Multi-Objective Optimal Number of V2G and Generation Scheduling Using Improved Self-organizing Hierarchical Particle Swarm Optimization

Witoon Prommee and Weerakorn Ongsakul

Abstract— *This paper proposes an improved self-organizing hierarchical particle swarm optimization with time-varying acceleration coefficient (ISPSO-TVAC) for solving multi-objective optimal number of vehicles to grid (V2G) and generation scheduling in a smart grid. V2G can discharge electricity to the grid to minimize generator fuel cost with valve point loading and emission of greenhouse gas. The proposed ISPSO-TVAC is a new hybrid between self-organizing hierarchical particle swarm optimization with time-varying acceleration coefficient (SPSO-TVAC) and two movement strategies for multi-objective PSO to avoid the crowded areas and explore new areas. ISPSO-TVAC can find a better compromised solution than weighting factor and non-dominated sorting genetic algorithm-II (NSGA II) on the modified ten-unit smart grid system. Accordingly, a better compromised solution leads to a better trade off solution between generator fuel cost and emission reduction.*

Keywords— ***Multi-objective self-organizing hierarchical particle swarm optimization, vehicle to grid, generators scheduling, and smart grid.***

1. INTRODUCTION

Smart grid is an intelligent power grid equipped with information and communication technology connecting renewable generators, energy storages, and electric vehicles (EVs) loads [1]. V2G is an energy storage technology which shows directional power flow between a vehicle's battery and the utility [2]. In Fig.1, there are various components including a smart home with renewable energy, and EVs. V2G is a small portable plant supplying the electricity to the grid at electricity parking lot charging stations. On the other hand, the EVs are charged from the grid when they return to smart homes. Independent System Operator (ISO) of utility can control optimal number of V2G and generation scheduling to minimize fuel generator cost and emission.

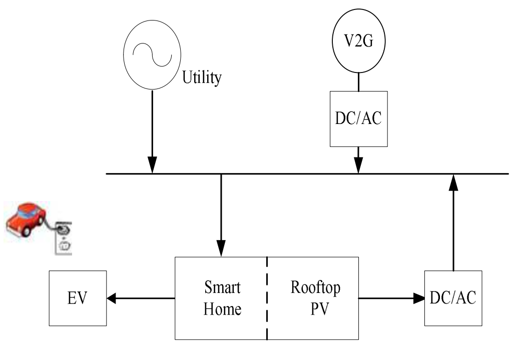

Fig.1. The diagram of smart grid with V2G.

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Optimal multiple electrical vehicles and generator scheduling are nonlinear programming problems which have been solved by various methods including lambda iteration [3], improved chaotic particle swarm optimization (ICPSO) [4], chaotic self-adaptive particle swarm optimization (CSAPSO) [5] and TVAC-IPSO [6]. For instance, the intelligent unit commitment with V2G in [3] was to minimize the generator fuel cost and emission by conventional PSO. However, the fuel cost function did not consider valve point loading effects. In [4, 5], improved chaotic particle swarm optimization (ICPSO) and Chaotic particle swarm optimization (CSAPSO) for dynamic economic dispatch (DED) problem were to minimize the total generator fuel cost with valve point loading effects. However, the greenhouse emission was not considered. The improved PSO with time-varying acceleration coefficients (IPSO-TVAC) method is used to optimize DED problem to schedule online power generation to minimize the total production cost over the specified time horizon [6]. The non-convex economic power with valve loading effect was solved by SPSO-TVAC [7]. Reinitializing the velocity vector whenever particle stagnated and striking proper balance between local and global searching, were added in conventional PSO to overcome premature convergence. SPSO-TVAC could find a better solution than adaptive weight PSO and passive congregation based PSO (PCPSO) [7]. However, SPSO-TVAC is developed for a single objective optimization problem which cannot find a trade-off solution in a multi-objective function. As a result, there is a need to further develop SPSO-TVAC for multi-objective optimization.

Optimal generator scheduling in economic dispatch (ED) for minimizing fuel cost and emission was solved by non-dominated sorting genetic algorithm-II (NSGAII) [8] and a hybrid multi-objective optimization algorithm based on differential evolution and PSO (MO-DE/PSO) [9]. The crowding distance (CD) [8, 9] was employed to assign the particles' leaders. However, CD cannot explore the unexplored space. Moreover, V2G and the best compromised solution are not considered.

For optimal multiple electrical vehicles scheduling in [10-12], unit commitment (UC) with V2G are considered in [10, 11]. A multi-objective operational scheduling proposed in [10] was minimizing the total operational costs and DG emission by augmented ε- constraint method. However, the valve point effect of generator fuel cost and emission are not considered. In [11], the optimal EV charging by mixed-integer linear programming (MILP) is to minimize the total operational costs. However, the emission is not considered. Optimal scheduling for charging and discharging of EV is solved by a convex program to minimize the total charging cost [12]. However, the total fuel costs and emission are not considered.

In this paper, an improved SPSO-TVAC (ISPSO-TVAC) is proposed to determine the optimal number of V2G and generator scheduling for minimizing multi-objective the generator fuel cost with valve point effect and greenhouse gas emission. SPSO-TVAC from [7] alone cannot find Pareto front solutions in the multi-objective problem. As a result, SPSO-TVAC and movement strategies of particles ($MS_1$and MS_2) are newly combined to avoid the crowded area and explore new areas in the converge space of the multi-objective problem. Moreover, the TVAC uses the varying acceleration coefficients with time to converge near the optimal solution. For minimizing FC_{new}, SPSO-TVAC from [7] for a single combined objective function is compared to differential evolution (DE), hybrid evolution programming and sequential quadratic programming (EP-SQP), hybrid particle swarm optimization and sequential quadratic programming (PSO-SQP), deterministically guided particle swarm optimization (DGPSO), modified hybrid evolution programming and sequential quadratic programming (MHEP-SQP), improved particle swarm optimization (IPSO), hybrid differential evolution method (HDE), improved differential evolution (IDE), artificial bee colony (ABC), modified differential evolution (MDE), covariance matrix adapted evolution strategy (CMAES), artificial immune systems (AIS), hybrid swarm intelligence based harmony search algorithm (HHS), artificial immune systems and sequential quadratic programming (AIS-SQP), chaotic sequence based differential evolution (CS-DE), chaotic differential evolution (CDE), improved chaotic particle swarm optimization (ICPSO), improved particle swarm optimization with time varying acceleration coefficients (IPSO-TVAC), and chaotic self adaptive particle swarm optimization (CSAPSO) on the ten-generator unit test system. In minimizing (FC_{new},E_{new}) without V2G, ISPSO-TVAC is compared to Weighting factor [7] and NSGAII [8]. Minimizing (FC_{new},E_{new}) with V2G by ISPSO-TVAC is finally compared with minimizing (FC_{new}+E_{new}) with V2G by SPSO-TVAC. The impact of 50,000 EVs with 50% of state of charge (SOC), the maximum number of V2G per hour is 5,000 EVs and 85% efficiency are considered in the test smart grid systems [3, 8].

