Minimum Load-Shedding Calculation Approach Considering Loads Difference

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***Abstract*--Load shedding is an efficient solution to improve power system reliability when a contingency occurs. Considering loads difference has great significance in the process of load shedding. This paper proposes a new minimum load shedding calculation approach based on multi objective optimization theory. The load shedding model proposed in this paper considers the loads difference and introduces the importance factor to describe the difference. This approach will first cut those less important loads and try to get the minimum total load shedding amount in the process of load shedding. The case results shows the rightness and validity of the approach proposed in this paper.**

***Index Terms*-load shedding, generation rescheduling, system reliability, multi objective optimization, loads difference.**

I. Introduction

To meet the increasing load demand in the future, new transmission network expansion planning scheme must be made. To get a best planning scheme, we must evaluate and modify the candidate planning schemes repeatedly, including the economy and security [4]. Minimum load shedding amount is an important index to evaluate the security of transmission system, so minimum load shedding calculation is an essential step in the process of making planning schemes [1].

The minimum load shedding calculation problem can be divided into two issues, one is to select load shedding points, another is to determine load shedding amount. In [2] a load shedding model based Seng-Cheol Kang's robust linear optimization theory is proposed which considers wind farm influence. In [3] considering the load uncertainty in demand an interval mode is proposed. In [7] it discussed the differences between the linear model and nonlinear model. A load shedding approach based on steady-state security region is proposed in [8]. Most papers proposed models just based on the security constraints of the power system, ignoring the loads difference. However, in reality to protect important loads we should first cut those less important loads in the process of load shedding.

In this paper, the multi objective optimization theory is applied to solve the minimum load shedding calculation problem and proposed a modified load shedding model considering the loads difference. In the proposed model, loads importance factors are used to describe the loads difference. By modifying the loads importance factors and weight coefficients the proposed approach can offer different load shedding schemes.

II. Multi Objective Optimization Theory

A. Multi Objective Optimization Model

Mathematically, linear optimization problem is just to seek the optimal value of one target function under a set of linear constraints. Usually, practical problems need to consider more than one target function, that being multi objective optimization problem. It can written as the following equations.

$$\min F(\mathrm{x}) = \{ f_1(\mathrm{x}) ...... f_n(\mathrm{x}) \} \tag{1}$$

$$x \in R^n \tag{2}$$

$$\text{s.t.} \quad A \bullet x \le b \tag{3}$$

$$B \bullet x = C \tag{4}$$

$$X_{\min} \le x \le X_{\max} \tag{5}$$

x is the vector of control variables. Equation (1) is a set of objective functions. Equation (3) is a set of inequality constraints, where **A** is a matrix and **b** is a vector. Equation (4) is a set of equality constraints. Equation (5) are the limits of control variables.

For a multi objective optimization problem, the objective functions usually are confliction, a sub-targets improvement is likely to cause one or the other more reduce the performance. So a solution x for all objective functions to be simultaneously minimized is impossible, that is to say a multi objective optimization problem have several optimal solutions.

A solution x_2 is said to be dominated by the other solution x_1 if x_1 is better than x_2 for at least one objective f_i and is not worse for any other f_i , as equation (6)

$$f_i(x_1) < f_i(x_2), f_j(x_1) \le f_j(x_2) \Rightarrow x_1 \succ x_2 \tag{6}$$

Where j=1, 2, … , k and $j \neq i$. The symbol $\succ$ denotes domination operator. The above concept is used to find a set of non-dominated solutions in search space. The solution space are called pareto optimal solutions [5].

B. Solution Method

Multi objective optimization is an effective tool for handing different incommensurable objectives with conflicting relations or not having any mathematical relation with each other [15]. The main solution methods for multi objective optimization problem are weight-sum method, ε −constraints method, goal-achieve method, etc.

Weight-sum method get a new objective function by equation (7) and try to get the optimal solution x^* for the new objective to be minimized.

$$\min f(\mathrm{x}) = \sum_{i=1}^{m} w_i \bullet F_i(\mathrm{x})^2, x \in \Omega \tag{7}$$

The weight-sum method transforms the multi objective optimization problem into a single objective optimization problem. Though simplified calculation, it also brings the problem that may paying too much attention on one objective while ignoring another one. $\varepsilon-$ Constraints method , shown by equation (8), try to get the optimal solution x^* for the main objective function to be minimized, while give a set constraints for other objective functions.

