An Under-frequency Load Shedding Scheme with Continuous Load Control Proportional to Frequency Deviation

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Abstract. Under frequency load shedding (UFLS) is an important measure to tackle with frequency drop caused by load-generation imbalance. In existing schemes, loads are shed by relays in a discontinuous way, which is the major reason leading to under-shedding and over-shedding problems. With the application of power electronics technology, some loads can be controlled continuously, and it is possible to improve the UFSL with continuous loads. This paper proposes an UFLS scheme by shedding loads continuously. The load shedding amount is proportional to frequency deviation before frequency reaches its minimum during transient process. The feasibility of the proposed scheme is analysed with analytical system frequency response model. The impacts of governor droop, system inertia, and frequency threshold on the performance of the proposed UFLS scheme are discussed. Cases are demonstrated to validate the proposed scheme by comparing it with conventional UFLS schemes.

1. Introduction

Frequency is an important index of power quality related to active power imbalance between generation and load and must be maintained within a limited range. Severe frequency deviation may not only affect the normal operation of electric equipment, but also damage the turbines permanently, which will bring huge economic losses. It is necessary to control frequency under severe disturbances.

UFLS is an important measure to keep the system frequency stability against severe disturbances [1]. Generally, the primary objectives of UFLS are to shed appropriate amount of loads to restrict frequency deviation. Existing UFLS methods can be divided into two types, traditional UFLS with shedding stages and adaptive UFLS. Other UFLS schemes based on the two types are also presented in literatures. For example, an optimal scheme in load shedding amount is designed in [2] for systems with high penetration of renewable generation based on traditional UFLS. Otherwise, an UFLS scheme with independent power system parameters is proposed in [3] for hybrid and multi-area power systems based on the adaptive UFLS scheme.

Specifically, traditional UFLS schemes with shedding stages determine the frequency threshold, tripping load and time delay of each stage before hand and shed the load step by step until frequency recovers. These schemes, if properly set, can shed appropriate amount of loads reliably under typical operating conditions. However, the discontinuity of total load shedding amount caused by shedding stages may lead to under-shedding for some cases [4]. Therefore, special stages with long time delay are usually added to the traditional schemes as backup to improve its adaptability under abnormal operating conditions [5]. Adaptive UFLS schemes estimate the power imbalance by calculating initial slope of frequency deviation, and modify shedding amounts online to adapt to a variety of

disturbances. To properly estimate the power imbalance, a supplement algorithm is necessary to acquire the initial rate of change of frequency and the system inertia constant accurately. Inaccurate initial slope or inertia may lead to poorly estimated imbalance [6].

With more and more devices powered by power electronics and controlled by smart controllers, some loads such as electric vehicles, mass storage, etc., can be controlled to change its power continuously [7]. The continuously controllable load is promising to participate in frequency control to improve the performance of UFLS, and overcome the problems of traditional schemes.

This paper proposes a novel UFLS scheme with continuously controllable loads. The rest of the paper is organized as follows. In section 2, the idea of the scheme is presented and its feasibility is analysed with the analytical system frequency response model. In section 3, the impact of some key parameters on the performance of the proposed scheme is checked, and frequency threshold for starting the UFLS is added to improve its practicability. In section 4, the proposed scheme is compared with two conventional UFLS schemes to illustrate its performance. Conclusions are made in section 5.

2. Load shedding scheme with continuous load control

2.1. Idea of the proposed scheme

The conventional UFLS schemes are to shed loads by activating relays installed in substations to trip transmission lines, and the loads supplied by the tripped lines are shed. It is reasonable to shed loads according to the exact power imbalance. However, due to the discrete nature of tripping transmission lines, the amount of shed load is discontinuous. It is possible that the same amount of loads is shed for different disturbances, which is not expected for UFLS. In order to ensure the reliability of conventional UFLS schemes, a certain margin and time delay must be considered since a large number of loads are lost in each action. Therefore, the discontinuity of total load tripping amount may lead to conservative UFLS schemes which have the risk of under-shedding or over-shedding under some conditions.

