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# Integrated Planning of Distribution Systems with Distributed Generation and Demand Side Response

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**Abstract**

The planning and operational issues of distribution systems have attracted more and more attentions from researchers with the development of Smart Grids. A new integrated planning model of distribution systems and the solution methods are proposed in this paper to investigate the way of improving the economy and reliability of distribution system planning by making full use of distributed generation (DG) and demand side response (DSR) resources. The planning objective function is formed by taking consideration of the investment and operation cost of DG, transmission loss cost, compensation cost for interruptible loads, purchasing electricity cost, and the environmental benefits after integration of DG. The integrated planning scheme will be acquired by introducing price induced interruptible load to distribution system planning model. A hybrid intelligent algorithm consisting of support vector machines (SVM) and particle swarm optimization algorithm (PSO) is proposed to solve the integrated planning model. The effectiveness and advantages of the model and algorithms and the necessity of considering the demand side resources are verified by simulation cases based on a real regional distribution system in China.
*Keywords*: Distribution network planning; integrated planning; distributed generation; demand side response; hybrid intelligent algorithm

## 1. Introduction

The problems of traditional energy shortage and environmental pollution are becoming more and more serious, and people pay more attention to renewable energy generation and demand side response (DSR) mechanism. DSR is very important for integrated planning of power distribution network, especially the current large-scale access of DG. The price of the interruptible load is an important content of DSR. The power companies and users signed the agreed price of interruptible load contract, and the power companies can cut off part of the users' load by making appropriate economic compensation. The load

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characteristics will be improved through determining the interruptible load and the interruption duration correctly.

Distribution network planning is a multi-objective integer programming problem, and with the addition of DSR and DG the planning dimension and the difficulty is increased. On the DG locating and capacity problem, an improved multi-objective harmony search algorithm is used to solve this optimization problem in [1]. In [2] the genetic algorithm is used to solve the optimization problem for minimizing system cost and maximizing DGs reliability. However, the power distribution network planning considering DG and DSR needs to be further studied.

In order to reflect the impact of DG and DSR on distribution network planning, the comprehensive planning framework based on DG and DSR (here mainly adopts the interruptible load management) is proposed in this paper. The planning objective function is formed by taking consideration of the investment and operation cost of DG, transmission loss cost, compensation cost for interruptible loads, purchasing electricity cost, and the environmental benefits after integration of DG. The hybrid intelligent algorithm based on SVM and PSO is used to get the best DSR plan and the position and capacity of DG. Finally, based on an actual 42 nodes distribution system in China, the economy and reliability of three schemes are compared to verify the effectiveness of integrated planning and the necessity of DSR.

## 2. Mathematical Model of Integrated Planning based on DG and DSR

Stochastic chance constrained programming (SCCP) is proposed by Charnes and Cooper, whose remarkable characteristic is that the constraints are satisfied at a certain confidence level.

SCCP model is usually expressed as follows [1]:

$$\begin{cases} Min\ \bar{f} \\ s.t.\ \ p_r\{f(x,\xi) \le \bar{f}\} \ge \beta \\ \qquad p_r\{g_i(x,\xi) \le 0, j=1,2,\cdots,v\} \ge \alpha \end{cases} \tag{1}$$

where $x$ and $\xi$ respectively present the decision vector and the random vector, $p_r\{\bullet\}$ presents the probability of an event, $\alpha$ and $\beta$ are the confidence levels which decision makers given in advance. $\bar{f}$ is the minimum value of the objective function at the confidence level $\beta$.

### 2.1. Objective Function

The planning objective function considers the investment and operation annual cost of DG, transmission loss cost, compensation cost for interruptible loads, purchasing electricity cost, and the environmental benefits after integration of DG.

The optimization objective is follows [2] in this paper.

$$\min C = C_{loss} + C_{DSR} + C_{DG} - C_b - C_e \tag{2}$$

where $C_{loss}$ is the annual loss cost, $C_{DG}$ is the investment and operation annual cost of DG, $C_{DSR}$ is the compensation cost for interruptible loads, $C_b$ is the saving cost for purchasing electricity, $C_e$ is the environmental benefits.

1) Annual loss cost:

$$C_{loss} = C_{ps} \times \sum_{i=1}^{k} (P_{loss\_i} \times \tau_{\max\_i}) \tag{3}$$

where $C_{ps}$ is the unit electricity selling price, $k$ is the number of branches in the distribution system, $P_{loss\_i}$ is the active power loss of the *i-th* branch, $\tau_{\max\_i}$ is the annual maximum load loss hours of the *i-th* branch.