$$\min F_p(\mathrm{x}), \mathrm{x} \in \Omega$$

$$\text{s.t.} \quad F_i(\mathrm{x}) \leq \varepsilon_i \tag{8}$$

Goal-achieve method first give a set of ideal objective function values F^* as the goal values and try to get an available optimal solution x_i by allowing positive and negative deviations between the available values F_i and the ideal values F^*. As equation (9)-(10)

$$F(\mathrm{x}) = \{F_1(\mathrm{x}), F_2(\mathrm{x}) ... F_m(\mathrm{x})\} \tag{9}$$

$$F^* = \{F_1^*, F_2^* ... F_m^*\} \tag{10}$$

Where equation (9) is a set of objective functions. Equation (10) are the ideal function values. The positive and negative deviations are controlled by the weight vector $\omega = \{\omega_1, \omega_2 ... \omega_m\}$. The goal-achieve method can be written equation (11).

$$\min \gamma$$

$$\text{s.t.} \quad F_i(\mathrm{x}_i) - \omega_i \gamma \leq F_i^*, i = 1, 2...., m \tag{11}$$

The ideal values F^* gives the goal point P, and the weight vector $\omega = \{\omega_1, \omega_2 ... \omega_m\}$ determines the search direction from P to the feasible region. When the weight value is positive, it tries to make the optimal value is less than the goal value. And when the weight value is negative, it tried to make the optimal value is greater than the goal value. Usually we set weight=goal or weight=abs(goal).By adjusting the coefficient we can get different optimal solution values. This paper will adopt this solution method to calculate the minimum load shedding amount.

III. Minimum Load Shedding Model

Assuming that the power system have n+1 buses, and m branches, where bus number is 0, 1, … ,n, branch number is 0, 1, … , m. Bus 0 is the balance bus, whose maximum output is g_0. The load demand of buses are $L = [L_1, L_2 ... L_n]$. The outputs of generators are $g = [g_1, g_2 ... g_n]$. The load shedding amount of buses are $d = [d_1, d_2 ... d_n]$. The loads importance factors of buses are $\omega = [\omega_1, \omega_2 ... \omega_n]$. The maximum transmission capacity of branches are $p_{\max} = [p_{\mathrm{m}1}, p_{\mathrm{m}2} ... p_{\mathrm{mn}}]$. The maximum and minimum outputs of generator i are $g_{i,\max}, g_{i,\min}$.

Based on the direct current model, the active power of branches can be calculated by equations (12) and (13).

$$P_i = S \bullet (\mathrm{G}_i - \mathrm{L}_i) \tag{12}$$

$$S = \begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & \cdot & & \cdot \\ \cdot & & \cdot & \cdot \\ s_{m1} & s_{m2} & \cdots & s_{mn} \end{bmatrix} \tag{13}$$

Where P_i is the vector of active power of branches, P_i is the vector of outputs of generators, L_i is the vector of load of buses. S is the incidence matrix, and it can be calculated by the parameters of branches and the network structure.

A. Objective Function

The minimum load shedding calculation problem can be divided into two issues, one is to select load shedding points, another is to determine load shedding amount. Here gives three objective functions which must be simultaneously minimized. These three components are as equations (14) to (16).

$$\min f_1(\mathrm{x}) = \sum_{i=1}^{n} d_i \tag{14}$$

Equation (14) represents the sum of load shedding amount where d_i is the load shedding amount of bus i. On the premise of power system security, the power system should ensure the power supply to users. So in the process of optimization the first goal is try to get the minimum value of equation (14).

$$\min f_2(\mathrm{x}) = \sum_{i=1}^{n} \omega_i \cdot \frac{d_i}{L_i} \tag{15}$$

Equation (15) represents the sum of weighted difference of loads and equals to total weighted load shedding. L_i is load of bus i and ω_i is importance factors of load i. $\omega=[\omega_1,\omega_2...\omega_n]$ represents the difference of loads, such as normal load takes $\omega=1$ while important load takes $\omega=1.2$. In the process of load shedding the important load should be protected and first cut those less important loads.

$$\begin{cases} \min f_3 = \sum_{i=1}^{n} k_i \\ k_i = \begin{cases} 1, d_i > 0 \\ 0, d_i = 0 \end{cases} \end{cases} \tag{16}$$

Equation (16) represents the sum of load shedding buses and equals to the total number of load shedding points. To simplify the load shedding operation, on the premise of meeting equation (14) and (15), try to minimize the load shedding points.

