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A Method for the Design of UFLS Scheme with Dynamic Correction

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ABSTRACT

This paper presents an adaptive Under Frequency Load Shedding scheme based on Wide Area Measurement System. Due to the lack of enough adaptability to the operation state of the system, the traditional successive approximation under frequency load shedding method will cause excessive cut or undercut problems inevitably. This method consists first in a comprehensive weight index including load characteristics and inertias of generators. Then active-power deficit calculation based on the Low-order Frequency Response Model, concerning the effect of voltage was put forward. Finally, a dynamic correction of the load shedding amount was proposed to modify the scheme. This approach was applied to IEEE-39 system and the simulation results indicated that the proposed method was effective in reducing the load shedding amount as well as the frequency recovery time.

Keywords: UFLS; WAMS; Active- power Deficit; Comprehensive Weight

1. Introduction

As the last resort against system blackouts, UFLS schemes implemented today are conventional and adaptive schemes. The former one is generally based on off-line calculation, shedding a predefined amount of load in case frequency and/or the rate of change of frequency (ROCOF) fall below a certain threshold with a time delay. While the latter one allocates the active- power deficit in each load shedding step, taking online conditions into account.

Reference [1] proposes a new methodology based on risk management and quantitative analysis for the time response curves, and coordination between UFLS and UVLS is studied. A UFLS scheme, based on non-recurve Newton algorithm to estimate the frequency and the frequency change ratio, is put forward [2]. Concerning the frequency characteristic difference of different load nodes, reference [3] puts forward a load shedding scheme base on comprehensive weights. References [4, 5] propose a low-order model to calculate the response of the system with disturbance. A load shedding method ensuring the stability of both frequency and voltage is studied in [6]. In a word, references mentioned above are all based on the low-order frequency response model to calculate the deficit power. Nevertheless, the model ignores the effect of voltage on the deficit power, resulting in some error in the deficit power calculation.

The literatures mentioned above, irrespective of the effect of generator inertia on the grid dynamic frequency,

seldom analyze the correlation properties of these two coupling parameters in UFLS. Besides, in the multi-machine system, there is a close relationship between the frequency variation and generator inertia time constant. As a result, the effect of generator inertia on the frequency shall not be neglected.

This paper proposes a new adaptive UFLS based on WAMS. The main elements of the proposed WAMS-based scheme are given below.

1) A power deficit calculation based on WAMS considering voltage effect factor.

2) A comprehensive load shedding criterion construction concerning load characteristics and the effect of generators on loads.

3) A dynamic correction of load shedding amount in accordance with the system self regulation ability and real-time frequency change rate.

2. Comprehensive Load Shedding Criterion

Considering the differences of load frequency characteristic and generation unit inertia, calculate the comprehensive weights of each node in the process of load shedding. Based on the weights obtained to allocate the load shedding amount and determine the location.

2.1. The Path Distribution Weight of Generator Inertia

In multi-machine system, the frequency variation with

active power disturbance has a close relationship with generator inertial time constant and disturbance site. Calculate the frequency change rate instantly when the disturbance occurs (3 time cycles after the disturbance), and use Equation (4) to calculate the deficit power P_{defi}(i=1,2,…n) of each unit to measure generator disturbance degree. In under-frequency state, the larger deficit power is, the greater degree of unit is. The nearby load of unit with large deficit power should be given priority to be cut to stabilize the system as soon as possible. Choose the maximum value P_{demax} as the base value to normalize all the P_{defi}. The disturbance degree weight then can be expressed by:

$$\beta_{ij} = P_{defi} / P_{def\,max},$$ (1)

In which, n stands for the number of generators; m is the number of loads; β_{ij} is the weight of jth load which is near to ith generator. As the analysis mentioned above, the larger β_{ij} is, the greater disturbance degree of unit is. Shed these sort of loads first can facilitate the recovery of frequency.

