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Article

Multiple Objective Compromised Method for Power Management in Virtual Power Plants

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Abstract: In practical optimization, a priority requirement for different objectives of multiple objective optimization problems should be considered. In this paper, the distributed power management of a Virtual Power Plant (VPP) with priority requirement is optimized by the compromised method. The operation optimization model of VPP is formulated as a fuzzy multiple objective optimization problem considering the satisfaction of customers and suppliers, the system stability, the power quality, and costs with operation limitations. The multiple objective optimization algorithm with the compromise of the satisfactory degree and the priority of objectives is studied based on the principle of two-step interactive satisfactory optimization. This method is also applied in a test system.

Keywords: multiple objective optimization; VPP; satisfaction decision making; priority

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1. Introduction

Renewable energy sources will play an increasingly central role in future power network. However, a great penetration of DG plants in distribution networks can reduce the technical verticality of the power system, because the power injection of dispersed generators, which are regulated individually with the exclusively own economic criterion, may have a significant impact on voltage profiles of networks [1,2]. An active management of the MV distribution network is required to guarantee correct working conditions [3]. The Virtual Power Plant (VPP), which is defined as an aggregation of different type generation units (electrical and thermal generators, CHP units, thermal storages, *etc.*), is regarded as an effective bridge between distributed energy resources (DERs) and future grid to avoid possible incompatibility between market requirements and technical feasibility [4,5].

The VPP works as one unit power plant connected to different points of the medium voltage distribution network and to the thermal one. In VPP, each participant has the possibility to receive or supply electrical energy in respect of stipulated contracts. A central manager defines each working set point on the basis of economic and technical criteria, thus the defined electrical and thermal trends are supplied at the lowest cost and high stability [6]. Under the control of the VPP manager, a mixed group of generation sources including renewable generation have additional benefits in improving supplying reliability, voltage stability, and power quality, as well as in reducing the overall costs and particularly any financial risk associated with imbalance and fuel price volatility [7,8]. So it is important to allocate the energy in VPP reasonably to guarantee these technical and financial benefits in correct working conditions.

The optimal operation of VPP mainly focuses on single objective of economic optimization aimed to minimization the cost of producing energy or maximizing the profit of the VPP with some limitations corresponding to the steady state operation constraints of the system and operation limits of the devices [9,10]. In this paper, the satisfaction of customers, the system stability, and the power quality are also considered as the objectives with the economic objective to formulate a multi-objective optimization problem.

In actual decision making situations, sometimes it is practical for the decision maker (DM) to consider the different preemptive priorities in multiple objective optimization problem [11,12]. The priority requirement for different objectives expresses the relative importance of multiple objectives, which means that some objectives have a higher priority for their achievement than the others under system constraints. Generally, there are one or several objectives in one level [13]. Another situation is that much of decision making in the real world takes place in a fuzzy environment where the parameters are not known precisely [14]. Tao *et al.* [15] propose the use of a linear satisfying and sufficiency degree model in place of the system-level and discipline-level optimizations in order to relieve the difficulties that the final optimal objectives are fuzzy sets due to the uncertain or fuzzy parameters.

A conventional way to solve fuzzy multiple objective optimization problem with priority is lexicographic optimization method, where the objectives are arranged according to their absolute importance [16]. However, this method is complicated and time-consuming. Li *et al*. [17] simplify this complicated optimization problem and divides it into two subproblems which can be solved in sequence. This method formulates two optimization problems by regulating parameters and optimization variables.

This paper considers the optimal operation of VPP as a multiple objective optimization problem with priority. The satisfactory degree and fuzzy method are adopted in the interactive decision making. The rest of this paper is organized as follows. In Section 2, the VPP and its supply chain are introduced. Section 3 describes the compromised multiple objective optimization problem of VPP with different priorities, as well as the two-step interactive satisfactory optimization method. Section 4 demonstrates the effectiveness and flexibility of the optimization approach by the application in a test VPP. A conclusion is made in Section 5.