B. Constraints

The inequality and equality constraints are described in equations (17) to (21). Active power balance equations are expressed as equations (17).

$$g_0 = \sum_{i=1}^{n} (\mathrm{g}_i + \mathrm{d}_i - \mathrm{L}_i) \tag{17}$$

Where g_0 is the active output of balance generator, g_i is the active output of generator i, L_i is the load of bus i, d_i is the load shedding amount of bus i.

$$P_L = S(\mathrm{g}+\mathrm{d}-\mathrm{L})^T \tag{18}$$

$$|P_L| \le P_{\max} \tag{19}$$

The active power transmitted by branch i can be calculated by equation (18). To ensure the security of the system, the active power transmitted by branch should be limited, as show in equation (19).

Control variables constraints are the active power of generators and load of buses which are shown by equations (20) and (21), respectively.

$$g_{i,\min} \le g_i \le g_{i,\max} \tag{20}$$

$$0 \le d_i \le L_i \tag{21}$$

This object of load shedding is achieved by optimal determination of control variables. Control variables are shown in Table 1.

TABLE I CONTROL VARIABLES

Bus / Control variables	No.1	…	No.n
Output	g_1	…	g_n
Load	d_1	…	d_n

C. Calculation Steps

Based above theory analysis and multi objective optimization model, here achieve the calculation of minimum load shedding amount by MATLAB. The steps are as follows:

Step 1, input the power system data, and analyze system state. If there are branches overloading, jump to step 2, otherwise exit.

Step 2, form the objective function model and constraints as equations (14) to (21). Input the initial control variables x^* and goal point F^*.

Step 3, if the value meets the constraints, jump step 4, otherwise jump step 6.

Step 4, check it by equation (11), whether the value is dominated by the other solution.

Step 5, if the value is the pareto optimal solution, jump to step 7, otherwise jump step 6.

Step 6, search next value in the feasible space by linear optimization program.

Step 7, output the pareto optimal solution and analyze the optimization results.

The Fig. 1 summarizes the basic steps of the minimum load shedding calculation process based on multi objective optimization theory.

IV. CASE STUDY

The proposed model and solution method are tested using the IEEE 9-bus test system which is shown in Fig. 2. Initial operating state and constraints of the system is shown in table 2 to table 4. Generator in bus 1 is considered as the reference generator. The importance factor of load 6 is 1.1 while others is 1. Branches transmission capacity constraints are shown in table 3.

TABLE II INITIAL STATE OF GENERATOR AND OUTPUT CONSTRAINTS

Bus NO.	Maximum Output （MW）	Minimum Output （MW）	Active Power （MW）
1	200	0	～
2	100	0	100
3	180	0	180