With the emerging continuously controllable loads, the problems caused by discontinuous load can be overcome. For traditional schemes, the final load shedding amount is successively approximate by the load of each stage based on transient state frequency deviation. In other words, there is a positive correlation between the amount of load shedding and the maximum of frequency deviation. In order to apply the rule to the scheme with continuous load, load shedding sensitivity is defined as the load shedding amount corresponding to per unit frequency deviation. Thereby, the load shedding amount is equal to

$$\Delta P_L = K \Delta f \tag{1}$$

where f is the frequency deviation at a certain point before frequency reaches the minimum in the transient process, and K is the coefficient of load shedding sensitivity.

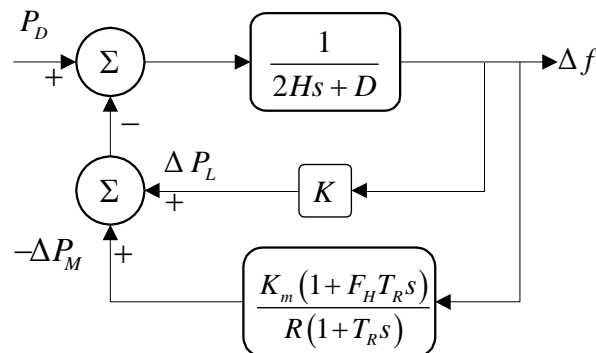### 2.2. Feasibility of the proposed scheme

Figure 1. System frequency response model with proposed UFLS scheme

In order to analyse the frequency response characteristics and optimize the control effect of the proposed scheme, the reduced system frequency response (SFR) model is used to calculate the transient state frequency analytically [8]. Obviously, the load shedding scheme of equation (1) can be represented by a negative feedback with K as a gain. Therefore, the frequency response during the load shedding process can be calculated by the model shown in figure 1. In the model, the system is described by the inertia constant (H), damping factor (D), reheat time constant (T_R), fraction of total power generated by high pressure (F_H), mechanical power gain factor (K_m) and governor droop factor (R). Moreover, during the transient process without load shedding, the response under the disturbance with initial active-power deficits (P_D) can still be calculated by the model by setting $K=0$.

The Laplace transform form of frequency deviation can be represented by equation (2),

$$\Delta f(s) = \frac{R}{(D+K)R+K_m}\left(\frac{(1+T_R s)P_D}{s^2 + 2\delta\omega_n s + \omega_n^2}\right) \tag{2}$$

where,

$$\omega_n^2 = \frac{(D+K)R+K_m}{2HRT_R} \tag{3}$$

$$\delta = \left(\frac{2HR + ((D+K)R + K_m F_H)T_R}{2((D+K)R+K_m)}\right)\omega_n \tag{4}$$

It should be noted that, the frequency response model is valid only before the frequency reaches its minimum. The equation (2) can be represented in time domain as (5),

$$\Delta f(t) = \frac{R \times P_D}{(D+K)R+K_m}\left(\frac{c_1\left(e^{\lambda_1 t}-1\right)}{\lambda_1} + \frac{c_2\left(e^{\lambda_2 t}-1\right)}{\lambda_2}\right) \tag{5}$$

where,

$$\lambda_{1,2} = -\delta\omega_n \mp \omega_n\sqrt{\delta^2-1} \tag{6}$$

$$c_{1,2} = \omega_n^2(1+T_R\lambda_{1,2})\big/\left(\lambda_{1,2}-\lambda_{2,1}\right) \tag{7}$$

Since the load shedding process is stopped when Δf reaches the minimum, based on equation (1) and (5), the total load shedding amount (P_{shed}) can be represented by equation (8),

$$P_{shed} = \frac{-KRP_D}{(D+K)R+K_m}\left(c_1\lambda_1^{-1}\left(\left(\frac{c_1}{-c_2}\right)^{\lambda_1/(\lambda_2-\lambda_1)}-1\right) + c_2\lambda_2^{-1}\left(\left(\frac{c_1}{-c_2}\right)^{\lambda_2/(\lambda_1-\lambda_2)}-1\right)\right) = C(K)\times P_D \tag{8}$$

$C(K)$ is function of K and can be treated as a constant with specific K. Therefore the total load shedding amount is proportional to the initial active power deficits. In other words, P_{shed} has the ability to adapt to the change of P_D.