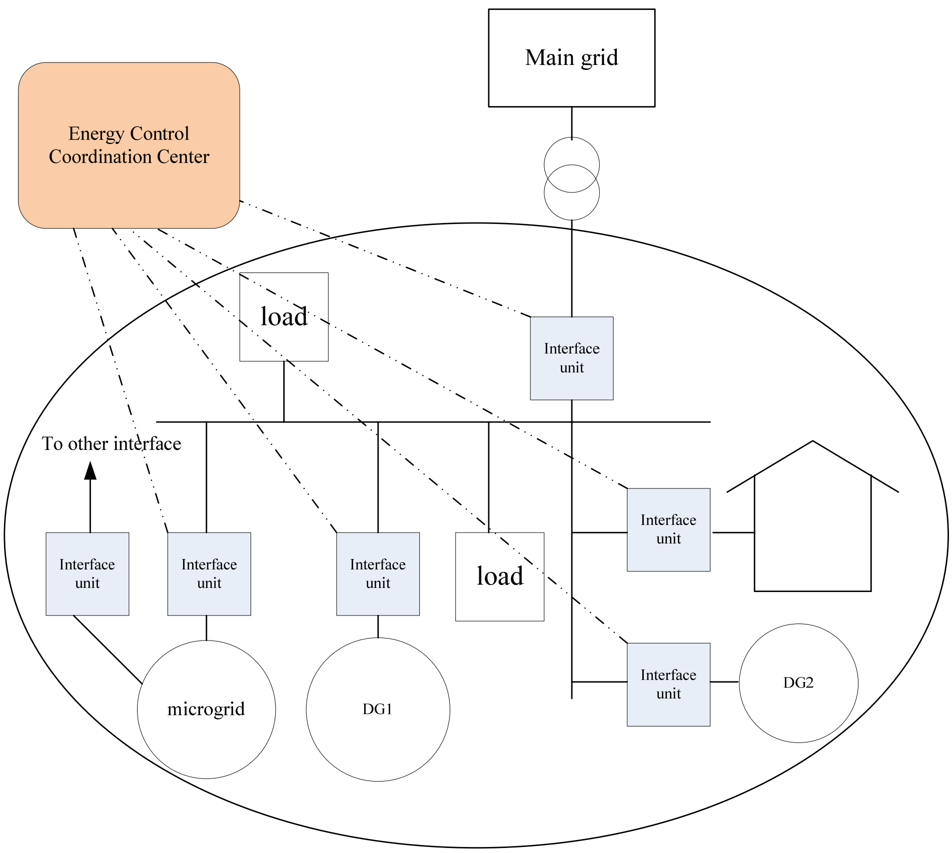
2. Power Management in VPP

2.1. VPP as a Bridge between DERs and Public Grid

A VPP is composed of persons (decision maker, DM and owners of energy sources in VPP), contracts, and entities (sources, storage devices and loads) [18]. It works as a single entity to the system operator and electricity markets and can be comparable to a conventional power plant with its own operating characteristics, such as schedule of generation, generation limits, and operating costs.

The structure of VPPs has been discussed in plenty of papers [3–10,18,19]. The VPP is considered as technical (TVPP) and commercial (CVPP) for its dual roles. However, the heart of a VPP is the energy control & coordination center (ECCC) which coordinates the power flows among DERs, loads and storage devices. This paper mainly focuses on the coordination (which is made in the CVPP layer) of ECCC and the interfaces of DERs and users to optimize DERS' utilization based on the real information of the energy offers and needs. The coordination model is shown as Figure 1.

Figure 1. The coordination model in VPP.



As shown in Figure 1, the energy control coordination center (ECCC) controls the power flow within the VPP, and exchanges power and information with the main grid through the interface units (IUs) [19]. In many situations, the interface unit (IU) is a convertor with communication to ECCC (also called agent in many papers [4]) from the technical point of view. It works at set point defined by the ECCC to control the power flow. Usually, two kinds of control strategies are used: (I) PQ control: the inverter is used to supply a given active and reactive power set-point; (II) Voltage source inverter (VSI) control: the inverter is controlled to “feed” the load with pre-defined values for voltage and frequency. Based on the load situation, the VSI real and reactive power output is defined and calculated [20]. The auxiliary service is provided through proper control strategy of the IU. The IU is controllable to guarantee allowed voltage level to each busbar in every DG working condition. The voltage of PCC is regulated by the IU consistent with the public grid. The detailed constitute of each IU is described in [20].

2.2. Electric Power Supply Chain in VPP

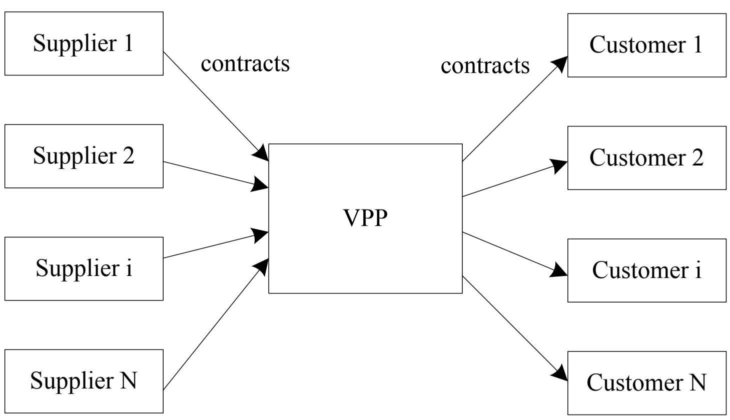
The supply and demand chain of a VPP is shown in Figure 2. As mentioned above, the suppliers are controllable through converters, including:

(1) Microgrids, which have their own objectives and publish their output schedules in contracts;
(2) Other suppliers which are scheduled by the VPP, such as wind farm or wind turbines which do not need any fuel, fuel batteries, and combined heat and power plants (CHP).

The customers include:

(1) The sensitive loads which require high reliability and power quality with priority according to the contracts. Usually these loads are also predictable, such as industrial loads.
(2) The public grid with the purchasing and selling contract. Form the view of the operators in public grid, it is expected the output power of the VPP is fixed to some extent according to the contrast especially when the power capacity of VPP is large.
(3) The controllable load according to the load demand side management by ECCC [21].
(4) The load which is random and can be shutdown in some situations according to the contracts, such as the smart houses and some unimportant loads.

Figure 2. Electric power supply chain of VPP.



