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# Research of Optimal Investment Size for Distribution Network Based on Improved Sequential Quadratic Programming Method

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## *Abstract*

*Installing distributed generators can effectively reduce network power consumption and improve power quality in the distribution network, but it will also bring some technical problems. Therefore, we need to study how to efficiently and quickly determine the optimal investment capacity of distributed generators in the distribution network. In this paper, we set the minimization of the power loss as the objective and establish the most investment scale decision-making model of distributed generation access to power distribution system. In terms of optimization algorithm, optimization time of traditional sequential quadratic programming will dramatically increase with the increasing number of variables and restraints. In order to pursue higher efficiency optimization, we apply the improved sequential quadratic programming that is fast sequential quadratic programming method for solving nonlinear problems of distributed generators optimal investment size. We apply the constructed model to systems with different nodes, and the results show that the proposed new optimization method is not only scientific and effective, and can significantly improve decision-making efficiency.*

***Keywords**: distributed generation; distribution network; fast sequential quadratic programming method; optimal investment size*

## 1. Introduction

In the traditional distribution system, energy flows only in one direction (from the distribution transformer of substation to the transformer of load point through distribution circuit)[1-3].Therefore, the planning project of traditional distribution system aims to increase the size of the transformer substation or build new substations by installing new transformers[4, 5].If additional equipment results in network overload, investment is needed to consolidate or build new lines to meet the load demand [6, 7].

The installation of distributed generation (DG) unit in medium and low voltage part of power grid has advantages in terms of economy and technology, so DG unit is an effective choice for investors to consolidate power distribution system. Besides, the installation of DG unit can effectively reduce the network power loss, improve power quality, and exert important roles in peak load regulation and voltage control [8-12].The advantages of DG unit can be summarized as follows [13, 14]:

- Modular construction, short delivery time and low investment risk
- Small module capacity and more close detection of load changes
- Small occupation area, and can be installed in the heartland without needing the approval of the government in land or looking for available area and land of units
- Vast space for technology

The installation of DG unit in the power grid, however, can bring some technical problems, such as voltage oscillation, fault current increase, and the change of energy flow direction [15, 16].Therefore, we need to research how to effectively and quickly determine the optimal investment capacity of DG unit in the power grid.

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Scholars at home and abroad have carried out extensive researches on the installation of DG unit in the distribution network system. For the foreign researches, the literature evaluates the effect after the DG unit in electric network with reliability index, and determines the optimal DG unit installation position and size. Literature takes the owners' benefit cost ratio under the constraint of certain grid as the target function from the aspect of micro grid owners. Literature reviews the different aspects of the problems that need considering in the power distribution system planning.

For the domestic researches, the literature analyzes the influence of DG grid connection on the steady state voltage distribution of the system and network loss through the actual examples. It concludes that the effect degree and effect law are closely related to the capacity, inter connected position and operation modes of DG. On the basis, it makes preliminary discussion on the optimal configuration of DG in distribution network, and studies a reasonable configuration method of DG. The results show that the obtained optimal inter connected position of DG can effectively improve the active power loss under the condition of satisfaction of the system voltage distribution. Literature introduces the commonly-used indexes in the analysis of the static voltage stability of power distribution network, calculates and analyzes the effect of various types of distributed power generation equipment and different installation positions in distribution network on the static voltage stability of system through examples. Besides, it discusses the static voltage stability indexes, and analyzes the relationship between the indexes and system load growth factor. Its conclusions have certain guiding roles for DG planning in distribution network. In addition, Literature puts forward quantitative analysis indexes, and on the basis, studies the influence of wind power generation with different operation modes on the comprehensive load characteristic of distribution network. It points out that the main influence factors of wind power generation on the load characteristic are connection capacity and position, and analyzes the influence of the two kinds of influence factors on the load characteristic according to the simulation experiment data.

On the basis of the comprehensive researches at home and abroad and considering the equality constraint of power balance equation and the inequality constraint of circuit capacity, node voltage, node phase angle and power factor, we establish the optimal investment size decision model for the connection of DG to the distribution network system, minimize the power loss of distribution system after DG units are connected and improve the system performance of DG after the connection of distributed power generation. Unlike the planning method of traditional system containing DG distribution network, the model adopts the improved sequential quadratic programming method (SQP)--fast sequential quadratic programming (FSQP) as the optimization method. We apply the model to different node systems, and consider the different scenarios of installing one and two DG units as well as the application of SQP and FSQP, and obtain the optimal investment size results of DG units under the different types of scenarios. The calculating-examples results show that the model and optimization method can effectively and quickly determine the optimal installed capacity of DG units, and provide a scientific and efficient investment decision method for DG distribution network access system.

