Load reduction algorithm for power grid low-frequency optimization

Shunjiang Wang¹, Huiwen Xu¹,⁵, Baoming Pu³, Weichun Ge¹ and Qianwei Liu⁴

¹ State Grid Liaoning Electric Power Supply Co., Ltd, Shenyang 110000, China
² School of Electric Power, Shenyang Institute of Engineering, Shenyang 110136, China
³ Chinese Academy of Sciences, Shenyang Institute of Computing Technology, Shenyang 110000, China
⁴ State Grid Corporation of China, Beijing 100031, China
⁵ E-mail: Chelsey_Xu@126.com

Abstract. Dynamic monitoring and effective control of system frequency is the key to ensure the normal operation of power system. In this paper, a hierarchical load shedding algorithm model is constructed, which can prevent the frequency from continuously decreasing when the system affects stability due to increased load, so as to avoid large area blackouts and system collapse. It is of great significance to the safe and stable operation of power system and the national economy. It has opened up a train of thought for studying the current system frequency control methods in smart grid.

1. Introduction

Frequency is one of the important parameters in the normal operation of power system. All kinds of electrical equipment can operate safely and effectively only under the rated frequency or within a certain fluctuation range [1]. Frequency imbalance often has a serious impact on the power supply, users and even the whole system, and stable frequency can ensure the balance between the supply and demand of active power, and ensure the safety of users and daily electricity consumption. Therefore, dynamic monitoring and effective control of system frequency is the key to ensure the normal operation of power system [2].

The stability of the system frequency mainly depends on the balance between the total power output of the prime mover and the total load power of the system. When the active power of the power system is unbalanced, there are two main stabilization measures: one is to increase the output of the generator, the rapid release of the system's rotating reserve capacity, that is, low-frequency speed control UFGC (Under Frequency Governor Control). The two is to reduce the load of the system, that is, UFLS Under Frequency Load Shedding. Low frequency load shedding as a means of control is the last line of defense in the two system. When there is a large active power shortage in the power system, it can prevent the frequency from dropping continuously, so as to avoid large area blackouts and system collapse. It is precisely because of the importance of this line of defense that avoided many large blackouts. However, we must also take into account the economic problems brought about by overcontrol. Therefore, it is of great significance for the safe and stable operation of the power system and the national economy to seek an optimized low-frequency load shedding method which can integrate practicability and economy.
In order to optimize the action effect of the low frequency load shedding model, many scholars have paid more attention to the optimization model which aims at the parameters of the low frequency load shedding, such as device layout, wheel number, load shedding and so on. [3] based on the consideration of load frequency and voltage characteristics, load shedding control is formulated as a linear programming problem to determine the load shedding location and load shedding capacity. [4] presents a global optimization algorithm for low-frequency load shedding scheme with coherence partitioning, which considers the effect of system topology changes on low-frequency load shedding. Low-frequency load shedding is a trajectory-driven control method [5]. Based on the traditional optimal control cost minimization model of low-frequency load shedding parameters, a parameter optimization model considering both the system frequency recovery trajectory and the minimum load shedding is proposed. [6-7] use neural networks and genetic algorithms to optimize load removal, but the total removal of all load nodes is taken as the optimization objective, and the difference of different load nodes is not considered. [8] suggests that the load with small frequency modulation effect coefficient should be removed first, and the important load should be placed at the last stage of load shedding, but the two are not taken into account. [9] considered the difference of frequency regulation effect coefficient and load importance, among different load nodes by comprehensive weights, it is neglected that the factor of load importance is superior to the frequency regulation effect in actual load shedding.

At present, the research on low frequency load shedding is mainly based on the direct method. For example, the exhaustive method can be used to find the optimal solution of load shedding [10]. However, when the number of tangents in the security and stability control system is large, a combined explosion will occur, so the exhaustive method is only applicable to the case of a small number of tangents [11]. There are two ways to implement the trial-and-error method. One is to complete the exhaustive search in sequence until the optimal load shedding point is found. Obviously, this method also needs a lot of calculation. The two is grading and grading. Based on the hierarchical algorithm, this paper summarizes a convenient and effective low-frequency hierarchical load shedding algorithm program.