As a trading entity, the micro-grid and DGs owned independently from the VPP have their own generation schedules and time-variable sale-prices based on the price information of the VPP. The DGs owned and managed by the VPP aim at the stability of the VPP, minimization of lineloss, and/or reduction of the environmental impact. The consumers can choose to buy power from or sell power to the VPP at any time they want. So the objectives of involved trading entities which are constituted of different sources vary according to their different characteristics.

In each time window, the suppliers and customers forecast their needs and requirements and then deliver the data to ECCC. The ECCC calculates the optimal operation points with an optimization method based on the delivered data and gives the compromised optimal solution to each IU. Then the contracts can be established. For the sake of power suppliers and customers as well as the stability of the power grid, the contents of contracts in the day-ahead, intraday market mainly include:

(1) The quantity and price of the electric power at different time segments;
(2) Some special requirements for power reliability and power quality;
(3) The fluctuating range of the set value;
(4) The penalty methods.

For the information above, it can be noticed that the suppliers and customers have different priority levels. Also, the overall objectives, such as max profit and power grid stability, are usually satisfied in different important levels. Since the planning period of VPP is shorter than the conventional power grid, a single solution must be automatically selected online which might be suboptimum, but satisfy the stability requirements of VPP and all of the requirements from the power suppliers and customers greatly.

3. Algorithm Formulation

The optimal schedule of a VPP can be formulated for each time period as a fuzzy multiple objective optimization problem with priority on the basis of interactive satisfaction. The decision variables are the output power schedule and bus voltages of the suppliers, the storage plan and the power sent to the public grid. Other parameters include the forecasted output powers and the forecasted consumption.

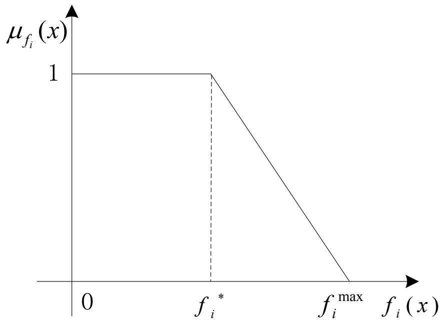
3.1. Multi-objective Optimization with Priority

The multi-objective optimization problem with priority based on satisfaction degrees can be defined as follows:

$$\begin{cases} \max(\mu_{f_1}(x),\ldots,\mu_{f_i}(x),\ldots,\mu_{f_k}(x)) \\ \mu_{f_i}(x) \in [0,1] \\ \mu_{f_i}(x)\left\{f_i \in level^j\right\} > \mu_{f_{i\,i}^{'}}(x)\left\{f_i^{'} \in level^{j+1}\right\} \\ x \in F \end{cases} \tag{1}$$

where x is the decision vector; F is the feasible solution of x; f_i is the objective function; $\mu_{f_i}(x)$ is the satisfaction degree of f_i; $\mu_{f_i}(x)\left\{f_i \in level^j\right\} > \mu_{f_{i\,i}^{'}}(x)\left\{f_i^{'} \in level^{j+1}\right\}$ represents that f_i has precedence over $f_i^{'}$. To simplify the calculation, the linear method to express satisfaction degree is used (Figure 3):

Figure 3. Linear description of the satisfaction degree.



where:

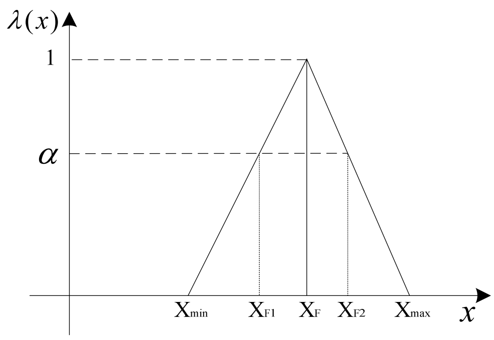
$$\mu_{f_i}(x) = \begin{cases} 1 & \text{if} \quad f_i(x) \le f_i^* \\ 1 - \dfrac{f_i^* - f_i(x)}{f_i^* - f_i^{\max}} & \text{if} \quad f_i^* < f_i(x) \le f_i^{\max} \\ 0 & \text{if} \quad f_i(x) > f_i^{\max} \end{cases} \tag{2}$$

f_i^* is the expected value of f_i; $f_i^{\max}$ is the max value of f_i in feasible solution. When $\mu_{f_i}(x) = 0$, $f_i\ (x)$ is totally dissatisfactory; when $\mu_{f_i}(x) = 1$, $f_i\ (x)$ is totally satisfactory; when $0 < \mu_{f_i}(x) < 1$, it depends on the decision-makers (DM) to evaluate the compromised results.

3.2. Fuzzy Description

The forecasted values from the suppliers or the ECCC and the suboptimal values delivered from the owners of the microgrid are regarded as fuzzy. As shown in Figure 4, the linear membership function is considered.