2) Compensation cost for interruptible loads:

$$C_{DSR} = \sum_{i=1}^{n_{DSR}} P_{DSR\_i} \times T_{DSR\_i} \times (C_{ps} + C_{pi}) \tag{4}$$

where $n_{DSR}$ is the number of interruptible loads, $P_{DSR\_i}$ and $T_{DSR\_i}$ respectively presents the interruptible load and interrupt time of the *i-th* interruptible load, $C_{pi}$ is the unit compensation cost for interruptible load.

3) Investment and operation annual cost of DG: $$C_{DG} = \sum_{i=1}^{n_{DG}} \left(\frac{a(1+a)^m}{(1+a)^m - 1} \times r_i \times P_{DG\_i} + W_{DG\_i}\right) \quad (5)$$

where $n_{DG}$ is the number of DGs, $a$ is the discount rate, $m$ is the durable years of DG, $r_i$ is the unit capacity cost of DG in the *i-th* node, $P_{DG\_i}$ is the power capacity of DG in the *i-th* node. $W_{DG\_i}$ is the annual operation cost of DG in the *i-th* node.

4) Investment and operation annual cost of DG: $$C_b = \left(\sum_{i=1}^{n_{DG}} P_{DG\_i} \times T_{DG\_i} + \sum_{i=1}^{n_{DSR}} P_{DSR\_i} \times T_{DSR\_i}\right) \times C_{pb} \quad (6)$$

where $T_{DG\_i}$ is the annual utilization hours of the *i-th* DG, $C_{pb}$ is the unit feed-in tariff.

5) Environmental benefits: $$C_e = \left(\sum_{i=1}^{n_{DG}} P_{DG\_i} \times T_{DG\_i} + \sum_{i=1}^{n_{DSR}} P_{DSR\_i} \times T_{DSR\_i}\right) \times C_{pe} \quad (7)$$

where $C_{pe}$ is the unit environmental cost of the thermal power plant. In general, the main pollutants of thermal power generation include sulfur dioxide, nitrogen dioxide, carbon monoxide, oxygen compounds, total suspended particulates, fly ash and slag etc.

### *2.2. Constraints*

1) Flow constraints:

$$\begin{cases} P_{DGi} - P_{Li} = V_i \sum_{j=1}^{n} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) \\ Q_{DGi} - Q_{Li} = V_i \sum_{j=1}^{n} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) \end{cases} \quad (8)$$

where $P_{DGi}$ and $Q_{DGi}$ are the active and reactive power injections in the *i-th* node by DGs, $P_{Li}$ and $Q_{Li}$ are the active and reactive power load in the *i-th* node, $V_i$ is the voltage amplitude of the *i-th* node, $G_{ij}$ is the conductance of the branch *i-j*, $B_{ij}$ is the susceptance of the branch *i-j*, $\theta_{ij}$ is the phase angle difference between the *i-th* node and the *j-th* node.

2) Voltage constraints: $$V_{\min} \le V_i \le V_{\max} \quad (9)$$

where $V_{\max}$ and $V_{\min}$ are the upper limit lower limit of voltage amplitude.

3) Branch power flow constraints: $$S_j \le S_j^{\max} \quad (10)$$

where $S_j^{\max}$ is the upper limit of the *j*-th line capacity.

4) Interruptible load constraints:

$$\begin{cases} P_{D\min\_i} \le P_{DSR\_i} \le P_{D\max\_i} \\ T_{D\min\_i} \le T_{DSR\_i} \le T_{D\max\_i} \end{cases} \quad (11)$$

where $P_{D\max\_i}$ and $P_{D\min\_i}$ are the upper limit lower limit of the interruptible load, $T_{D\max\_i}$ and $T_{D\min\_i}$ are the upper limit lower limit of the interruption duration annually.

5) Installed capacity constraints of DG: $$0 \le S_{DGi} \le S_{Li} \quad (12)$$

where $S_{DGi}$ is the installed capacity of the *i-th* DG, $S_{Li}$ is the maximum permissible installed capacity of the *i-th* DG.