2. Level load shedding optimal model

2.1. Objective function

When the load in the system is more or the power supply is less, it will cause a decrease in frequency. The algorithm first decides the load shedding $\Delta P$ amount of the system according to the frequency $\Delta f$, so as to ensure the balance between power supply and load.

The objective function of optimal load reduction is:

$$\min |\Delta P - (\alpha_1 + \alpha_2 + \ldots + \alpha_n)|$$

(1)

where $\Delta P$ represents the total load shedding of the system, $\alpha_i$ represents the load shedding in the first grades to the n level. It should be noted that if the load shedding time is set as $t_0$, the whole process needs to consider the time $t_0 + t$ generates $\Delta P$ (uncontrollable ultra-short-term load forecasting, ultra-short-term optical power forecasting and ultra-short-term wind power forecasting), $\Delta P_0 + \Delta P_1$ is the required $\Delta P$.

The load is divided into several grades, and the importance of each load increases sequentially, set as $x_1, x_2, x_3, \ldots x_n$.

For the first level, the middle load value is in turn as $a_1, a_2, a_3, \ldots a_n$, the load level of the second grades is $b_1, b_2, b_3, \ldots b_n$, to the m level.

When $\Delta P - \sum_{j=1}^{n} a_j > 0$, the first stage load was totally removed.

When $\Delta P - \sum_{j=1}^{n} a_j - \sum_{j=1}^{m} b_j > 0$, the first, second level was completely removed.
By analogy, until the next level, when
\[ \Delta P - \sum_{j=1}^{n} a_j - \sum_{j=1}^{n} b_j - \sum_{j=1}^{n} x_j < 0 \]  
(2)

The excision point can be determined in the rank.

2.2. Constraint conditions
The constraints of low frequency load shedding optimization control mainly include capacity constraints of load shedding nodes and total load shedding capacity constraints.

The upper and lower limits are used as references for the constraint of steady-state and dynamic frequencies. According to the literature requirements, the steady-state frequency recovery value \( f_s \) should be no less than 49.5 Hz. The dynamic frequency value \( f_d \) overshoot caused by overloading does not exceed 51Hz. After the low frequency load shedding operation, the system frequency can be raised to 49.5~50 Hz as soon as possible without overshoot and hover.

Therefore, the inequality constraints of the optimal scheme selection include the upper and lower bounds of the load shedding capacity, the total load shedding capacity, the steady-state frequency and the dynamic frequency.

1) The load shedding is between 5% and 7% (5% ≤ \( \Delta P \) ≤ 7%).
2) The total load shedding is between 10% and 40% (10% ≤ \( \Delta P \) ≤ 40%).
3) The steady-state frequency is between 49.5 and 50 Hz (49.5 ≤ \( f_s \) ≤ 50).
4) The dynamic frequency is between 47 and 51 Hz (47 ≤ \( f_d \) ≤ 51).

The calculation of optimal load shedding can be roughly divided into two problems: the choice of load shedding point and the determination of load shedding quantity. Considering the problems of safe and reliable power supply and economic operation, the load shedding of the whole system should be minimized and the objective function should be established.

\[ \min f_1(x) = \sum_{i=1}^{n} \alpha_i \]  
(3)

In this process, it is also necessary to determine whether the load has been removed. Judgment basis: 1) the switch is not open. 2) the load telemetry value is still there. 3) balance the input and output power on the bus. If it is not removed, it should give instructions again and give up after three consecutive null and void. Go to the next load point and continue. The more lines involved, the stronger the convergence. If there are some similar minimum values, try to select fewer lines to reduce the load.

3. Low frequency load shedding optimization scheme

3.1. Design of multi-input multi-output nonlinear control system
Considering the multi-input multi-output affine nonlinear control system:

\[
\begin{align*}
\dot{x} &= f(x) + G(x)u \\
y &= h(x)
\end{align*}
\]  
(4)

where \( x = [x_1 \cdots x_n]^T \in \mathbb{R}^n \) is the state column vector, \( G(x) = [g_1(x) \cdots g_n(x)] \in \mathbb{R}^{n \times m} \) is the \( n \times m \)-dimensional control matrix, \( f(x) = [f_1(x) \cdots f_n(x)]^T \in \mathbb{R}^n \) and \( g_j(x) = [g_{1j}(x) \cdots g_{nj}(x)]^T \in \mathbb{R}^n \) are the \( n \)-dimensional smooth vector field, \( u = [u_1 \cdots u_m]^T \in \mathbb{R}^m \) is the control column vector, \( y = [y_1 \cdots y_m]^T \in \mathbb{R}^m \) is the output column vector; \( h = [h_1(x) \cdots h_m(x)]^T \in \mathbb{R}^m \) is the output function vector.

