Unit Commitment Model in Smart Grid Environment Considering Carbon Emissions Trading

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***Abstract*—With the development of smart grid, demand-side resources (DSR) will play an increasingly important role in the power balance of supply and demand. In addition, the requirement of a low-carbon smart grid means some policy backgrounds, such as carbon emissions trading (CET), should not be ignored. Under these circumstances, it is a good idea to construct a novel unit commitment (UC) model. This paper proposes a model that not only takes advantage of various resources on the demand side, such as electric vehicles, demand response, and distributed generation, but also reflects the effects of CET on generation schedule. Then, an improved particle swarm optimization (IPSO) algorithm is applied to solve the problem. In numerical studies, we analyze the impacts of DSR and CET on the results of UC, respectively. In addition, two meaningful experiments are conducted to study the approaches to allocate emission quotas and the effects of price transmission mechanism.**

***Index Terms*—Carbon emission quotas, carbon emissions trading (CET), demand response (DR), distributed generation (DG), electric vehicle (EV), improved particle swarm optimization (IPSO), smart grid, unit commitment (UC).**

NOMENCLATURE

Index

b	Index of bus.
i	Index of generating unit.
j	Index of electric vehicle (EV).
t	Index of hour.

Variables and Functions

DGa_t	Distributed generation (DG) used by its owners at time t.
DGb_t	Output of grid-connected DG at time t.
DGC	Total cost (TC) of DG.
DRC	TC of demand response (DR).
DR_t	"Output" of DR at time t.
EC	Emission cost.
$E_{i,t}$	Emission of unit i at time t.
$E_{\mathrm{V2G},t}$	Emission of vehicle-to-grid (V2G) at time t.
FC_i	Fuel cost of unit i.
$I_{i,t}$	*On*/*off* status of unit i at time t.
$Iter$	Current number of iteration.
pc	Probability of crossover.
$P_{i,t}$	Output of unit i at time t.
pm	Probability of mutation.
$SC_{i,t}$	Start-up cost of unit i at time t.
$SoC_{t,j}$	State of charge of EV j at time t.
TC	TC of unit commitment (UC).
$V2GC$	TC of V2G.
$V2G_t$	Output of V2G at time t.
$V2G_{t,j}$	Output of V2G of EV j at time t.
$X_{i,t}^{on}, X_{i,t}^{off}$	Duration of continuously *on*/*off* of unit i at time t.
η_t	Penetration rate of DG at time t.

Sets and Constants

a_{DGb}, b_{DGb}, c_{DGb}	Cost coefficients of DG.
a_{DR}, b_{DR}, c_{DR}	Cost coefficients of DR.
a_i, b_i, c_i	FC coefficients of unit i.
$a_{\mathrm{V2G},t}$, $b_{\mathrm{V2G},t}$, $c_{\mathrm{V2G},t}$	Cost coefficients of V2G at time t.
B	Set of buses.
$boundup$, $bounddown$	Maximum and minimum of x_{il}.
$c\text{-}cost_i$	Cold start cost of unit i.
$C_{0,j}$	Initial charging state of EV j.
C_j	Charging state of EV j.
$Cshour_i$	Cold start hour of unit i.
$DGb_{t,max}$	Upper limit of grid-connected DG at time t.
DR_{dmax}	Upper limit of DR within a day.
$DR_{t,max}$	Upper limit of DR at time t.
Eq_i	Emission quota of unit i.
Eq_{V2G}	Emission quota of V2G.
G_b	Set of generators at bus b.
$h\text{-}cost_i$	Hot start cost of unit i.
K_{ij}	Transmission capacity for the transmission line linking buses i and j.
L_{ij}^b	Line flow distribution factor for the transmission line linking buses i and j due to the net injection at bus b.
$Load_t$	Original load demand at time t.
m	Quantity of EVs work in V2G mode.

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$MaxIter$	Maximum numbers of iteration.
MU_i/MD_i	Minimum continuous *on*/*off* time of unit i.
N	Quantity of generator units.
$P_{i,min}$, $P_{i,max}$	Minimum and maximum output of unit i.
PL_t	Network loss at time t.
pr_e	Carbon emissions trading (CET) price.
R_t	Spinning reserve capacity.
SoC_{min}	Lower limit of *SoC* at each hour.
$[\mathrm{t}_1, t_2]$	Available period of V2G.
$V2G_{max}$	Upper limit of V2G.
$V2G_{t,max}$	Maximum available V2G capacity at time t.
α_i, β_i, γ_i	Emission coefficients of unit i.
η_{max}	Upper limit of DG's penetration rate.
ε	Set of transmission lines linking two buses.

