An Under-Frequency Load Shedding Optimization Scheme Based on Power Tracing

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***Abstract*—Under-frequency load shedding (UFLS) is the last line of defense to prevent large-scale blackouts. The conventional UFLS scheme does not distinguish the location of the disturbance, and adopts the equal amount or equal proportion load shedding to distribute the amount of load shedding indistinctively without considering the effect of fault generator position on frequency recovery. Considering this, this paper proposed a UFLS scheme based on power tracing. Firstly, this paper analyzed the power transmission relationship and obtained the transmission path between generators and loads based on the superposition theorem. Secondly, this paper distributed the amount of load reduction according to flow tracking results of the faulty power supply, and developed a UFLS optimization scheme with targeted load shedding. At last, the verification was performed in the IEEE 39-bus system. The simulation results demonstrate the superiority of this scheme.**

Keywords—power system; frequency stablity; UFLS; power flow tracing

I. INTRODUCTION

For the problem of power system unbalanced power generation and power consumption, the control scheme can be mainly divided into two types—change of system generator output and change of system load. In terms of the outputs of generators are insufficient, Under Frequency Governor Control (UFGC) and Under Frequency Load Shedding (UFLS) are generally used[1-3]. However, the effective implementation of UFGC is limited by the rotating spare capacity in the system and its scheduling speed. If the rotational reserve capacity is insufficient or the outputs of generators adjustment speed are limited, which is difficult to meet the post-accident system emergency control requirements, UFLS will be activated to control and select partial load to be removed, which becomes a necessary and last choice for system stability control.

For a half century, research on UFLS has mainly been divided into stationary and dynamic two schemes[4]. The stationary one is a traditional scheme based on the value of frequency and the setting of established delay, and the dynamic scheme is a semi-adaptation method and an adaptive method that dynamically determine the amount of load shedding according to the rate of frequency change. On this basis, [5] suggests that the basic rounds in low frequency and low voltage load shedding control schemes be divided into load reduction and quick load reduction zones. [6] determines the activated time of load shedding device based on the rate of the system frequency difference change. The load shedding device can be activated in a relatively short time, and the transition time is also shortened. For regional power shortages, [7] has optimized the load shedding plan for the disturbed area. It proposes to remove the loads near the power plant which is out of operation due to the accident. In the scheme above, all load shedding at different locations are taken into account in each round, and the impact of load shedding locations on frequency recovery is not considered.

Related regulations indicate that the order of automatic under-frequency load shedding should be set up according to the importance of the loads. However, in the case of the same importance level of loads, the relevant regulations about how to choose the load shedding location and how much should to be removed are still a blank. [8] proposed a load shedding algorithm for determining load shedding sequence based on sensitivity of power vacancy and determining load reduction in time domain simulation. [9] proposed a load shedding strategy that considers frequency stability and voltage stability. Choose the bus with poor voltage stability as load shedding location, and allocates more load shedding. [10] comprehensively considered the load importance and load frequency characteristics, and combines the electromechanical transient simulation with the particle swarm algorithm to optimize the ratio of load cut at each step.

The above methods all have better performance, but they did not take into account the influence of the location of the disturbance on the frequency recovery, and neglected that the impact of the disturbance on each load node is different. This paper establishes a under-frequency load shedding optimization scheme based on power flow tracing. Based on the steady-state power flow information at the moment before the fault occurs, the power supply and demand relationship between the generator and the load is obtained through the multi-power tracing. When a generator's output power suddenly reduce or generator is removed, according to the results of the power flow tracing, the distribution of load shedding is carried out according to the ratio of power transmission to the failed power supply. The practical example demonstrates the superiority of the method in this article.

II. POWER FLOW TRACING

In power system, electromagnetic power is generated by the generator, transmitted through a line and supplied to the load, causing the power loss due to the line impedance. For a multi-machine system, each generator contributes differently to the power of each load node. The bi-directional complex power tracing method is proposed in [11], which can clarify the supply and demand relationship between generators and loads and obtain the proportion of the outputs of each generator in the electromagnetic power supplied to a certain load.

