Research on Location and Capacity Planning of Datacenters in Smart Grids with Renewable Sources

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Abstract. Considering the huge power consumption and controllable characteristic of datacenters, they can be potential loads integrated into smart grids with renewable sources so as to consume the generated energy which is usually intermittent and unstable, in order to keep the smart grid more stable. In this paper, we attempt to exploit the possible impact of datacenters in smart grids with renewable sources and focus on the location and capacity planning of the datacenter construction. Subject to voltage and branch power constraints, we formulated the problem to find the optimal datacenter location and capacity and proposed an algorithm to solve it based on genetic algorithm. Then, we analyzed the total power loss of the grid system under different conditions and the impact by the change of datacenter locations. Experimental results show that the approach proposed in this paper can find better solutions for location and capacity planning of several datacenters, so as to reduce the total loss of the power grid and maintain the stability of the power grid more effectively.

Introduction

Driven by global challenges such as energy shortages, climate change and growing demand for electricity, modern power systems are undergoing massive revolutions and reconstruction. In the early 21st century, the "smart grid" [1] was proposed to build a smart low-carbon green grid. At the same time, major cloud service providers such as Microsoft, Google and Amazon are working hard to build large-scale datacenters, which consumes huge amount of energy and significantly increases the electricity load on the construction site, which might have impact on the grid. Nowadays, smart grid technology is transforming into an interactive network with the goal of reducing the overall cost of electricity delivered to end users. With the sustainable development of modern power grids, emerging technology trends have had a profound impact on the operation of power distribution systems. Take distributed renewable energy generation facilities as an example, which can be effectively integrated into the smart grid to balance power and demand at different locations to perform appropriate frequency adjustments.

In recent years, relevant research has been conducted on the impact of datacenters and renewable energy in the smart grid. Su et al. [2] took the maximum access capacity of the distributed power source in the power grid as the objective function considering the access location and access capacity and other factors, using genetic algorithm and Newton-Raphson algorithm to solve the maximum access capacity model. Sang et al. [3] studied the influence of changing photovoltaic power supply capacity on the grid voltage distribution and network loss. When the photovoltaic power source permeability increases to a certain extent, it will generate reverse tidal current, and the system node voltage and power loss can also vary greatly. Zhou et al. [4] analyzed the correlation between distributed power output and load and established the constraint-planning model based on the power flow of the distribution network. Liu et al. [5] established a mathematical model of voltage deviation and voltage fluctuation caused by load and distributed photovoltaic power sources under various distributions, and derived that several loads and distributed photovoltaic power supply capacity can meet the voltage under the same distribution conditions of the feeder quality.
requirements for distributed photovoltaic power supplies allow access to a range of capacities. Wang [6] the effectiveness of the algorithm in distributed power access is verified by the voltage variation curve and system power consumption and analyze the voltage reactive power continuous control effect of the distribution network connected to the distributed power supply. Tang [7] proposed combining continuous method and collapse method the static voltage stability analysis of power system, which effectively avoids the limit of branch power in the process of voltage critical point. Wu Jiaqiao [8] established a single-objective mathematical model of investment construction cost and operating cost in the distribution network planning process, solving the optimal planning of the distribution network through improved genetic algorithm. Yan [9] used the combination of convex optimization and simulated annealing in the interactive system of the solar plants and smart grid to make the placement more valuable and maximize the profit. Most of the prior research considered only the impact of datacenters or renewable penetrations on the grid, without considering the interaction between smart grids and datacenters.

In this paper, the impact of datacenters and solar plants integrated into grid is considered and analyzed. In addition, the location and capacity planning of multiple datacenters in the grid with renewable sources is also studied. Section II introduces the system modeling method and optimization constraints. Section III demonstrates the problem solution. In Section IV we attempt to find the optimal location of multiple datacenters in the smart grid integrated with solar power generations, under the constraints of voltage and power limitation. Section V concludes the whole paper and discusses about the future work.

System Modeling and Problem Description

System Modeling

Consider a power grid and let N denote the set of all power buses, indexed by $i$. The power buses are interconnected through branches forming the grid topology. Each bus $i \in N$ could connect to traditional and/or renewable power generators and various load devices. In our system model, some loads of the power grid may include large datacenters which support cloud services. In this grid, assume that there are $k$ solar plants and $m$ datacenters, each of which is connected to one of the bus nodes.