With regard to the ownership of the load, the shortest electric distance from load node to generator is adopted to differentiate the ownership. Assume the number of node is a, the number of edge is b, calculate the adjacency according to the weighted power system network theory. Apply Floyd algorithm to the matrix WG to figure out the shortest electric distance matrix D. Calculate all the electric distance from jth load node to all the generators according to matrix D, choose the shortest distance to obtain the load weight β_{ij}.

2.2. Load Frequency Characteristic Weight

Load active-frequency characteristic refers to the characteristic that the load active power varies with the change of frequency:

$$P_L = a_0 P_{LN} + a_1 P_{LN}(\frac{f}{f_N}) + a_2 P_{LN}(\frac{f}{f_N})^2$$
$$+ ... + a_n P_{LN}(\frac{f}{f_N})^n$$ (2)

In which, a_i is the proportion of load which is proportional to the i times of frequency; P_{LN} is the rated load of system; f_N is the rated frequency.

In real power system, the load which is proportional to the 3 times of frequency is rather fewer; Equation (12) can be simplified by Equation (13):

$$P_{L*} = a_0 + a_1 f_* + a_2 f_*^2 + a_3 f_*^3$$ (3)

Further, we can obtain:

$$K_L = \frac{dP_{L*}}{df_*} = a_1 + 2a_2 f_* + 3a_3 f_*^2$$ (4)

In which, K_L is the load frequency regulation coefficient and each load corresponds to different K_L.

When the frequency drops, the load with bigger K_L absorbs less active power from the system. Therefore, calculate the reciprocals of K_{L1}，K_{L2}，K_{L3}…K_{Lm} and choose the maximum value($1/K_{Lmin}$) as the base value to normalize all the coefficients. The load static characteristic weight then can be expressed by:

$$\lambda_j = \frac{K_{L\,min}}{K_{Lj}}$$ (5)

In which, K_{Lj} is the frequency regulation coefficient of jth load node; K_{Lmin} is minimum value of m coefficients.

The analysis indicates that shed the load with small K_L first can reduce the absorption of active power from system, facilitating the recovery of frequency. The greater λ_j is, the KL is smaller, in order to make full use of load self frequency regulation ability, the load with greater λ_j should be chosen as the key target of load shedding.

2.3. The Comprehensive Weight

Considering the load static characteristic and the disturbance degree load weight comprehensively, a weighted product of these two weights is proposed. In the process of load shedding, the real-time frequency variation of each node can be provided by WAMS, which can be utilized to calculate the load characteristic and disturbance degree, so as to figure out the comprehensive weight of each load node to act as the criterion of load shedding amount and site.

Define the comprehensive weight as:

$$\varphi_j = \lambda_j \cdot \beta_{ij}, \forall i, j$$ (6)

In the process of UFLS, the load with greater comprehensive weight is preferred to be assigned large shedding amount to recover the system as soon as possible.

3. Deficit Power Calculation Base on WAMS

3.1. Deficit Power Calculation Based on Frequency Response Model

In order to estimate the deficit power of whole system accurately, it is reasonable to imagine an equivalent generation unit that describes the average behavior of all the generators. This equivalent unit is called COI. The inertia constant and frequency of COI are defined respectively as follows:

$$f_{COI} = \frac{\sum_{i=1}^{n} H_i \cdot f_i}{\sum_{i=1}^{n} H_i}$$ (7)

In which, f_i is the frequency of ith generator；n is the number of generators.

$$H_{eq} = \frac{\sum_{i=1}^{n} H_i \cdot S_i}{\sum_{i=1}^{n} S_i} \qquad (8)$$

In which, H_i is the inertia constant of ith generator；Si is the rated power of ith generator.

According to the frequency variation curve the WAMS provided, the frequency variation rate of the initial disturbance moment can be calculated by numerical calculation method:

$$\frac{df(n)}{dt} = \frac{(f(n) - f(n-1))}{T_i} \qquad (9)$$

Then the deficit power can be obtained by:

$$P_{def} = \frac{2H_{eq}}{f_N} \frac{df_{COI}}{dt} S_{eq} \qquad (10)$$

$$S_{eq} = \sum_{i=1}^{n} S_i \qquad (11)$$

In which, the f_N is the rated frequency.