I. INTRODUCTION

ONE OF the most typical features of smart grid is to activate components on the demand side. The Chinese Government has been promoting the popularization of EVs, trying to exploit the potential of DR, and encouraging the applications of grid-connected DG in recent years. In smart grid environment, these demand-side resources (DSR) are invigorated. They will participate in the power balance of supply and demand to a greater extent. Traditional UC models and methods are bound to encounter a great change. Some scholars have done researches in related topics. V2G and its impact on the cost and emission of power system are studied on basis of UC model in [1]–[3]. The significance and feasibility of DR and its role in supply-demand schedule are examined in [4]–[6]. Economical operation of DG and chance-constrained schedule of active network with DG are researched [7]–[9]. These researches have illustrated the potential of DSR to be involved in UC in day-ahead market. However, few researchers have considered all the typical demand-side elements simultaneously with conventional generators to make an overall optimal schedule.

On the other hand, since power system is one of the main carbon emitters, smart grid is expected to be low-carbon in various aspects [10]–[15]. As for UC, the goal should regard the carbon emission in addition to generating cost. Some remarkable works have been done to combine the cost objective and emission objective. Typical methods are to convert one objective into a constraint [16], or treat the weighted sum of cost and emission as the overall objective [1]. Nevertheless, cost and emission do not share the same dimension, which poses a challenge to combine them together reasonably and effectively. To solve this issue, CET is worthy of close attention. With the increasing pressure of emissions reduction, many countries are promoting the development of CET. For example, some pilot projects have been set-up in China since Jun. 2013, and the Chinese Government aims to explore the establishment of a national carbon trading market in 2015. CET converts the emission to a kind of cost reasonably, so it will effectively strike a balance between pursuing minimum cost and minimum emission in the process of UC. Under this circumstance, a new UC model is indispensable. Researches in this area are quite limited at present. A model with carbon trading to investigate the influence of emission constrains on generation scheduling is built in [17]. The UC problem with carbon trading is translated into an emission-constrained UC in [18].

Moreover, smart grid enables some low-carbon DSR available for commitment, which will enlarge the impacts of CET on power system operation. Conversely, the application of CET will promote the utilization of DSR to get the optimal solution to the daily schedule of power supply-demand balance.

To solve the UC problem, more and more researchers tend to utilize intelligent optimization algorithms. Typically, particle swarm optimization (PSO) has been widely used in recent ten years owing to its good performance in convergence rate and solution precision [1], [19], [20]. However, the main disadvantage of PSO is that it may work out a local optimal solution instead of the global optimal solution. Some scholars [21]–[23] have begun to make some modifications to this algorithm to solve the UC problem more accurately.

This paper proposes a novel UC model. Not only traditional thermal generators on the supply side but also the DSR, such as V2G, DR, and DG, are considered to make daily generation schedule in the smart grid environment. Furthermore, CET is taken into account in the UC model. We observe CET's impacts on the results of UC and research the effects of approaches to allocate emission quotas and price transmission mechanism, respectively. In addition, the PSO algorithm is improved to have more chances to obtain the global optimal solution to the UC problem.

II. PROBLEM FORMULATION

A. Smart Grid Environment

With the development of smart grid, DSR become more active [24]. They may play an increasingly essential part in power system operation. In this paper, V2G, DR, and DG are considered in the UC model.