There are u nodes in the electrical network, where the generator node number is from 1 to m, and the load nodes number is from $m+1$ to n. The network node admittance matrix is **Y**, and the voltage of each node is known (See Figure I).

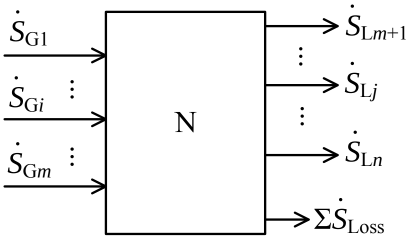

FIGURE I. *U*-NODE ELECTRIC NETWORK

Where, i=1,…,m; j=m+1,…,n;

$\dot{S}_{Gi}$ is input complex power for generator node i;

$\dot{S}_{Lj}$ is output complex power for load node j.

Convert j-th load power to admittance y_{Lj}

$$y_{Lj} = (\frac{S_{Lj}}{U_j})^* \frac{1}{U_j} \tag{1}$$

Where, $\dot{U}_j$ is the voltage of j- load;

Add load admittance y_L into the node admittance matrix **Y** and obtain a new node admittance matrix **Y'**, which includes the influence of all loads.

When generator j acts alone, the node injection current matrix $\dot{\mathbf{I}}_{Gi}$ can be expressed by:

$$\dot{\mathbf{I}}_{Gi} = [\underset{i-1}{0,...,0}, \dot{I}_{Gi}, 0,...,0] \tag{2}$$

Where, $I_{Gi} = [\frac{S_{Gi}}{U_i}]^*$.

Then, node voltage matrix $\dot{\mathbf{U}}_{Gi}$ can be obtained as follows.

$$\dot{\mathbf{U}}_{Gi} = (\mathbf{Y}')^{-1}\dot{\mathbf{I}}_{Gi} \tag{3}$$

The branch circuit of load- j as generator i acts alone, $\dot{I}_{Gi-Lj}$, is computed as.

$$\dot{I}_{Gi-Lj} = y_j \dot{U}_{Gi-j} \tag{4}$$

With original network voltage, these above currents can be converted back to the actual complex power, which represents the part of load power supplied by the specific generator in the original network. The complex power transported from generator i to load j, S_{Gi-Lj}, can be expressed by:

$$S_{Gi-Lj} = (U_{Gi-j} \cdot y_{Lj})^* \cdot U_i \tag{5}$$

Thus, the power transmission of the i-th generator can be represented by Figure II.

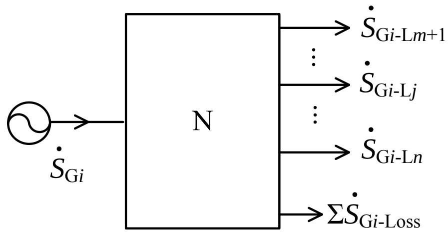

FIGURE II. POWER TRANSMISSION OF J-TH GENERATOR

The output complex power of the i-th generator can be expressed as

$$S_{Gi} = \sum_{m+1}^{n} S_{Gi-Lj} + \sum_{m+1}^{n} S_{Gi-Loss} \tag{6}$$

The output active power of the i-th generator, P_{Gi-Lj}, can be written as

$$P_{Gi} = \sum_{m+1}^{n} P_{Gi-Lj} + \sum P_{Gi-Loss} \tag{7}$$

III. UFLS OPTIMIZATION SCHEME

A. Amount of Load Shed

In order to realize the frequency control in the emergency state, many literatures proposed a frequency dynamic response model based on the simplified equivalent single-machine system [12], which can be used to estimate the frequency response of a large power system or its isolated islands to sudden load disturbances. The system power shortage is estimated based on the system's inertial center frequency instantaneous change rate (ROCOF). Its expression is

$$\Delta P = 2H_s \left.\frac{\mathrm{d}f_{COI}}{\mathrm{d}t}\right|_{t=0} \tag{8}$$

Where,

H_s is the inertia constant of the system;

f_{COI} is the system inertial center frequency.

