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Multi-layer optimization for grid-connected micro-grid power planning considering metabolic capacity

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Abstract. Optimizing the energy structure，ensuring the reliability of power supply and improving the utilization of renewable energy sources are the primary objectives of micro-grid power planning. This paper takes wind / light/ storage micro- grid as an example , defines the concept of metabolic capacity to describe the ability of renewable utilization in a micro- grid, presents a new multi-layer optimization method to study the life-cycle cost of a micro-grid planning. The upper layer optimizes the type, the capacity, and allocation combinations of micro-grid power sources; The middle layer optimizes the system operation considering the network subsidy policy which State Grid newly carried out and the real-time electricity prices synthetically; The lower layer calculates the cost of micro-grid reliability cost based on reliability cost-benefit analysis. A modified Immune Particle Swarm Algorithm is designed to optimize the proposed three layer goals. As examples results shown, the proposed multi-layer optimization strategy and the Immune Particle Swarm Algorithm are very effective to coordinate the relationship in depth among the factors of economy, reliability and economic dispatch during micro- grid planning, it reduces the redundant investment micro-grid power supply efficiently, meanwhile ,increases the use of renewable energy and guarantees the system reliability .

Introduction

Along with the continuous economic development，the public has increasing attention on the world energy shortage and environmental pollution issues. Developing and utilizing new energy has become the trend of the times , and the construction and development of new energy has stepped into a new stage of greater optimized configuration on a large scale[1]. Given the wind and solar energy which are of the feature of Intermittency, volatility and the complementary with the time ,optimizing the configuration of wind/solar/ storage in a micro-grid can improve the entire micro-grid energy utilization efficiency and reliability of power supply[2]。

The research above are the foundation of the follow-up work, but there generally exists the following important issues: 1)Most studies just focus on the isolated grid power planning, and few grid-connected planning research has in-depth studies on the coupling relationship between the investment planning, economic dispatch and reliability involved. 2)Most planning studies mentioned above take the better economic power configuration solution as the primary goal which can meet the power balance constraints, but how the other related factors influence the economic operation and the planning of the micro-grid are seldom involved. These factors, include, but may be not limited to, the utilization of current renewable energy sources，the grid-connected policy and regulation and the network subsidy policy. In fact, these factors above should be taken into full consideration because they will have an important impact on the configuration of micro-grid in practice.

Multi-layer optimization model

Basic framework research. In the 1970’s, Bracken and Mcgill first put forward the concept of multi-layer planning, this is an idea that optimization system possesses with hierarchical structure. Its decision-making mechanism is as follow: first, the upper makes a decision which directly affects the feasible region and the objective function of other layers; Then other layers, under the restriction of the uppers, affects the objective function and the efficient solution of the upper layer through the feedback of their optimal solution to the upper ; The upper adjusts the decision-making strategy according to the feedback until achieve the optimal objective function of the upper value. This decision-making mechanism leads the lower to make a decision that will be conducive to the overall system by affecting the decision environment of the lower's , instead of giving a direct guidance by the upper . This mechanism can fully excavate the multi-layer coupling relationship among the factors in different layers to make the solution optimal under the overall environment.

The idea of two-layer optimization design[13] has been used in the optimal planning of transmission system and distribution system ,reactive power optimization, and other fields. The layered-design application has been less adopted in the power planning for micro-grid. Because both the economy and reliability factors in economic operation and planning should be taken into account, it is profitable to integrate the reliability factors into the economic ones in multilayer way.Figure1 is the proposed multi-layer optimization logic diagram：

