergence plot of the problem formulation solved by the GA is shown in Fig. 9. The daily scheduling results from the GA are illustrated in Fig. 10. Table 5 addresses the COPD-IDS results of the modified IEEE 30-bus system solved by GA. The results indicate that both the GA

***Table 1**: Cost function and limit of IEEE-30-bus system.*

Generator	$F(P_{Gi}) = a_i + b_i \cdot P_{Gi} + c_i \cdot P_{Gi}^2$			$P_{Gi}^{\min}$	$P_{Gi}^{\max}$
Bus	a_i	b_i	c_i	MW	MW
1	0	2	0.00375	50	200
2	0	1.75	0.01750	20	80
5	0	1	0.06250	15	50
8	0	3.25	0.00834	10	35
11	0	3	0.02500	10	30
13	0	3	0.02500	12	40

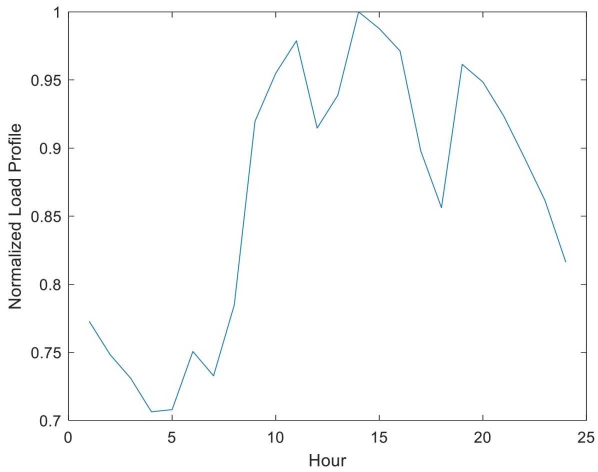

***Fig. 4**: Load profile used for the study.*

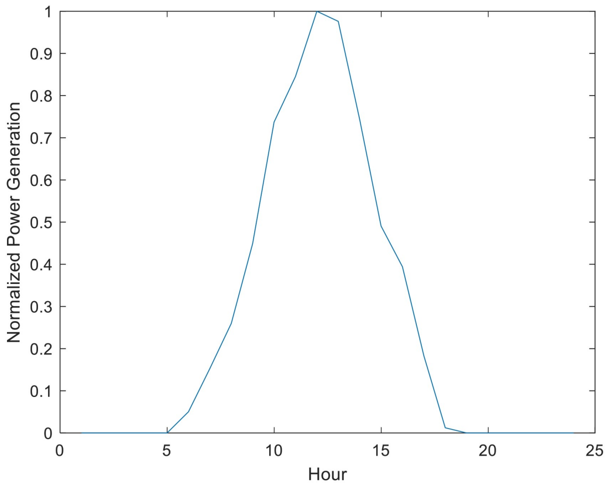

***Fig. 5**: Non-firm power generation profile for the study.*

***Table 2**: Buses connected to the VPP.*

Bus	VPP Size (MW)
2	20
5	20
7	20
8	20
21	20

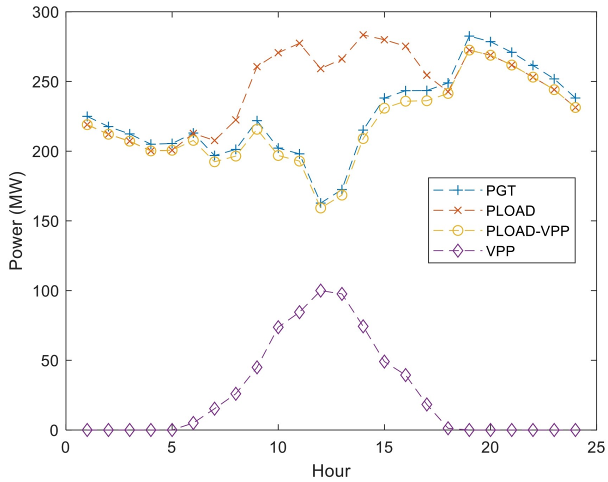

***Fig. 6**: Base case results for the modified IEEE 30-bus system*
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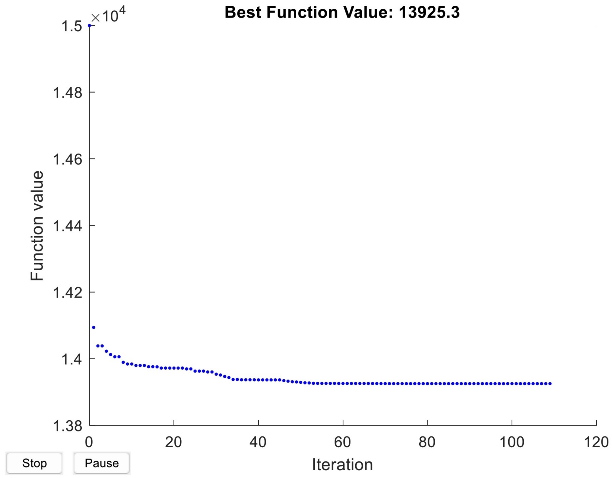

***Fig. 7**: Computational convergence of the modified IEEE 30-bus system solved by PSO.*

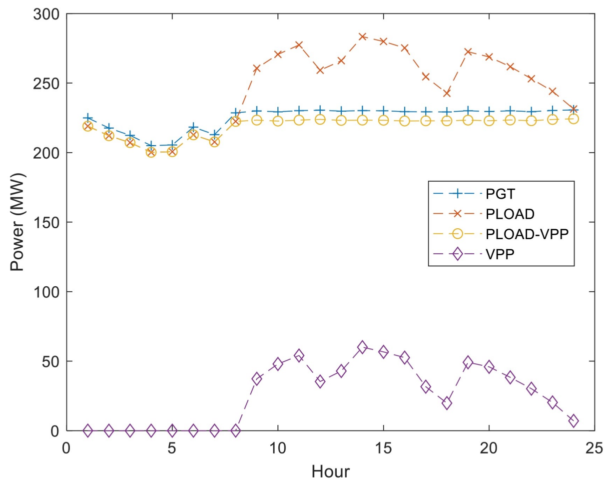

