Dhawale *et al.*
Journal of Electrical Systems and Inf Technol (2023) 10:4
https://doi.org/10.1186/s43067-023-00069-2

Journal of Electrical Systems
and Information Technology

RESEARCH **Open Access**

An optimal solution to unit commitment problem of realistic integrated power system involving wind and electric vehicles using chaotic slime mould optimizer

Dinesh Dhawale[1,2*], Vikram Kumar Kamboj[1,3] and Priyanka Anand[4]

*Correspondence:
ddhawale56@gmail.com

[1] School of Electronics and Electrical Engineering, Lovely Professional University, Punjab, India
[2] Electrical Engineering, Priyadarshini College of Engineering, Nagpur, Maharashtra, India
[3] Schulich School of Engineering, University of Calgary, Alberta, Canada
[4] Electronics and Communication Engineering, Bhagat Phool Singh Mahila Vishwavidyalaya, Khanpur Kalan, Haryana, India

Abstract

Plug-in electric vehicles (PEVs) could be integrated into power networks to meet rising demand as well as provide mobile storage to help the electric grid operate more efficiently. The most efficient charging and discharging of PEVs are required for the effective utilization of this potential. PEVs with poor charging management may see a spike in peak demand, resulting in increased generation. To take advantage of off-peak charging benefits and avoid load shedding, PEVs charging and discharging must be intelligently scheduled. This paper offers a solution to optimal generation scheduling and the impact of vehicle to grid (V2G) operation in the presence of wind as a renewable energy source using the chaotic slime mould algorithm (CSMA). Further, the effectiveness of the proposed simulation results for a 10-unit system incorporating V2G operation has been compared with other well-known optimization techniques such as harmony search algorithm (HAS), chemical reaction optimization(CRO), genetic algorithm and artificial neural network(GA-ANN), particle swarm optimization (PSO), and cuckoo search (CS). The comparative analysis of the results reveals a significant cost savings in power generation.

Keywords: Chaotic slime mould algorithm (CSMA), Unit commitment (UC), Optimum scheduling (OS), Vehicle to grid (V2G), Optimization

Background

The majority of existing generation and transportation systems rely solely on fossil fuels, resulting in massive pollution and adverse impacts on the atmosphere. To ensure the long-term viability of these finite energy sources, it is essential to use them very precisely and economically. The incorporation of electric vehicles (EVs) has resulted in a decrease in the use of conventional petroleum-based transportation systems during the last few years. The main sources of battery charging are electric power utilities. A well-coordinated charging and discharging cycle, on the other hand, could help to reduce overall fossil fuel usage and pollutant emissions. Meanwhile, due to progress in power electronics, battery technology, and controller topologies, surplus power stored in batteries might be sent back to utilities via a convertor plant at the consumer's location. V2G technology has various advantages, including (i) alternative energy sources, (ii) energy diversification, (iii) pollution reduction, and (iv) increased performance and efficiencies. It also provides voltage regulation, harmonic filtering, and primary frequency control.

Overview of wind power and electric vehicles

Power developed by a wind turbine depends upon wind speed. As wind velocity continuously changes, power generated is always fluctuating. A large number of methods are available for predicting the uncertainties associated with wind power. In this study, Weibull function [1] is used for evaluating uncertainties in wind and mathematically represented as,

$$pdk_1(c, k1, \lambda) = \frac{k_1}{\lambda}\left(\frac{c}{\lambda}\right)^{k_1-1} \exp\left[-\left(\frac{c}{k_1}\right)^{k_1}\right] \tag{1}$$

As the power generated by wind is uncertain, variable due to randomness of wind velocity expressed as,

$$Pw = \begin{cases} 0 & (c^h \le \text{cin } or \ c^h \ge c_{\text{out}}) \\ Pwr & (c_r \le c^h \ge c_{\text{out}}) \\ \frac{(c-\text{cin})}{cr-cin} & (c_{\text{in}} \le c^h \ge c_r) \end{cases} \tag{2}$$

From Eq. (2), when wind speed c^h is less than or equal to minimum rated velocity, wind power is zero. Wind power is equal to the rated wind power, when wind speed is greater than rated speed. So, this shows that wind power is a discrete variable. The probability of wind power being 0,P_{wr} is calculated as per Eqs. (3) & (4), respectively, and described below:

$$\begin{gathered} P_r(P_w = 0) = \text{d}f(c_{\text{in}}) + [1 - \text{d}f(c_{\text{out}})] \\ \text{For } Pw = 0, \text{ Pr} = \left[1 - \exp -\left(\frac{c_{\text{in}}}{\lambda}\right)^{k_1}\right] + \exp\left[-\left(\frac{c_{\text{out}}}{\lambda}\right)^{k_1}\right] \end{gathered} \tag{3}$$

The probability density function depends upon v_{in} and v_r as the wind power is a continuous variable and it can be written as,

$$pdf(P_w) = \frac{KLv_{\text{in}}}{(P_{wT})^2}\left[\frac{1 + \left(LP_w/P_{\text{WR}}\right)c_{\text{in}}}{\lambda}\right] \times \exp\left[-\left(\frac{1 + \left(LP_w/P_{\text{WR}}\right)c_{\text{in}}}{\lambda}\right)^{k}\right] \tag{4}$$

The facility of the spinning reserve to meet the sudden demand may be fulfilled by the empirical formulas shown in Eq. (4). The base section of the load curve is considered for maximum wind power generation. A typical load pattern for maximum wind power supplied is plotted for a 24-hour duration as shown in Fig. 1.

EVs operate by consuming the stored energy in batteries and act as an excess load on existing system [3]. EVs may be broadly classified as: battery operated vehicles, PEVs and hybrid electric vehicles. With the advancement in battery technologies, a large variety of EVs are being recently manufactured on a large scale. Some of the electrochemical battery categories are given in Table 1. In [4], a systematic approach towards V2G planning

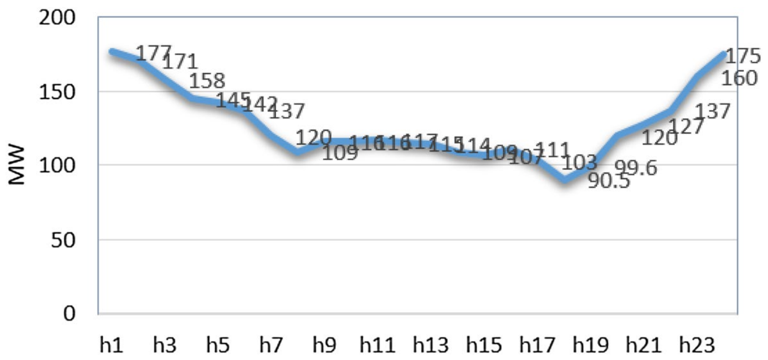


Fig. 1 Wind variation cycle [2]

Table 1 Types of batteries [5]

Battery name	Parameters						
	Efficiency	**Self-discharge per day**	**Capital cost ($/KWh)**	**Life time (charging/discharging Cycles)**	**Energy density (Wh/kg)**	**Storage duration**	**Environmental impacts (water & soil)**
Lead acid battery	75–80	0.1–0.3%	120–150	500 /700	30–50	Long term	Dangerous
Nickel cadmium	85–90	0.2–0.6%	800–1500	600 /800	50–75	Long term	Dangerous
Lithium-ion battery (Li-ion)	85–90	0.1–0.3%	300–1300	300 / 500	75–200	Long term	Rather low
Sodium sulphur battery (NaS)	80–90	20%	300–500	600 / 800	150–240	Short term	Dangerous