Figure 4. Fuzzy description of *x*.



where:

$$\lambda(x) = \begin{cases} 0 & \text{if} \quad x \le X_{\min} \\ \dfrac{x - X_{\min}}{X_F - X_{\min}} & \text{if} \quad X_{\min} < x \le X_F \\ \dfrac{X_{\max} - x}{X_{\max} - X_F} & \text{if} \quad X_F < x \le X_{\max} \\ 0 & \text{if} \quad x > X_{\max} \end{cases} \tag{3}$$

The α-cut set of x is:

$$\alpha(x) = \{x \mid \lambda(x) \geq \alpha\} = \{X_{F1} \leq x \leq X_{F2}\} \tag{4}$$

where α is given according to the history data: the delivered schedules and the actual output powers of jth supplier. c_j is the reference of α and can be scored as:

$$c_j = \frac{1}{24}\sum_{i=1}^{24} (P_j^i - P_{jset}^i) \Big/ P_{jset}^i \tag{5}$$

where, c_j is the credit score of jth supplier in the VPP; P_{jset}^i is ith hour final planned output power delivered to the ECCC by the suppliers a day ahead; P_j^i is the actual output power supplied by the jth supplier in VPP.

3.3. Two-Step Compromised Method

The objectives are grouped into different levels according to the priority order. In this paper, preemptive priorities of the multiple objective optimization problem are expressed as (for example, three levels):

$$\begin{cases} \mu_{f_i}(x)\left\{f_i \in level^1\right\} - \mu_{f_i^{'}}(x)\left\{f_i^{'} \in level^2\right\} > k_1 \\ \mu_{f_i^{'}}(x)\left\{f_i^{'} \in level^2\right\} - \mu_{f_i^{''}}(x)\left\{f_i^{''} \in level^3\right\} > k_2 \end{cases} \tag{6}$$

where $k_1 \in [0,1]$ and $k_2 \in [0,1]$ present the difference of satisfying degrees between two levels. The objective in level 1 with higher satisfying degree is more important than level 2 and level 3. With the preemptive priority structure, objectives which belong to level 1 achieve their goal as much as possible.

The priority structure is established considering the special users in VPP whose power supply objectives must be satisfied foremost. Another consideration is the importance extent of different objectives, such as stability and economic objectives.

To compromise the max satisfying degree and the priority structure, a two-step interactive satisfactory method is used [17]. This method simplifies the complicated optimization problem by dividing it into two sub-problems and solving them in sequence with high computation efficiency. The first step is to find maximum overall satisfactory degree β^t treated as the given condition of the next step optimization, as shown in (7):

$$\begin{cases} \max \beta \\ s.t. \mu_{f_i}(x) \geq \beta \\ x \in F \end{cases} \tag{7}$$

In the second step a decision variable γ is used to relax the crisp priority relationship. This method is also applied with the interaction of DM. Then, relation (6) should be represented as:

$$\begin{cases} \mu_{f_i}(x)\left\{f_i \in level^1\right\} - \mu_{f_i^{'}}(x)\left\{f_i^{'} \in level^2\right\} > k_1 + \gamma_1 \\ \mu_{f_i^{'}}(x)\left\{f_i^{'} \in level^2\right\} - \mu_{f_i^{''}}(x)\left\{f_i^{''} \in level^3\right\} > k_2 + \gamma_2 \end{cases} \tag{8}$$

where $\gamma_i \in [\max(-k_1, -k_2), \min(1-k_1, 1-k_2)]$. When $\gamma \to 0$, the solution satisfies the priority structure best. So the second sub-problem is modeled as:

$$\begin{cases} \min\|\gamma\| \\ s.t.\mu_{f_i}(x) \geq \beta_r^t \\ \mu_{f_i}(x)\left\{f_i \in level^j\right\} - \mu_{f_{ii}^{'}}(x)\left\{f_i^{'} \in level^{j+1}\right\} > k_j + \gamma_j \\ x \in F \end{cases} \tag{9}$$

where, β_r^t is the regulated satisfactory degree and smaller than β^t. It represents the regulation of differences among the practical priorities and preemptive priorities.

3.4. Objective Functions

The optimization objectives are the minimum values of the objective functions. Different objective functions are considered as following:

(1) Maximize profit. For ECCC, the economic maximization objective is considered as:

$$f_1 = \sum_{j=1}^{ns} P_{supply}^j k_{supply}^j + \sum_{j=1}^{nv} P_{vpp}^j k_{vpp}^j + \sum_{j=1}^{nt} P_{storage}^j k_{storage}^j - \sum_{j=1}^{nl} P_{load}^j k_{load}^j \tag{10}$$

where f_1 is the minus profit of VPP; *ns* is the number of suppliers; *nt* is the number of storage devices; *nl* is the number of loads; *nv* is the number of sources owned and managed by VPP; P_{supply}^j is the power supplied by the *j*th supplier which is not totally owned by VPP; k_{supply}^j is the sale price of the output power supplied by *j*th supplier; P_{load}^j is the *j*th demanded load power; k_{load}^j is the price of the power energy sold to the *j*th load; P_{vpp}^j is the power supplied by the *j*th source which is totally owned by VPP; k_{vpp}^j is the producing cost of the *j*th source with consideration of the building cost; $P_{storage}^j$ is the stored power of *j*th storage device; $k_{storage}^j$ is the storage cost of the *j*th storage device.

The following relationship is satisfied:

$$\sum_{j=1}^{nl} P_{load}^j = \sum_{j=1}^{ns} P_{supply}^j + \sum_{j=1}^{nv} P_{vpp}^j - \sum_{j=1}^{nt} P_{storage}^j - P_{loss} \tag{11}$$

where P_{loss} is the power loss of the VPP.