The rest of this paper is organized as follows: Section 2 presents the problem formulations including single combined objective and multi-objective functions. In Section 3, the IPSO-TVAC method is applied for multi-objective optimal multiple V2G and generator scheduling in the smart grid system. Section 4 shows its numerical results. In Section 5, conclusion is given.

2. PROBLEM FORMULATION

Mathematically, the multi-objectives function can determine a trade-off solutions whereas the single combined objective function is simply a sum of each weighted objectives. The objective functions and constraints can be formulated as:

2.1 Single Combined Objective function

The single combined objective function is to minimize total cost (*TC*) as [3]:

$$\underset{(N_{V2G,t},P_{i,t})}{\text{Minimize}} \quad TC \tag{1}$$

where $N_{V2G,t}$ is number of vehicles to grid at hour *t*, $P_{i,t}$ is output power of i^{th} unit at hour *t*, respectively.

The total running cost and emission equation is defined as [3]

Minimize

$$TC=\sum_{t=1}^{H}\sum_{i=1}^{N}\left[W_c(FC_i(P_{i,t})+SC_i(1-U_{i,t-1}))+W_e(E_i(P_{i,t}))\right]U_{i,t} \tag{2}$$

where

W_c, W_e are weight factor of a cost function and an emission function (1, 1),

$FC_i(P_{i,t})$ is the fuel cost function of i^{th} unit at time *t*,

SC_i is the start up cost of i^{th} unit,

$U_{i,t}$ $U_{i,t-1}$ is the i^{th} unit status at hour *t* and *t*-1 (on /off),

$E_i(P_{i,t})$ is the emission function of i^{th} unit at time *t*.

2.2 Multi-objective functions

The multi-objective function is to minimize the improved fuel cost function [8]

$$\underset{(N_{V2G,t},P_{i,t})}{\text{Minimize}} \quad \{FC_{new}, E_{new}\} \tag{3}$$

Subject to:

Maximum number of V2G limit over H hours,

$$\sum_{t=1}^{H} N_{V2G,t} \le N_{V2G}^{\max}, \tag{4}$$

Power balance equation,

$$\sum_{i=1}^{N} U_{i,t} P_{i,t} + P_{V2G,t} = P_{D,t} + P_{Loss,t}\ ,\ t = 1,\ldots H, \quad (5)$$

Generator operating limit,

$$P_i^{\min} \le P_{i,t} \le P_i^{\max}\ ,\ i = 1,\ldots N, \quad (6)$$

Maximum hourly number of V2G limit,

$$0 \le N_{V2G,t} \le 5000\ ,\ t = 1,\ldots,H. \quad (7)$$

where

$N_{V2G}^{\max}$ is the maximum number of vehicles to grid (50,000 units),

$N_{V2G,t}$ is the number of vehicle to grid at hour *t*,

$P_{loss,t}$ is the real power loss at hour *t*,

$P_{D,t}$ is the load demand power at hour *t*,

$P_{V2G,t}$ is the total real power of electric vehicle to grid at hour *t*,

$P_i^{\max}, P_i^{\min}$ are the maximum and minimum real power of unit *i*.

(a) Generator fuel cost with valve point loading (FC_{new})

Here, the valve point loading effects are considered by adding a rectified sinusoidal component to a quadratic function as:

$$FC_{new} = \sum_{t=1}^{H} \sum_{i=1}^{N} (a_i P_{i,t}^2 + b_i P_{i,t} + c_i + \left| d_i \sin(e_i (P_{i,t,\min} - P_{i,t})) \right|) \quad (8)$$

where

a_i, b_i, c_i, d_i, e_i are the cost coefficients of i^{th} unit [8],

$P_{i,t}$ is the output power of i^{th} unit at hour *t*,

$P_{i,t,\min}$ is the minimum output power of i^{th} unit at hour *t*.

(b) Start cost (SC)

The startup cost is considered only in the total cost (*TC*) when the thermal unit restarts. Moreover, the startup cost related to the temperature of the boiler is given as:

$$SC_i(t) = \begin{cases} HSC_i, MD_i \le X_{i,t}^{off} \le H_i^{off} \\ CSC_i, X_{i,t}^{off} > H_i^{off} \end{cases} \quad (9)$$

$$H_i^{off} = MD_i + CSH_i \quad (10)$$

where

$SC_i(t)$ is the startup cost of i^{th} unit at time *t*,

HSC_i is the hot startup cost of i^{th} unit,

MD_i is minimum down time of i^{th} unit,

$X_{i,t}^{off}$ is continuously off time of i^{th} unit to time *t*,

CSC_i is the cold startup cost of i^{th} unit,

CSH_i is cold start time of i^{th} unit,

H_i^{off} is sum of minimum down time and cold start time of i^{th} unit.

(c) Emission of greenhouse gas (Enew)

Here, the quadratic emission function considering sulphur oxides (SO_x) and nitrogen oxides (NO_x) is improved by adding a new exponential component.

$$E_{new} = \sum_{t=1}^{H} \sum_{i=1}^{N} \left(\alpha_i P_{i,t}^2 + \beta_i P_{i,t} + \gamma_i + \xi_i \exp\left(\lambda_i P_{i,t}\right) \right) \quad (11)$$

where

$\alpha_i, \beta_i, \gamma_i, \xi_i, \lambda_i$ is the emission coefficients of i^{th} unit [8],

$P_{i,t}$ is the output power of i^{th} unit at hour *t*.