3.2. The Voltage Influence Factors of Deficit Power Calculation

The frequency response model ignores the effect of voltage on the deficit in the initial disturbance moment. However, in the process of frequency decrease, node voltage also drops in the meantime, which reflects an existence of a coupling relationship between the active power deficit and the reactive power deficit [7,8]. In the 1~2 seconds of disturbance, voltage variation acts as the leading role in the effect on the change of load active power, henceforth, the frequency replaces the voltage to play a decisive role. Due to the fact that the change of load reflects the deficit active power, at the initial disturbance moment, the voltage will change immediately; therefore, the instantaneous response of load to the voltage variation can not be ignored. The load model concerning the influence of voltage is built below:

$$P_L = \sum_{j=1}^{m} P_{L0, j} \left(\frac{U_j}{U_{0, j}}\right) \qquad (12)$$

On the basis of [9], the deficit power calculations considering the effect of load voltage mutation are given as follows:

$$P_{def} = P_{tur} - P_L \qquad (13)$$

$$P_{shed} = P_{tur} - P_{L0} \qquad (14)$$

$$P_{shed} = P_1 + P_2 \qquad (15)$$

$$P_1 = \frac{2H_{eq}}{f_N} \frac{df_{COI}}{dt} S_{eq} \qquad (16)$$

$$P_2 = \sum_{j=1}^{m} P_{L0, j} \cdot \left[\left(\frac{U_j}{U_{0, j}}\right)^{\alpha} - 1\right] \qquad (17)$$

In which, P_{tur} is the output of turbine; P_L is the load; P_{shed} is the deficit power concerning the voltage influence; m is the number of load nodes; $P_{L0,j}$ is the active power of jth load node before disturbance, $U_{0,j}$ is the voltage of jth load node before disturbance, U_j is the voltage of jth load node after disturbance; α is the voltage influence factor and α=1 is chosen in this paper. The calculation result of Equation (9) is chosen as the base value of load shedding amount.

4. UFLS Scheme with Dynamic Correction

On the basis of the measurement data provided by WAMS, calculate the deficit power using Equation (9) as the base UFLS shedding amount. With reference to the real UFLS, the conditions for activation of individual steps are equal to the following threshold frequencies: 49.2 Hz, 49 Hz, 48.8 Hz. All of the four predefined distributions $P_{shed,k}(k =1,2,3)$ are set in accordance with the traditional UFLS scheme: 30%, 30%, 40% of the deficit power.

Due to the effect of speed governor and load frequency characteristic, after each load shedding step implemented, the frequency change rate does not remain constant, which will lead to the change of deficit power. Prior to the implementation of load shedding, the frequency decreases dramatically, i.e. the frequency drop rate is the largest. After each load shedding step, the frequency is relieved, which in return reduces the deficit power, reducing the corresponding load shedding amount. However, the traditional scheme lacks of the correction of load shedding, which will inevitably result in overcut, so it's necessary to adjust the predefined load shedding steps to the primary frequency-control reaction. It is obvious from Equation(4) that the deficit power is a nearly linear function of frequency change rate, in general, the $x\%$ lowering of P_{def} is reflected in an $x\%$ lowering of frequency change rate. Based on this linearity concept, before the kth shedding step is activated, with the use of WAMS, monitor the changes in df_{COI}/dt between two neighboring shedding steps and compare it to the initial($df_{COI, max}/dt$)value, and the percentage change of df_{COI}/dt is calculated:

$$\Delta_k\% = \frac{df_{COI, k-1}/dt - df_{COI, k}/dt}{df_{COI, max}/dt} \cdot 100 \qquad (18)$$