(2) Minimal lineloss

$$f_2 = \sum_{i=1}^{N} \sum_{j=1}^{N} G_{ij}(U_i^2 + U_j^2 - 2U_i U_j \cos\theta_{ij}) \tag{12}$$

where *N* represents the number of the power lines; G_{ij} denotes the conductance of the line *ij* connected with bus *i* and bus *j*; U_i and U_j refer to the voltages of bus *i* and bus *j*; θ_{ij} denotes the phase angle difference of the voltages of bus *i* and bus *j*. Therefore, less value of f_2 is preferred.

(3) Voltage stability index:

$$f_3 = \sqrt{\sum_{i=1}^{n_l} (1 - u_i)^2} \tag{13}$$

where:

$$u_i = \frac{u_r^i}{u_{rated}^i}$$

n_l represents the number of the buses; u_r^i is the voltage of the bus i; u_{rated}^i is the rated voltage of the bus i.

(4) Ordered suppliers: Part of microgrids supply certain quantity of electric power to the VPP according to the contract. This index can be represented as the fluctuation of the power supply:

$$f_4 = \sqrt{\sum_{i=1}^{n_m} (1 - m_i)^2} \tag{14}$$

where:

$$m_i = \frac{m_r^i}{m_{set}^i}$$

and n_m represents the number of the microgrids; m_r^i is the output power of the microgrid i; m_{set}^i is the set output power of the microgrid i in contract.

(5) Ordered customers: Part of customers have special requirements for voltage, and the voltage supply index is:

$$f_5 = \max\left\{ \left| \sqrt{(1 - \frac{u_c^i}{u_{cset}^i})^2} - \varepsilon_{set}^i \right| \right\} \tag{15}$$

where, u_c^i is the voltage of the bus connected to customer i; u_{cset}^i is the set voltage of the bus connected to customer i; ε_{set}^i is the set voltage deviation of the bus connected to customer i.

The criteria for the optimal problem are as follows:

(1) the wind turbine and solar energy are preferred for environmental protection;
(2) the output power to the public grid is preset one-day ahead;
(3) the actual lines are represented as an ideal line with impedance;
(4) the reliability requirements of the customers are satisfied by the suitable topology design of the VPP.

3.5. The Constraints of the Power Suppliers

The power suppliers are controllable DGs with IUs. So the constraints include:

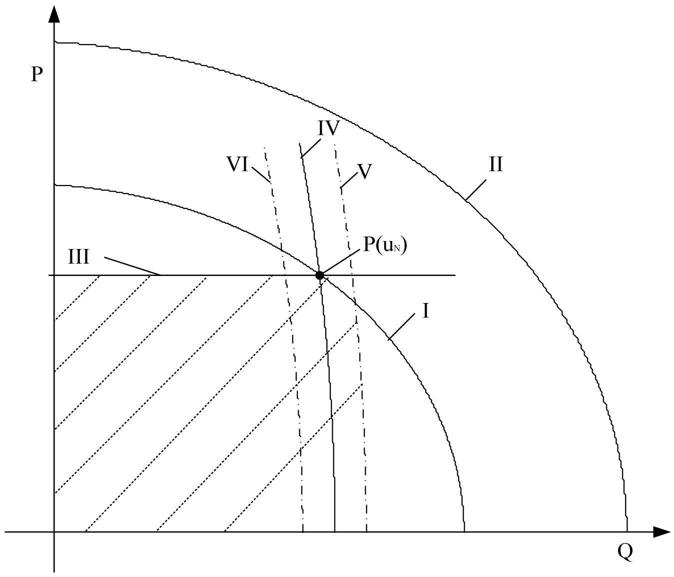
(1) All Feeder lines must operate within their line capacity. The transmission capability of the feed is a basic requirement in VPP operations.

(2) The DGs should operate within the pre-specified maximum limit. The rated powers of the converters have to be pre-determined depending on the maximum power flowing through them. The power suppliers cannot supply/absorb more power than the pre-specified maximum limit [22].

A typical representation of the constraint is shown in Figure 5, where line I represents the output limit of the convertor according to the current limit of its components; line II is the transmission limit of the feed line; line III is the rated output active power constraint; line IV is the transmission power when the source works at rated voltage; line V is the transmission power when the source voltage is 95% u_N; line VI is the transmission power when the source voltage is 105% u_N. The shadow in Figure 5 is the feasible solution set:

$$F=\begin{cases} P_{\min}^{i} \le P^{i} \le P_{\max}^{i} \\ Q_{\min}^{i} \le Q^{i} \le Q_{\max}^{i} \\ U_{\min}^{i} \le U^{i} \le U_{\max}^{i} \end{cases} \tag{16}$$

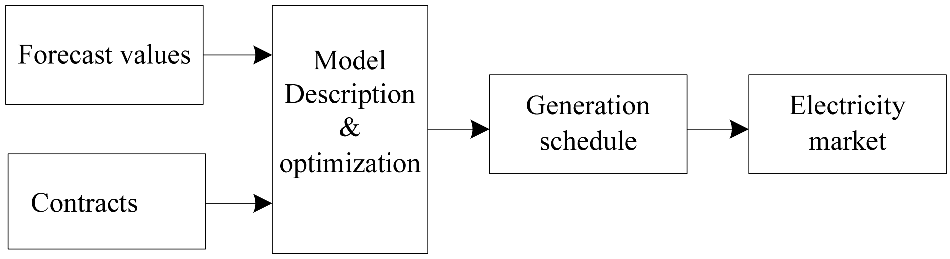
Figure 5. Constraints presentation.