## 2. Model Building

### 2.1. Objective Function

The optimal investment size decision of DG units is a problem of constrained nonlinear optimization. The objective function is to minimize the actual power loss of distribution network, as shown in formula (1).

$$\min W_{total} = \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n}\mathrm{P}\left\{Y_{ij}\right\}\left|\left[\left|U_i\right|^2+\left|U_j\right|^2-2\left|U_i\right|\left|U_j\right|\cos\varphi_{ij}\right]\right| \tag{1}$$

$$In\ which, \varphi_{ij} = \varphi_i - \varphi_j$$

In the formula (1), $W_{total}$ denotes the total power loss of distribution network; $\mathrm{P}\left\{Y_{ij}\right\}$ refers to real part of complex power; $Y_{ij}$ indicates the admittance matrix between node $i$ and node $j$; $n$ denotes the number of nodes in distribution network; $U_i$ and $U_j$ refer to the voltage amplitude of node $i$ and node $j$ respectively; $\delta_{ij}$ indicates the phase difference between node $i$ and node $j$; $\varphi_i$ and $\varphi_j$ denote the phase position of node $i$ and node $j$ respectively.

## 2.2. Constraint Condition

(1)Power balance constraint

The whole process of the optimization of optimal investment size of DG units should satisfy the equality constraints of power balance equation including constraints of active power balance and reactive power balance, as shown in formula (2) and (3).

$$P_i - \left|U_i\right|\sum_{j=1}^{n}\left|U_j\right|\left(G_{ij}\cos\varphi_{ij} + B_{ij}\cos\varphi_{ij}\right) = 0 \tag{2}$$

$$Q_i = \left|U_i\right|\sum_{j=1}^{n}\left|U_j\right|G_{ij}\sin\varphi_{ij} + B_{ij}\sin\varphi_{ij} = 0 \tag{3}$$

In the formula (2) and (3), $P_i$ denotes the active power of node $i$; $G_{ij}$ refers to real part of admittance matrix; $B_{ij}$ indicates the imaginary part of admittance matrix; $Q_i$ signifies the reactive power of node $i$;

(2) Circuit capacity constraint

$$\sum_{i=1}^{m_{DG}}\left(P_{DG_i} + jQ_{DG_i}\right) \le P_{total} + jQ_{total} \tag{4}$$

$$\max\left\{L_{ij}\right\} \le L_{ij}^{\max} \tag{5}$$

In the formula (4) and (5), $m_{DG}$ denotes the number of the installed DG units; $P_{DG_i}$ indicates the real active power of DG units; $Q_{DG_i}$ signifies the reactive power of DG units; $P_{total}$ refers to the allowable maximum active power of grid circuits; $Q_{total}$ denotes allowable maximum reactive power of grid circuits; $L_{ij}$ indicates apparent power flow of circuit branch $ij$; $L_{ij}^{\max}$ signifies the allowable maximum apparent power of circuit branch $ij$.

(3) Node voltage excursion constraint

$$\left|U_i^{\min}\right| \le \left|U_i\right| \le \left|U_i^{\max}\right| \tag{6}$$

In the formula (6), $V_i^{\min}$ signifies the allowable minimum voltage value of node $i$; $V_i^{\max}$ indicates allowable maximum voltage value of node $i$.

(4) Node phase angle constraint

$$\varphi_i^{\min} \le \varphi_i \le \varphi_i^{\max} \tag{7}$$

In the formula (7), $\varphi_i$ indicates phase angle value of node $i$; $\varphi_i^{\min}$ and $L_{ij}^{\max}$ signify the allowable minimum and maximum of phase angle value of node $i$ respectively.

(5) Power factor constraint

When the DG units operate within the allowable power factor scope, the relevant constraints are shown in formula (8).

$$\eta_{DG}^{\min} \le \eta_{DG} \le \eta_{DG}^{\max} \tag{8}$$

In the formula (8), $\eta_{DG}^{\min}$ and $\eta_{DG}^{\max}$ indicate the minimum and maximum of power factor of DG units respectively; $\eta_{DG}$ signifies the operation power factor of DG units.

(6)DG penetration rate constraint

$$0 \le \gamma_{DG} \le \gamma_{\mathrm{DG}}^{\max} \tag{13}$$

In the formula (13), $\gamma^{DG}$ signifies DG penetration rate; $\gamma_{\max}^{\mathrm{DG}}$ indicates maximum value of DG penetration rate.