1) V2G: Smart grid is an ideal platform for the interactions between the system operators and EVs [25]. With the related techniques getting mature, it is feasible for EV to sold electricity back to the grid. There is supposed to be an aggregator to communicate between the system operator and a great number of EV owners [26]. If an EV is inactive for a certain period, its owner can sign a contract with the system operator for commitment via the load aggregator. The sum of V2G can be treated as a special unit. Considering there is an increasing marginal cost to involve more EV owners, the cost function of V2G is assumed to be a quadratic function

$$V2GC\left(V2G_t\right) = a_{\mathrm{V2G},t} + b_{\mathrm{V2G},t} V2G_t + c_{\mathrm{V2G},t} V2G_t^2. \tag{1}$$

Some basic constraints should be taken into account. Firstly, in case of emergent use of EV's owners, a lower limit of *SoC* is considered (2). Secondly, for the sake of safe operation of the gird, an upper limit on total output of EVs at each hour should be stipulated (4). Thirdly, now that EV may not be connected to the grid all the 24 h, it is sensible to set a time range limit when EV is available for the system operator (5). Fourthly, the available capacity of V2G at each hour has an upper limit, respectively

$$SoC_{t,j} \geq SoC_{min} \tag{2}$$

$$SoC_{t,j} = \frac{C_{0,j} + \sum_{u=1}^{t} G2V_{u,j} - \sum_{u=1}^{t} V2G_{u,j}}{C_j} \tag{3}$$

$$V2G_t = \sum_{j=1}^{m} V2G_{t,j} \leq V2G_{max} \tag{4}$$

$$V2G_{t,j} = 0, t \notin [\mathrm{t}_1, \mathrm{t}_2] \tag{5}$$

$$V2G_t \leq V2G_{t,max}. \tag{6}$$

2) DR: By virtue of smart meter, electric power consumers are able to have a bidirectional communication with the grid [27]. It is possible for them to have a response, such as load curtailment, to the incentive signal and price signal [28]. This paper focuses on the incentive-based DR considering current state of electricity market. A load aggregator exists to interact with tens of thousands of scattered power users [26]. It gathers all the distributed DR resources and signs contract with the system operator. Consequently, the total contribution of DR is treated as a special unit in our UC model. DR's cost function is also assumed to be a quadratic function

$$DRC\left(DR_t\right) = a_{\mathrm{DR}} + b_{\mathrm{DR}} DR_t + c_{\mathrm{DR}} DR_t^2. \tag{7}$$

There are two constraints on DR in our model for the sake of power users' habits and interests. Upper limits are set on demand curtailment at each hour and within a day as follows:

$$DR_t \leq DR_{t,max} \tag{8}$$

$$\sum_{t=1}^{24} DR_t \leq DR_{dmax}. \tag{9}$$

3) DG: In smart grid environment, the power system has a higher tolerance for DG. With more DG connecting to the grid, they should be taken into consideration in UC model.

DG is divided into two types. One is direct use by the power consumers, noted as *DGa* in this paper, leading to reduction of load demand in UC problem. The other one is the power can be sold to the grid, denoted by *DGb*. In this situation, the sum of DG acts as a special unit if an aggregator is considered as discussed in [29]. This special unit has its own cost coefficients and cost function

$$DGC\left(DGb_t\right) = a_{DGb} + b_{DGb} DGb_t + c_{DGb} DGb_t^2. \tag{10}$$

Two constraints of DG are taken into account. Firstly, since DG's output is subject to natural resource and weather condition, so an upper limit on available DG at each hour is considered (11). Secondly, now that DG tends to be intermittent and volatile, an upper limit on its penetration rate should be set (12), to ensure a reliable operation of the power system

$$DGb_t \leq DGb_{t,max} \tag{11}$$

$$\eta_t = \frac{DGb_t}{\sum_{i=1}^{N}\left(P_{i,t} I_{i,t}\right) + V2G_t + DGb_t} \leq \eta_{max}. \tag{12}$$

B. CET

1) Carbon Emission Quotas: CET is also called cap-and-trade, which reveals that setting a cap is the step in the first place [30]. The cap of all the generators in this paper is supposed to be a certain proportion of the original overall emissions. Each generator gets an emission quota. The actual emission of a unit may be greater or lower than its cap, because of the quota trades.

A key point is how to allocate the quotas among different units. This paper assumes that the emission quota of a unit mainly depends on its emission intensity, i.e., the average amount of emission for generating one unit of electricity. Two concrete approaches are proposed. For each method, it is essential to solve the UC problem without CET and calculate the total output and emissions of each unit in advance. Then, emission intensity of each unit will be determined. After that, classify units into several groups according to their emission intensity level from high to low. The keynote of the first approach is to make the quotas of all the units less than or equal to their original emission level. The second approach is to reduce the emission quotas of units in high emission groups, while raise the quotas of units in low emission group. These two methods share the same gist: the sum of the quotas of all the units should be equal to the overall cap.