3.6. Optimization Process

In this paper, the fuzzy multiple objective optimization algorithm with compromise of the satisfactory degree and the importance and priority of objectives is given based on the principle of two-step interactive satisfactory optimization. The flowchart of optimization process is shown in Figure 6. The forecast values of each time period include the load forecast, the predicted output power of the DGs owned by the VPP, as well as the quantity and price of the electric power supplied by the ones owned independently from the VPP. The final generation schedule is established by the ECCC through the optimization process.

Figure 6. Flowchart of operation.



The optimization process for each time period is as follows:

Step 1: Collect the information about the original contracts and the forecasted values at a time period: the supply plan and demand plans of the DGs and the loads in VPP delivered to the ECCC.

Step 2: Determine the ranges of x. The DM gives the value c_j according to (5) and α-cut sets of x are obtained.

Step 3: Regulate α and calculate the initial individual objective values. DM determines objective functions and their priority structure, the desirable targets k.

Step 4: Get the power flow and calculate the individual minimum and maximum values of objective functions under the given constraints to determine the membership functions of the objectives. If needed, the DM may set the target values instead of the individual minimum and maximum values.

Step 5: Get the maximum overall degree $\beta^t = \min(\beta_1, ..., \beta_i, ..., \beta_k)$ according to (7). And $\beta_i = \mu_{f_i}(x)$ are the satisfying degrees of the individual objectives. If it satisfies (8), the optimization can be stopped and the satisfactory solution is acquired. Otherwise, it goes to next step.

Step 6: Reduce β^t and solve (9) using optimal algorithm, and get γ.

Step 7: If $\gamma_i \in [\max(-k_1, -k_2), \min(1-k_1, 1-k_2)]$, the DM decides whether the solution is satisfactory or not. If it is not satisfactory, go to step 6; otherwise, stop optimization and the optimal solution is achieved. If there is no feasible solution, go to step 6.

4. Case Study

Figure 7 shows the configuration of the test example. The numbers 1–9 represent the equivalent injection nodes which are the total output powers of the constitution of the renewable generation sources and/or loads located closely (the thermal demands are met by the nearby thermal generators; the relative output electrical power of thermal generators are considered); the nodes 1, 4, 5, 6 are the controllable power sources within the control area of the VPP; node 6 is connected with the storage device and it is also the only one interface with the public grid in the VPP; the nodes 2 and 9 are microgrids owned independently from the VPP; node 3 is the uncontrollable load with given demand curve in advance; node 7 is the controllable load with purchasing contract that loads such as the air-conditioner can be disconnected for 1 hour and the increasing bound is limited [22]; node 8 is the residential load that can be shut down when energy shortage occurs. The intelligent devices (or IU) are equipped in these controllable source nodes to receive the orders from ECCC and control the output powers and node voltages. The power flow is calculated with the method presented in [23]. The line impedance is 0.1 + *j*0.12 Ohms/km; the maximum allowable line current is 128 A. Table 1 lists the forecasted power of nodes 1–9 at *j*th hour (the time window is 1 hour here) and Table 2 is the line lengths, where, 1–9 are the line numbers. The negative supplying power presents purchasing power from the VPP. When the loads fluctuate, the suppliers and the storage devices can share the load with certain principles [22]. The costs are shown in Table 3.

Figure 7. An example system.

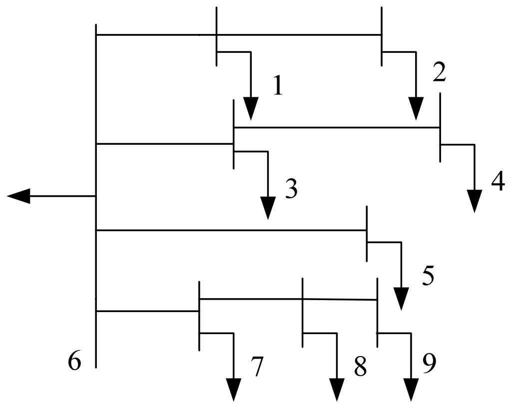


Table 1. Forecasted power of each equivalent node at *j*th hour.

Node No.	1	2	3	4	5	6	7	8	9
Forecasted Power at *j*th hour (MW)	−0.107	−0.1	0.1	−0.2	−0.3	0.46	0.1	0.1	−0.105

Table 2. Line lengths.