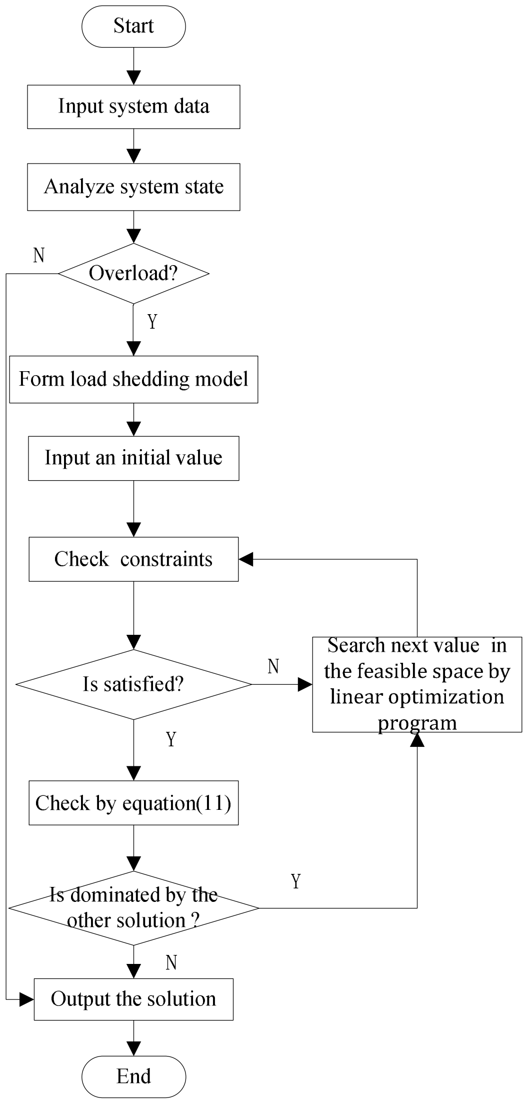

Fig. 1. The basic steps of minimum load shedding calculation process

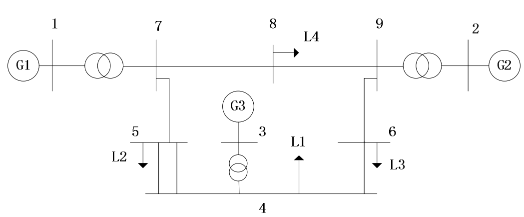

Fig.2 IEEE 9-bus test system

TABLE III INITIAL STATE AND IMPORTANCE FACTOR OF LOADS

Bus NO.	Load （MW）	Importance Factor
4	50	1
5	150	1
6	100	1.1
8	100	1

TABLE IV PARAMETERS AND TRANSMISSION CONSTRAINTS OF BRANCHES

BUS NO.	Reactance （pu）	Transmission Constraints(MW)
1，7	0.0567	180
2，9	0.0586	180
3，4	0.0625	180
4，5	0.1610	100
4，6	0.0720	80
5，7	0.0850	80
6，9	0.1008	100
7，8	0.0920	100
8，9	0.1700	100

To test the proposed model, here establish three load shedding models with different set of objective functions. Model I: Ignoring the difference of loads, establish the load shedding model with the single objective function as equation (14). Model II: Considering the difference of loads, establish the load shedding model with two objective functions as equations (14) to (15). Model III: To simplify the load shedding operation, establish the load shedding model with three objective functions as equations (14) to (16).

Table 5 shows the initial operating state, all the branches meet the constraints of the system.

TABLE V INITIAL OPERATION STATE

BUS NO.	Transmission Constraints(MW)	Active Power （MW）
1，7	180	120
2，9	180	100
3，4	180	180
4，5	100	73.2
4，6	80	56.8
5，7	80	76.8
6，9	100	43.2
7，8	100	43.2
8，9	100	56.8

Here gives three system states to test the proposed load shedding model. As follows

State I: branch 8-9 out of service. Branch 6-9 fault results in branch 4-5 overloading. To ensure the security of transmission system, the loads should be optimized. By rescheduling the generation, the overloading problem is eliminated. So there is no need load shedding. The rescheduled generation is shown in table 6.

TABLE VI RESCHEDULED GENERATION IN STATE I

Bus NO.	Initial generation （MW）	Rescheduled generation （MW）
1	120	160
2	100	60
3	180	180

State II: Generator 2 out of service. Due to the transmission capacity constraints of transformer 1-7 and 3-4, the maximum power supplied by the system is 360 MW, so some load should be cut off. Calculate the minimum load shedding amount using the proposed three models, and the results are shown in table 7.

TABLE VII LOAD SHEDDING RESULTS IN STATE II

Bus NO.	Load (MW)	Load Shedding Amount (MW)		
		Model I	Model II	Model III
4	50	10	13.33	0
5	150	10	13.33	24.25
6	100	10	0	0
8	100	10	13.33	15.75
Sum		40	40	40

Table 7 gives three different load shedding schemes by model I to III. First, meeting the security constraints, the minimum load shedding amount is 40 WM, if ignoring the difference of loads the load shedding amount shared by all buses; considering the load 6 is more important , the model II first cut off the load of other buses; the model 3 simplified the load shedding operation by just giving two load shedding points.

State 3: branch 6-9 out of service. Branch 6-9 fault results in branch 5-7 and branch 4-6 overloading. To ensure the security of transmission system, the loads should be optimized. Calculate the minimum load shedding amount using the proposed three models, and the results are shown in table 8.

TABLE VIII LOAD SHEDDING RESULTS IN STATE III

Bus NO	Load (MW)	Load Shedding Amount (MW)		
		Model I	Model II	Model III
4	50	5.6	10.6	0
5	150	8.62	9.4	4.25
6	100	20.48	20	20
8	100	5.3	13.33	15.75
Sum		40	40	40

Table 8 shows that to meet security constraints of the system, the minimum load shedding amount is 40 MW. The results of model II shows that though the load 6 is important, due to the transmission constraints of branch 4-6, 20 MW must be cut off. By modifying the importance factors the proposed model can offer a reasonable load shedding schemes.

V. CONCLUSION

In this paper, the multi objective optimization theory is applied into calculation the minimum amount of load shedding. The proposed model established the inequality and equality constraints by considering maximum permissible power flow and system power balance. The objective function considered the difference of loads and tried to simplify the load shedding operation. The above results shows the rightness and validity of the approach proposed in this paper. The proposed minimum load shedding calculation approach can be used to evaluate the candidate planning scheme and help the user to modify it.

VI. REFERENCES

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