It can be proved in equation (9) that P_{shed} is exactly equal to $-P_D$ as K goes to infinity.

$$\lim_{K\to\infty} P_{shed} = \lim_{K\to\infty}\frac{-KRT_R}{2HR+(DR+K_m F_H)T_R+KRT_R}P_D = -P_D \tag{9}$$

Equation (9) confirmed that P_{shed} is always less than $-P_D$ whatever the value of K is. It means that the proposed scheme is adaptive with a proper K and there is no risk of over-shedding. In conclusion, the proposed UFLS scheme is able to shed appropriate amount of loads by determining a proper K based on system parameters.

3. Impact of system parameters and frequency threshold on the proposed scheme
Although the load shedding amount of scheme presented in section 2 has a satisfactory adaptability with the load-generation imbalance, there are still some limitations that need to be considered in the

application. In order to check the impact of system parameters and threshold on scheme performances, the model proposed in section 2 is analysed in this section as P_D=-0.2, H=4s, T_R=8s, D=1, F_H=0.3, K_m=0.95, R=0.05.

3.1. Impact of governor droop and inertia

The simplified system has 6 parameters based on the model shown in figure 1. It is showed in equation (8) that the P_{shed} depends on system parameters as well as K under certain P_D. In this paper, the impact of the parameters is analysed taking the governor droop factor and inertia constant for example.

The reciprocal of governor droop factor ($1/R$) represents the character of primary frequency control. For different power systems, the frequency regulating parameter R is adjusted accordingly. With different units participating in frequency regulation, the effective R will be changed. Thus it is needed to check the impact of R on the performance of UFLS.

The inertia H shows the system size of different systems and the great H means the system is prone to survive with disturbance. However, for system with little H, e.g., micro-grids, operated in isolated mode, its frequency stability can be deteriorated. Thus, the impact of H on UFLS is also needed to be discussed.
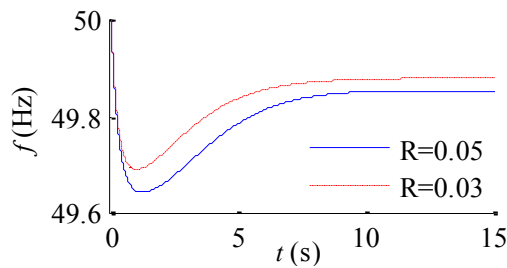

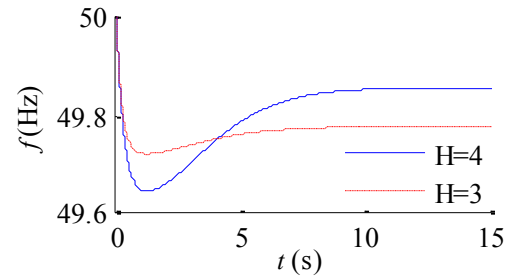**Figure 2.** Frequency responses with K=20.   **Figure 3.** Frequency responses with K=20.

The impact of the governor droop factor and inertia constant on load shedding amount and frequency responses is shown in figure 2 and figure 3. It should be noted that steady state frequency is more decisive than minimum of transient state frequency since the ability of intercepting the frequency decline is efficient enough to limit the minimum of transient state frequency. In terms of steady state frequency, the effect of frequency restoration with R=0.03 is better than R=0.05, while, the frequency restoration effect of H=4 is better than H=3. Therefore, the load shedding amount should be increased with R and decreased with H. That is to say K should be set to different values with different systems.

3.2. Impact of frequency threshold

Generally, UFLS needs an action threshold so that the UFLS relays have the ability to avoid the occasional contingencies in which the frequency restoration can be completed with the spinning reserve capacity generation. The technical rules for power system automatic under-frequency load shedding in China stipulates that the action threshold should not higher than 49.25 Hz. Therefore, the equation (1) needs to be replaced by equation (10) where $\Delta f_{threshold}$ is the frequency deviation based on nominal value in per unit. The equation (10) means that the UFLS will not be started when the frequency higher than $f_{threshold}$ (in Hz) and the amount of load shedding is proportional to frequency deviation after that.