## 3. Optimization Program

SQP is a traditional effective way of solving the approximate optimal solution of nonlinear programming, and possesses the advantages of higher convergence speed. However, the optimization time of the method increases sharply with the increase of the number of variables and constraints, so it does not apply to solving more complex nonlinear problems with more constraint conditions.

In order to pursue higher optimization efficiency, we use improved SQP - RSQP to solve the nonlinear problem of optimal investment size of DG units. By solving continuous iterative approximation Lagrange function of quadratic programming sub problems, and designing linear search direction, we obtain a better solution of quadratic programming problem.

The distributed network usually has radial topology, and larger low reactance and resistance ratio (X/R) than other transmission grids. Therefore, we replace the Newton’s method of traditional SQP with the forward-backward substitution method based on two basic circuit theories (staircase method) and then we solve the power balance equation of distributed distribution network. With the use of the method, we speed up the whole optimization process, and also can make the balance equation nonlinear so as to simplify the whole sequence quadratic programming problem. Figure 1 shows the optimization process of FSQP.

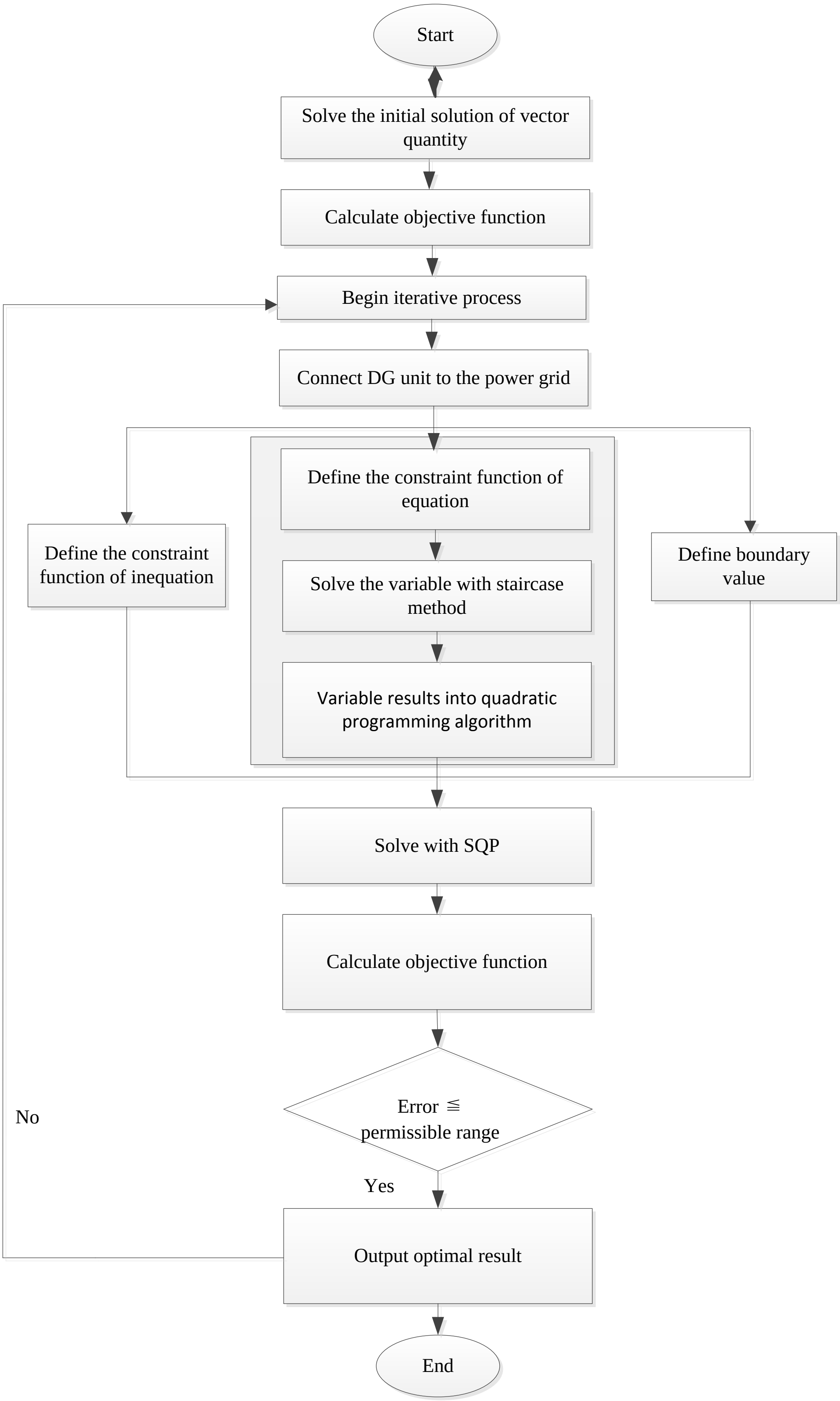

Figure 1.Fast Sequential Quadratic Programming Optimization Process

# 4. Calculating-examples Analysis

## 4.1. Calculating-examples Environment

We apply the model to two kinds of distribution network systems with radial structure, use FSQP to obtain the optimal investment size of DG units, and verify the effectiveness of the optimization method. The first detection system is a distributed network system with 69 nodes, and it has one main major circuit and 8 branch circuits. The single line diagram of system to polity is given in Figure 2.In the system, the total active and reactive power demand are 3828.82kW and 2713.46kVAR respectively. The second detection system is a distributed network system with 33 nodes and it has one major circuit and3 branch circuits. In the system, the total active and reactive power demand are 5237.53kW and 3257.46kVARrespectively. Figure 3 shows its topology structure. We obtain the related parameters of the two kinds of detection systems from the standard test system data of IEEE.

We consider setting up four kinds of scenario under each of the test system to better compare and analyze the results. The descriptions of scenarios are as follows:

1)Scenario 1: install only one DG unit in distribution network to optimize the system network loss and then solve through SQP.

2)Scenario 2: install two DG units in distribution network and solve through SQP.

3)Scenario 3:Consider installing one DG unit and two DG units in the distribution network to compare with Scenario 1 and Scenario 2, solve with FSQP to verify the efficiency and execution effectiveness of FSQP.