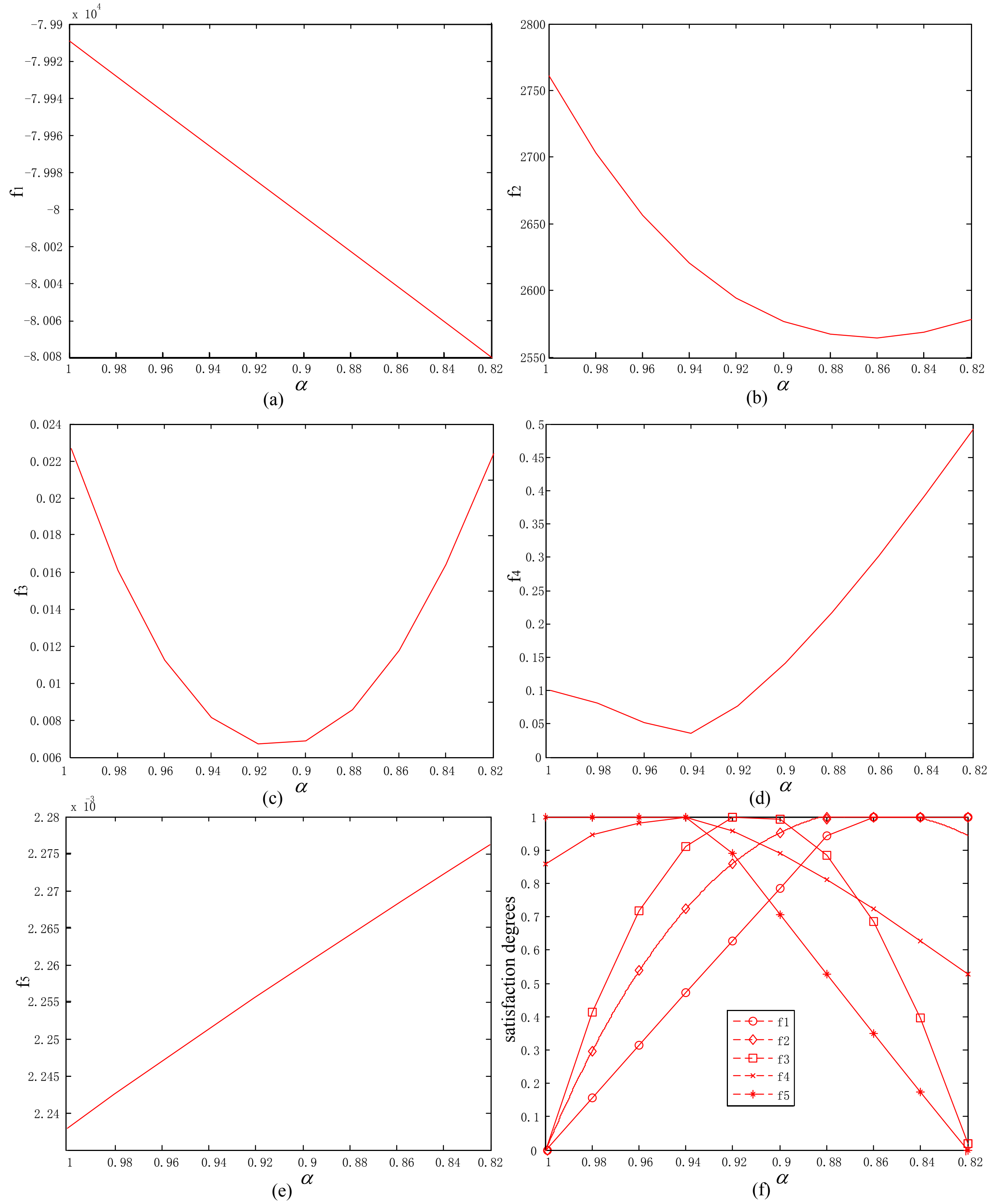
Line									
Line	**Node *i***	**6**	**1**	**6**	**3**	**6**	**6**	**7**	**8**
	Node *j*	**1**	**2**	**3**	**4**	**5**	**7**	**8**	**9**
Length (km)		1	6	3	7	12	5	3.5	5

Table 3. The costs.

	Name	Price
Fuel/Energy	Natural gas	¥2.05/m^3
	H_2	¥160.00/40 L(12.8 MPa)
	O_2	¥15.00/40 L(12.8 MPa)
Selling	Busy time	¥0.83/kWh
	Normal time	¥0.49/kWh
	spare time	¥0.17/kWh
Purchasing	Busy time	¥0.65/kWh
	Normal time	¥0.38/kWh
	spare time	¥0.13/kWh

When α ranges from 1 to 0.82, the minim goal values of the five objectives are shown in Figure 8a–e. The satisfaction degrees are shown in Figure 8f.

Figure 8. (**a**) Goal value of the objective f_1/yuan in RMB; (**b**) Goal value of the objective f_2/W; (**c**) Goal value of the objective f_3; (**d**) Goal value of the objective f_4; (**e**) Goal value of the objective f_5; (**f**) Satisfaction degrees of the five objectives.



The maximum overall satisfactory degree is obtained and shown in Figure 9. Where, $\eta = \max(\beta_r^t)$. Supposing the priority structure has three levels, the optimization results of different priority structures are shown in Figure 10 and Table 4. The areas of I-VII in Figure 10 are shown in Table 4. The relationship between maximum overall satisfactory degree and priority requirement of the multiple objectives is compromised by regulating the parameter γ. The priority structure will be better satisfied as the $\|\gamma\|$ goes smaller.