(d) The total real power loss (PLoss)

The total transmission loss is approximated by the B-matrix coefficients as [8].

$$P_{Loss,t} = \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} P_{i,t} B_{ij} P_{j,t} + 2 P_{N,t} \sum_{i=1}^{N} B_{N,t} P_{i,t} + B_{NN} P_{N,t}^2 \quad (12)$$

where

$B_{ij}, B_{NN}, B_{N,t}$ is the transmission loss formula coefficients,

$P_{j,t}$ is the output power of j^{th} unit at hour *t*.

3. IMPROVED SELF-ORGANIZING HIERARCHICAL PARTICLE SWARM OPTIMIZATON FOR MULTI-OBJECTIVE OPTIMAL NUMBER OF V2G AND GENERATION SCHEDULING

Particle Swarm Optimization (PSO) is a population random search method which learns from the previous personal and global best position memory of the particle swarm movement to guide particles to better positions.

ISPSO-TVAC is the proposed PSO which composes of SPSO-TVAC and two practical movement strategies for soving multi objective optimization.

(a) Self-organizing hierarchical PSO with time-varying acceleration coefficient (SPSO-TVAC)

For conventional PSO, the particles may converge prematurely to local optima when the particle velocity becomes zero. In SPSO-TVAC, the velocity vector of a particle is reinitialized when it stagnates in the search space. Moreover, TVAC is used to control the global and local exploration of the swarm. The updating particle velocity and position equation of SPSO-TVAC are shown as [13].

$$v_{i,d}^{k+1} = c_1 \times r_1 \times \left(p_{i,d}^k - x_{i,d}^k \right) + c_2 \times r_2 \times \left(g_{i,d}^k - x_{i,d}^k \right) \quad (13)$$

$$x_{i,d}^{k+1} = x_{i,d}^{k} + v_{i,d}^{k+1} \quad (14)$$

where, $p_{i,d}^{k}$ and $g_{i,d}^{k}$ denotes the position of the personal and global best at particle i at the k^{th} generation on two dimensions which represent generator powers and the number of V2G.The time varying acceleration coefficients of the personal and global best components (c_1, c_2) are determined by:

$$c_1 = c_{1,\max} - \left(\frac{c_{1,\max} - c_{1,\min}}{k_{\max}} \right) \times k \quad (15)$$

$$c_2 = c_{2,\min} - \left(\frac{c_{2,\min} - c_{2,\max}}{k_{\max}} \right) \times k \quad (16)$$

where, $c_{1,max}$, $c_{1,min}$ are the maximum and minimum acceleration coefficient of the personal best. $c_{2,min}$, $c_{2,max}$ are the minimum and maximum acceleration coefficient of the global best. $k_{\max}$ is the maximum number of generations. All parameters are shown in Table 1.

SPSO-TVAC can overcome this weakness by reinitializing the velocity vector of a particle whenever it stagnates during the search as [13]

If $v_{i,d}^{k+1} = 0$ and $r_3 < 0.5$ then

$v_{i,d}^{k} = r_4 \times v_{d,\max}^{k}$

else

$v_{i,d}^{k} = -r_5 \times v_{d,\max}^{k}$

$v_{i,d}^{k+1} = sign\left(v_{i,d}^{k}\right) \times \min\left(abs\left(v_{i,d}^{k}, v_{d,\max}^{k}\right)\right)$

end

$$v_{d,\max}^{k} = \left(\frac{x_{d,\max}^{k} - x_{d,\max}^{k}}{R} \right) \quad (17)$$

where, $x_{d,\max}^{k}$ and $x_{d,\min}^{k}$ representing supplying real power size and number of V2G, are the maximum and minimum particle position on d th dimension at generation k. R is chosen as 5 which is a mean value for reinitializing the velocity of particles. r_1, r_2, r_3, r_4, r_5 are random numbers in the range [0, 1].

(b) A global guidance located in the least crowded areas and perturbation with different evolution

Two practical movement strategies (MS) are used to avoid the crowded areas and explore new areas [14]. In the first movement strategy (MS_1), the particles with higher crowding distances (CDs) are located in the less crowded area. In the second movement strategy (MS_2), the particles with lower CDs are located in the more crowed area. The particles $y_{R1,d}^{k}$ and $y_{R2,d}^{k}$ guide the better direction by D vectors summation and the candidate particle will be moved at a new position by the time varying acceleration coefficients in Fig. 2.

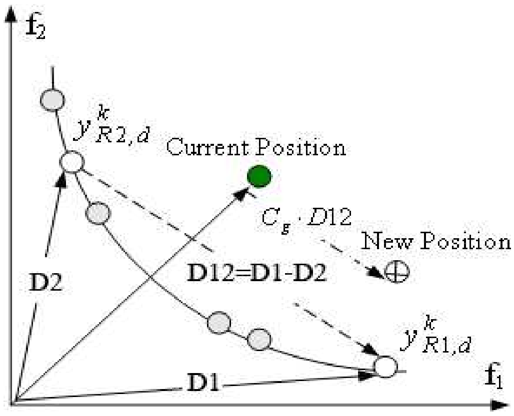

Fig. 2. The direction of MS1 and MS2 in bi-objective space.

Combination of MS_1 and MS_2 algorithm can be described in 4 steps as follows.

Step 1: Calculate *CD* by the Eq. 18 in Fig. 2, [14].

$$CD_i = \sum_{j=1}^{m} \sum_{i=2}^{|\varepsilon|-1} \frac{\varepsilon[i+1]_j - \varepsilon[i-1]_j}{f_j^{\max} - f_j^{\min}} \quad (18)$$

where, CD_i is the crowding distance (*CD*) of solution i. $|\varepsilon|$ and m are the number of solutions and objectives. $f_j^{\max}$ and $f_j^{\min}$ are maximum and minimum of function j. $\varepsilon[i+1]_j$ and $\varepsilon[i-1]_j$ are solutions adjacent to $\varepsilon[i]_j$. CD_1 and $CD_{|\varepsilon|}$ the crowding distance of solution 1st and the final number of solutions. CD_1 and $CD_{|\varepsilon|}$ are ignored.