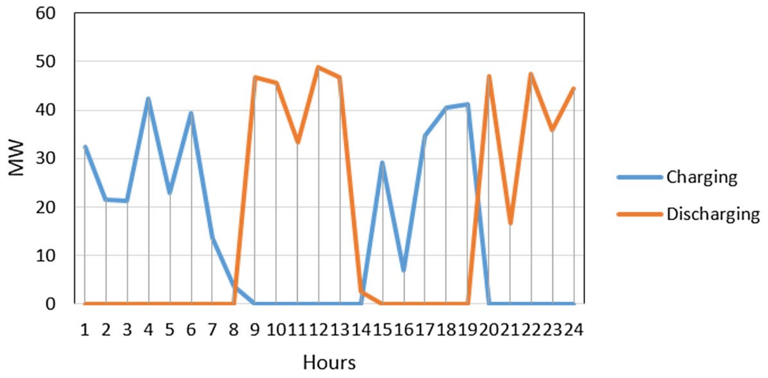


Fig. 2 EV- Charging/discharging pattern [6]

is explored for cost minimization. Further, availability of large number of charging facilities either while transportation or during parking bounds huge attraction of consumers. A typical charging/discharging pattern is selected as shown in Fig. 2

Overview of vehicle to grid operation

EVs can store or generate 4 KW to 80 KW-Hr on average, and if a well-coordinated system is available, widespread use of these vehicles may be viable. The unplanned charging and discharging of such a huge number of EVs could disturb the power system's dynamics and stability. However, a common power aggregator that can bring together a group of EVs and present the entire system to the grid as a single system could result in significant power contribution. The power aggregator should keep a keen watch on performance so that a large enough number of vehicles may engage in V2G operations. Figure 3 depicts a simplified model that explains the various operations that fall under the V2G framework [7].

Optimization approaches for UC-V2G

The concept of smart grid technology enables a large number of consumers to take participate in energy conservation by selling back excessive power to grid. Advancement in battery technology enables to design desired sizing and providing efficient facilities for controlled charging and discharging. The UC problem becomes rather more complex by this increased power injection. Thus, it becomes necessary to have proper co-ordination of UC-V2G operation by fixing various UC and V2G constraints. The complexities of intermittent nature of wind energy and electric vehicles are coordinated, and unit commitment problem is resolved using mixed integer linear programming [8]. A power dispatch with 15 conventional units and 3 wind farms along PEV is incorporated in shifting of EV and wind power injection effectively to reduce the generation cost. Chemical reaction optimization technique is employed for economic generation scheduling incorporating V2G operation [9]. The charging and discharging patterns of electric vehicles were correctly formulated for

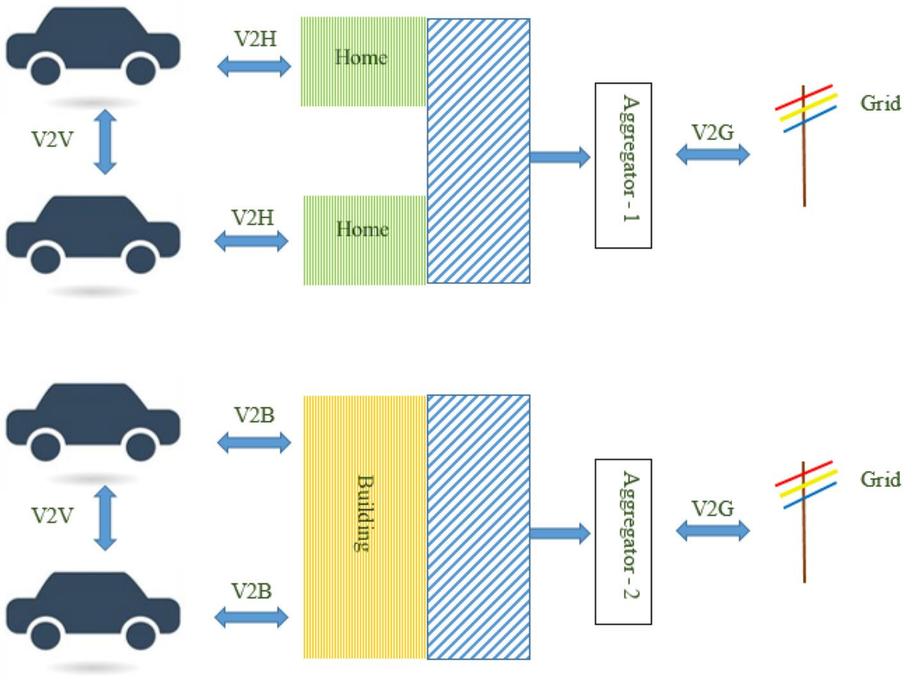


Fig. 3 Schematic representation of V2G operation

cost minimization and enhancing system reliability by using genetic algorithm [10]. Virtual power of parking lot is fed back to grid using GA-ANN method for removing additional cost of small units required for reserve [11]. Complexities in conventional UC due to large number of grid-able electric vehicles were effectively resolved by using particle swarm optimizer algorithm. PSO enables to provide solution for cost minimization and low emission [12].The subsequent section presents construction of unit commitment problem using proposed CSMA algorithm.

Construction of unit commitment problem

Mathematical formulation

The generation schedule must be planned well in advance such that sufficient power is always available to meet forecasted load demand with reliability. This could be more effective if a sufficient amount of power is contributed by renewable energy sources. Various mathematical equations satisfying system constraints are formulated to meet load demand including the cost of fuel, starting cost, and shunt down cost. The total fuel cost (F_T) is determined by summing up generation cost of each individual unit for a defined time interval. It can be mathematically represented as:

$$F_T = \sum_{i=1}^{H} \left[\sum_{i=1}^{N} \left(a_i P_{i,h}^2 + b_i P_{i,h} + c_i \right) U_{i,h} + ST_{c(i)} (1 - U_{i(h-1)}) U_{i,h} \right] \ \$/hr \tag{5}$$

where a_i b_i and c_i are the fuel cost function expressed in $\$/\mathrm{h}$, $\$/\mathrm{MWh}$, and $\$/\mathrm{MWh}^2$, respectively.

Mathematically, start-up cost $ST_{c(i)}$ can be expressed as the sum of cold start-up ($\mathrm{CSch}(i)$) and hot start-up cost (HSch) of ith unit, respectively.

$$\mathrm{ST}_{c(i)} = \begin{cases} \mathrm{HSch}(i); & \mathrm{MD}t(i) \leq T_{\mathrm{h}i}^{\mathrm{OFF}} \leq (\mathrm{MD}t(i) + \mathrm{CSh}(i)) \\ \mathrm{CSch}(i); & T_{\mathrm{h}(i)}^{\mathrm{OFF}} \rangle (\mathrm{MD}t(i) + \mathrm{CSh}(i)) \end{cases} \quad (i \in N; \mathrm{h} = 1, 2, 3, \ldots.., H) \tag{6}$$

Unit commitment problem needs to provide optimum solution within certain constraints. The major constraints involved in UC problem are:

(i) Operating limit constraints
(ii) Load balance constraints
(iii) V2G constraints
(iv) Spinning reserve constraints

Operating limits constraints

There is a limit below which power generation is not economical due to some technical limitations. Similarly, power generation should not be more maximum power generation limit. These power generation limits for a particular unit are calculated from the heat rate curve and fuel cost coefficient limits.

$$P_{g\,\min(i)} \leq P_{g(i)} \leq P_{g\,\max)(i)} \ (i \in 1, 2, \ldots., N \ ; \ \mathrm{h} \in 1, 2, \ldots., \mathrm{H}) \tag{7}$$