***Fig. 8**: Results for the COPD-IDS with the modified IEEE 30-bus system solved by PSO.*

***Table 3**: Base case results for the modified IEEE 30-bus system.*

Hour	Optimal System Power Gen. (MW)	VPP Power Gen. (MW)	Load (MW)	Load VPP (MW)	Total Cost ($/hr)
1	224.97	0.00	219.01	219.01	579.54
2	217.65	0.00	212.12	212.12	557.38
3	212.38	0.00	207.17	207.17	541.66
4	205.00	0.00	200.19	200.19	519.88
5	205.48	0.00	200.65	200.65	521.28
6	213.01	5.03	212.75	207.72	543.51
7	196.87	15.29	207.68	192.39	496.26
8	201.26	25.98	222.44	196.46	508.96
9	221.87	44.94	260.64	215.70	570.12
10	202.20	73.72	270.62	196.90	511.70
11	198.08	84.51	277.39	192.88	499.73
12	162.77	100.00	259.23	159.23	401.60
13	172.46	97.60	266.08	168.48	427.76
14	215.12	74.35	283.40	209.05	549.81
15	238.11	49.07	279.91	230.84	620.07
16	243.38	39.41	275.27	235.86	636.61
17	243.49	18.32	254.49	236.17	636.97
18	248.95	1.23	242.65	241.42	654.30
19	282.55	0.00	272.49	272.49	764.74
20	278.55	0.00	268.80	268.80	751.22
21	270.92	0.00	261.78	261.78	725.74
22	261.53	0.00	253.10	253.10	694.87
23	251.85	0.00	244.12	244.12	663.56
24	238.13	0.00	231.34	231.34	620.15
Total of Day	**5406.58**	**629.45**	**5883.33**	**5253.88**	**13997.43**