The design problem of multi-input and multi-output nonlinear control system is to find the state quantity feedback control rate of (5)
\[ u(t) = k(x) \] 

where \( u(t) = [u_1(t) \cdots u_m(t)]^T \) and \( k(t) = [k_1(t) \cdots k_r(t)]^T \) make the multi-input multi-output nonlinear control system (4) becomes a stable closed-loop control system that meets certain performance requirements.

### 3.2. Relative order of multi-input multi-output nonlinear system

The relative order of multi-input multi-output nonlinear control system (4) is defined as follows:

**Definition 1:** for multi-input multi-output (4), if neighborhood \( U \subseteq \mathbb{R}^n \) and positive integer set \( \{r_1, r_2, \cdots, r_m\} \) of \( x_0 \) exist, it satisfies:

1. For \( 0 \leq k_i \leq r_i - 2 \), \( L_{ij}^{r_i-k_i} h_i(x_0) = 0, \quad \forall x \in U, \quad j = 1, 2, \cdots, m, \quad i = 1, 2, \cdots, m \):
2. For \( k_i = r_i - 1 \) a \( m \times m \) matrix of order

\[
\bar{B}(x_0) = \begin{bmatrix}
L_{11}^{r_1-1} h_1(x_0) & \cdots & L_{1m}^{r_1-1} h_m(x_0) \\
\vdots & & \vdots \\
L_{m1}^{r_m-1} h_1(x_0) & \cdots & L_{mm}^{r_m-1} h_m(x_0)
\end{bmatrix}
\]

If it is nonsingular, then \( \{r_1, r_2, \cdots, r_m\} \) is called the relative order of the vector of the system at point \( x_0 \). \( r = r_1 + \cdots + r_m \) is called the total relative order of the system, where each relatively order \( r_i \) corresponds to the input function \( h_i(x) \).

For the convenience of the following discussion, the relative order accumulation variable \( h_i(x) \) is introduced as follows:

\[
\sigma_i = \sum_{j=1}^i r_j \quad (i = 0, 1, 2, \cdots, m)
\]

Obviously, there should be an equal relationship between \( \sigma_0 = 0, \quad \sigma_1 = r_1, \quad \sigma_m = r, \quad r \geq m \).

In a multi-input and multi-output system, if the relative order of the vector of the output function \( h(x) \) of the system Formula (4) is \( \{r_1, \cdots, r_m\} \), then the \( y_1, \cdots, y_m \) derivatives of the output \( \{y_1, \cdots, y_m\} \) with respect to time can be obtained as follows:

\[
\begin{align*}
\dot{y}_1 &= L_{ij} h_i(x) + L_{ji} L_{ij}^{r_j-1} h_j(x) \cdot u_j + \cdots + L_{jm} L_{ij}^{r_j-1} h_m(x) \cdot u_m \\
& \vdots \\
\dot{y}_m &= L_{ij} h_i(x) + L_{ji} L_{ij}^{r_j-1} h_j(x) \cdot u_j + \cdots + L_{jm} L_{ij}^{r_j-1} h_m(x) \cdot u_m
\end{align*}
\]

Obviously, as long as:

\[
\begin{align*}
\dot{y}_1 &= L_{ij} h_i(x) + L_{ji} L_{ij}^{r_j-1} h_j(x) \cdot u_j + \cdots + L_{jm} L_{ij}^{r_j-1} h_m(x) \cdot u_m = v_i \\
& \vdots \\
\dot{y}_m &= L_{ij} h_i(x) + L_{ji} L_{ij}^{r_j-1} h_j(x) \cdot u_j + \cdots + L_{jm} L_{ij}^{r_j-1} h_m(x) \cdot u_m = v_m
\end{align*}
\]

An exact set of linearized equations with input \( v_1 \cdots v_m \) to output \( y_1 \cdots y_m \) is obtained, and the input/output pairs are decoupled from each other.