Load balance constraints

The load demand is found to never remain constant, and it continuously changes over the entire span of the considered time interval. It is desired that the overall power generated by all the committed units (N) for a particular duration (h) should always satisfy the connected load demand (*DL*). Therefore, at any instant of time, the power supplied by thermal unit and additional wind power should always be equal to power demand.

$$\sum_{i=1}^{N} P_{g(i)}U_{i,h} + P_g^w = D_L \qquad (i = 1, 2, \ldots.., N) \tag{8}$$

Case-1: During charging of vehicle (grid to vehicle)

$$\sum_{i=1}^{N} P_{g(i)}U_{i,h} + P_g^w = D_L + D_h^V \qquad (i = 1, 2, \ldots.., N) \tag{9}$$

Case-2: During discharging (vehicle to grid)

$$\sum_{i=1}^{N} P_{g(i)}U_{i,h} + P_g^w + D_h^V = D_L \qquad (i = 1, 2, \ldots.., N) \tag{10}$$

The power outputs of the *NG* generating units at a particular time period have to satisfy the forecasted load. For arbitrary free unit power outputs *Phi*, (i=1, 2, NG), it is assumed that the Rth reference unit power output is constrained by the power balance equation as:

Table 2 Chaotic functions [14]

Sr. No	Chaotic name	Mathematical description
1	Chebyshev	$y_{i+1} = \cos\left(\cos^{-1}(y_i)\right)$
2	Iterative	$y_{i+1} = \mathrm{Sin}\left({}^{a\pi}/_{y_i}\right),\ a = 0.7$
3	Sinusoidal	$y_{i+1} = ax_i\,\mathrm{Sin}(\pi xi)\,;\ a = 2.3$
4	Sine	$y_{i+1} = \frac{a}{4}\,\mathrm{Sin}(\pi yi)\,, a = 4$
5	Circle	$y_{i+1} = \mathrm{mod}\left(y_i + b - \left({}^{a}/_{2\pi}\right)\mathrm{Sin}(2\pi y_i),\ 1\right);\ a = 0.5,\ b = 0.2$
6	Piecewise	$\begin{cases} {}^{y_i}/_{p} & 0 \le y_i \langle p \\ {}^{(y_i - p)}/_{(0.5-p)} & p \le y_i \langle 0.5 \\ {}^{(1-p-y_i)}/_{(0.5-p)} & 0.5 \le y_i \langle 1-p \\ {}^{(1-y_i)}/_{p} & 1-p \le y_i \langle 1 \end{cases} ,p = 0.4$
7	Gauss/mouse	$\begin{cases} 1, & y_i = 0 \\ \frac{1}{\mathrm{mod}\,(y_i,1)} & \text{otherwise} \end{cases}$
8	Singer	$y_{i+1} = \mu\left(7.86y_i - 23.3y_i^2 + 28.75y_i^3 - 13.301875y_i^4\right),\ \mu = 1.07$
9	Logistic	$y_{i+1} = a y_i (1 - y_i),\ a = 4$
10	Tent	$y_{i+1} = \begin{cases} (y_i/0.7), & y_i < 0.7 \\ (10/3)(1-y), & y_i \ge 0.7 \end{cases}$

$$P_{Rh} = D_L - \sum_{i=1}^{NG} P_{g(i)} U_{i,h} + P_g^w \qquad (i = 1, 2, \ldots.., N) \tag{11}$$

Case-1: During charging of vehicle

$$P_{Rh} = \left(D_L - \sum_{i=1}^{N} \left(P_{g(i)}\ U_{i,h}\ +\ P_g^w \right)\ -\ D_h^V \right) \qquad (i = 1, 2, \ldots.., N) \tag{12}$$

Case-2: During discharging

$$P_{Rh} = \left(D_L - \sum_{i=1}^{N} \left(P_{g(i)} U_{i,h} + P_g^w \right) - D_h^V \right) \qquad (i = 1, 2, \ldots.., N) \tag{13}$$

V2G constraint

V2G technology enables a fixed number of registered vehicle to participate in UC. EVs are assumed to be charged during off-load period by utility grid or from renewable energy sources. Charging–discharging duration depends upon battery size and charging facilities. It is assumed that all vehicles charged by stand-alone system available at the parking slot.

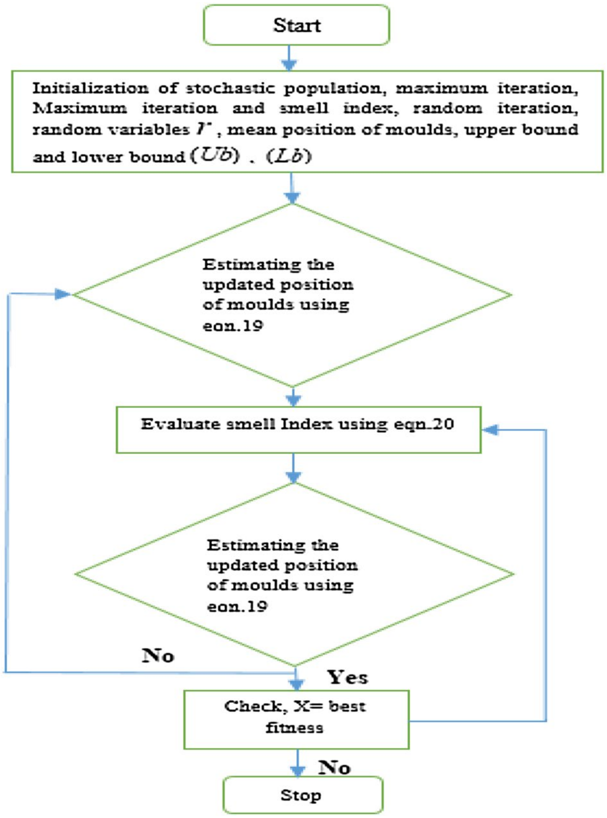


Fig. 4 Flow chart of chaotic SMA

$$\sum_{t=1}^{H} N_{V2G}\,(t) = N_{V2G}^{\mathrm{Max}}(t) \tag{14}$$

Spinning reserve constraints

Unpredictable disturbances, such as sudden load demand or unexpected tripping of lines or generators, necessitate the availability of additional generation capacity. Spinning reserve is the term given to this additional generation capability. To meet demand while maintaining an adequate reserve margin, optimal generation allocation must be planned ahead of time. Wind penetration adds additional electricity, which assists to contribute towards total power generation. As a result of the additional power provided by wind energy, the load on thermal units may be reduced. Mathematically, spinning reserve is given as:

$$\sum_{i=1}^{N} P_{g\,\max(i)} U_{i,\mathrm{h}} + P_{g(\mathrm{h})}^{W} \geq D_{L(\mathrm{h})} + \mathrm{SP}_{R(\mathrm{h})} \qquad (\mathrm{h} = 1, 2, \ldots.., H) \tag{15}$$

Grid to vehicle

$$\sum_{i=1}^{N} P_{g\,\max(i)} U_{i,\mathrm{h}} + P_{g(\mathrm{h})}^{W} \geq D_{L(\mathrm{h})} + \mathrm{SP}_{R(\mathrm{h})} + D_{\mathrm{h}}^{V} \qquad (\mathrm{h} = 1, 2, \ldots.., H) \tag{16}$$

Vehicle to grid

$$\sum_{i=1}^{N} P_{g\,\max(i)} U_{i,\mathrm{h}} + P_{g(\mathrm{h})}^{W} \geq D_{L(\mathrm{h})} + \mathrm{SP}_{R(\mathrm{h})} - D_{h}^{V} \qquad (\mathrm{h} = 1, 2, \ldots.., H) \tag{17}$$

CSMA mathematical formulation

Slime moulds have received a level of admiration in recent times. The slime mould mentioned in this article is usually Physarum polycephalum. Typically, the plasmodium forms a network of protoplasmic tubes connecting the masses of protoplasm at the food sources, which is efficient in terms of network length and elasticity [13]. The slime mould even flows vibrantly in the situation of food scarcity, which aids in comprehending how slime mould search, move, and connect food in a changing environment. It can judge positive and negative feedback, when a secretion approaches the target and determines the most effective approach to capture food. While foraging, slime mould uses empirical principles based on currently available insufficient data to decide whether to start a fresh search and leave the existing place.