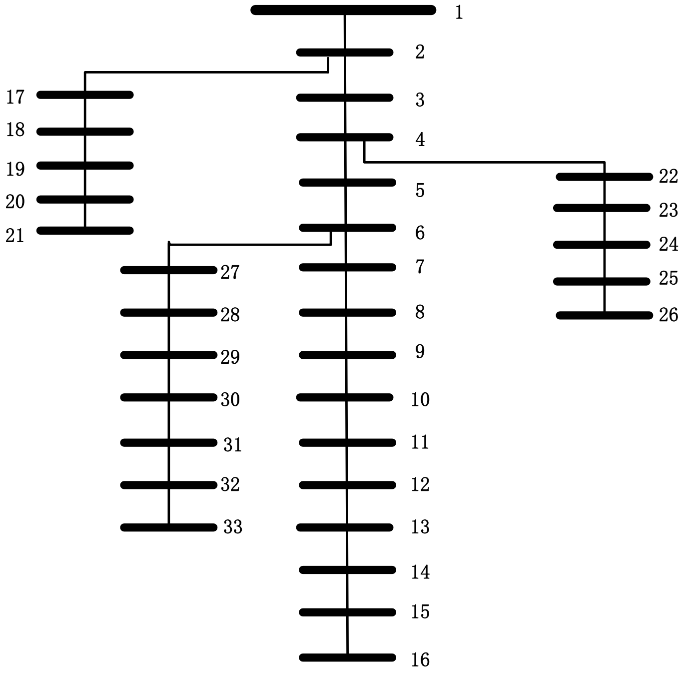

Figure 2.Topology Diagram of System with 33 Nodes

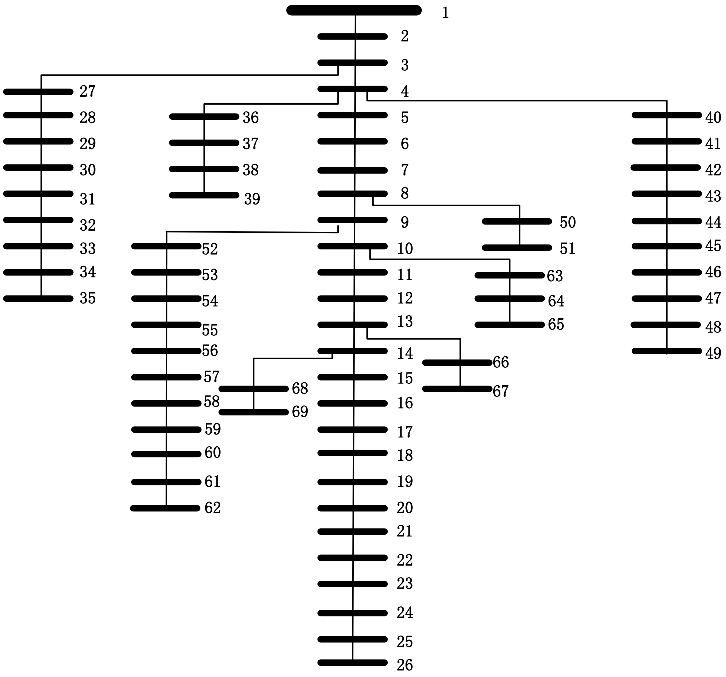

**Figure 3. Topology Diagram of System with 69 Nodes**

### 4.2. Results Analysis

We apply MATKAB toolbox to solve the optimal DG investment size and power loss under different scenarios and record the different solving time of the optimization program. The solving results of two node systems in Scenario 1are shown in Table 1. Besides, the solving results of two node systems in Scenario 2 are shown in Table 2.

**Table 1. Solving Results of Two Node Systems in Scenario 1 (Installing only One DG Unit)**

| Installing only one DG unit | Node system | Optimal installation capacity of DG (kW) | Power loss (kW) | Optimizing time (sec.) |
|---|---|---|---|---|
| | 33 nodes | 1791.96 | 73.38 | 1.756 |
| | 69 nodes | 1917.23 | 24.15 | 3.889 |

**Table 2. Solving Results of Two Node Systems in Scenario 2 (Installing Two DG Units)**

| Installing two DG units | Node system | Optimal installation capacity of DG (kW) | | Power loss (kW) | Optimizing time (sec.) |
|---|---|---|---|---|---|
| | | DG1 | DG2 | | |
| | 33 nodes | 1310.92 | 813.14 | 31.40 | 2.233 |
| | 69 nodes | 1490.55 | 324.37 | 13.68 | 4.127 |

According to the results of Table 1 and Table 2, for the distribution network system, the installation of DG unit can effectively reduce the system power loss. Compared to the installation of one DG unit in the distribution network, the installation of 2 ones has more obvious effect in reducing power loss. In the system with 33 nodes, for example, the total power loss of the system consumes is 73.38kW when one DG unit is installed in the distribution network. By contrast, the total power loss drops to 31.40kW, reducing by41.98kW when one DG unit is installed in the distribution network. Such result shows that the increase of DG units can exert more obvious beneficial impact on the distribution network optimization.

In terms of the investment size of DG units, the Table 1 and Table 2 show that the installation of two DG units can enlarge or reduce the optimal investment size of DG. For example, in the system with 33 nodes, the optimal investment size of installation of 2 DG units increases by 332kW relatively to the installation of only one DG unit. However, in the system with 89 nodes, the optimal investment size of installation of 2 DG units decreases by 102.31kW relatively to the installation of only one DG unit.