Additionally, V2G causes some emissions because the electricity in the EV may come from thermal power generation. Hence, the aggregator of V2G should be considered in CET market. Since it is quite a new resource with different operating features and development scales with generators in supply side, the quota of V2G is determined independently.

2) Price of Carbon Emissions Rights: Since there will be a great quantity of companies in various sectors in the CET market, this paper assumes that the quantity is so large that the CET of generator units will not affect the trading prices. We use the average price in four CET markets in China on Feb. 14th, 2014, i.e., 46.745 yuan per ton. It is \$7.708 per ton considering the exchange rate on that day. Calculations in this paper are based on this price named pr_e.

In UC problem, CET means that an "emission cost" should be determined

$$EC = \sum_{i=1}^{N}\left[\left(\sum_{t=1}^{24} E_{i,t} - Eq_i\right) \times pr_e\right] + \left(\sum_{t=1}^{24} E_{\mathrm{V2G},t} - Eq_{\mathrm{V2G}}\right) \times pr_e. \tag{13}$$

Evidently, the overall emission cost consists of the cost of generators and the cost of V2G. The cost appears when their emissions get higher than their quotas, which means they have to spend money to buy extra emission quotas.

The emission of a thermal unit is usually presented as a quadratic function of its power output

$$E_{i,t}\left(P_{i,t}\right) = \alpha_i + \beta_i P_{i,t} + \gamma_i P_{i,t}^2. \tag{14}$$

The emission caused by V2G is assumed to be its output multiplied by the average emission intensity of all the generators in this paper, since it is impossible to figure out which generator the electricity in EVs' batteries comes from.

C. UC Model

A novel UC model considering DSR and CET is proposed.

1) Objective: The general objective of UC is to minimize the *TC* to achieve the supply-demand balance of power. The *FC*s and *SC*s of thermal units are counted as follows [1]:

$$FC_i\left(P_{i,t}\right) = a_i + b_i P_{i,t} + c_i P_{i,t}^2 \tag{15}$$

$$SC_{i,t} = \begin{cases} h-cost_i & MD_i \le X_i^{off} \le H_i^{off} \\ c-cost_i & X_i^{off} > H_i^{off} \end{cases} \tag{16}$$

$$H_i^{off} = MD_i + Cshour_i. \tag{17}$$

In view of V2G, DR and grid-connected DG, the cost objective in this paper should also include the three sorts of costs presented in (1), (7), and (10). Besides, the emission cost defined in (13) is also taken into account in the objective function. The *TC* of UC is

$$\begin{aligned} TC = & \sum_{t=1}^{24}\sum_{i=1}^{N}\left[FC_i\left(P_{i,t}\right)I_{i,t} + I_{i,t}\left(1-I_{i,t-1}\right)SC_{i,t}\right] \\ & + \sum_{t=1}^{24}\left[DRC\left(DR_t\right) + V2GC\left(V2G_t\right) + DGC\left(DGb_t\right)\right] \\ & + EC. \end{aligned} \tag{18}$$

2) Constrains: UC model usually contains power balance constraint, spinning reserve constraint, generation limits constraint, minimum *on*/*off* time constraint and network security constraint as follows [19].

$$\sum_{i=1}^{N}\left(P_{i,t}I_{i,t}\right) = Load_t - DR_t - V2G_t - DGa_t - DGb_t + PL_t. \tag{19}$$

$$\sum_{i=1}^{N}\left(P_{i,t,max}I_{i,t}\right) + V2G_{t,max} + DR_{t,max} \ge Load_t + PL_t + R_t. \tag{20}$$

$$P_{i,min} \le P_{i,t} \le P_{i,max}. \tag{21}$$

$$\left.\begin{aligned} \left(1-I_{i,t+1}\right)MU_i \le X_{i,t}^{on} \quad & I_{i,t}=1 \\ I_{i,t+1}MD_i \le X_{i,t}^{off} \quad & I_{i,t}=0 \end{aligned}\right\}. \tag{22}$$

$$\begin{aligned} -K_{ij} \le \sum_{b\in B} L_{ij}^b & \left(\sum_{i\in G_b} P_{i,t} + V2G_t^b + DGb_t^b - Load_t^b \right. \\ & \left. + \; DR_t^b + DGa_t^b\right) \le K_{ij}, \forall (i,j) \in \varepsilon. \end{aligned} \tag{23}$$

In light of V2G, DR and DG, it is indispensable to add the constraints of these resources as shown in (2), (4)–(6), (8), (9), (11), and (12) to the general UC optimization model.