It can also be proved that if the system (4) has relative order \( \{r_1, \cdots, r_m\} \) of the vector, then the row vector group \( Dh(x), DL_j h(x), \cdots, Dh_m(x), DL_j h_m(x), \cdots, DL_j^{r_j-1} h_m(x) \) are linearly independent in the neighborhood.

**Definition 2:** if (4) of multi-input multi-output nonlinear system has relative order \( \{r_1, \cdots, r_m\} \) of the vector, the following \( r \times n \) order Jacobian matrix can be obtained. The rank in neighborhood \( U \subseteq \mathbb{R}^n \) is \( r \).
3.3. State feedback completely accurate linearization design

For the nonlinear system Equation (4), when \( r = r_1 + \cdots + r_n \), as long as the non-linear transformation:

\[
\begin{align*}
  z &= \begin{bmatrix} z_1 \\ \vdots \\ z_m \end{bmatrix}, \\
  \Phi(x) &= \begin{bmatrix} h_1(x) \\ \vdots \\ h_m(x) \end{bmatrix}, \\
  \Phi(x) &= \begin{bmatrix} \phi_1(x) \\ \vdots \\ \phi_m(x) \end{bmatrix}
\end{align*}
\]

(10)

\[
\Phi(x) = z
\]

(11)

The Jacobian of the transformation is of full rank. With this transformation, the nonlinear system Equation (4) can be completely and precisely linearized into the following first standard form:

\[
\begin{align*}
  \dot{z}_1 &= z_2, \quad \dot{z}_2 = z_3, \ldots, \dot{z}_m = v_1, \\
  \vdots &
\end{align*}
\]

(12)

\[
\begin{align*}
  \dot{z}_{m+1} &= z_{m+2}, \quad \dot{z}_{m+2} = z_{m+3}, \ldots, \dot{z}_n = v_m
\end{align*}
\]

where

\[
\begin{align*}
  v_1 &= L^+_1 h_1(x) + L_{r_1} L^+_1 h_1(x) u_1 + \cdots + L_{r_m} L^+_1 h_1(x) u_m, \\
  \vdots &
\end{align*}
\]

(13)

Equation (11) can be abbreviated as

\[
\begin{align*}
  \dot{z} &= Az + Bv \\
  y &= Cz
\end{align*}
\]

(14)

where

\[
\begin{align*}
  A &= diag[A_1, \ldots, A_m], \\
  A_{i, i} &= \begin{bmatrix} 0 & I_{r_i - 1} \\ 0 & 0 \end{bmatrix}, \\
  B &= diag[B_1, \ldots, B_m], \\
  B_{i, i} &= \begin{bmatrix} 0 & 0 & \cdots & 1 \end{bmatrix}^T, \\
  C &= diag[C_1, \ldots, C_m], \\
  C_{i, i} &= \begin{bmatrix} 1 & 0 & \cdots & 0 \end{bmatrix}^T, \\
  z &= \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_m \end{bmatrix}, \\
  v &= \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_m \end{bmatrix}.
\end{align*}
\]

From (11), the nonlinear feedback control law \( u \) of \( x \) space can be obtained as

\[
\begin{align*}
  u &= -B^{-1}(x)\tilde{a}(x) + \tilde{B}^{-1}(x)v
\end{align*}
\]

(15)

where \( \tilde{a}(x) = [L^+_1 h_1(x) \cdots L^+_m h_m(x)]^T \).

According to the grade classification, the optimal load shedding calculation steps are as follows:

1) Input system data, read the system status and calculate to determine whether load shedding is needed.
2) The objective function and constraint conditions are formed and transformed into multi-objective optimization models.
3) Formatives (1) - (4) form of objective function, target value series, and initial decision variables.
4) Search for a new non inferior solution \( X \) in the feasible domain by applying the target attainment method.
5) Judge whether \( x \) is the optimal solution, if not, jump to step (4), otherwise to step (6).
6) Output the optimal solution and output the load shedding result.