Mould may divide its biomass to exploit other resources on the information of some other rich high-quality food information, even if a food source is abundant. It may modify their search patterns dynamically depending on the quality of food sources [14].The concept of probability distribution is captured by lot of meta-heuristics algorithms to gain randomness. Chaotic maps could be beneficial if randomness due to ergodicity, idleness and randomness properties are properly utilized. These chaotic criteria's are fulfilled by Eq. (18).

$$O_{k+1} = f(O_k) \tag{18}$$

In Eq. (1), O_{k+1} &$f(O_k)$ are the $(k+1)$th & kth chaotic number, respectively. The action of chaotic function is dependent on initial value O_0. In the proposed work, from the 10 most commonly used chaotic strategies presented in Table 2, Tent chaotic function has been combined with basic CSMA algorithm to search space more enthusiastically and comprehensively.

The optimization procedure for the CSMA algorithm consists of the following eight steps:

Step 1 Specify the input parameters required by SMA and random chaotic function to solve the optimization problem defined by Eq. (21). Moulds position, population size, maximum iteration and smell index associated food searching, random iteration, random variables r, mean position of moulds, upper bound and lower bound (Ub), (Lb) are according initiated.

Step 2 Initialization of stochastic population (X_i=1, 2, 3.....,N) and maximum iteration number is taken as *ier*_max.

Step 3 Calculate the fitness of all slime mould and estimating the updated position of moulds.

$$\overrightarrow{X(t+1)} = \begin{cases} \overrightarrow{X_b(t)} + \overrightarrow{v_b}.\left(\overrightarrow{\mathrm{W}}.\overrightarrow{X_A(t)} - \overrightarrow{X_B(t)}\right), & r < p \\ \overrightarrow{v_c}.\overrightarrow{X(t)}, & r \geq p \end{cases} \tag{19}$$

Step 4 Enhancing the search process by clubbing chaotic strategy.

Step 5 Calculating the

$$\overrightarrow{\mathrm{W(smell\,index(i))}} = \begin{cases} 1 + r.\log\left(\frac{bF - S(i)}{bF - wF} + 1\right), & \text{condition} \\ 1 - r.\log\left(\frac{bF - S(i)}{bF - wF} + 1\right), & \textit{others} \end{cases} \tag{20}$$

Step 6 For each search iteration using sinusoidal chaotic function, the positions of p, vb, vc are updated

$$\begin{aligned} & r_o = rand; \\ & r_o(t+1) = 2.3 \times r_0^2 \times \mathrm{Sin}(Pi.r_0) \\ & r_1 = r_0(t+1); \end{aligned} \tag{21}$$

Step 7 The eqn. for upgrading the positions of agents (i.e. to wrap food) is given as:

$$\overrightarrow{X^*} = \begin{cases} rand.(UB - LB) + LB, \; rand < z \\ \overrightarrow{X_b(t)} + \overrightarrow{v_b}.\left(\mathrm{W}.\overrightarrow{X_A(t)} - \overrightarrow{X_B(t)}, \; r < p\right) \\ \overrightarrow{v_c}.\overrightarrow{X(t)}, \; r \geq p \end{cases} \tag{22}$$

Step 8 With the up gradation in the search process, the value of $\overrightarrow{v_b}$ vibrantly changes between [− a,a] and $\overrightarrow{v_c}$ varies between [− 1,1] and at last shrinks to zero. This is known to be as 'grabbling of food'.

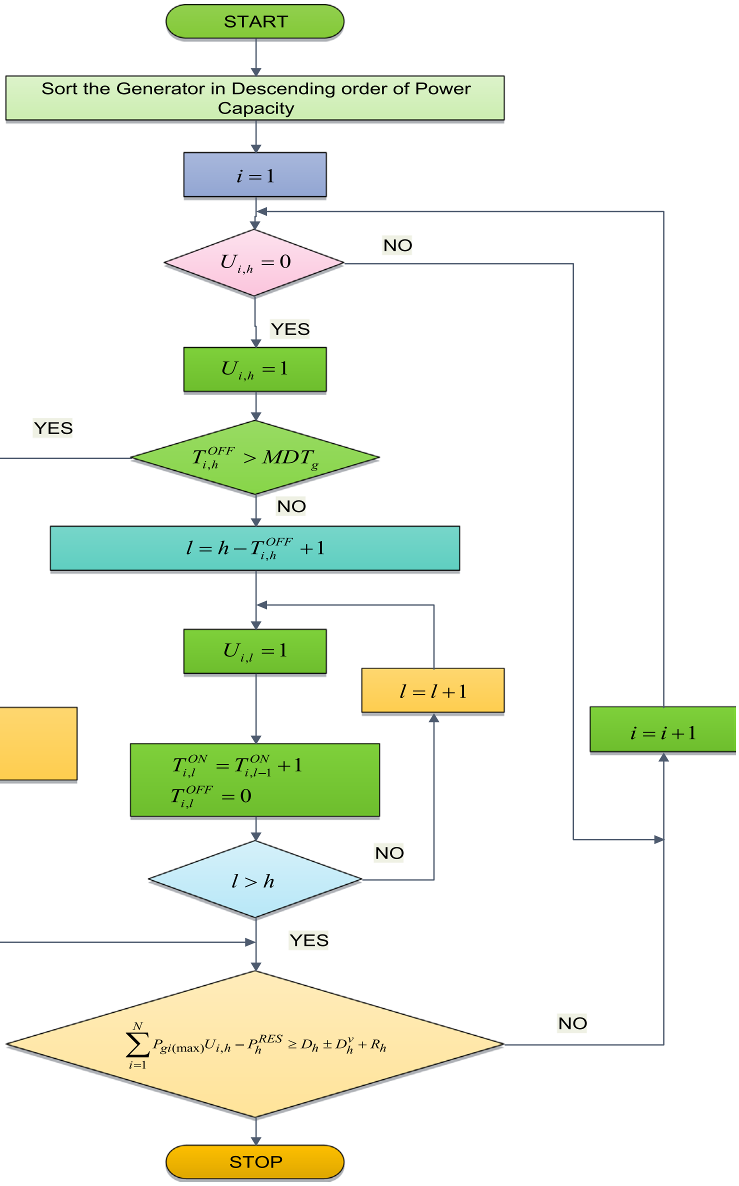


Fig. 5 Flow chart for spinning reserve repairing

The flow chart for optimization procedure for the CSMA algorithm is shown in fig. 4.

Implementation of proposed CSMA algorithm for unit commitment problem

The CSMA method is an innovative meta-heuristic algorithm that has an excellent ability of exploration and exploitation and effectively utilized to solve the unit commitment problem of a hybrid system. For a particular test system, the proposed algorithm selects an optimal generating schedule as a binary variable showing ON/OFF status. The following steps elucidate the procedure of a unit commitment problem [15].