In this paper, the active power is calculated by the method proposed in [9], and the active power injected into the bus node can be calculated by

$$P_i = P_{i}^{Gen} - P_{i}^{Load}. \quad (1)$$

wherein $P_{i}^{Gen}$ and $P_{i}^{Load}$ denote the total power generation and power consumption at bus $i$ respectively. With respect to the grid, the total power generation and consumption are balanced.

Let $P_{i}^{Rs}$ and $P_{i}^{Urs}$ denote the renewable (solar energy) and traditional power generations respectively. The total generated power is calculated as follows:

$$P_{i}^{Gen} = P_{i}^{Rs} + P_{i}^{Urs}. \quad (2)$$

Similarly, the total load on the bus node $i$ can be divided into the total power consumption of the datacenters and other kinds of loads.

$$P_{i}^{Load} = P_{i}^{dc} + P_{i}^{other}. \quad (3)$$

Problem Formulation

(1) Objective

System loss is an important economic indicator for measuring the operation of the smart grid. Reasonable location planning of solar plants and datacenters might effectively reduce the total loss of the system. Therefore, the total loss is used as the optimization objective, which can be
calculated as follows.

\[ P_{\text{loss}} = \sum_{i=1}^{n} R_i (P_i^2 + Q_i^2) / U_i^2. \]  

(4)

where in, \( i = 1, 2, 3 \ldots, n \), \( n \) represents the total number of buses in the grid, \( P_{\text{loss}} \) is the resistance on the bus node, and \( P_i \) and \( Q_i \) denote the active and reactive power of the bus node respectively.

(2) Constraints

Power flow calculation is a very important analytical method for power systems, which can help to predict the impact of various network structure changes on system security. After the datacenters and the solar plants integrated into the power grid, the load flow balance should be met, as follows:

\[ P_i^{rs} = P_i^{DC} + U_i \sum_{j=1}^{n} U_j (G_{ij} \cos \delta_j + B_{ij} \sin \delta_j). \]  

(5)

\[ Q_i^{rs} = Q_i^{DC} + U_i \sum_{j=1}^{n} U_j (G_{ij} \cos \theta_j - B_{ij} \sin \theta_j). \]  

(6)

where in \( i = 1, 2, 3 \ldots, n \), and \( j \in i \) means that the bus node \( i \) connected to the bus node \( j \). \( \Delta P_i \) and \( \Delta Q_i \) are the errors of active power and reactive power, \( P_i \) and \( Q_i \) denote the active and reactive power of the bus node respectively. \( U_i \) and \( U_j \) represent the voltage of the bus node \( i \) and the bus node \( j \), respectively. \( G_{ij} \), \( B_{ij} \) and \( \delta_{ij} \) respectively represent the conductance, susceptance, and phase angle difference between the bus node \( i \) and the bus node \( j \).

In addition, the following inequality constraints should be considered.

1) Power generation constraint

Due to natural environment condition, operating conditions and other factors, the output capacity constraints of solar plants are expressed as:

\[ 0 \leq S_{i}^{rs} \leq S_{i}^{rs, \text{max}}. \]  

(7)

here \( S_i^{rs} \) is the input capacity of the solar plant onto the bus node, and \( S_i^{rs, \text{max}} \) is the maximum allowed input capacity of the solar plant onto the bus node.

2) Power balancing constraint

In order to balance the impact of grid-connected solar plants and make full use of renewable energy, when planning the capacity of the datacenter, the total consumption of multiple datacenters and the total power generation of the solar plants should be balanced, as follows:

\[ \sum_{i=1}^{k} S_i^{rs} = \sum_{i=1}^{m} S_i^{DC}. \]  

(8)

where \( S_i^{DC} \) is the datacenter capacity deployed at bus \( i \).

3) Voltage constraints

When the solar power station and the datacenter are connected to the smart grid, the power grid changes the original power flow state, which will cause voltage changes. Unreasonable voltage deviation will cause problems in the operation of the power grid. The voltage deviation is specified in the standard 'Power Quality - Supply Voltage Deviation' [10]. Therefore, the voltage at each bus \( i \) should be controlled within a certain range, as follows:

\[ U_M (1-\epsilon_1) \leq U_i \leq U_M (1+\epsilon_2). \]  

(9)

4) Branch power constraints

While the voltage is stable, the limitation of the branch power is often neglected. It is possible
that although the voltage in the smart grid has not reached the critical point, the power flowed through some branches has already exceeded. This lacks practical significance for the loss determination indicators of the power grid. For the branch power constraint, it is treated as a constraint condition of the optimization problem. The branch power constraint can be expressed as follows:

\[ |P_{ij}| \leq P_{ij,\text{max}}. \]  

(10)

where \( |P_{ij}| \) and \( P_{ij,\text{max}} \) are the branch power between the bus node \( i \) and the bus node \( j \), respectively, and the maximum power allowed via the branch.