4. Calculation example analysis of low-frequency hierarchical optimized load shedding

In order to further verify the effectiveness of the proposed method, a simulation system model is designed, which consists of 5 artificial classification levels, 50 sets of load nodes, the load data as shown in Table 1. Under the initial conditions, the load curve of the system is shown in Figure 1. The
active load of the system is 7873.5 MW. The load reduction capacity of 50 load points in the power grid is optimized, and the bus frequency of the load point is observed.

![Figure 1. Load curve of system at initial condition.](image1)

Table 1. Assuming failure scenarios.

| Scene | $P_s / MW$ | Percentage of vacancy |
|-------|------------|-----------------------|
| 1     | 1072.37    | 13.62                 |
| 2     | 3061.43    | 38.88                 |

1. Set two typical faults (as shown in Table 1).
2. Calculate according to the above optimization model.
3. Obtain the load shedding capacity that meets the optimal comprehensive cost requirements under different fault conditions, as shown in Figure 2 (the data in the table is a percentage).
4. The corresponding simulation model is established in PSASP. In the case of insufficient active power, the traditional scheme and the optimization scheme are used respectively to simulate and analyze the frequency recovery curve of the system.

The two curves in Figure 2 represent the load curve of the initial state and the end state of load shedding respectively.

![Figure 2. Load curve of system at different fault condition.](image2)
To sum up, the model of load shedding according to grades ensures the minimum overall cost of load shedding while taking into account the differences and adjustment effects of each load node. Under the above two different power shortage accidents, the overall cost is relatively small, and the steady state frequency. The level is basically the same as the traditional scheme, and the frequency dynamic fluctuation curve has also been improved to a certain extent.

5. Conclusions
In this paper, an effective load shedding optimization scheme is proposed by constructing a hierarchical load shedding algorithm model. The simulation cases in various fault scenarios are validated by the simulation system. The results show that the proposed scheme can remove the unimportant loads with serious disturbance, low load rate and low load shedding cost when dealing with different active power shortage disturbances, and has lower comprehensive cost and better frequency recovery characteristics than the traditional load shedding scheme. The performance curve makes the system tend to be stable in a shorter time, which opens up a new way to study the current frequency control methods in smart grid.

Acknowledgement
This paper was supported by Science and Technology Project of State Grid Corporation of China (SGLNXT00SJYYXX1900760).

References
[1] Welti T and Devantier A 2006 Low-frequency optimization using multiple subwoofers Journal of the Audio Engineering Society 54 347-364
[2] Li C, Wu Y, Sun Y, et al. 2020 Continuous under-frequency load shedding scheme for power system adaptive frequency control IEEE Transactions on Power Systems 35 950-961
[3] Adardour A, Andrieu G and Reineix A 2014 On the low-frequency optimization of reverberation chambers IEEE Transactions on Electromagnetic Compatibility 56 266-275
[4] Yue X, Boroyevich D, Lee F, et al. 2018 Beat frequency oscillation analysis for power electronic converters in de nanogrid based on crossed frequency output impedance matrix model IEEE Transactions on Power Electronics 33 3052-3064
[5] Ding S, Zhang C, Gong Q, et al. 1999 A new fast algorithm for microprocessor-based protection AC sampling Automation of Electric Power Systems 23 18-20
[6] Wang T, Wang H and Xie H 2010 Networked synchronization control method by the combination of RBF neural network and genetic algorithm International Conference on Computer and Automation Engineering 3 9-12
[7] Ghaedi M, Shojaeipour E, Ghaedi, et al. 2015 Isotherm and kinetics study of malachite green adsorption onto copper nanowires loaded on activated carbon: Artificial neural network modeling and genetic algorithm optimization Spectrochimica Acta 142 135-149
[8] Huang H and Li F 2013 Sensitivity analysis of load-damping characteristic in power system frequency regulation IEEE Transactions on Power Systems 28 1324-1335
[9] Xie D, He H, Chang X, et al. 2010 An approach to design power system under frequency load shedding scheme taking coherent area and global optimization into account Power System Technology 34 106
[10] Shahla M and Babak G 2019 Performance improvement of distribution networks using the demand response resources IET Generation, Transmission & Distribution 18 74-77
[11] Samarakoon K, Ekanayake J and Jenkins N 2012 Investigation of domestic load control to provide primary frequency response using smart meters IEEE Transactions on Smart Grid 3 282-292