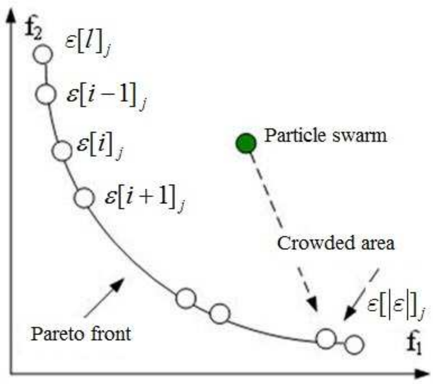

Fig. 3. The parameters of CD in bi-objective space.

Step 2: Sort in a decreasing order of *CD* values.

Step 3: The particles are randomly selected from top 10% ($y_{R1,d}^{k}$) and bottom 20% ($y_{R2,d}^{k}$) of *CDs* as the global guidance in Fig. 2.

Step 4: Update velocity of particle i^{th} at dimension d^{th} at iteration k+1 as following [14]

$$v_{i,d}^{k+1} = c_1 \times r_1 \times \left(p_{i,d}^{k} - x_{i,d}^{k}\right) + c_2 \times r_2 \times \left[\left(y_{R1,d}^{k} - x_{i,d}^{k}\right) + \left(y_{R1,d}^{k} - y_{R2,d}^{k}\right)\right] \quad (19)$$

$y^k_{R1,d}$ and $y^k_{R2,d}$ are randomly selected particles R_1 and R_2 from top 10% of the *CD* order sorted of ascending in elite group for dimension d at iteration k (global guidance). For considering the personal guidance ($p^k_{i,d}$) in the multi-objective minimization, $p^1_{i,d} = x^1_{i,d}$ initially. After the first generation, $p^k_{i,d} = x^k_{i,d}$ if $FC_{new}\left(x^k_{i,d}\right) < FC_{new}\left(p^{k-1}_{i,d}\right)$. Otherwise, the personal guidance position stays at $p^{k-1}_{i,d}$.

(c) Improved multi-objective self-organizing hierarchical PSO with time-varying acceleration coefficient (ISPSO-TVAC)

In this paper, SPSO-TVAC cannot form Pareto-front solutions for the multi-objective problem. As a result, SPSO-TVAC is improved by adding movement strategies (MS_1 and MS_2) to find Pareto-front solutions. Optimal number of V2G and generation scheduling is to minimize generator fuel cost and emission. V2G can reduce greenhouse gas emission and shave peak load. ISPSO-TVAC procedure for optimal generator schedule and number of V2G management can be described in 8 steps as follows.

Step 1: Initialize 20 particles with random position and zero velocity. Set the iteration counter (k) =1.

$$x^k_{i,d} = \begin{bmatrix} P_{G1,1} & P_{G1,2} & P_{G1,3} & . & \cdots & P_{G1,24} \\ P_{G2,1} & . & . & . & \cdots & P_{G2,24} \\ P_{G3,1} & . & . & . & \cdots & P_{G3,24} \\ \cdots & \cdots & \cdots & . & \cdots & \cdots \\ P_{GN,1} & P_{GN,2} & P_{GN,3} & . & \cdots & P_{GN,24} \\ N_{V2G,1} & N_{V2G,2} & N_{V2G,3} & . & \cdots & N_{V2G,24} \end{bmatrix}$$

Step 2: $$P_{Gj,t} = P_j^{\min} + r \times \left(P_j^{\max} - P_j^{\min}\right) \quad (20)$$

$$N_{V2G,t} = N_{V2G}^{\min} + r \times \left(N_{V2G}^{\max} - N_{V2G}^{\min}\right) \quad (21)$$

where, r is a random number in the range [0, 1]. $P_{Gj,t}$ and $x_{V2G,t}$ present power of generator unit j at time (t) and the number of V2G at time (t).

Step 3: Calculate generator fuel cost and emission by Eqs. (9) and (13).

Step 4: Determine a global non-dominated front.

Step 5: Keep members in an elite group.

Step 6: If the generation counter reaches 100, go to step 8. Otherwise, go to the next step.

Step 7: Update guidance, velocity, and position by ISPSO-TVAC. Update the iteration counter *k = k+1*, return to step 2.

Step 8: Determine the compromised solution by max-min approach method as following [15]

$$\max\left\{\min_j\left\{\frac{FC_{\max} - FC_j}{FC_{\max} - FC_{\min}}, \frac{E_{\max} - E_j}{E_{\max} - E_{\min}}\right\}\right\} \quad (22)$$

Step 9: Stop.

4. SIMULATION RESULTS

For a single combined objective function, the 10 unit system with load demand and the unit characteristics of 10 unit system are from [3] which is the benchmark of multiple V2G in Table 3. However, it is only used for single objective similar to single combined objective. For multi-objective function, the 10 unit system is modified by adding V2G from [8] with load demand, ten-unit characteristics, and the transmission loss coefficients.

For the proposed model, EVs are charged during off peak period from smart homes and discharge to the grid at parking lots during on peak period. The number of V2G at hour t is set to be less than 10% of all EVs in a power system. In EV characteristics, 15 kW as average battery capacity per a vehicle unit, 5,000 units as maximum number of V2G at each hour, 50% departure state of charge (SOC), and 85 % efficiency are given. The EV power supplying at hour t can be expressed as:

$$P_{V2G,t} = 15kW \cdot N_{V2G,t} \cdot 0.85 \cdot 0.5 \quad (23)$$

where

$P_{V2G,t}$ is the total real power of electric vehicle to grid at hour t,

$N_{V2G,t}$ is the number of vehicle to grid at hour t.