III. SOLUTION METHODOLOGY

PSO was proposed by Kennedy and Eberhart in 1995 [31]. Each particle in PSO has a specific position that represents a potential solution to the optimization problem. All the particles keep updating their velocity so that their positions may change after each iteration. Since the particles never stop trying to move to better positions, they are expected to find the best position in the space.

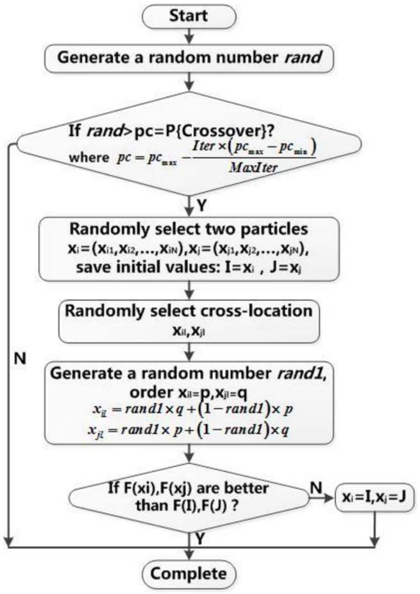

Fig. 1. Flowchart of the crossover operator.

However, PSO has a principal drawback that particles tend to lose themselves in local optimal solution [22]. After a number of iterations, particles may lack the motivation to search the space that is wide enough to cover the global optimal position, particularly when they are very close to local optimal positions. The adverse effects tend to be more serious to solve multidimensional problems. Some scholars have made some modifications to resolve the drawback [21]–[23]. Authors have improved the general PSO algorithm by employing crossover operator and mutation operator that are similar to those typical operators in genetic algorithm (GA). This modified algorithm is called improved particle swarm optimization (IPSO). The aim is to enhance the probability of particles to find the global optimal position. Crossover and mutation operators will be conducted with a specified probability at the end of each iteration. Specific steps of these two operators are illustrated in Figs. 1 and 2, respectively.

IV. NUMERICAL STUDIES

The studies have been conducted on the ten-unit system and the IEEE 30 bus system. The program is coded in MATLAB 7.8.0 on a computer with Intel Core 2.50 GHz and 4 GB RAM.

A. Ten-Unit Case

Firstly, we do a relatively simple case study on the ten-unit system to verify the effectiveness and the superiority of the novel algorithm in this paper, the IPSO. The ten-unit system is one of the most popular choices in the papers related to UC and it is especially suitable to test the algorithm

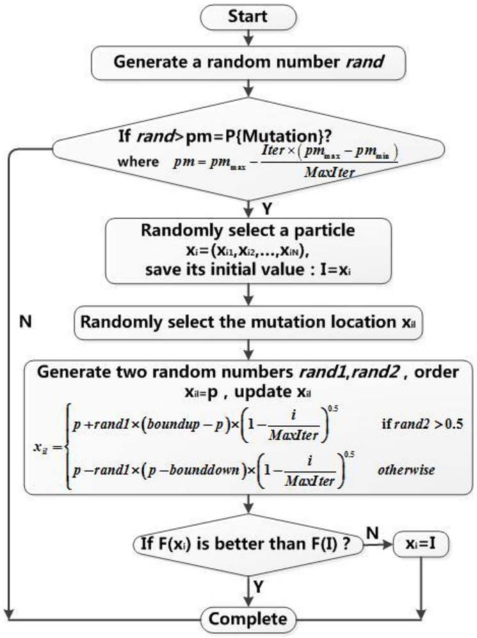

Fig. 2. Flowchart of the mutation operator.

TABLE I
COMPARISON OF THE PERFORMANCES OF IPSO AND OTHER ALGORITHMS IN PUBLISHED REFERENCES

	Total Cost ($) (Best Solution)		Total Cost ($) (Best Solution)
IPSO	564376	PSO [20]	567029
MHPSO [22]	564419	GA [32]	565825
BPSO [23]	565814	BF [33]	564842
LR-PSO [23]	565870	ALR [34]	565508

performance [20]–[23]. Relevant parameters of the system can be found in [22]. No CET or DSR is considered here to ensure that it is a fair and reasonable comparison.