Keeping in mind the presented linearity concept, the frequency variation rate change gradient $\Delta_k\%$ demonstrates the change in deficit power. As a result, the upcoming shedding step can be altered from its predefined value $P_{shed,k}$ according to:

$$P'_{shed, k} = P_{shed, k} - \Delta_k\% \qquad (19)$$

After the achievement of kth shedding amount, the requirement of control rapidity is taken into account to

introduce a new method to distribute the $P'_{shed,k}$ in combination with the proposed comprehensive load weight. The shedding amount of each load node is calculated by:

$$P_{shed,j} = P'_{shed,k} \times \frac{\varphi_j}{\sum_{j \in M} \varphi_j} \qquad (20)$$

In which, M is a set of all load nodes. Consequently, activate each shedding step according to the thresholds to gradually restore the frequency.

The detailed process of UFLS is shown in **Figure 1**.

5. Test System Proposed UFLS Scheme

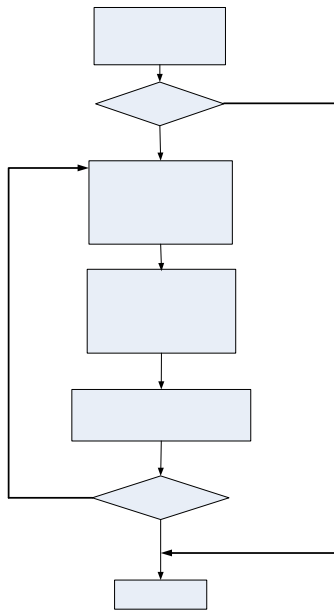A load shedding procedure was tested on an island of a 39-bus IEEE test system, which is given in **Figure 2**.
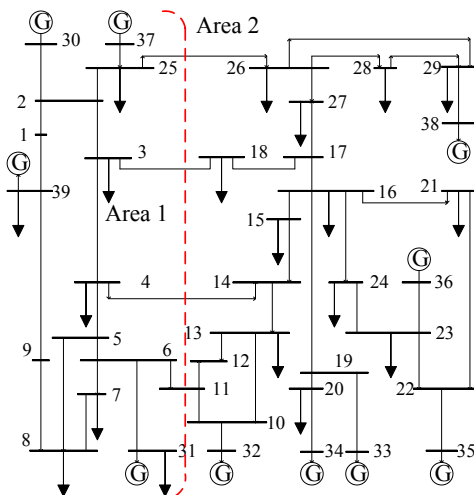

Figure 1. Flow chart of UFLS.

Figure 2. IEEE39 nodes power system.

At 4 seconds, line 25-26, 3-18, 4-14 and 6-11 are cut simultaneously; area 1 becomes an isolated grid with a large deficit power. **Figure 3** demonstrates the variation of frequency provided by WAMS at the very moment that the grid splits.

This paper selects the data from WAMS within 3 time cycles after disturbance, using Equation (3) calculates and averages, as the system frequency variation rate of this moment. At the instant that frequency drops, calculates the deficit power of this moment using Equation (5) as the base load shedding amount. The variation of voltage while islanding is shown in **Figure 4**.

The combination with **Figure 3** and **Figure 4** indicates that the voltage of load nodes also plunges dramatically at the instant frequency declines, especially 1-2 s after disturbance. Henceforth, due to the regulation of excitation system, the voltage gradually restores while the frequency continues to decrease. It verifies that the voltage variation plays the leading role on the change of load active power at the initial stage of disturbance; the frequency replaces it as main factor afterwards. Irrespective of the influence of voltage, the deficit power is: P_{def} =5.5025 p.u and it is P_{def} =5.3911 p.u when voltage is
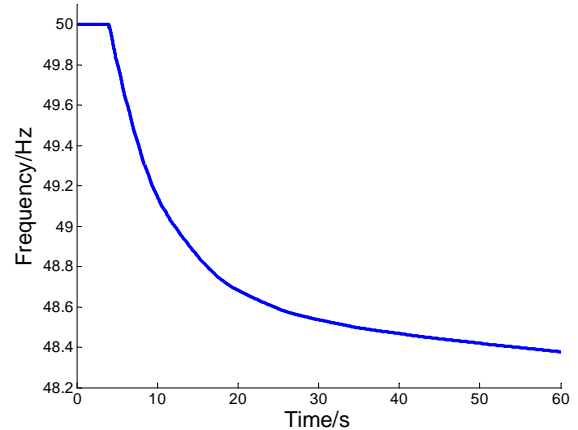