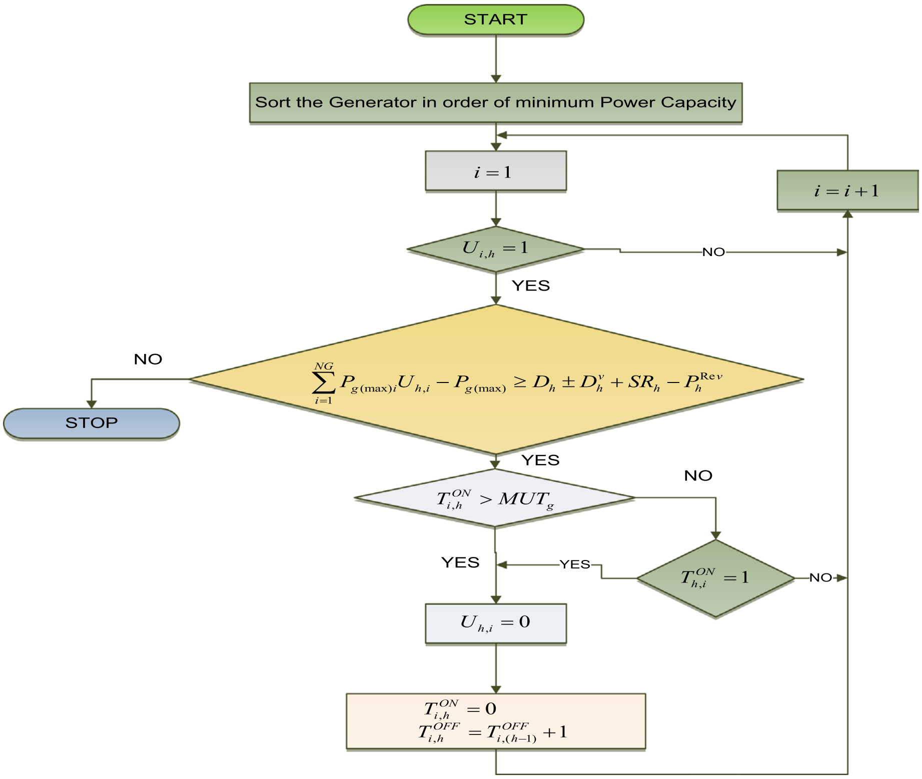


Fig. 6 Flow chart for the decommitment of excessive generating units

Table 3 Standard IEEE 10-unit system [16]

Unit parameter	**Generating units**									
	U1	**U2**	**U3**	**U4**	**U5**	**U6**	**U7**	**U8**	**U9**	**U10**
Max Pn	455	455	130	130	162	80	85	55	55	55
Min Pn	150	150	20	20	25	20	25	10	10	10
An	1000	970	700	680	450	370	480	660	665	670
Bn	16.19	17.26	16.6	16.5	19.7	22.26	27.74	25.92	27.27	27.79
Cn	0.00048	0.00031	0.002	0.00211	0.00398	0.00712	0.00079	0.00413	0.00222	0.00173
UpTn	8	8	5	5	6	3	3	1	1	1
DwTn	8	8	5	5	6	3	3	1	1	1
HSUn	4500	5000	550	560	900	170	260	30	30	30
CSUn	9000	10,000	1100	1120	1800	340	520	60	60	60
Tn_{COLD}	5	5	4	4	4	2	2	0	0	0
INSn	8	8	− 5	− 5	− 6	− 3	− 3	− 1	− 1	− 1

Step 1 The status of a unit for generation scheduling is expressed through their position. In this study, we define the status of a unit as a binary number: 0 indicates de-committed unit, and 1 is for committed unit. Once the generation schedule is for a particular load demand is selected, the data of units are stored in integer matrix U_{NG} as,

Table 4 Parameters of PEVs [5]

Parameters of PEVs	Specification
battery capacity (maximum)	25 kWh
battery capacity(minimum)	10 kWh
battery capacity(average)	15 kWh
charging/discharging frequency	1 per day
departure state of charge (δ)	50%
total efficiency (η)	85%

$$U_{NG} = \begin{bmatrix} u_1^1 & u_1^2 & \cdots & u_1^H \\ u_2^1 & u_2^2 & \cdots & u_2^H \\ \vdots & \vdots & \vdots & \vdots \\ u_G^1 & u_G^2 & \cdots & u_G^H \end{bmatrix}$$

Step 2 Enter UCP input parameters, i.e. Maximum power limit, minimum power limit, fuel cost coefficient

Step 3 Set iteration counter, $i = 0$ and initialize random position of search agents.

Step 4 Calculate the priority list of each search generator according to characteristics of each generating units.

Step 5 Modify search agent position to satisfy reserve constraints.

Step 6 Repair each search agent position for minimum Up/Down time violation.

Step 7 Verify generator output power or else increment iteration count by 1 and go to step 5.

Constraints repair strategy

Typically unit commitment programmes are designed to represent the operations of a centrally dispatched power system that is the portfolio of generators all scheduled in a coordinated way to meet aggregated electricity demand. The goal is always to minimize the cost of doing this subjected to constraints. During the major scheduling by CSMA, there may be a possibility that CSMA may fail to fulfill essential constraints such as minimum up/downtime, and spinning reserve. So, deviations in these constraints are needed to be repaired. In this paper, the strategy adopted is a heuristic search to tackle the UC problem.

Constraints related to minimum up /minimum downtime

Once a unit is started, it should not be turned off immediately before reaching MUT. This is required to satisfy economic, mechanical, and design limitations. Similarly, any unit which is once de-committed should not put online immediately. These constraints are required to be calculated in advance by using the following recursive relation:

Table 5 Unit allocation and active power schedule for 10-unit test system with 10% SR using CSMA

Time (h)	Generation scheduling of committed units										Power (MW)	Start-up cost	Hourly fuel cost
	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10			
1	455	245	0	0	0	0	0	0	0	0	700	1620	13,683
2	455	295	0	0	0	0	0	0	0	0	750	0	14,554
3	455	370	0	0	25	0	0	0	0	0	850	560	16,809
4	455	455	0	0	40	0	0	0	0	0	950	0	18,598
5	455	390	130	0	25	0	0	0	0	0	1000	0	20,051
6	455	360	130	130	25	0	0	0	0	0	1100	520	22,387
7	455	410	130	130	25	0	0	0	0	0	1150	0	23,262
8	455	455	130	130	30	0	0	0	0	0	1200	170	24,150
9	455	455	130	130	85	20	25	0	0	0	1300	180	27,251
10	455	455	130	130	162	33	25	10	0	0	1400	0	30,058
11	455	455	130	130	162	73	25	10	10	0	1450	60	31,916
12	455	455	130	130	162	80	25	43	10	10	1500	30	33,890
13	455	455	130	130	162	33	25	10	0	0	1400	0	30,058
14	455	455	130	130	85	20	25	0	0	0	1300	0	27,251
15	455	455	130	130	30	0	0	0	0	0	1200	0	24,150
16	455	310	130	130	25	0	0	0	0	0	1050	0	21,514
17	455	260	130	130	25	0	0	0	0	0	1000	120	20,642
18	455	360	130	130	25	0	0	0	0	0	1100	60	22,387
19	455	455	130	130	30	0	0	0	0	0	1200	430	24,150
20	455	455	130	130	162	33	25	10	0	0	1400	30	30,058
21	455	455	130	130	85	20	25	0	0	0	1300	0	27,251
22	455	455	0	0	145	20	25	0	0	0	1100	0	22,736
23	455	420	0	0	25	0	0	0	0	0	900	0	17,685
24	455	345	0	0	0	0	0	0	0	0	800	0	15,427
Overall Cost of generation = **563,698.15824**													