**Table 3.Comparative Results of Optimization Time of Two Different Optimization Methods**

| Node system | scenario | Optimizing time (sec.) | | The shortened time of FSQP relatively to SQP |
|---|---|---|---|---|
| | | FSQP | SQP | |
| 33 node system | Installing one DG unit | 1.754 | 4.959 | 64.63% |
| | Installing two DG units | 2.231 | 7.286 | 69.38% |
| 69 node system | Installing one DG unit | 3.894 | 10.820 | 64.01% |
| | Installing two DG units | 4.233 | 10.097 | 58.08% |

The comparative optimization results of execution time and efficiency of different optimization methods (SQP and FSQP) are listed in Table 3.The two optimization methods obtain the same optimal investment size of DG. However, in terms of execution efficiency, the results of Table 3 clearly show FSQP can significantly shorten the optimization execution time of model results relatively to the traditional SQP, improving the solving efficiency by about 2/3.

## 5. Conclusions

1) With the minimum power loss as the objectives, we establish the optimal investment size decision model of distributed power distribution network system. The model takes into account of the equality constraint of power balance equation as well as the inequality constraints of circuit capacity, node voltage and phase angle and power factors. The comparison results obtained by the application model show that the installation of DG units in distribution network system can effectively reduce the system power loss and improve the efficiency of the distribution network and power supply quality.

2) Unlike the planning of traditional distribution network distribution network system, we replace Newton’s method in traditional SQP with staircase method to process power balance equation, improve the traditional SQP, and obtain optimization method of FSQP.

3) We solve the optimal DG installation size in the distribution network system with different nodes through traditional SQP and FSQP respectively. The results show that the two optimization methods obtain the same results, but FSQP shortens two-thirds of solving time relatively to the traditional SQP, suggesting that the proposed new optimization method not only is of scientific nature and effectiveness, but also can significantly improve the efficiency of decision-making.

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