Consider the influence of voltage variation , the power shortage is generally corrected to obtain the total amount of load reduction as followings[13]:

$$P_{\text{shed}} = 1.05\Delta P \tag{9}$$

B. Optimized Method For Load –Shed Distribution

In general, the nodes near the disturbance site are disturbed to a greater extent. The closer to the disturbance location, the faster the frequency falls. And vice versa. Therefore, there is the need for targeted distribution of the amount of load shedding, rather than undifferentiated.

According to the results of the power flow analysis, the larger the active power provided by the generator *i* to the load *j* in steady state is, the greater the power shortage of the load when the *i*-th generator fails. The majority of this shortage will be compensated by other generators, which means that other generators will take more load that they should not have undertaken. Therefore, reducing the load based on the power supply ratio of the generator *i* to each load is beneficial and reasonable for the system frequency restoration.

The load –shed distribution scheme based on power tracing can be described as:

1) Obtain the pre-fault steady-stat flow. According to the system operating parameters and topology, compute the amount of active power that the fault generator to each load node in the steady state through power tracing.

2) Determine the active power shortage of the system from the instantaneous frequency change rate of the disturbance. Considering the influence of the voltage change and reactive power shortage during the load shedding, correct total load shedding amount $\boldsymbol{P}_{\textbf{shed}}$.

3) According to the actual operation status and the importance level of the load, establish a load-reducible node set ***B***, and determine the shed-capacity of each load node.

4) Distribute the load that should be shed based on the fault generator power tracing results, and the amount of *k*-th ($k \in \boldsymbol{B}$) load reduction is

$$P_{\text{shed},k} = \frac{P_{\text{G}i-\text{L}k}}{\sum\limits_{k\in B} P_{\text{G}i-\text{L}k}} \cdot P_{\text{shed}} \tag{10}$$

IV. SIMULATIONS AND RESULTS

The validity of the proposed scheme has been proven by the testresults of the IEEE 10-machine 39-bus test system. The power system wiring diagram is shown in Figure III. Among them, 39th-node is a equivalent generator, which represents the network connected to this power system, and its load have to be kept. Besides, the load of node 31 is plant electric consumption. Therefore, the set of load-removable nodes ***B***= {3, 4, 7, 8, 12, 15, 16, 18, 20, 21, 23, 24, 25, 26, 27, 28, 29}.

Assumed that the generator G3 failed and has been disconnected, the system will lose 650 MW active power supply. Using BPA software for this system simulation, the rated frequency is 50 Hz and the generator is a 2-axis model considering general damping winding, equipped with a self-excitation static excitation system and a governor .The load adopts the constant impedance model without considering the influence of the change of frequency.

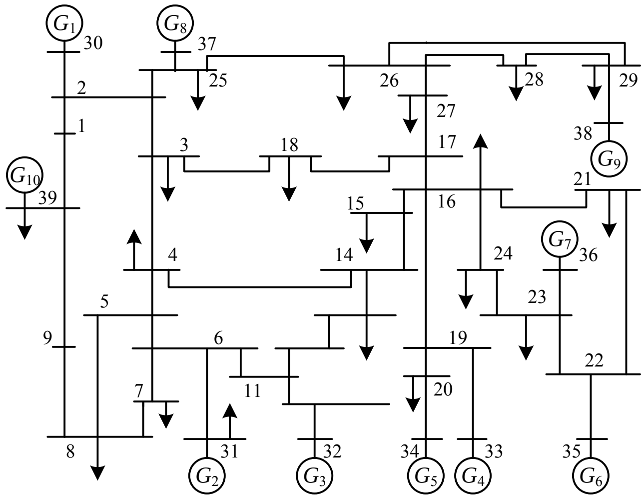

FIGURE III. IEEE 10-GENERATOR 39-BUS SYSTEM

According to the instantaneous rate of change of frequency (ROCOF), the amount of load shed is suggested to be 625MW. The load shedding scheme proposed in this paper (marked as Scheme 1) is compare with the traditional equal-amount load shedding method (Scheme 2) and equal -proportion load shedding method (Scheme 3). The results of the load-shed distribution are shown in Table I.