Figure 9. The maximum overall satisfactory degree.

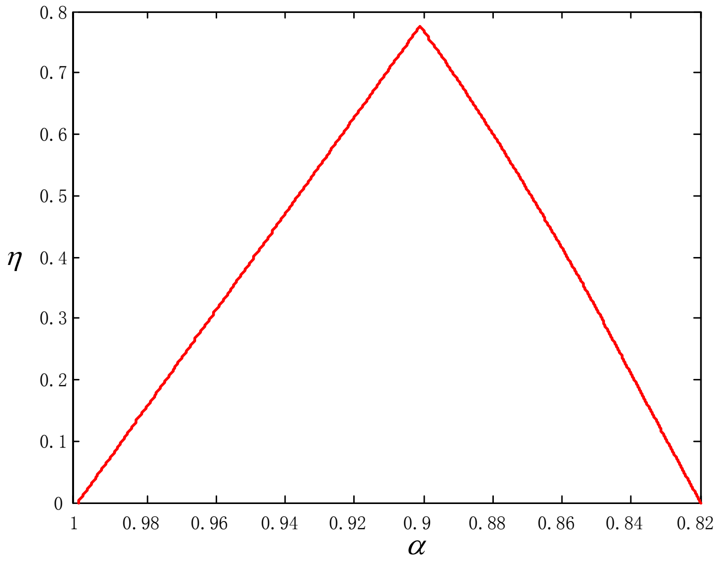


Figure 10. Priority structures and their regulation.

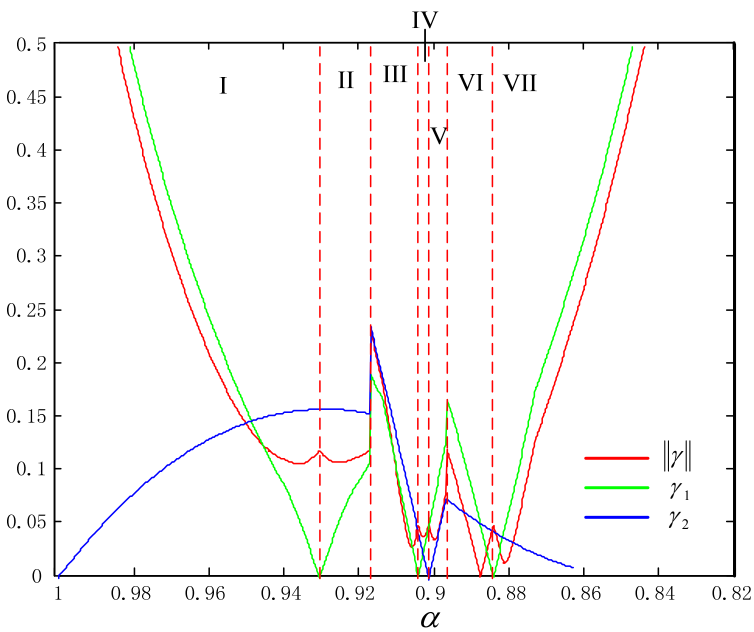


Table 4. Optimization results.

Areas	Level 1	Level 2	Level 3	Min
I	f_5 f_4	f_3 f_2	f_1	0.1077
II	f_5 f_3	f_4 f_2	f_1	0.1086
III	f_3 f_5	f_2 f_4	f_1	0.0282
IV	f_3 f_2	f_5 f_4	f_1	0.0384
V	f_3 f_2	f_5 f_1	f_4	0.0356
VI	f_2 f_3	f_1 f_5	f_4	0.0014
VII	f_2 f_1	f_3 f_5	f_4	0.0134

Suppose that the requirement of η is $\eta > 0.6$ and the preemptive priority structure is:

Level 1: f_3 and f_2;

Level 2: f_4 and f_5;

Level 3: f_1.

k: $k_1 = 0.05$, $k_2 = 0.05$

From Figure 9, it can be concluded that $\alpha \in [0.88,0.924]$ is the feasible area for the optimization problem with this priority structure. And priority structures in areas II–VII can also be chosen according to DMs' preference. If the preset priority structure is in area IV, the optimal solution can be achieved with the satisfaction degrees of (0.7663, 0.9052, 0.9934, 0.7865, 0.8799). The corresponding final voltage solutions are shown in Table 5.

Table 5. Final voltage solutions.

Bus No.	1	2	3	4	5	6	7	8	9
V (p.u.)	0.9866	0.9915	1.0032	0.9672	1.0310	0.9998	1.0475	1.0391	0.9971
Ang. (Rad.)	−0.0339	−0.1486	−0.0556	−0.2886	−0.6078	−0.0009	0.0427	0.0327	−0.0123

5. Conclusions

This paper establishes a fuzzy multiple objective optimization model for power management in VPPs according to the interaction of suppliers, demanders, and DM. The preemptive priorities are considered and a two-step interactive satisfactory optimization method with preemptive priorities is applied to obtain the optimal solutions. Then the compromised solutions and their satisfaction degrees which are also useful reference information for DM's decision-making are given. It allows the operator to choose the satisfactory one among the different solutions for each time window. The optimization results of the test system show its effectiveness, flexibility and efficiency in the application of the power distribution in a VPP.

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