Table 1. Parameters of ISPSO-TVAC and NSGAII

Method	ISPSO-TVAC	NSGAII [8]
Particles size	20	20
Number of iterations	100	100
Movement Strategies	MS_1, MS_2, TVAC	Crossover, Mutation
c_1 ($c_{1,\max}$ - $c_{1,\min}$)	Decreasing (2.5-0.5)	Crossover probability = 0.9
c_2 ($c_{2,min}$ - $c_{2,\max}$)	Increasing (0.5-2.5)	Mutation probability = 0.2

In Table 2, the minimum, average, and maximum generator fuel cost of SPSO-TVAC are clearly less than the other methods [5, 6] with 30 particles and 1,000 iterations on the 10-unit test system for ten trials. The SPSO-TVAC can find better solutions than others in [5, 6] because the particles are reinitialized when they are stagnated in the local trap. As a result, the new velocity of each particle can avoid getting stuck at a local optimal solution. Moreover, time-varying acceleration coefficients (TVAC) can control the global search and converge to a better solution.

Table 2. Comparison statistical results for optimal economic dispatch on the ten-unit test system with V2G in 100 trials for the single combined objective function

Method	Minimizing FC_{new}		
	Minimum ($)	Average cost ($)	Maximum ($)
DE [6]	1,019,786	NA	NA
EP-SQP [6]	1,031,746	1,035,748	NA
PSO-SQP [6]	1,027,334	1,028,546	1,033,986
DGPSO [6]	1,028,835	1,030,183	NA
MHEP-SQP [6]	1,028,934	1,031,179	NA
IPSO [6]	1,023,807	1,026,863	NA
HDE [6]	1,031,077	NA	NA
IDE [6]	1,026,269	NA	NA
ABC [6]	1,021,576	1,022,686	1,024,316
MDE [6]	1,031,612	1,033,630	NA
CMAES [6]	1,023,740	1,026,307	1,032,939
AIS [6]	1,021,980	1,023,156	1,024,973
HHS [6]	1,019,091	NA	NA
AIS-SQP [6]	1,029,900	NA	NA
CS-DE [6]	1,023,432	1,026,475	1,027,634
CDE [6]	1,019,123	1,020,870	1,023,115
ICPSO [6]	1,019,072	1,020,027	NA
IPSO - TVAC [6]	1,018,217	1,018,965	1,020,417
CSAPSO [5]	1,018,767	1,019,874	NA
SPSO-TVAC	***1,013,432***	***1,015,989***	***1,019,786***

Table 3. Unit commitment results on the ten-unit system for the single objective function

Method	Total emission (kg/day)	Total running cost ($/day)	Min $\{TC\}$
Without V2G			
Lambda [3]	260,066	565,325	825,392
SPSO-TVAC	***190,190***	***494,350***	***684,540***
With 50,000 V2G			
Lambda [3]	257,391	559,367	816,758
SPSO-TVAC	***187,600***	***483,710***	***671,320***

In Table 3, for unit commitment minimizing combined total running cost and emission without considering valve point loading effect, SPSO-TVAC gives a lower total cost and emission than lambda with and without V2G. The proposed V2G management strategy can reduce the total emission and running cost from 257,391.18 kg/day and $559,367.06 /day to 187,600 kg/day and $483,710 /day, respectively. However, the sum of minimum weighted running cost ($/day) and total emission (kg/day) can give only one solution which may not lead to the best trade-off solution. Therefore, the multi-objective needs to find non-dominated solutions on the Pareto-front curve which is solved by ISPSO-TVAC. The best trade-off solution will be selected by max-min approach using Eq. (22).

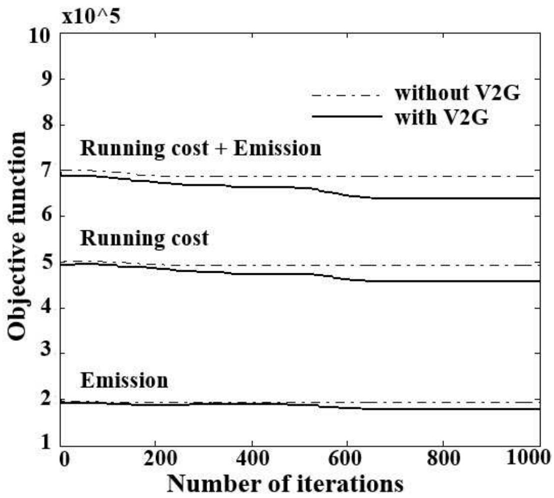

Fig. 4. Convergence characteristics of SPSO-TVAC of combined objective function of unit commitment with V2G and without V2G

In Fig. 4, the convergence characteristics of SPSO-TVAC of UC without and with V2G are shown. The running cost and emission converge within 1,000 iterations. With V2G, the running cost V2G is lower than those without V2G because V2G supply power to serve load demand. As a result, V2G can further reduce the running cost and emission. However, SPSO-TVAC cannot solve the compromised solution of multi-objective. In this paper, SPSO-TVAC is modified by adding MS_1 and MS_2 to display Pareto-optimal front and determine the compromised solution for multi-objective function.

Table 4. Comparison of multi-objective economic dispatch minimizing total emission and total generator fuel cost

Case / Methods	Total generator fuel cost, FC_{new} (10^6 $/day)	Total emission, E_{new} (10^5 kg/day)
1. Minimizing $\{FC_{new}, E_{new}\}$ without V2G		
Weighting factor [8]	2.5251	3.1246
RCGA [8]	2.6563	3.0412
NSGA-II [8]	2.5226	3.0994
ISPSO-TVAC	***2.1432***	***2.0960***
2. Minimizing $\{FC_{new} + E_{new}\}$ with 50,000 V2G		
SPSO-TVAC	***2.6552***	***3.6563***
3. Minimizing $\{FC_{new}, E_{new}\}$ with 50,000 V2G		
ISPSO-TVAC	***1.7932***	***1.5220***

In Table 4, for Case 1, ISPSO-TVAC can find a better compromised solution than the weighting factor, RCGA, and NSGA-II method for optimal generators scheduling problem because two practical movement strategies are used to avoid the crowded areas and explore new areas. ISPSO-TVAC can search a better direction than the weighting factor, RCGA, and NSGA-II method, which lack exploring new area and the global best guiding. In Case 2, for minimizing $\{FC_{new}, E_{new}\}$ with 50,000 V2G, the optimal number of EVs and generators scheduling by ISPSO-TVAC can reduce emission from 209,600 kg/day to 152,200 kg/day and generator fuel cost from $2,143,200 /day to $1,793,200 /day because of V2G. In Case 3, minimizing $\{FC_{new} + E_{new}\}$ with 50,000 V2G, the compromised solution of Case 3 is better than the solution of single combined objective function of Case 2 because multi-objective ISPSO can better handle conflicting objective functions than a single combined objective by SPSO-TVAC .