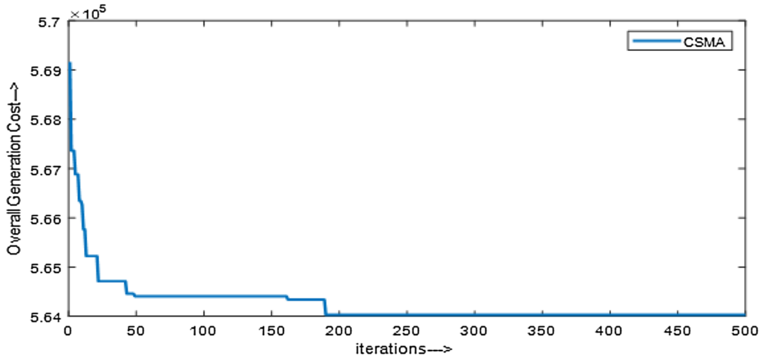


Fig. 7 Convergence curve for 10 units system

$$
\begin{aligned}
&T^{i,j}_{g,on} = \left\{ T^{i-1}_{g,on} + 1;\ if\ u^{i}_{j} = 1 \right\} \\
&T^{i,j}_{g,on} = 0\ if\ u^{i}_{j} \ = 0 \\
&T^{i,j}_{g.off} = T^{i-1}_{g,off} + 1;\ if\ \ u^{i}_{j} \ = 0 \\
&T^{i,j}_{g,OFF} = 0\,;\ if\ u^{i}_{j} \ \ = 0
\end{aligned}
\tag{22}
$$

Handling of spinning reserve constraints

The CSMA algorithm may sometimes perform unenviably to satisfy spinning reserve constraint. This happens to handle minimum up/down constraint, and excessive spinning reserve is needed. Thus, this spinning reserve constraint requirement should be handled heuristically. The PSEUDO code is shown in appendix-1, and whole process to repair spinning reserve requirement is represented in Fig. 5

De-committing of excess of units

During repair process of MDT/MUT and spinning reserve, some of the units may get unnecessarily ON. To avoid this situation that could result in excessive cost for running those units, some of the units need to be shut-down. The PSEUDO code is shown in appendix-2, and flow chart for de-committing of excessive units is shown in fig. 6.

Results & discussion for unit commitment problem

In this section, results of standard IEEE test system with conventional UC and UC-EV system are presented. The test systems are simulated MATLAB 2018a Windows 10, CPU@2.10Ghz-4GB RAM Core i5. To check the performance of the CSMA method for solving the unit commitment, standard test system of IEEE is taken into concern.

Overview of assumptions

(i) It is assumed that system is considered as lossless.
(ii) Operating cost of V2G is omitted in this study

Table 6 Generation scheduling for 10-unit system with wind penetration using CSMA

Time (h)	Generation scheduling of committed units										Power (MW)	Start-up cost	Hourly fuel cost
	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10			
1	455	245	0	0	0	0	0	0	0	0	700	1620	13,683
2	455	295	0	0	0	0	0	0	0	0	750	0	14,554
3	455	370	0	0	25	0	0	0	0	0	850	560	16,809
4	455	455	0	0	40	0	0	0	0	0	950	0	18,598
5	455	390	130	0	25	0	0	0	0	0	1000	0	20,051
6	455	360	130	130	25	0	0	0	0	0	1100	520	22,387
7	455	410	130	130	25	0	0	0	0	0	1150	0	23,262
8	455	455	130	130	30	0	0	0	0	0	1200	170	24,150
9	455	455	130	130	85	20	25	0	0	0	1300	180	27,251
10	455	455	130	130	162	33	25	10	0	0	1400	0	30,058
11	455	455	130	130	162	73	25	10	10	0	1450	60	31,916
12	455	455	130	130	162	80	25	43	10	10	1500	30	33,890
13	455	455	130	130	162	33	25	10	0	0	1400	0	30,058
14	455	455	130	130	85	20	25	0	0	0	1300	0	27,251
15	455	455	130	130	30	0	0	0	0	0	1200	0	24,150
16	455	310	130	130	25	0	0	0	0	0	1050	0	21,514
17	455	260	130	130	25	0	0	0	0	0	1000	120	20,642
18	455	360	130	130	25	0	0	0	0	0	1100	60	22,387
19	455	455	130	130	30	0	0	0	0	0	1200	430	24,150
20	455	455	130	130	162	33	25	10	0	0	1400	30	30,058
21	455	455	130	130	85	20	25	0	0	0	1300	0	27,251
22	455	455	0	0	145	20	25	0	0	0	1100	0	22,736
23	455	420	0	0	25	0	0	0	0	0	900	0	17,685
24	455	345	0	0	0	0	0	0	0	0	800	0	15,427

Overall Cost of generation = 492,522.21780

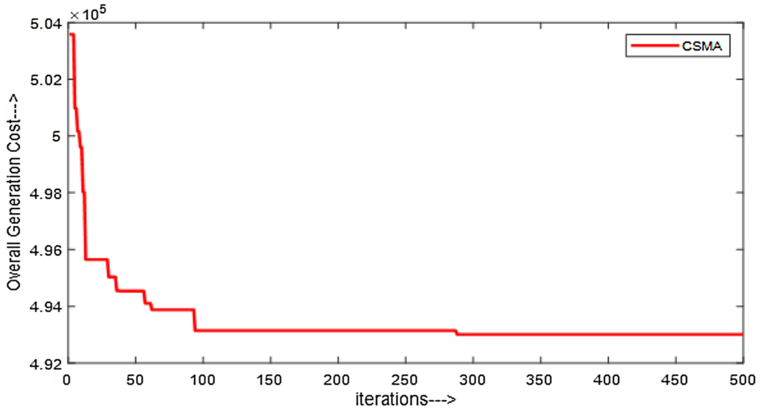


Fig. 8 Scheduling for 10 units system with wind penetration

(iii) A fleet of 40,000 electric vehicles are taken into consideration. Out of which 8000 vehicles are assumed to wire for V2G operation at any instant.
(iv) Wind power forecasting error cost is not considered as it is out of scope in the present research
(v) Simulation with different wind penetration levels, capacity of thermal generation and participation of PEVs are kept fixed

A standard IEEE 10-unit system presented in Table 3 is considered for simulation study with 40000 PEVs. Spinning reserve requirement is assumed to be 10% of the hourly load demand in 24 hour scheduling time period. Parameters of PEV are depicted in Table 4. Table 5 shows unit allocation and active power scheduling for 10-unit system. Figure 7 shows convergence curve for 10 unit system with 10% SR.Table 6 illustrates unit allocation and active power scheduling for 10-unit system with wind. Figure 8 shows convergence curve for 10 unit system with 10% SR with wind using CSMA. Table 7 shows unit allocation and active power scheduling for 10-unit system with V2G penetration using CSMA. Figure 9 shows convergence curve for 10 units system with EV penetration. Figure 10 shows cost comparison for 10 unit system with EV penetration using CSMA method.Further, effectiveness of the proposed simulation results for a 10 unit system incorporating wind and V2G operation has been compared with other well-known optimization techniques such as HSA[8], CRO[8], GA-ANN[8], PSO[8] and CS[8]. The comparative analysis of the results shows a significant cost reduction for V2G operation using proposed CSMA method (Table 8).