In summary, the optimization problem required in this paper is to find a reasonable location and capacity configuration scheme to minimize the objective as Eq.(4) subject to the constraints as Eq.(5)-(10).

**Location and Capacity Planning Method**

As can be seen the description in Section II, the constraint optimization problem we established is an NP-hard problem, and the value of the objective function cannot be directly obtained by an explicit calculation formula. Hence, we designed an approach based on the genetic algorithm to find the close-to-optimal solution. Genetic Algorithm (GA) is a stochastic parallel search algorithm based on the principles of natural selection and genetics. Starting from a randomly initialized population, after multiple iterations, individuals with higher fitness are continuously used to generate next generation. The main concepts can be leveraged for grid planning, power station location and constant volume and other complex power system optimization problems [11].

**Chromosome Coding and Population Initialization**

In binary encoding form, if one datacenter is put onto one bus, the corresponding element of the chromosome is set to 1, otherwise 0. Figure 1 gives an example, which shows the situation that two datacenters are put onto bus 2 and 6.

![Figure 1. An example of chromosome coding.](image)

**Fitness Function**

The fitness function is the significant basis for achieving the survival of the fittest. It can be evaluated by the degree of adaptation of each individual in the population to the environment to obtain the best value. The goal in this paper is to minimize the total loss of the power grid, so we adopt the loss function Eq. (4) as the fitness function.

**Select Operation**

The select operation is to make the probability of inheriting a good chromosome individual to the next generation higher. In this paper, we take the tournament method to select the eminent individual to inherit to the next generation. Then repeat this select operation until the new population size reaches the original population size.

**Cross Operation**

In the genetic algorithm, cross operation can simulate the process of gene recombination in nature and can pass the better genes to the next generation. Then, the new individual might have a better genetic organization. An example of the specific operation process is shown in Figure 2. After the cross operation of \( \text{father1} \) and \( \text{father2} \) that intersecting at index 5, new chromosomes will be generated as \( \text{child1} \) and \( \text{child2} \).
**Mutation Operation**

The most important function of the mutation operation is to select the position of bus location in the datacenter. We need to randomly select a chromosome who need the mutation operation according to a certain probability, and finally mutate according to a certain law. An example of the mutation operation process is shown in Figure 3.

![Mutation Operation](image)

The original chromosome indicates that two datacenters are placed on bus 5 and bus 7. After the mutation operation, the new chromosome indicates that two datacenters are located on bus 6 and bus 7.

**Experiment and Analysis of Results**

In the following experiments, we use the IEEE 30-node standard power grid system [12] to test and verify the proposed method in Section III. As shown in Figure 4, bus 1 is a balanced node, Buses 2, 5, 8, 11, 13 are PV nodes(power generation), while are PQ nodes (load node). We use the DEAP simulation tool [13], which is a new evolutionary genetic algorithm framework for rapid prototyping and testing. It is designed to make the algorithm clear and the data structure transparent. From the simulation results, we can see the voltage change and get the power grid loss of each bus node.

In the process of our experiments, we simulated two datacenters and one solar plant in IEEE 30 bus framework. Buses 2-30 are chosen as candidate locations. The goal optimization is to equalize the amount of electricity generated by the solar plant to the power consumption delivered to the two datacenters. The parameters in the genetic algorithm are set as follows: the population size is 50, and the probability of crossover and mutation is 0.5 and 0.2, respectively.

![Power Grid System Diagram](image)
In our experiment, we first fixed the location of a solar plant and use the proposed method in this paper to find the best location and capacity allocation scheme for both datacenters. Here assume a 40MW solar plant has been established and integrated at bus 5 and two corresponding datacenters are planned to be constructed to consume the electricity generated by solar plant. Through the algorithm proposed in this paper, we find that the power loss is minimized when the two datacenters are located at nodes 10 and 12 and their capacities are 6 MW and 34 MW, respectively. The following were set up for comparison:

Case1: Two datacenters are placed at bus 10 and bus 12;
Case2: Two datacenters are placed at bus 6 and bus 7, near the solar plant;
Case3: Two datacenters are placed at the bus 25 and bus, away from the solar plant;
Case4: Both datacenters are placed on the bus 5;
Case5: Two datacenters are placed on bus 5 and bus 30, one co-located with the solar plant and one away from the solar plant.

| Case | Datacenter1 location | Datacenter1 capacity (MW) | Datacenter2 location | Datacenter1 capacity (MW) |
|------|----------------------|---------------------------|----------------------|---------------------------|
| Case1 | 10                   | 6                         | 12                   | 34                        |
| Case2 | 6                    | 6                         | 7                    | 34                        |
| Case3 | 25                   | 6                         | 26                   | 34                        |
| Case4 | 5                    | 6                         | 5                    | 34                        |
| Case5 | 5                    | 6                         | 30                   | 34                        |

Under the five scenarios, respectively, the corresponding power loss is shown in Figure 5. Figure 6 shows the power grid loss of the datacenter1 deployment capacity from 0-40 MW in the five cases. As can be seen from Figure 5 and Figure 6, the power loss is greatly different depending on the location of the datacenter. The overall power loss of case1 is the smallest, and the power loss is the largest under case3.

![Figure 5. Comparison of power loss of datacenter placement and deployment in different scenarios.](image)

![Figure 6. Power loss distribution different cases.](image)

Secondly, the genetic algorithm in this paper also constrains the problem of voltage violation and
branch overload in the datacenter access location and capacity change. The voltage limit [10] standard is shown in Table 3. The specific voltage and branch power changes are shown in Figure 7 and Table 4.

Table 2. Voltage amplitude limit.

| Node type | Lower limit of amplitude (p.u) | Maximum amplitude (p.u) |
|-----------|-------------------------------|-------------------------|
| Balance   | 0.95                          | 1.05                    |
| PV        | 0.95                          | 1.1                     |
| PQ        | 0.95                          | 1.05                    |

Figure 7. Voltage comparison datacenter position and capacity changes different case.

As can be seen from Table 3 and Figure 7, the voltage is relatively stable in case1, case2, case4, and case5. In case3, the voltage amplitude of the bus 26 is 0.856 p.u., which exceeds the range specified by the voltage deviation. Since the voltage limit is violated, the stability of the grid will be impacted.

Similarly, violating the branch power limitation will also have impact on the stability of the grid. Based on the IEEE 30-branch power data, some of the allowed ranges of branches are shown in Table 4.

Table 3. Range of partial branch power.

| branch flow | case1 | case2 | case3 | case4 | case5 |
|-------------|-------|-------|-------|-------|-------|
| 22→24       | 0.00  | -20   | 0.00  | 0.00  | 15.88 |
| 23→24       | -1.6  | 1.93  | 10.74 | 1.00  | 7.04  |
| 24→25       | -0.8  | -1.11 | 12.04 | -1.21 | 13.85 |
| 25→27       | -7.59 | -4.67 | -26.61| -4.76 | 9.92  |
| 28→27       | 20.93 | 17.97 | 40.96 | 18.67 | 43.19 |

Table 4. Branch power comparison of different cases.

It can be seen from Table 3 and Table 4 that in the scenarios of case 3 and case 5, the active power of the branches 22→24, 24→25, 25→27, 28→27 exceeds the range specified by the branch power, and this possibly lead to a safety hazard. The experimental results show that the location choices of solar plants and datacenters have obvious impact on grid power loss. Through the optimization algorithm proposed in this paper, we can get the optimal solution as follows: the datacenter with the capacity of 6MW connected to the bus node 10, and the datacenter with the capacity of 34MW connected to the bus node 12. Experiment results show that the proposed model and algorithm can find a better allocation scheme for datacenter placement and capacity planning.
Conclusions and Future Work

The integration of datacenters and solar plants into the power grid will change the power flow state of the whole grid, thereby affecting the performance and availability of the grid. Different locations to integrate them may cause excessive voltage deviation, or the branch power limit violation, which may affect the stability of the power grid. In this paper, our optimization objective is to minimize the loss resulted by the integration of solar plants and datacenters into the grid under the voltage and branch power constraints. Based on the ideas of genetic algorithm, the optimized algorithm is designed and implemented, which provides an effective method for solving the established problem. Depending on the specific grid configuration, multiple datacenter location placement and capacity configuration optimal solutions can be analyzed and solved. At present, the current work mainly considers the power grid loss. In the future, we should consider incorporating more factors to focus on the overall cost in the planning of constructing distributed datacenters.

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