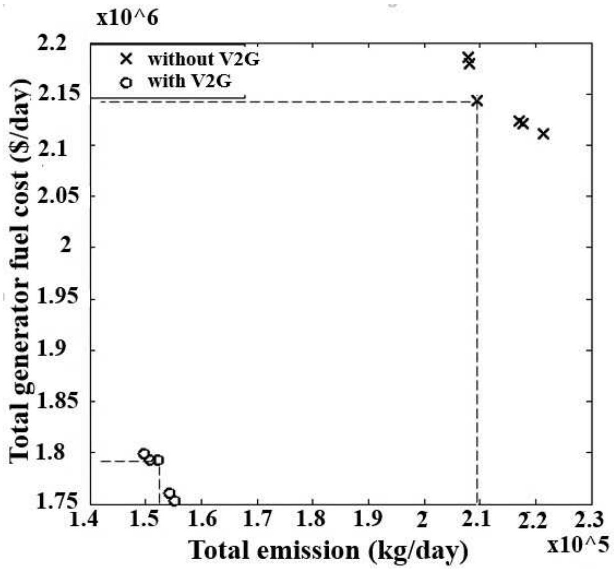

Fig. 5. Comparison of Pareto-optimal front of the proposed ISPSO-TVAC with V2G and without V2G.

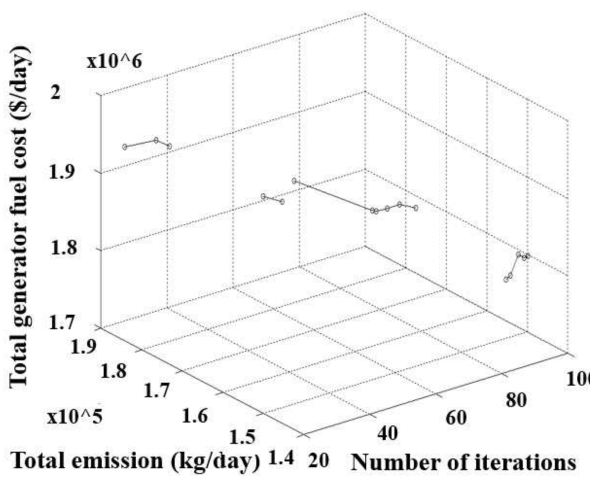

Fig. 6. Convergence characteristics of ISPSO-TVAC.

In Fig. 5, the non-dominated solutions for minimizing FC_{new} and E_{new} with and without V2G are shown. The Pareto front with V2G is lower or better than the Pareto fronts without V2G because V2G can reduce emission and generator fuel cost. The compromised solution is the trade-off solution in the middle of the Pareto fronts with and without V2G.

The convergence characteristics to Pareto front solutions are shown in Fig. 6. Obviously, better Pareto front are obtained as it converges. Note that FC_{new} is selected to be a personal guide for ISPSO-TVAC.

5. CONCLUSION

In this paper, the proposed ISPSO-TVAC method effectively determines the best trade-off solution for multi-objective optimal number of V2G and generator scheduling on the modified ten-unit test system. Moreover, ISPSO-TVAC with V2G is beneficial to minimize generator fuel cost and emission on a smart grid system. The optimal parking lots placement considering state of charge (SOC) of EVs and cutting off peak demands for minimizing total real power loss remains to be investigated.

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APPENDIX

Table A. Optimal multiple V2G and unit commitment on the ten-unit system by ISPSO-TVAC without valve point effect

t (hr.)	$P_{1,t}$ (MW)	$P_{2,t}$ (MW)	$P_{3,t}$ (MW)	$P_{4,t}$ (MW)	$P_{5,t}$ (MW)	$P_{6,t}$ (MW)	$P_{7,t}$ (MW)	$P_{8,t}$ (MW)	$P_{9,t}$ (MW)	$P_{10,t}$ (MW)	No. of vehicles	Running Cost ($)	Emission (kg)
1	435.40	256.36									1,292	13,555	6,481
2	455.00	250.98									1,384	13,787	6,905
3	455.00	162.60		63.77							1,568	15,112	6,229
4	455.00	282.61		67.25							1,753	16,138	7,612
5	455.00	465.44	55.66	88.09							1,845	18,919	7,672
6	455.00	282.48	47.13	39.00	104.00						2,030	21,492	8,089
7	455.00	246.09	33.94	67.05	105.55						2,122	19,338	7,620
8	455.00	235.93	90.72	97.66	127.97						2,214	21,096	7,847
9	455.00	275.28	31.98	58.64	67.17	48.20	47.90				2,399	22,606	8,389
10	455.00	174.38	63.98	111.02	56.96	48.70	50.95	51.62			2,583	23,803	7,735
11	455.00	225.45	39.68	35.93	104.75	30.15	59.77	46.88	14.06		2,675	24,745	8,377
12	455.00	258.76	113.90	109.54	44.27	54.65	49.70	31.91	30.62	42.76	2,768	28,784	9,458
13	455.00	342.66	32.68	69.21	62.28	30.74	48.45	48.17			2,583	24,978	9,815
14	455.00	250.64	30.03	83.21	138.86	70.40	70.01				2,399	24,748	8,400
15	455.00	282.24	81.28	67.87	121.94						2,214	21,116	8,280
16	455.00	169.38	34.09	89.44	63.96						1,937	17,536	6,816
17	455.00	213.51	72.64	54.02	87.47						1,845	18,833	7,206
18	455.00	154.15	122.98	47.09	62.93						2,030	18,043	6,926
19	455.00	212.44	62.70	37.10	72.00	55.88	46.28				2,214	21,527	7,594
20	455.00	280.70	36.43	111.65	135.64	32.62	65.43	45.68			2,583	26,672	9,216
21	455.00	287.68	57.97	42.53	78.10	70.69	34.15				2,399	22,910	8,593
22	455.00	357.65	66.71	89.65	39.01						2,030	20,866	9,494
23	455.00	232.69		74.94							1,661	15,397	6,955
24	455.00	150.00									1,476	12,032	5,889

Total running cost = $483,710.00, Total emission = 187,600.00 kg.