The performances of the IPSO algorithm and other published ones are compared. The best result for the ten-unit system obtained by IPSO is compared with those of Modified Hybrid PSO [22], Binary PSO [23], Lagrangian Relaxation with PSO [23], PSO [20], GA [32], Bacterial Foraging [33], and Adaptive Lagrangian Relaxation [34]. From Table I, we can safely draw the conclusion that the IPSO proposed by us has more excellent capability to yield the optimal solution.

B. IEEE 30-Bus Case

To demonstrate the application of our UC model, a case study on IEEE 30-bus system [35] is implemented. The load curve is determined according to the actual data of city in Northern China. V2G, DR, and grid-connected DG are set at buses 5, 12, and 21, respectively, since the load demands at these buses are quite high compared with other buses, which means more possibilities for the DSR to exist there. Their cost coefficients obtained from the aggregators are shown in Table II. These coefficient settings are simplified to some extent here. For example, the time-varying cost of V2G only contains two levels according to the load demand. Nevertheless, it means the same for the model in this paper if these coefficients are more complicated in practice. The DG in this paper is assumed to be from renewable energy resources, thereby the emissions of DG and DR are supposed to be zero.

TABLE II
COST COEFFICIENTS OF DSR

	V2G ($9 \le t \le 14$ or $20 \le t \le 21$)	V2G ($1 \le t \le 8$ or $15 \le t \le 19$ or $22 \le t \le 24$)	DR	DGb
a($/h)	8.0	7.0	4.0	10.0
b($/MWh)	2.4	2.3	2.2	2.6
c($/MWh²)	0.03	0.03	0.05	0.01

TABLE III
SCENARIO SETTINGS

	Scenario Description
Scenario 1	No DSR. No CET.
Scenario 2	DSR considered. No CET.
Scenario 3	No DSR. CET considered.
Scenario 4	Both DSR and CET considered.
Scenario 5	The second approach to allocate the emission quotas. (Both DSR and CET considered.)
Scenario 6	The electricity price is adjusted according to the effect of CET. (Both DSR and CET considered.)

Some other parameters in our model are assumed as follows. The lower limit of *SoC* is 30%. The average of *SoC* before dispatching is 70%. The average battery capacity of EVs is 22 kWh. The quantity of EVs that can conduct V2G is 7000. In order to facilitate management, this paper assumes that the system operator will only sign contract of V2G if the EVs are available in the evening. Accordingly, the available periods of all the EVs are the same in this paper, assumed 20–24 o'clock. The available capacity of V2G at these hours is 18, 17, 16, 15, and 14 MW, respectively. The maximum bearing capacity of the grid for V2G is assumed to be 18 MW at each hour. The upper limit of demand curtailment response is 5% of total load demand in this hour, and the upper limit within a day is 240 MWh. Now that solar power may be the main DG source, the available DG is set higher during the day. Specifically, it is 30 MW between 7 o'clock and 17 o'clock and 15 MW during the other time, among which two-thirds are used by consumers themselves and one-third would be sold to the grid. The upper limit of DG penetration rate is 6%. The spinning reserve capacity is assumed 10% of load demand [32]–[34]. Price elasticity of electricity consumption is 0.2 [36].

This paper considers six scenarios as shown in Table III. The first four scenarios are set to study the influences and effects of DSR and CET. The fifth scenario is set to research the approaches to allocate emission quotas. The sixth scenario is set to explore the effect of price transmission mechanism.

The emission quota of the six units in Scenario 3 is based on the total emission in Scenario 1, while the emission quota in Scenarios 4–6 are on basis of the total emission in Scenario 2. The first approach to allocate quotas is used in Scenarios 3, 4, and 6. The emission quota of V2G is assumed to be 100% of its initial level in this paper.