Conclusion

In this paper, standard IEEE 10 unit system has been simulated with and without V2G by applying CSMA method for minimizing the overall cost. Results revealed that proposed method is effective in solving economic despatch problem very precisely. To check the effectiveness of proposed algorithm, results are compared with other methods. The

Table 7 Generation scheduling for 10-unit system with wind and EV penetration using CSMA

Time (h)	Generation scheduling of committed units										Power (MW)	Start-up cost	Hourly fuel cost
	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10			
1	405	150	0	0	0	0	0	0	0	0	555	1450	11,208
2	450	150	0	0	0	0	0	0	0	0	601	0	11,957
3	455	258	0	0	0	0	0	0	0	0	713	170	13,914
4	455	367	0	0	25	0	0	0	0	0	847	560	16,763
5	455	401	0	0	25	0	0	0	0	0	881	60	17,352
6	455	392	0	130	25	0	0	0	0	0	1002	0	20,059
7	455	434	0	130	25	0	0	0	0	0	1044	0	20,783
8	455	355	130	130	25	0	0	0	0	0	1095	60	22,294
9	455	397	130	130	25	0	0	0	0	0	1137	750	23,039
10	455	455	130	130	49	20	0	0	0	0	1239	30	25,339
11	455	455	130	130	85	20	25	0	0	0	1300	60	27,246
12	455	455	130	130	121	20	25	0	0	0	1336	0	27,995
13	455	455	130	130	44	0	25	0	0	0	1239	0	25,610
14	455	449	130	130	25	0	0	0	0	0	1189	0	23,937
15	455	382	130	130	25	0	0	0	0	0	1122	60	22,772
16	455	206	130	130	25	0	0	0	0	0	946	260	19,699
17	455	192	130	130	25	0	0	0	0	0	932	170	19,455
18	455	310	130	130	25	0	0	0	0	0	1050	0	21,515
19	455	402	130	130	25	0	0	0	0	0	1142	60	23,115
20	455	455	130	130	53	0	0	0	0	10	1233	0	25,560
21	455	416	130	130	25	0	0	0	0	0	1156	0	23,374
22	455	436	0	0	25	0	0	0	0	0	916	0	17,957
23	455	249	0	0	0	0	0	0	0	0	704	0	13,754
24	431	150	0	0	0	0	0	0	0	0	581	0	11,626
Overall Cost of generation = 490,013.6840													

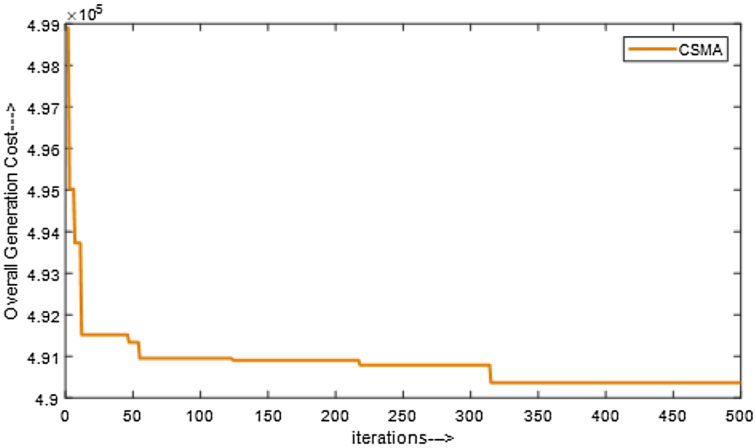


Fig. 9 Convergence curve for 10 units system with wind and EV penetration

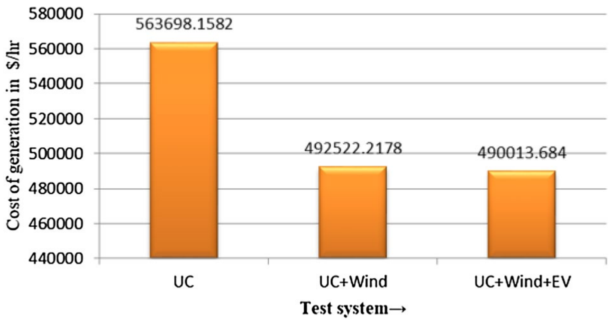


Fig. 10 Cost comparison for 10 units system with EV penetration

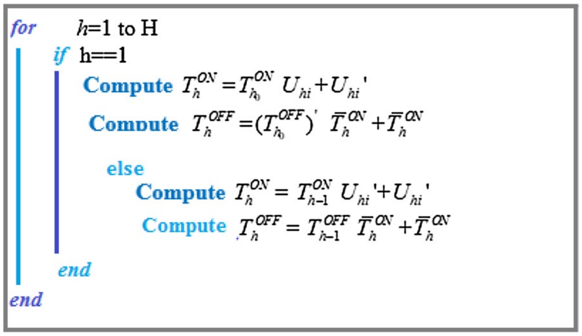
Table 8 Comparison 10-unit system (10% SR) for thermal-V2G using CSMA with other algorithms

Method	Cost without V2G in $	Cost with V2G in $
HAS [17]	573,879.34	554,134.59
CRO [9]	-	564,727.87
GA-ANN [11]	564,714	557,554.9
PSO [18]	563,741.83	559,0813.6
CS [19]	561,284.56	554,016.60
CSMA[Proposed Method]	*563,698.1582*	*490,013.6840*

comparative analysis reveals that proposed method outperforms in all aspects. Thus, proposed method is a cost effective solution for solving UC problem with due effect of renewables and EV.

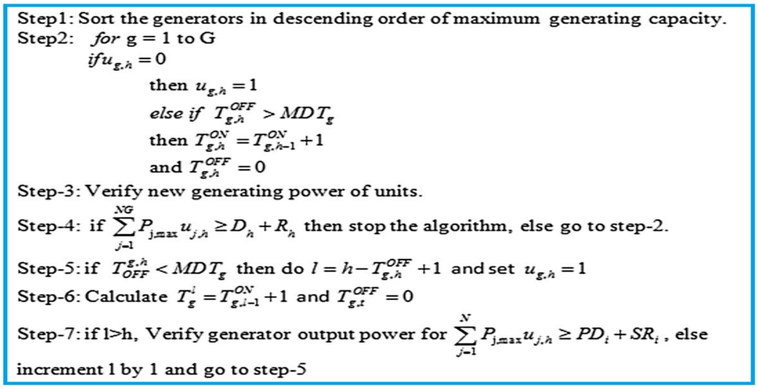
Appendix

(1) Pseudo code for satisfying minimum up and down using heuristic repair mechanism.



```
for     $h$=1 to H
    if h==1
        Compute $T_h^{ON} = T_{h_0}^{ON} U_{hi} + U_{hi}'$
        Compute $T_h^{OFF} = (T_{h_0}^{OFF})' \bar{T}_h^{ON} + \bar{T}_h^{ON}$
    else
        Compute $T_h^{ON} = T_{h-1}^{ON} U_{hi}' + U_{hi}'$
        Compute $T_h^{OFF} = T_{h-1}^{OFF} \bar{T}_h^{ON} + \bar{T}_h^{ON}$
    end
end
```