Table A shows optimal number of V2G and generator scheduling on the given time by ISPSO-TVAC for minimizing combined total running cost and emission without valve point loading effects in Table 3

Table B. Optimal generator scheduling by ISPSO-TVAC on the modified smart grid system for minimizing $\{FC_{new}, E_{new}\}$ without V2G of Case 1 in Table 4

t (hr.)	$P_{1,t}$ (MW)	$P_{2,t}$ (MW)	$P_{3,t}$ (MW)	$P_{4,t}$ (MW)	$P_{5,t}$ (MW)	$P_{6,t}$ (MW)	$P_{7,t}$ (MW)	$P_{8,t}$ (MW)	$P_{9,t}$ (MW)	$P_{10,t}$ (MW)	No. of V2G	Running Cost ($)	Emission (kg)
1	191.78	358.45	193.96	242.87	175.12	118.68	100.92	84.39	38.476	27.778	-	99,560	11,103
2	234.09	155.57	125.81	88.65	188.29	124.43	81.66	73.09	48.713	11.996	-	71,880	5175
3	152.10	372.41	246.26	246.64	143.81	104.62	38.57	87.73	39.710	38.361	-	97,140	11,968
4	265.51	323.81	197.55	116.70	201.84	110.67	84.73	78.93	40.092	23.101	-	97,280	9,320
5	315.09	294.28	228.41	184.79	202.73	120.99	27.39	74.64	46.086	26.449	-	103,650	10,939
6	254.52	190.53	135.01	178.91	78.32	100.79	111.63	50.61	39.242	22.518	-	76,940	6,051
7	225.66	243.10	166.95	107.36	176.20	74.57	96.36	90.86	47.163	31.094	-	80,650	6,400
8	238.86	292.47	111.86	116.42	154.89	91.45	86.07	102.27	63.558	35.865	-	86,540	6,810
9	383.30	168.04	132.99	233.31	135.84	100.64	73.28	78.43	42.257	26.567	-	97,680	10,487
10	244.59	193.88	134.98	178.75	112.47	80.96	48.15	52.38	40.523	23.753	-	74,470	5,823
11	231.27	244.48	147.49	105.88	185.58	94.52	51.74	55.32	31.141	26.238	-	78,210	6,141
12	245.59	194.97	149.52	177.16	186.66	109.70	98.71	80.28	34.995	27.294	-	82,450	6,769
13	169.66	265.37	102.33	262.18	202.84	87.72	45.62	87.23	24.312	27.692	-	81,600	8,040
14	185.50	257.01	196.17	179.19	98.22	134.18	119.67	78.85	51.257	16.425	-	82,580	7,242
15	229.00	351.44	257.20	188.66	160.29	118.59	59.15	105.76	42.303	34.954	-	102,200	11,354
16	222.17	366.55	108.02	151.67	173.93	122.55	68.60	81.98	26.822	30.679	-	93,000	9,127
17	256.56	277.22	301.93	205.57	172.04	83.75	42.34	85.92	53.287	41.703	-	98,640	11,275
18	261.49	169.32	286.38	159.81	169.16	78.97	43.57	79.23	40.758	29.154	-	84,880	8,772
19	177.50	224.62	289.28	97.92	140.25	94.17	58.18	100.21	54.301	32.512	-	79,050	7,769
20	243.56	262.16	220.27	93.98	147.62	99.46	78.36	78.80	39.765	25.956	-	85,970	7,430
21	181.28	352.55	176.90	160.09	160.94	80.86	33.40	79.85	48.475	31.963	-	88,940	8,698
22	296.72	428.30	102.41	97.75	181.39	139.90	63.22	108.40	57.713	21.973	-	110,450	14,072
23	371.29	192.65	276.89	213.24	192.47	129.14	105.23	95.89	43.850	25.051	-	109,690	13,001
24	271.93	195.22	86.77	108.27	142.69	130.33	107.98	94.53	35.400	36.744	-	79,790	5,808

Total generator fuel cost = $2,143,200.00, Total emission =209,600.00 kg.

Table C. Optimal multiple V2G and generator scheduling by ISPSO-TVAC on the modified smart grid system for minimizing $\{FC_{new} + E_{new}\}$ with V2G of Case 2 in Table 4