## 3. Hybrid Intelligent Algorithm

In recent years,PSO is widely used in power system optimization problems. But by using PSO for solving chance constrained programming problem, it need to estimate the random function through the random simulation [3], so the estimated value of power loss under a variety of wind scenes should be calculated through many times of power flow calculation. To make the estimates are as accurate as possible, the number of the simulation must increase, which makes the solution process is very time-consuming. In addition, stochastic simulation is used to test the feasibility of the solution and calculate the fitness of each particle of the swarm in the process of iteration. When the number of particles and the number of iterations are large, the estimation process by using stochastic simulation will be very time-consuming. In practical application, the efficiency of the algorithm is a very important problem. Actually what we need is the relative comparison of each solution, calculating the exact value of the objective function is not necessary in the solving process, so we can seek an approximate estimation algorithm. As a new intelligent algorithm, SVM has achieved good performance in function approximation [4]. In order to accelerate the solving process, SVM model can be trained to replace the traditional power loss calculation.

Therefore, the hybrid intelligent algorithm is used to solve the integrated planning of distribution systems with DG and DSR, the process of Hybrid Intelligent Algorithm can be listed as follows:

(1) Input the original data and get the information of nodes, branches, equipment parameters, then determine the limit of voltage, current-carrying capacity, DG installed capacity and interruptible load.

(2) Establish the mathematical model of integrated planning.

(3) Under a series of wind scenes based on weibull distribution[5], generate some planning randomly and calculate the power transmission loss. Then these data form the training set for the approximation function.

(4) Use the genetic algorithm (GA) to optimize the parameters of SVM kernel function, then train the SVM model and get the SVM approximation function.

(5) Generate the initial particle swarm and test the feasibility of these initial particles.

(6) Get the target value (power loss) of each particle by the SVM approximation function.

(7) Calculate the fitness (overall cost of the planning scheme) of each particle based on the target value according to the objective function of integrated planning.

(8) Update the velocity and position of the initial particle based on PSO.

(9) Update the particle and test its feasibility.

(10) Back to step 6, repeat until termination condition is satisfied.

## 4. Analytical Examples

A practical 42 nodes distribution network is researched in this paper, and the wiring diagram is shown in Fig. 1. The total length of all the lines is 26 km; the total number of users is 5974, including 7 industrial users, 2 power plant electricity loads, 5938 agricultural users or businesses users. A chemical plant whose annual peak load reaches 1737kW is the largest industrial user in this distribution network, and the rest of the industrial electricity loads are less than 400 kW. So the chemical plant is chosen as an interruptible load for DSR.

Here we assume that the unit compensation cost for interruptible load is 0.6 Yuan/kWh, the unit electricity selling price is 0.74 Yuan/kWh, the unit feed-in tariff of thermal power plant is 0.48 Yuan/kWh, the unit environmental cost of the thermal power plant is 0.1171 Yuan/kWh [6], the unit capacity investment cost of wind turbine is 6300 Yuan/kWh, the durable years of wind turbine is 25 years, the discount rate is 0.1, the population size of PSO is 20, the iteration number is 500, the wind scene simulation number of each training sample is 200 and the number of training samples for SVM is 2500.

In order to test the accuracy and efficiency of the hybrid intelligent algorithm, the traditional method combined with stochastic simulation and PSO is used to solve the SCCP of integrated planning at first. The number of random wind samples is 200, the confidence level of objective function $\beta$ is 0.5, and the confidence level of voltage constraints $\alpha$ is 0.95. In addition, the SCCP of integrated planning is solved with the hybrid intelligent algorithm. The optimization results of these two algorithms are shown in Table 1. In DG optimization scheme, the value before the parentheses is the access node of DG, the value between the parentheses is the access capacity (kW) of DG. In the interruptible load scheme, the value before the parentheses is the interruptible load (kW) which is drawn up by the power supply enterprise and the chemical plant, the value between the parentheses is the interruption duration (hour).