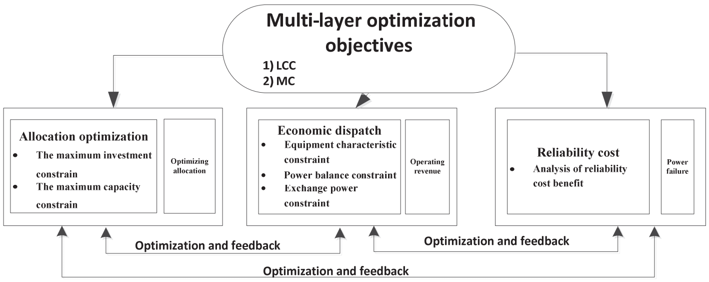


Fig.1 multi-layer optimization logic diagram of micro grid

This paper cites the concept of Life Cycle Cost, (LCC)[14].LCC gives consideration not only to the one-off investment cost of the initial micro-grid planning equipments, but also to the cost generated by the operation, malfunction and maintenance of the entire system within recommended limits. The core idea of proposed multilayer planning strategy in this paper is to optimize the LCC of the micro-grid in a multi-level optimization approach, which integrates different influence factors into the planning target. As fig.1 shows. The best micro-grid power supply configuration scheme with the optimal investment can be obtained by the upper through the other twos' feedback of economic operation optimization and reliability calculation. LCC mainly considers the investment and maintenance cost, the operation benefit and the reliability cost of micro grid. The objective function expression is as follows:

$$\min LCC = C_f + C_{gr} + C_r \tag{1}$$

In the formula, C_f is the cost of investment and maintenance in micro grid; C_{gr} is the benefit from the micro grid operation ; C_r is the reliability cost of micro grid.

Optimal micro-grid power supply configuration model (Upper Layer)

Objective function . The goal of micro-grid configuration optimization is to determine the best layout of the power supply for the optimum economical efficiency and reliability ,on the premise of normal operation. It mainly considers The investment and maintenance cost of micro grid are major concerned, the concrete expression is follows:

$$C_f = \sum_{i=1}^{N} (C_{li} + C_{opi})x \tag{2}$$

In the formula, N is power supply types(including energy storage); x_i is the number of the Ith kind of power supply; C_{li} is the investment of the Ith kind of power; C_{opi} is the maintenance cost of the Ith kind of power.

Constraint conditions. 1)Investment constraints: Suppose the largest investment of planning is $F_{\max}$. The investment restriction Constraints in the micro-grid power planning is as follows：

$$F < F_{\max} \tag{3}$$

Capacity constraints: The maximum capacity of micro-grid power installed is also limited by the environment and paving areas. Suppose $P_{v\max}$ represents the maximum capacity of photovoltaic installed, $P_{w\max}$ is the maximum installed capacity of wind turbine generator, $E_{c\max}$ represents the maximum installed capacity of storage batteries. The concrete constraints are as follows:

$$\begin{cases} P_v < P_{v\max} \\ P_w < P_{w\max} \\ E_c < E_{c\max} \end{cases} \tag{4}$$

Model of micro-grid economic dispatch (Middle Layer)

Objective function. According to “Opinions about doing the work well on distributed grid-connected service”[11]which is newly released by State Grid： surplus electricity produced by the distributed energy which accesses to the low voltage distribution network is allowed to incorporate into the power network, and the power grid enterprise will purchase all the surplus electricity according to the national policy. At the same time, due to the limitation of the grid integration for the renewable energy and the physical capacity of the tie lines of the distribution network, the electricity purchasing or selling from or to the main network tends to be bound by the grid-connected policies and regulations of the micro grid[15]. These two policies certainly will influence the configuration and operation of the grid-connected micro grid which contains renewable energy. Therefore, financial subsidies of surplus power and the policy of restrictions on power purchasing or selling needs to be taken into an extra consideration , along with the economic factors ,when studies the grid-connected micro-grid power planning .

Optimal scheduling model selects hour as dispatching scale and selects the maximum operation revenue as the objective function. The cost mainly includes contents as follows: the revenue of electricity sold to main grid, the cost of electricity purchased from the main network, and the cost of power losses in operation. Its formula is as follows:

$$C_{gr} = \sum_{t=1}^{8760} (P_{sell}(t) w_{st} + P_{buy}(t) w_{bt})(1+\eta) \tag{5}$$

In the formula, $P_{sell}(t)$ is the electricity quantity sold to main grid at time t； w_{st} is micro-grid spot price； $P_{buy}(t)$ is the electricity quantity purchasing from main grid at time t； w_{bt} is the spot price of main grid； η is the loss coefficient of micro-grid power energy.