$$\Delta P_L = K\left(\Delta f - \Delta f_{threshold}\right) \tag{10}$$

The impact of threshold on load shedding amount is showed in figure 4. It shows that the characteristic which the load shedding amount always less than the load-generation imbalance on longer exists when $f_{threshold}$=49.25 Hz. However, the P_{shed} still increases with greater K and will not exceed the initial imbalance until K is greater than 75. The impact of threshold on frequency responses is shown in figure 5. It is clear that the minimum transient frequency and the steady state frequency with $f_{threshold}$=49.25 Hz are significantly less those with $f_{threshold}$=50 Hz. As a result, K should be determined based on the effect of frequency restoration within certain range.
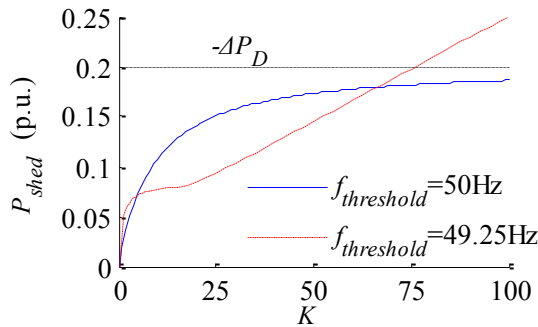
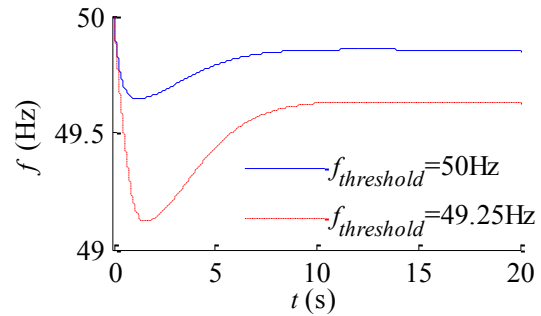**Figure 4.** Load shedding amount with different threshold.

Figure 5. Frequency responses with different R.

4. Case study

The steady state frequency under a severe disturbance should restore to a security value. It is specified as 49.5 Hz by the technical rules for power system automatic UFLS in China to ensure the turbine can operate continuously. Assume a system with H=4s, T_R=8s, D=1, F_H=0.3, K_m=0.95, R=0.05 and the maximum of possible active power imbalance is 40%.

Scheme 1 is the UFLS scheme proposed in this paper with $f_{threshold}$=49.25 Hz. With the 40% imbalance, the K for which the steady state frequency is exactly restored to 49.5 Hz is 25. Therefore, to restore the steady state frequency to 49.5 Hz with any size of imbalance less than 40 %, K should be set to 25 or more. In the follow tests, the load shedding sensitivity is set to 30 due to security margin. Scheme 2 is a traditional UFLS and has 7 stages, whose he thresholds are 49.25, 49.00, 48.75, 48.50, 48.25, 48.00, 47.75 Hz and the corresponding load shedding ratios are 4%, 5%, 6%, 6%, 6%, 6%, 6%. In addition, each stage has a delay equal to 0.2s. Scheme 3 is an adaptive UFLS and shed the load in two equal-sized stages by estimating the value of imbalance [9]. The frequency threshold and delay of the first stage is set to 49.25 Hz and 0.2 s. The second stage is triggered in 0.2s after the first stage action.
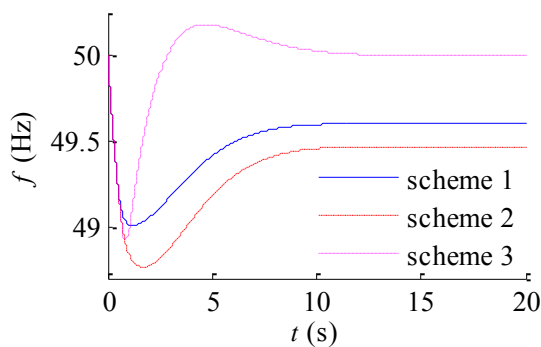

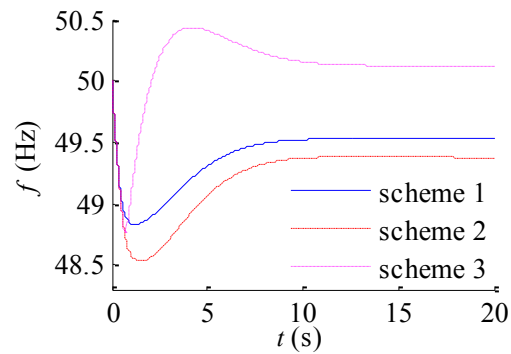**Figure 6.** Frequency responses of 3 schemes without estimation error.