TABLE IV
DAILY GENERATION AND EMISSION OF EACH UNIT IN EACH SCENARIO

		Unit1	Unit2	Unit3	Unit4	Unit5	Unit6	V2G	DR	DGb
Scenario 1	Total Generation (MWh)	3558	891	296	173	181	73	-	-	-
	Total Emission (ton)	4342	1209	627	464	477	185	-	-	-
Scenario 2	Total Generation (MWh)	3503	787	261	94	154	60	48	169	92
	Total Emission (ton)	4033	1061	517	233	347	146	59	0	0
Scenario 3	Total Generation (MWh)	3579	920	299	138	167	69	-	-	-
	Total Emission (ton)	4386	1254	645	294	353	162	-	-	-
Scenario 4	Total Generation (MWh)	3510	808	251	73	107	46	52	221	101
	Total Emission (ton)	4081	1105	491	145	241	97	63	0	0
Scenario 5	Total Generation (MWh)	3534	825	257	57	74	36	53	232	103
	Total Emission (ton)	4207	1137	504	66	77	59	61	0	0

TABLE V
EMISSION INTENSITY OF EACH UNIT IN SCENARIO 2

Unit	Emission Intensity (ton/MWh)	Unit	Emission Intensity (ton/MWh)
Unit 1	1.15	Unit 4	2.48
Unit 2	1.35	Unit 5	2.57
Unit 3	1.98	Unit 6	2.42

TABLE VI
COST AND EMISSION IN ALL SCENARIOS

	Total Cost ($)	Total Emission (ton)		Total Cost ($)	Total Emission (ton)
Scenario 1	17644	7304	Scenario 4	19909	6232
Scenario 2	15086	6454	Scenario 5	19819	6184
Scenario 3	22998	7094	Scenario 6	19567	6161

TABLE VII
INDICATORS RELATED TO EMISSION REDUCTION IN THE LAST FOUR SCENARIOS

	Total Emission Quota (ton)	Expected Emission Reduction (ton)	Actual Emission Reduction (ton)	Degree of Completion (%)
Scenario 3	6573	730	210	28.8
Scenario 4	5809	645	222	34.4
Scenario 5	5809	645	270	41.8
Scenario 6	5809	645	293	45.4
	Corresponding Cost Increase ($)		Average Cost for Emission Reduction ($/ton)	
Scenario 3	5354		25.5	
Scenario 4	4823		21.8	
Scenario 5	4733		17.5	
Scenario 6	4481		15.3	

Because of the page limit, we cannot show all of the solutions in detail. Instead, the daily output and emission of each unit in the first five scenarios are listed in Table IV.

The daily emission intensity of each unit in Scenario 2 is shown in Table V. As introduced in Section II, we divide the six units into three groups in terms of their emission intensity. To start with, it is necessary to calculate the average emission intensity of the six units. Two crucial points in the criterion here are 75% and 125% of the average emission intensity. For example, if the intensity of a unit is larger than 125% of the average, it belongs to Group A. Therefore, Unit 5 is classified to Group A, Units 3, 4, and 6 to Group B, while Units 1 and 2 to Group C. The result is valid in quota allocation in Scenarios 4–6. Similarly, the quota allocation in Scenario 3 can be worked out according to the emission intensity of all the units in Scenario 1.

The *TC* and total emission in each scenario are shown in Table VI. Total emission quotas, expected emission reductions, actual emission reductions, degrees of completion, corresponding cost increases, and the average costs for emission reduction of the last four scenarios are shown in Table VII.

C. Discussion

1) Impacts of DSR: DSR tend to make more contributions to the supply-demand balance of power in smart grid environment. DR and DG are far more eco-friendly than thermal generators in supply side. Moreover, DSR can even be more economical than conventional generators, especially during the peak-load hours when the marginal cost for power generating rises dramatically.

The results of Scenarios 2, 4, and 5 listed in Table IV shows that various resources in demand side have the potential and capacity to participate in power balance in smart grid.

Table VI shows that the *TC* and emission in Scenario 2 is 14.50% and 11.64% less than those in Scenario 1 and the *TC* and emission in Scenario 4 is 13.43% and 12.15% less than those in Scenario 3. These reductions in cost and emission illustrate the advantages of DSR.

DSR tend to promote the emission reduction effect of CET. Table VII reflects that the total emission in Scenario 4 is better than that in Scenario 3. The reason is that DSR offer more options to replace the output of high carbon generators. Meanwhile, Table VII also reveals that the average cost for emission reduction is significantly less if DSR are considered.