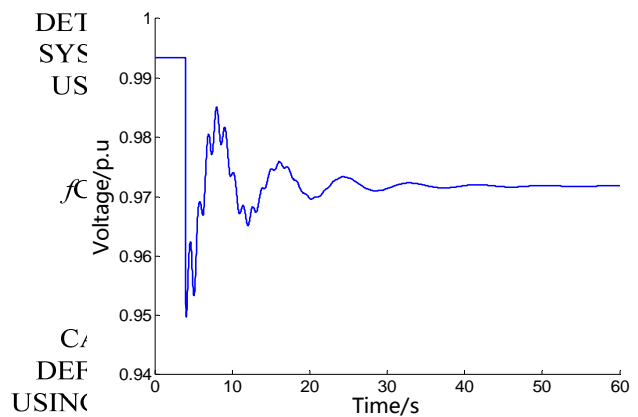**Figure 3. The frequency variation curve while islanding.**

Figure 4. The voltage variation curve while islanding.

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taken into account. It is obvious that the voltage mutation can not be ignored in the estimation of deficit power. It will cause great error or even likely lead to problems such as overcut without concerning the influence of voltage.

It is a fact that the estimated deficit power is not identical to the actual value. It is vital to modify the loadshedding amount of each stage to ensure a precise control.

The frequency variation rate of inertia center is recorded maximum at the beginning of disturbance: $max(df_{COI}/dt)=-0.8695$ Hz/s. When the frequency reaches the first frequency threshold 49.2 Hz, the df_{COI}/dt is measured and $\Delta_1\%=4.9\%$ is calculated by Equation (11). Applying Equation (13), the shedding amount of first step is modified and the actual amount is: $P_{shed1}' = 30\%-4.9\% = 25.1\%$. Calculate the comprehensive weight of each load node by Equation (11) and distribute the load-shedding amount using Equation (14). The comparison of load shedding amount is listed in **Table 1**.

The load shedding corrections of each step are $\Delta_2\% = 1.4\%$, $\Delta_3\% = 0.47\%$ respectively. The total shedding amount with dynamic correction is 6.77% less than the base value, which fully demonstrates the effectiveness of the dynamic correction.

In order to validate the effectiveness of the proposed comprehensive weight, three UFLS schemes with dynamic correction are compared. Scheme 1 is the one proposed in this paper with 4 steps; Scheme 2 distributes the shedding amount according to the load characteristics; Scheme 3 sheds load by the load proportion, namely, the lager the load is, the more it sheds. After the activation of first step, the frequency recovery curves of each scheme are shown in **Figure 5**.

It can be seen from **Figure 5** that the proposed Scheme 1 can restrain the decrease of frequency quickly due to the fact that enough load-shedding amounts are ensured in the first step. The frequency stabilizes at 48.45668 Hz, better than 48.41676 Hz of Scheme 2 and 48.37678 Hz of Scheme 3.

After all the steps activated, the frequency recovery curves are shown in **Figure 6** and the shedding amounts are listed in **Table 2**.