Figure 7. Frequency responses of 3 schemes with estimation error.

The frequency responses are shown in figure 6 when the system loss 30% of power generation, in particularly, scheme 3 is performed with accurate estimate value. It can be seen that scheme 1 and 3 can restore the steady state frequency above 49.5 Hz. However, an under-shed is found in scheme 2. Specifically, the steady frequency of scheme 1 is 49.60 Hz since the imbalance is less than the maximum of possible active power imbalance. Besides, the steady state frequency of scheme 2 is slightly lower than 49.5 Hz since the minimum of the transient state frequency is near the threshold of third stage and the steady state frequency of scheme 3 is exactly 50 Hz since the estimate imbalance is accurate. To make full use of the spinning reserve, it is not necessary for UFLS to restore the frequency to the nominal value.

The frequency responses are shown in figure 7 when the system generation loss is 40%. It should be noted that the estimate imbalance is wrong with the value equal to 45%. Obviously, only the steady state frequency of scheme 1 can still restore to 49.5 Hz, while, an over-shed due to inaccurate estimation is found in scheme 3. The steady frequency of scheme 1 is 49.52 Hz. It means the proposed scheme can reliably restore the frequency in any disturbance which active power imbalance less than 40%.

The results in figure 6 and 7 are only 2 representative examples of a large number of simulations. It is shown that even if the mal-operation occurs due to the low adaptability of traditional schemes or low estimation accuracy of adaptive schemes, the proposed scheme can still shed load so appropriately that the frequency can restore to a security value with continuous load.

5. Conclusions

A UFLS scheme is proposed to adapt to the development of continuous load. The proposed scheme inherits from the traditional UFLS schemes briefly and shed the load proportional to the frequency deviation using the continuity of the load. In order to describe the proportional relationship, the load shedding sensitivity is defined in this paper. And then, the scheme feasibility is verified without the starting threshold and the adjusted capacity of the continuous load. Although the frequency response characteristics of the scheme are affected by system parameters and frequency threshold, the scheme can still obtain the control effect similar to that of reduce ordered-model. Example shows that the proposed scheme has a great improvement in adaptability with continuous load.

Acknowledgement

References

[1]   2004 IEEE Guide for Abnormal Frequency Protection for Power Generating Plants *IEEE Std C37.106-2003*

[2]   Spallarossa P and Del Rosso A 2016 Underfrequency load shedding scheme for systems with large penetration renewable variable generation *Biennial Congress of Argentina* p 1-7

[3]   Ketabi A and Fini M H 2015 An underfrequency load shedding scheme for hybrid and multiarea power systems *IEEE Trans. Smart Grid* **6**(1) p 89-91

[4]   Delfino B, Massucco S, Morini A 2001 Implementation and comparison of different under frequency load-shedding schemes *Poc. IEEE Power Eng. Soc. Summer Meeting* p 307-312

[5]   Li C, Liu Y and Qiu X 2013 Optimization of Under-frequency Load Shedding Schemes Based on Transient Frequency Deviation Security *Automation of Electric Power System* **37**(4) p 51-56

[6]   Rudez U and Mihalic R 2016 WAMS-Based Underfrequency Load Shedding With Short-Term Frequency Prediction *IEEE Trans. Power Del.* **31**(4) p 1912-20

[7]   Li Y, Ng L B, Trayer M and Liu L 2012 Automated Residential Demand Response:Algorithmic Implications of Pricing Models *IEEE Trans. Smart Grid* **3**(4) p 1712-21

[8]   Anderson P M and Mirheydar M 1990 A low-order system frequency response model *IEEE Trans. Power Syst.* **5**(3) p 720-29

[9]   Anderson P M and Mirheydar M 1992 An adaptive method for setting underfrequency load shedding relays *IEEE Trans. Power Syst.* **7**(2) p 647-55