2) Impacts of CET: The direct effect of CET is to achieve an obvious emission reduction, as shown in Table VI. Total emission in Scenario 3 is 2.88% less than that in Scenario 1, and total emission in Scenario 4 is 3.44% less than that in Scenario 2. Meanwhile, the average emission intensity decreases correspondingly. The emission reduction extents are acceptable considering the cap.

By comparing the results of Scenarios 1 and 3 shown in Table IV, it is noticeable that the units act as the main emitters, such as Units 4–6, have lower output if CET is carried out. Meanwhile, the units that have relatively lower emission intensity, such as Units 1 and 2 have much greater output. Actually, the price to purchase emission quota increases the operation cost of high carbon units. As mentioned previously, there is a challenge to combine the cost objective and emission objective. A weighted sum is a typical choice but there are few good ideas on stipulating the weighting factors. Our model has done a good job to strike a balance between the economic objective and environment objective.

Similarly, we can find the same trend by comparing the results of Scenarios 2 and 4 as shown in Table IV. In addition, outputs of DSR clearly increase after considering CET. As low-carbon resources, DR and DG have more outputs. The growth of DR's output is more obvious than DG. The reason is that DR has greater potentials for commitment if the power consumers are provided with enough incentives. However, getting more DG is mainly subject to the weather conditions and the absorption capability of the grid.

3) Effects of Approaches to Allocate the Emission Quotas: A crucial point of CET is how to allocate the emission quotas. This paper proposes two typical approaches to perform this task in power system. The aim is to render CET a better effect on reducing carbon emissions. Scenarios 4 and 5 are control experiments on this issue. Two approaches have been proposed in Section II. The first one is used in Scenario 4, and the second one is used in Scenario 5. They share the same cap, 90% of the total emission level in Scenario 2.

Evidently, the result obtained in Scenario 5 is better in terms of all the indicators. As shown in Table VI, the *TC* is $90 less and the total emission is 48 ton less. Moreover, the emission reduction in Scenario 5 is closer to the expected level. Table VII shows that the degree of completion in Scenario 5 is 7.4 percentage points higher than that in Scenario 4, while the average cost for emission reduction is 19.31% lower. By comparing the results of Scenarios 4 and 5 listed in Table IV, we can draw the conclusion that the second approach to allocate quotas has better effects to exert pressure on high carbon units and exploit the potential on low carbon units, so the overall result of the whole power system is better.

4) Effects of the Price Transmission Mechanism: When it comes to the effect of CET, another significant issue is the price transmission mechanism. The total generating cost tends to ascend if CET is carried out. As shown in Table VI, the growth rate is 30.34% and 31.97%, respectively in scenarios with or without DSR. If this cannot be transmitted to the electricity price for end power users, the effect of CET would be very limited. This problem is particularly serious in China, because the electricity price is relatively fixed.

An experiment is designed here. The load demand may decrease as the price going up. Therefore, less electricity and primary energy will be consumed, which should be the keynote of CET. Comparing Scenario 6 to Scenario 4, we can find that both the *TC* and the total emission experience a reduction as shown in Table VI. Besides, the degree of completion on the total emission quota is 11.0% points higher, while the average cost for emission reduction is 29.60% lower if the price transmission mechanism is considered.

V. CONCLUSION

This paper develops a novel UC model in smart grid environment considering V2G, DR, DG as well as CET. The UC optimization problem is solved by the IPSO algorithm.

Numerical studies verify the capability of DSR to participate in the power supply-demand balance. The *TC* and the total emission decrease evidently by virtue of DSR. The effect is more obvious if CET is carried out, because DSR offer great options for system operator to replace the high carbon traditional generators that are under pressure of CET.

Thanks to CET, generators with relatively low emission intensity and DSR are more likely to be dispatched. Then, this paper researches two typical points on CET policy. One is how to allocate the emission quotas. The conclusion is that we should make the quotas of some low carbon units greater than their original emission level, instead of providing all the units with quotas that are less than or equal to their original emissions. The other is the importance of price transmission mechanism. CET raises the price of utilizing fossil energy. If the change in generating cost can be transferred to the electricity sales price, the effect of CET on the emission reduction of power sector will be better.

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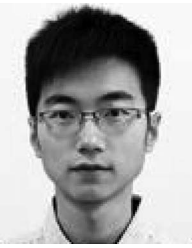

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