The recovery time of the scheme proposed in this paper is 29.38 s, while Scheme 2 is 32.27 s and Scheme 3 is 34.96 s. The total load shedding amount of Scheme 1 is 5.0261 p.u, Scheme 2 is 5.0214 p.u and Scheme 3 is 5.0337 p.u. Without considering the load characteristics or other factors, the recovery time and shedding amount of Scheme 3 is unsatisfied. The shedding amount of first step is largest in Scheme 1. However, it is of significance to ensure the load shedding amount in first step to guarantee the frequency recovery. Although, the loads shed of Scheme 1 are more than Scheme 2, the recovery curve rises dramatically, better than that of Scheme 2 and 3. Besides, the recovery time is shortest, which proves that an effective control has been implemented at the key site to meet the demand for control rapidity. Considering the two aspects above, the UFLS scheme with dynamic correction makes full use of the self frequency recovery ability to significantly reduce the total shedding amount compared with the traditional one. Scheme 1 distributes

Table 1. The results of dynamic correction.

Scheme	Load shedding steps		
	1st step	2nd step	3rd step
Traditional scheme	30%	30%	40%
Dynamic scheme	25.1%	28.6%	39.53%

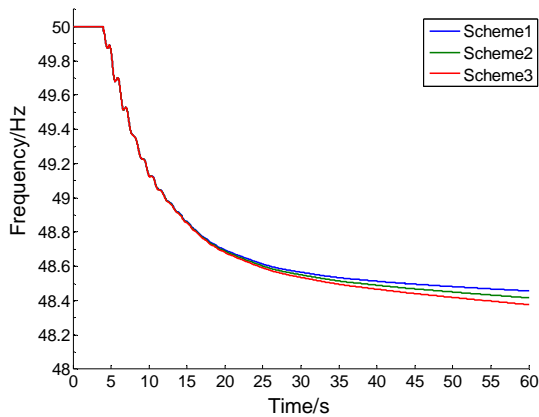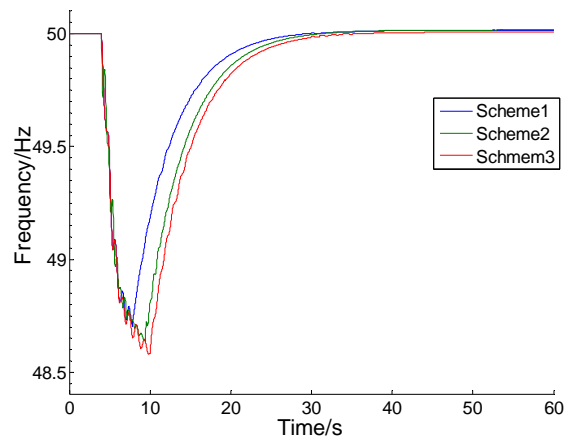**Figure 5. The frequency recovery curves of different under-frequency load shedding schemes after the first step.**

Figure 6. The frequency recovery curves of different under-frequency load shedding schemes.

Table 2. The total amount of shedding load of each scheme.

	Scheme 1	Scheme 2	Scheme 3
1st step	1.3531	1.3474	1.3489
2nd step	1.5419	1.5432	1.5512
3rd step	2.1311	2.1308	2.1336
total	5.0261	5.0214	5.0337
Recovery time	29.38s	32.27s	34.96s

loadshedding amount in accordance with the synthetic weigh proposed. Although the shedding amount of scheme1 is not the least, the frequency stabilizes faster at a small cost. Therefore, Scheme 1 is optimal by a comprehensive comparison.

6. Conclusions

This paper proposes a new adaptive UFLS scheme base on WAMS, the main research achievements and conclusions are as follows:

1) Combine the UFLS with WAMS and modify the traditional UFLS with adaptive UFLS, effectively shortening the time delay of frequency control.

2) The frequency variation rate of the COI is adopted and the influence of voltage is taken into account to estimate the deficit power.

3) In order to lower the shedding amount, a procedure is given for dynamically adjusting the amount of the shedding steps to adapt to the primary frequency-control response, which reduces the possibility of overcut and unnecessary load losses.

4) A multi-factor comprehensive weight is proposed to distribute the load shedding amount, which facilitates the recovery of frequency as soon as possible.

The proposed method provides a new reference and idea for the online application of frequency-control.

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