***Table 4**: Results of the proposed COPD-IDS with the modified IEEE 30-bus system solved by PSO.*

Hour	Optimal System Power Gen. (MW)	VPP Power Gen. (MW)	Load (MW)	Load VPP (MW)	Total Cost ($/hr)
1	224.97	0.00	219.01	219.01	579.54
2	217.64	0.00	212.12	212.12	557.38
3	212.38	0.00	207.17	207.17	541.66
4	205.00	0.00	200.19	200.19	519.88
5	205.48	0.00	200.65	200.65	521.28
6	218.30	0.00	212.75	212.75	559.37
7	212.92	0.00	207.68	207.68	543.27
8	228.62	0.00	222.44	222.44	590.71
9	229.97	37.27	260.64	223.37	594.85
10	229.93	47.39	270.62	223.23	594.72
11	229.83	54.33	277.39	223.06	594.41
12	229.77	36.03	259.23	223.20	594.24
13	229.84	42.89	266.08	223.19	594.45
14	230.00	60.25	283.40	223.15	594.94
15	229.97	56.75	279.91	223.17	594.86
16	229.76	52.25	275.27	223.02	594.20
17	229.79	31.23	254.49	223.26	594.31
18	229.82	19.25	242.65	223.40	594.39
19	229.92	49.29	272.49	223.20	594.70
20	230.06	45.43	268.80	223.37	595.13
21	229.78	38.60	261.78	223.18	594.27
22	230.06	29.57	253.10	223.53	595.13
23	229.66	20.89	244.12	223.23	593.89
24	229.61	8.04	231.34	223.30	593.75
Total of Day	**5403.12**	**629.45**	**5883.33**	**5253.88**	**13925.33**

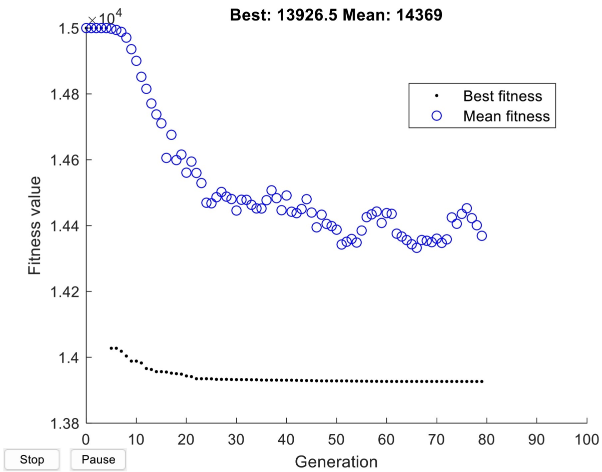

***Fig. 9**: Computational convergence of the modified IEEE 30-buses system solved by the GA.*

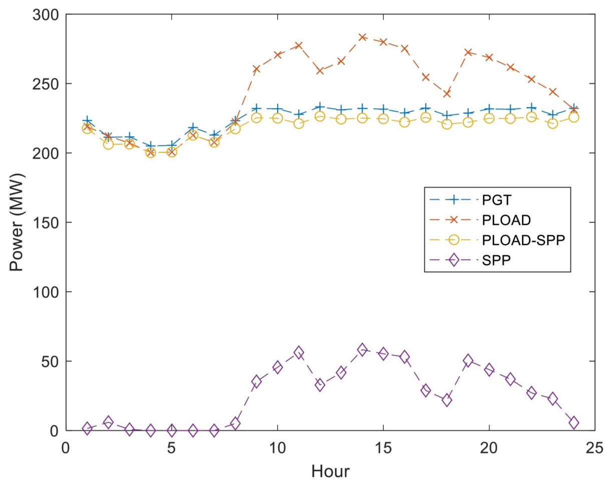

***Fig. 10**: The COPD-IDS results for the modified IEEE 30-bus system solved by the GA.*

and PSO can reduce the total daily operating cost of the system by solving the proposed COPD-IDS. Moreover, the total daily cost solution obtained from PSO is 13925.33 $/day, lower than the 13926.54 $/day from the GA.