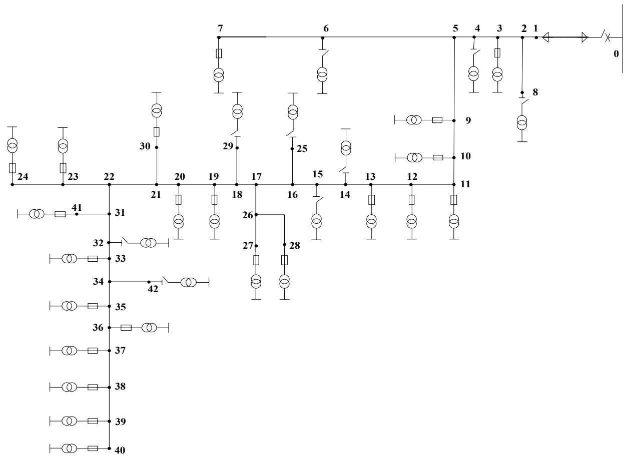


Fig. 1. Diagram of the example distribution system

Table 1. Optimization results

| Algorithm | DG optimization scheme | Interruptible load scheme | Objective value (Yuan) | Planning time (Second) |
|---|---|---|---|---|
| Stochastic simulation | 12(40), 15(60), 25(190), 33(10) | 330(1210) | 5112592 | 4978 |
| Hybrid intelligent algorithm | 10(50), 13(50), 25(180), 30(10) | 360(1190) | 5119780 | 1662 |

The optimization scheme solved with hybrid intelligent algorithm can achieve valid effect, and the relative error of objective value is only 0.14%, the calculation error caused by the SVM approximation function is still in the tolerance range. At the same time, only few times of power flow calculation are needed for the SVM training samples. The planning time reduced from 4978 seconds to 1662 seconds due to avoid the power flow calculation for each particle of every generation in the PSO.

In order to research the economy and reliability of the integrated planning with DG and DSR, the hybrid intelligent algorithm is used to solve the planning schemes under three cases. The costs of each plan under three cases are shown in Table 2.

Table 2 shows that the not only does the cost of power loss reduce, but also the problem of overload and blocking is alleviated after integrated planning with DG and DSR. Especially in the case of the global energy shortage, the DG is the environment-friendly green power, and the interruptible load measures are conducive to energy-saving emission reduction work, and bring considerable environmental benefits. As can be seen from the planning scheme, the interruptible load is about 20.7 percent of the chemical plant's annual peak load and the chemical plant can adopt energy-saving measures to consume less electricity on the premise of meeting constantly production need. In addition, the DG equipment cost will gradually reduce with the development of the technology of DG. The economic advantages of integrated planning with DG and DSR will be more and more obvious.

Table 2. Costs of different planning schemes

| Cost (Yuan) | Traditional planning without DG or DSR | Planning with DG only | Integrated planning with DG and DSR |
|---|---|---|---|
| $C$ | 6863894 | 5127256 | 5119780 |
| $C_{loss}$ | 6863894 | 5330981 | 5305620 |
| $C_{DSR}$ | 0 | 0 | 257040 |
| $C_{DG}$ | 0 | 460835 | 222737 |
| $C_b$ | 0 | 534230 | 535080 |
| $C_e$ | 0 | 130330 | 130537 |

The ETAP electrical engineering software is used to model the 42 nodes distribution network, and the results of reliability indices of the planning schemes are shown in Table 3.

Table 3. Reliability of different planning schemes

| Reliability index | Traditional planning without DG or DSR | Planning with DG only | Integrated planning with DG and DSR |
|---|---|---|---|
| SAIFI (Interruptions/Customer) | 4.3613 | 4.1286 | 4.1086 |
| SAIDI (Hours/Customer) | 13.2209 | 10.5965 | 10.0965 |
| CAIDI (Hours/Customer Interruption) | 3.031 | 2.567 | 2.457 |
| ASAI（%） | 99.85 | 99.88 | 99.88 |

According to Table 3, in the event of substation and some lines faults, DG can supply power to the important loads to meet the electricity needs for short-term production and life, so that the power supply reliability rate increase. Moreover, on the premise of safe operation of network and reliable power supply, the access number and capacity of DG will reduce by proper implementation of interruptible load management measures so that the impact of intermittent power output from DG can be avoidable. Then the reliability indices of distribution network have been further improved.

## 5. Conclusion

The integrated planning model with DG and DSR is established in this paper, and the SCCP model based on stochastic simulation for DGs can avoid the conservative optimization results caused by deterministic constraints. In order to improve the computing speed, the hybrid intelligent algorithm combined with SVM and PSO is used to the integrated planning model. The optimization results show that the hybrid intelligent algorithm can save much time for power flow calculation and also get achieve valid accuracy. The calculation results show that this algorithm is effective and feasible based on a practical 42 nodes distribution network. The economy and reliability of three planning schemes are compared to show that the integrated planning with DG and DSR can reduce the cost of network loss and bring the considerable environmental benefits, then DSR can make up for the defects of DG intermittent output characteristics and improve the reliability of power supply.

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