Metabolic capacity level (MCL). This article defines the metabolic capacity level of micro grid as the ratio of the amount of energy abandoned in operation to the time of normal power supply. The better the micro grid to absorb and use the wind and light energy is, the stronger the reliable power supply is, the lower the metabolic capacity level of micro grid is ,and vice versa . The MCL definition is as follows:

$$MC = \sum_{t=1}^{8760} Q(t) / (8760 - \sigma \sum_{t=1}^{8760} k_t) \tag{6}$$

In the formula, $Q(t)$ is the power abandoned at time t and it is a positive value. k_t represents whether the micro grid is in a failure state, $k_t \in \{0,1\}$ (0 represents the failure state). σ is weighting parameter.

The power abandoned $Q(t)$ of wind/light/storage micro grid is as follows：

$$Q(t) = P_n(t) - P_{load}(t) - (E_c - E(t)) - P_{ex\max} \tag{7}$$

In the formula， $P_n(t)$ is the total output of wind turbines and photovoltaic modules at time t, $P_{load}(t)$ is the load power of micro grid at time t, E_c is the total capacity of micro-grid storage battery, $E(t)$ is the energy capacity of micro-grid storage battery, P_{exmax} is the maximum power exchanged between micro grid and main grid.

Constraint conditions. Equipment characteristics constraints Output models of wind turbine and photovoltaic are shown in [6 ~ 9], therefore will not be discussed here. Storage battery, as energy storing element， can trace the load demand through the way of controlling the process of the charge and discharge of energy storage devices fast by the energy storage controller . Its energy storage status is also with coupling on time (The situation of energy storage at this moment is influenced by that at last time.). Its formula is as follows：

$$E(t) = E(t-1)(1-\sigma_B) + P_{bt}(t-1)X_t \tag{8}$$

In the formula, $E(t)$ and $E(t-1)$ represent respectively the capacity of storage battery at time *t* and *t-1;* σ_B is the attrition rate itself of storage battery; $P_{bt}(t-1)$ is the exchanged power between storage battery and outside at time *t-1*； X_t is the state of charge-discharge of the storage battery,.

Because the charging-discharging power is connected with battery life, this article sets maximum charging- discharging power of storage battery per unit time at 25% of the rated capacity and the charging-discharging power constraint as follows:

$$0 \le P_{bt} \le 0.25 E_c X_t \tag{9}$$

To ensure the safe operation of the system and the normal power generation of micro grid under extreme conditions $X_t \in \{-1,0,1\}$ like grid fault, this article sets the depth of discharge constraint as follows:

$$SOC_{\min} \le SOC_t \le SOC_{\max} \tag{10}$$

In the formula, $SOC_{\min}$、SOC_t、$SOC_{\max}$ are respectively the states of charge(soc) of storage battery at time *t* and it's top and bottom limitation. Setting $SOC_{\min}$ the 20% ~30% of the total volume and $SOC_{\max}$ the 80%~100% of the total amount are generally preferable. This paper uses VRB-50 storage battery with a standard rated capacity of $50\text{kW}\cdot\text{h}$,and the impact of external environment on the charge and discharge of storage battery are ignored.

Power balance constraint Under ideal conditions, the micro-grid system should keep power balanced at any time. In other words, the micro-grid output (including energy storage output), the power exchanged between micro grid and the main grid , electrical load and the load shedding should be balanced shape

2)

$$P_n(t) = P_{load}(t) + P_{bt}(t)X_t - P_{cut}(t) + P_{sell}(t) - P_{buy}(t) \tag{11}$$

In the formula, $P_{buy}(t)$ is the load shedding power of dispatching interval at time *t*.