t (hr.)	$P_{1,t}$ (MW)	$P_{2,t}$ (MW)	$P_{3,t}$ (MW)	$P_{4,t}$ (MW)	$P_{5,t}$ (MW)	$P_{6,t}$ (MW)	$P_{7,t}$ (MW)	$P_{8,t}$ (MW)	$P_{9,t}$ (MW)	$P_{10,t}$ (MW)	No. of V2G	Fuel Cost ($)	Emission (kg)
1	8.72	252.05	97.59	165.82	166.45	81.90	45.71	73.73	42.56	26.93	706	66,170	5,096
2	282.22	177.48	122.17	144.52	82.22	105.70	34.60	87.47	43.22	18.17	1,912	75,870	5,816
3	344.47	244.50	195.11	105.26	96.83	84.47	31.23	74.31	51.15	17.61	2,040	91,300	8,606
4	190.20	145.87	270.61	226.92	215.21	97.94	84.11	97.39	53.57	17.86	984	82,710	9,022
5	421.48	279.26	95.90	175.91	171.99	75.05	38.31	113.61	64.94	25.39	2,840	111,180	13,541
6	244.92	429.81	205.44	240.15	115.87	126.35	66.19	115.35	24.00	46.58	2,085	112,580	16,003
7	419.19	437.49	101.37	145.39	212.94	126.49	103.26	75.20	53.54	21.77	831	132,970	20,843
8	429.17	309.01	230.89	238.55	173.32	140.98	40.60	106.88	71.60	26.99	1,249	128,400	17,955
9	455.00	304.98	126.98	201.25	76.96	80.31	54.22	112.73	26.32	41.73	3,846	117,090	18,142
10	455.00	176.86	94.49	187.31	204.10	108.00	135.80	93.75	38.38	22.10	2,022	111,730	16,962
11	455.00	203.41	80.63	309.14	246.09	200.18	33.78	72.59	37.00	17.75	3,548	124,960	20,716
12	455.00	175.12	83.86	127.35	239.58	106.59	76.01	83.80	23.53	14.62	1,896	105,490	16,219
13	455.00	283.12	209.72	123.55	117.85	99.57	110.95	99.22	85.80	48.71	3,011	122,930	18,195
14	438.49	450.31	312.34	172.24	219.38	158.29	33.07	72.59	37.00	17.75	1,961	148,170	28,676
15	337.22	423.66	281.67	161.82	215.10	90.70	93.27	82.49	54.13	34.70	188	127,150	18,249
16	392.23	324.55	180.44	195.11	122.15	122.82	29.59	98.47	47.91	29.63	1,733	113,830	13,321
17	287.96	394.02	235.41	118.09	197.19	74.92	45.16	50.32	44.28	26.24	997	106,510	12,898
18	314.54	237.79	304.23	121.58	223.77	149.92	98.29	69.49	70.26	29.53	1,342	104,860	11,724
19	389.16	403.16	264.96	283.59	94.93	68.96	47.05	99.83	71.78	31.78	3,255	131,670	19,811
20	455.00	206.24	388.96	145.56	209.59	196.15	89.60	147.34	64.03	47.79	2,967	134,630	24,799
21	372.01	416.26	287.48	230.70	214.23	105.48	94.20	76.62	77.73	29.62	3,075	136,350	20,243
22	252.86	405.33	275.69	140.65	181.77	101.43	102.67	74.99	64.91	25.85	280	112,030	14,333
23	270.41	177.43	255.39	186.09	82.36	137.46	66.42	76.09	28.69	36.71	2,338	85,560	8,359
24	81.16	238.48	161.58	203.81	162.08	92.82	65.78	77.94	37.04	32.06	4,894	71,040	6,101

Total generator fuel cost = $2,655,200.00, Total emission = 365,630.00 kg.

Table D. Optimal multiple V2G and generator scheduling by ISPSO-TVAC on the modified smart grid system for minimizing $\{FC_{new}, E_{new}\}$ with V2G of Case 3 in Table 4

t (hr.)	$P_{1,t}$ (MW)	$P_{2,t}$ (MW)	$P_{3,t}$ (MW)	$P_{4,t}$ (MW)	$P_{5,t}$ (MW)	$P_{6,t}$ (MW)	$P_{7,t}$ (MW)	$P_{8,t}$ (MW)	$P_{9,t}$ (MW)	$P_{10,t}$ (MW)	No. of V2G	Fuel Cost ($)	Emission (kg)
1	215.85	169.76	117.55	156.80	85.77	77.97	86.76	87.34	41.274	11.423	769	68,170	4,898
2	232.36	142.74	151.14	143.12	128.77	117.71	73.58	79.49	25.834	31.914	823	71,170	5,244
3	206.15	142.75	155.91	76.69	80.91	62.59	65.46	68.43	44.320	11.842	933	60,580	4,171
4	220.35	221.70	114.73	114.70	119.02	85.82	76.55	71.78	49.548	12.943	359	71,560	5,082
5	302.00	149.28	148.02	133.11	92.72	61.56	43.76	52.33	35.758	11.705	1098	72,890	5,985
6	226.63	171.35	105.93	92.08	190.50	64.41	34.23	75.11	43.314	24.017	1208	68,200	4,827
7	295.56	156.06	184.11	130.13	146.76	60.48	80.33	59.10	40.548	19.958	1263	78,970	6,645
8	261.29	196.38	119.16	164.87	125.85	148.25	71.33	88.85	22.065	14.478	1317	79,370	6,289
9	155.58	145.10	183.17	68.71	120.49	88.98	59.00	53.31	40.871	25.412	1427	59,090	4,151
10	439.64	205.22	88.48	199.77	126.03	70.57	24.18	61.62	30.483	17.429	1540	100,630	14,138
11	268.24	306.83	152.91	83.58	133.28	93.17	30.33	62.47	46.111	32.285	1592	86,480	7,371
12	237.10	150.27	109.65	103.12	78.50	70.13	51.24	78.26	47.533	12.431	1647	63,510	4,307
13	228.33	174.29	186.76	77.87	143.23	85.70	60.14	68.50	42.633	25.147	1537	71,370	5,348
14	168.63	318.65	114.68	144.50	79.19	75.73	51.32	54.41	40.931	29.793	1427	75,320	6,278
15	209.13	247.07	93.07	186.44	76.91	91.29	49.68	49.98	31.595	10.715	1317	71,310	5,776
16	215.92	228.71	143.21	129.79	159.37	64.77	25.98	62.47	22.561	18.190	1153	71,590	5,652
17	234.58	141.11	256.39	166.97	123.74	67.04	73.23	97.26	46.288	20.788	1098	76,780	7,305
18	186.93	287.92	95.75	173.67	91.41	64.95	23.17	61.36	21.269	27.385	1208	72,440	6,058
19	239.54	190.01	179.55	163.82	92.25	109.18	33.58	84.45	45.978	25.464	1317	76,130	6,142
20	190.95	194.63	92.42	68.98	130.56	121.16	44.98	60.28	29.447	14.421	1206	63,160	4,152
21	161.29	221.50	104.58	117.01	100.30	83.80	57.99	74.31	33.511	28.305	1427	64,310	4,289
22	331.34	165.86	88.12	61.10	92.93	83.94	58.44	64.31	39.095	21.230	1208	75,430	5,966
23	439.23	197.75	172.28	83.32	165.84	95.04	63.93	77.57	36.302	29.515	988	104,330	13,892
24	356.53	244.29	147.71	70.61	115.63	86.18	45.59	78.02	39.241	22.352	878	90,430	8,260

Total generator fuel cost = $1,793,200.00, Total emission = 152,200.00 kg.

Tables B and D show the compromised solutions which include optimal number of V2G and generator scheduling using ISPSO-TVAC considering valve point loading effect without and with V2G in Table 4.