(2) PSEUDO code for spinning reserve repairing.



```
Step1: Sort the generators in descending order of maximum generating capacity.
Step2:   for g = 1 to G
         if $u_{g.h} = 0$
             then $u_{g.h} = 1$
             else if $T_{g.h}^{OFF} > MDT_g$
             then $T_{g.h}^{ON} = T_{g.h-1}^{ON} + 1$
             and $T_{g.h}^{OFF} = 0$
Step-3: Verify new generating power of units.
Step-4: if $\sum_{j=1}^{NG} P_{j.max} u_{j.h} \geq D_h + R_h$ then stop the algorithm, else go to step-2.
Step-5: if $T_{OFF}^{g.h} < MDT_g$ then do $l = h - T_{g.h}^{OFF} + 1$ and set $u_{g.h} = 1$
Step-6: Calculate $T_g^l = T_{g.l-1}^{ON} + 1$ and $T_{g.t}^{OFF} = 0$
Step-7: if l>h, Verify generator output power for $\sum_{j=1}^{N} P_{j.max} u_{j.h} \geq PD_i + SR_i$, else
increment l by 1 and go to step-5
```

Nomenclature

a_i, b_i and c_i	Fuel cost coefficients
$\mathrm{CS(h)}$	Cold starting hour of the *i*th unit
$\mathrm{CSc}_{i,\mathrm{h}}$	Cold start-up cost
D_L	Demand at 'h' hour
F_T	Total fuel cost
$itn_{\max}$	Maximum iterations
NG	Number of generators
MUT	Minimum uptime
MDT	Minimum downtime
$P_{g \max (i)}$	Maximum generation by *i*th unit
$P_{g \min (i)}$	Minimum generation by *i*th unit
$P_{g (i)}$	Minimum generation by *i*th unit
P_g^w	Power contributed by renewable energy
$P_{R(\mathrm{h})}$	Output power available at *R*th unit at 'h' hours
ST_{C_i}	Start-up cost of *i*th generating unit
SD_{C_i}	Shut-down cost of *i*th generating unit
$\mathrm{SR}_{(\mathrm{h})}$	Spinning reserve at 'h' hour
$T_{i.\mathrm{h}}^{\mathrm{ON}}$	Time for which *i*th unit is continuously ON
$T_{i.\mathrm{h}}^{\mathrm{OFF}}$	Time for which *i*th unit is continuously OFF
$U_{i,\mathrm{h}}$	Status of *i*th unit

Acknowledgements
Not applicable.

Author contributions
DD has analysed and interpreted the data regarding the scheduling of each power generating units for 24 h duration and also drafted the work or substantively revised it and act as major contributor in writing the manuscript. VK has made substantial contribution to research design and handled all MATLAB coding in the work. PA has contributed in renewables data analysis and overall reformation of the work. All authors have read and approved the manuscript, and the content of the manuscript has not been published or submitted for publication elsewhere.

Funding
This research work has not been funded by any source or agencies.

Availability of data and materials
The data sets used and /or analysed during current research study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare that they have no competing interests.

Received: 7 August 2022 Accepted: 2 January 2023

References

1. Hetzer J, Yu DC, Bhattarai K (2008) An economic dispatch model incorporating wind power. IEEE Trans Energy Convers 23:603–611. https://doi.org/10.1109/TEC.2007.914171
2. Purwadi A, Ikhsan M, Hariyanto N, Heryana N, Haroen Y (2013) Wind speed calculation by using electrical output and wind turbine power curve, In: Proceedings of-2013 international conference on informanation and technology electrical engineering, Intelligent green technology sustainable development. ICITEE 2013, pp 420–423. https://doi.org/10.1109/ICITEED.2013.6676279.
3. Dai S, Gao F, Guan X, Yan CB, Liu K, Dong J, Yang L (2020) Robust energy management for a corporate energy system with shift-working V2G. IEEE Trans Autom Sci Eng. https://doi.org/10.1109/TASE.2020.2980356
4. Gnann T, Plötz P, Kühn A, Wietschel M (2015) Modelling market diffusion of electric vehicles with real world driving data – German market and policy options. Transp. Res. Part A Policy Pract. 77:95–112. https://doi.org/10.1016/j.tra.2015.04.001
5. Huda M, Tokimatsu K, Aziz M (2020) Techno economic analysis of vehicle to grid (V2G) integration as distributed energy resources in Indonesia power system. Energies. https://doi.org/10.3390/en13051162
6. Maghsudlu S, Mohammadi S (2018) Optimal scheduled unit commitment considering suitable power of electric vehicle and photovoltaic uncertainty. J Renew Sustain Energy. https://doi.org/10.1063/1.5009247
7. Haque ANMM, Ibn Saif AUN, Nguyen PH, Torbaghan SS (2016) Exploration of dispatch model integrating wind generators and electric vehicles. Appl Energy 183:1441–1451. https://doi.org/10.1016/j.apenergy.2016.09.078
8. Mousavi-Taghiabadi SM, Sedighizadeh M, Zangiabadi M, Fini AS (2020) Integration of wind generation uncertainties into frequency dynamic constrained unit commitment considering reserve and plug in electric vehicles. J Clean Prod 276:124272. https://doi.org/10.1016/j.jclepro.2020.124272
9. Yu JJQ, Li VOK, Lam AYS (2013) Optimal V2G scheduling of electric vehicles and unit commitment using chemical reaction optimization. 2013 IEEE Congr Evol Comput CEC 2013. https://doi.org/10.1109/CEC.2013.6557596
10. Wang Q, Gao Y, Zhang J (2014) Research on electric vehicle orderly charging and discharging considering unit running cost and effectiveness of power system operation, In: POWERCON 2014 - 2014 international conference on power system technology towards Green, efficiency of Smart Power System Proceedings. pp 996–1000. https://doi.org/10.1109/POWERCON.2014.6993936.
11. Bioki MMH, Jahromi MZ, Rashidinejad M (2013) A combinatorial artificial intelligence real-time solution to the unit commitment problem incorporating V2G. Electr. Eng. 95:341–355. https://doi.org/10.1007/s00202-012-0263-5
12. Saber AY, Venayagamoorthy GK (2010) Intelligent unit commitment with vehicle-to-grid -A cost-emission optimization. J Power Sources 195:898–911. https://doi.org/10.1016/j.jpowsour.2009.08.035
13. Adamatzky A (2012) Slime mold solves maze in one pass, assisted by gradient of chemo-attractants. IEEE Trans Nanobioscience. 11:131–134. https://doi.org/10.1109/TNB.2011.2181978
14. Dhawale D, Kamboj VK, Anand P (2021) An effective solution to numerical and multi-disciplinary design optimization problems using chaotic slime mold algorithm. Springer, London. https://doi.org/10.1007/s00366-021-01409-4
15. Dhawale D, Kamboj VK (2020) A new hybrid harris hawks optimizer for solving global optimization problems, In: HHHO-IGWO: Proceedings of international conference on computation, automation and knowledge management ICCAKM 2020, pp 52–57. https://doi.org/10.1109/ICCAKM46823.2020.9051509.
16. Dhawale D, Kamboj VK (2020) An effective solution to unit commitment problem in presence of sustainable energy using hybrid Harris Hawk's optimizer, In: 2020 international conference on decision aid sciences and applications DASA 2020, pp 469–472. https://doi.org/10.1109/DASA51403.2020.9317057.

17. Priya RP (2015) A solution to unit commitment problem with V2G using harmony search algorithm. Int. J. Adv. Res. Electr. Electron. Instrum. Eng. 04:1208–1214. https://doi.org/10.15662/ijareeie.2015.0403005
18. Saber AY, Venayagamoorthy GK (2009) Unit commitment with vehicle-to-grid using particle swarm optimization. 2009 IEEE Bucharest PowerTech Innov Ideas Towar Electr Grid Futur. https://doi.org/10.1109/PTC.2009.5282201
19. Amel Terki HB (2019) Cuckoo search algorithm for solving the problem of unit-commitment with vehicle-to-grid, In: Proceedings of the 4th international conference on electrical engineering and control applications, pp 77–92

Publisher's Note