In the test case, the difference between the non-dispatching strategy of the DERs and the proposed

***Table 5**: Results for the proposed COPD-IDS with the modified IEEE 30-bus system solved by the GA.*

Hour	Optimal System Power Gen. (MW)	VPP Power Gen. (MW)	Load (MW)	Load VPP (MW)	Total Cost ($/hr)
1	223.39	1.50	219.01	217.51	574.72
2	211.37	5.96	212.12	206.17	538.64
3	211.56	0.78	207.17	206.39	539.23
4	205.00	0.00	200.19	200.19	519.88
5	205.48	0.00	200.65	200.65	521.28
6	218.31	0.00	212.75	212.75	559.37
7	212.92	0.00	207.68	207.68	543.27
8	223.21	5.12	222.44	217.32	574.18
9	232.06	35.30	260.64	225.35	601.30
10	231.85	45.58	270.62	225.04	600.63
11	227.79	56.26	277.39	221.13	588.15
12	233.18	32.81	259.23	226.41	604.74
13	231.08	41.72	266.08	224.36	598.26
14	232.11	58.25	283.40	225.15	601.46
15	231.52	55.28	279.91	224.63	599.63
16	228.84	53.12	275.27	222.15	591.39
17	232.29	28.88	254.49	225.62	601.99
18	226.98	21.93	242.65	220.72	585.68
19	228.71	50.43	272.49	222.06	590.99
20	231.75	43.84	268.80	224.97	600.33
21	231.45	37.02	261.78	224.76	599.42
22	232.66	27.12	253.10	225.98	603.13
23	227.50	22.93	244.12	221.19	587.25
24	232.16	5.63	231.34	225.71	601.61
Total of Day	**5403.18**	**629.45**	**5883.33**	**5253.88**	**13926.54**

COPD-IDS is approximately 72.10 $/day. This information can be further investigated as dispatchability value of the DERs for the SO to set the policy for VPP encouragement and regulation.

Table 6 addresses the summary results of the base case, COPD-IDS using the GA, and COPD-IDS with the PSO. The results show that the proposed COPD-IDS can minimize the total daily cost by coordinating the optimal hourly dispatch to the optimal scheduling of DERs.

Moreover, the total daily loss of the system is reduced by the proposed method. Furthermore, the results indicate that the COPD-IDS solved by the PSO provides a superior solution compared to the GA.

5. CONCLUSION

A method for coordinating optimal power dispatch (OPD) incorporating the scheduling of distributed energy resources (DERs) (COPD-IDS) is proposed in this paper. The objective of the proposed COPD-IDS is to minimize the total daily operating cost. The simulation results on the modified IEEE 30-bus system under practical load and DERs daily profile conditions indicate that the proposed COPD-IDS can successfully minimize the total daily operational cost of an electricity system with dispatchable DERs using the VPP concept.

***Table 6**: Summary results for the base case, COPD-IDS using the GA, and COPD-IDS with the PSO of the modified IEEE 30-bus system.*

Results	Optimal Dispatch with Non-Firm DERs (Base Case)	COPD-IDS Using GA	COPD-IDS Using PSO
Total Daily Load (MWh)	5883.33		
DERs Daily Power Generation (MWh)	629.45		
Optimal Daily System Power Generation (MWh)	5406.58	5403.18	5403.12
Total Daily Loss (MWh)	152.70	149.30	149.24
Total Daily Cost ($/Day)	13997.43	13926.54	13925.33

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