3) The maximum exchange power constraint: In order to ensure safe operation, the micro-grid purchasing and selling electricity from the main grid policies is limited by grid-connected policies and regulations. This article sets $P_{ex\max}$ as the upper limit exchange power between each time interval of the main grid and micro-grid, and purchasing and selling power can't be conducted at the same time.

$$\begin{cases} P_{s-sm}(t) < P_{ex\max} \\ P_{buy}(t) < P_{ex\max} \end{cases} \tag{12}$$

Immune Particle Swarm Optimization Solution

Improved Particle Swarm Optimization Algorithm

Particle Swarm Optimization (PSO) Algorithm has the advantages of simple structure and fast running speed, but it is easy to be trapped in the local optimum and appeared premature convergence.

Variety and immunological memory are the important characteristics of AIA (Artificial Immune Algorithm). Integrating the characteristics of AIA into PSO will make the particles concentration greater and selective probability smaller; otherwise, the result is one the contrary. In this way, it can not only reserve the individual with high adaptability, but also ensure the variety of particle and avoid the premature convergence.

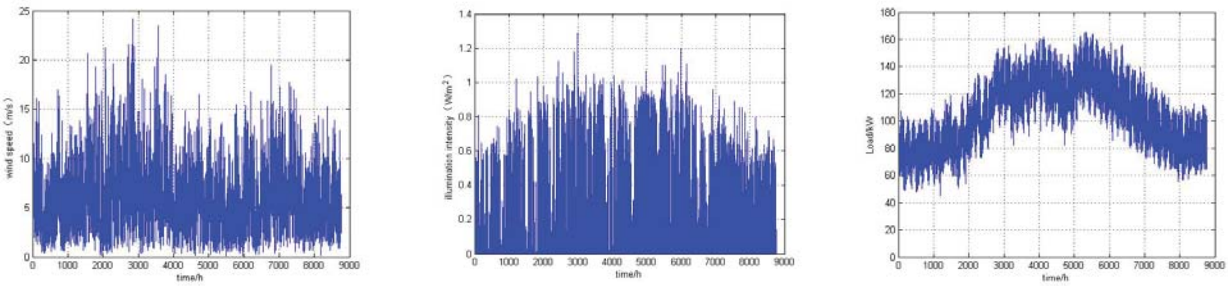
Construction of fitness function of IPSO

Ideal point method is to set metrics to determine the distance from the particle in the planning feasible region to the ideal point, and to make the "distance" between the optimal solution and the ideal point of these planning issues as small as possible based on this metrics. In this article, the ideal point will be composed of LCC_{min} and MCL_{min} available , and particles will be compared with the ideal point and optimized through the proposed multi-layer optimization method by iteration.

Examples research

Examples summary

According to the historic data of one commuty in north China, this article forecasts the wind power, illumination intensity and load demand of one year by using Monte Carlo simulation, and the results are shown in figure 2. A optimal configuration scheme of a wind/light/storage micro-grid generation system in this community will be caculated by using the strategy and model proposed in this paper. The related parameters of the micro source are shown in table 1.



(a) annual wind speed predication curve (b)annual illumination intensity predication curve (c)annual load curve predication

Fig.2 The initial related prediction data of the micro-grid configuration

Tab.1 Technology parameters of the micro power

Wind turbine		Photovoltaic cell		Storage baterry	
stand-alone rated power	10kW	derating factor	0.083	unit capacity	50kW·h
working life	15 years	rated power	8.3kW	rate of self loss	0.008
hub height	15 m	working life	15years	the maximum discharge rate	0.4
cut-in wind speed	3m/s	cost of sets	6195Yuan/kW	the maximum charge rate	0.3
cut-out wind speed	24m/s	operation and maintenance cost	2300yuan/year	the maximum ,minimum SOC	0.25,0.90
cost of sets	6000yuan/kW			working life	1300yuan/kW
Operation and maintenance cost	2000yuan/year			operation and maintenance cost	700yuan/year

Specific parameter settings related in the micro-grid planning are as follows: The maximum investment is 12 million yuan; The installed capacity of photovoltaic generation is limited by the paving surface and its maximum capacity is 150 kW; The amount of wind turbines is up to 40 limited to the constraint of space such as residential green zone.The biggest installed capacity of the storage battery is 1600kW·h. According to the agreement of electricity purchasing and selling between the micro grid and the main grid, the exchange power with main grid ($P_{ex\max}$)is no more than 50 kW at every time. The SOC value of storage battery is set as [0.3, 0.95], and the SOC value at the start and end time of the dispatching cycle is 0.6.