TABLE I. RESULTS OF LOAD-SHED DISTRIBUTION OF EACH SCHEME

Node	Scheme 1(MW)	Scheme 2(MW)	Scheme 3(MW)
3	50.32	38.5	39.96
4	77.82	38.5	62.04
7	38.38	38.5	39.01
8	83.96	38.5	64.77
12	1.32	8.5	1.05
15	41.01	38.5	39.71
16	38.75	38.5	40.82
18	19.27	38.5	19.61
20	64.85	38.5	84.38
21	28.4	38.5	34
23	24.13	38.5	30.71
24	38.69	38.5	38.29
25	24.96	38.5	27.79
26	15.35	38.5	17.25
27	31.05	38.5	34.87
28	20.43	38.5	25.56
29	27.64	38.5	35.18

The frequency setting value of the UFLS device is 49.5 Hz, with a delay of 0.2 s. Figure IV shows the change of the system frequency of each scheme, and the performance of three load shedding schemes is shown in Table II

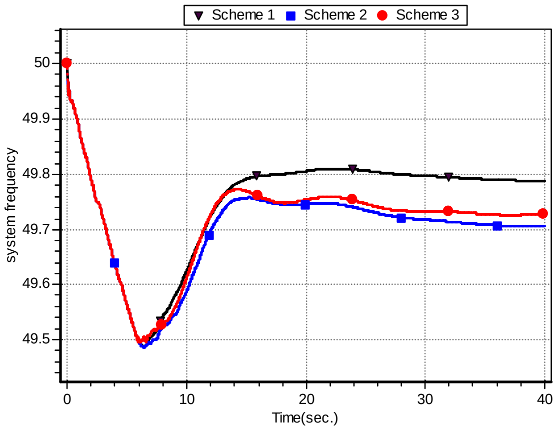

FIGURE IV. SYSTEM FREQUENCY CHANGE OF EACH SCHEME

TABLE II. COMPARISON OF LOAD-SHEDDING PERFORMANCES AMONG DIFFERENT SCHEMES

Scheme	Load Shed (MW)	Minimum Frequency(Hz)	Steady - State Frequency (Hz)	Restoration Duration (s)
1	625	49.489	49.792	25.2
2		49.487	49.706	28.8
3		49.495	49.727	24.5

The simulation results shows that the lowest frequency during restoration of frequency in Scheme 1 is 49.489 Hz, which is a little difference from other plans, and satisfies the technical regulations of UFLS .In terms of steady-state frequency, the Scheme 1 has reached the point of 49.792 Hz, which is higher than Scheme 2 (49.706 Hz) and scheme 3 (49.727 Hz),which proves the difference of influence of different fault locations on the active power of load i. targeted distribution of the load shed according to the perturbation location can get a more stable frequency to meet the system frequency quality requirements with the same amount of load shed.

In addition, because of the electric power equipment and utilization equipment are designed at the rated frequency, the change of the system frequency will cause damage to the production equipment, the decline of product quality and the reduction of production efficiency, thereby resulting in economic loss. In order to comprehensively evaluate performances the load shedding schemes, it is necessary not only to pay attention to the level of the frequency recovery, but also to the duration of frequency restoration .Further observation can be obtained that the restoration duration of Scheme 1 is 25.2 s. It is lower than Scheme 2 (28.8 s) and not too different from Scheme 3 (24.5 s), which satisfies the quickness of the frequency recovery.

From the above, it can be seen that the load-shedding strategy proposed by this paper takes into account the degree and time for frequency recovery, effectively prevent the further drop of frequency. It shows better control performance and higher control efficiency, which effectively improves the reliability of the system.

V. CONCLUSION

This paper points out that the design of the traditional UFLS scheme distributes the same amount of load shedding to each load, with neglecting the influence of different disturbance positions on the frequency recovery. In this paper, we propose a UFLS scheme based on power tracing. On the basis of the pre-fault steady-state power flow, the power transmission relationship between the fault generator and the load node is obtained by the power tracing, and a new UFLS scheme is proposed according to the amount of the load shedding by the rate of the load active transmission.

In the rest of this paper, the IEEE 10 bus 39-bus system is simulated and compared with the other two schemes. The simulation results show that under the same control cost, the proposed scheme can obtain faster rate of frequency recovery and closer to the steady state of the rated operating frequency of the system. It improves the effect of the system frequency recovery and the reliability of the system power supply.

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