Assuming that the network subsidy of new energy is 0.2 yuan/kW·h, then the TOU of micro-grid electricity purchasing and selling are shown in table 2.

Tab.2 Time-of-use power price

Time frame	Price of purchasing electricity/ (yuan/错误!未找到引用源。)	Price of selling electricity/ (yuan/错误!未找到引用源。)
23:00~7:00	0.3711	0.5811
7:00~9:00 12:00~14:00 16:00~19:00 21:00~23:00	0.8756	0.9756
9:00~12:00 14:00~16:00 19:00~21:00	0.6947	0.7347

Optimization method comparison

This article has the micro grid planning optimal configuration with strategies of single layer, bilayer, multilayer and the multi-layer optimization based on MCL studied by using IPSO, Then compared and analyzed the results based on EXC (Energy Excess Percentage)[5]and LOLP (Loss Of Load Probability)[2].

The single-layer optimization (SLO) strategy is to optimize the investment cost in an isolated network mode, the LOLP <0.1 is regarded (power supply reliability is greater than 90%) as a constraint condition to.The BLO (Bi-layer optimization) is to combined goals of SLO with LOLP to realize bi-objective optimization.The MLO (Multi-layer optimization) is to study the LCC of the micro-grid under the grid-connected state.On the basis of MLO,the Multi-layer optimization based on MCL (MLO-MCL) is to further analyze the impact of the metabolic capacity on optimization configuration. Results of different optimal configuration schemes using different optimization strategies are shown in table.3.

Tab.3 The result of optimal configuration

	Single layer optimization	Bi-level optimization	Multi-layer optimization	MLO-MCL
N_w(C)	28	33	30	26
N_g(C)	2713	2547	2550	1147
N_b(C)	15	38	29	36
EI/ten thousand yuan	753.89	988.53	851.76	769.97
MCL	43.354	33.514	15.543	0.7975
LOLP	0.0898	0.0119	0.0017	0.0046
EXC	0.1928	0.2318	0.1086	0.0397

Note: N_w is the number of wind turbines; N_g is the number of solar cells; N_b is the number of batteries; EI(Economic indicator) is the economic cost of the planning.

From the above analysis can be known, with less investment , the MLO-MCL strategy can integrate the different goals of economic and reliability indexes in planning and operation effectively, reflect their contribution to the micro grid.The configuration scheme of micro grid optimized by the MLO-MCL strategy and the IPSO has high power supply reliability, can meet the requirment of energy conservation and emission reduction by inreasing the absorption of renewable energy.

Conclusions

This paper has focused on the impact of the metabolic capacity and multi-layer optimization on optimizing the configuration of micro grid, analyzed the advantages of IPSO algorithm and the performance of the proposed strategy and algrithm, and the relationship between metabolic capacity and life-cycle cost of micro grid has been aso studied. As the results shown, The MCL has considerable influence on the final configuration sheme of micro grid. Thus, while optimizing the configuration of micro grid, a planning configuration scheme with good metabolic capacity level and optimal economy of whole life-cycle is recommended in practice. The proposed multi-layer optimization model based on the LCC and MCL of the micro-grid planning has integrated the economic operation and reliability factors into micro-grid planning targets well together.The effectiveness of the designed IPSO has also been reflected by the simulation results too.The planning sheme optimized by the proposed strategy and algrithm in this paper can meet the requirements of many aspects in micro grid planning ,such as reduction the redundant investment micro-grid power supply, increasement in the utilization of wind and solar energy,improvement of the system reliability,etc.

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