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Adaptive Under-Frequency Load Shedding Scheme in System Integrated with High Wind Power Penetration: Impacts and Improvements

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Abstract: As the requirements of economical operation and reliability on power grid are enhanced gradually nowadays, the existing under frequency load shedding (UFLS) scheme is not quite fit for the modern power system that integrates high wind power. In this paper, the impacts of high wind power penetration on the UFLS are discussed thoroughly. A novel adaptive load shedding (LS) scheme is presented taking the high wind power penetration into account. In the proposed scheme, the equivalent inertia constant (EIC) is calculated accurately to improve the power deficit accuracy so as to reduce the error of LS. The dynamic correction of power deficit is able to solve the negative effects of the wind power output random reduction/the wind generator tripping. Besides, the locking criterion is capable of avoiding the influences of the wind power output random increase on the LS, thus cutting down the LS costs and even preventing the frequency overshoot. Moreover, in terms of the LS parameters setting, the coordination of the low frequency protection of the wind generator and the frequency threshold is addressed. The location and capacity model of LS, which is based on the load characteristics, can ameliorate the frequency recovery process. Finally, the validity and robustness of the proposed scheme are verified in the simulations on the IEEE-39 bus system with high wind power penetration.

Keywords: equivalent inertia constant (EIC); high wind power penetration; load shedding locking criterion; power deficit dynamic correction; under frequency load shedding (UFLS)

1. Introduction

The penetration of wind power is growing rapidly in the modern power system in recent years around the world [1]. The Global Wind Energy Council statistics report [2] shows that as of 2014, the global wind power capacity had reached 369.6 GW in total and the new installed capacity reached 51.5 GW. By the end of 2014 in China, the new installed capacity was 23.2 GW, which increased by 44.2% since 2013. And the total installed capacity reached 114.6 GW, which was caused by an increase of 25.4% during 2013. As of 2014, some great offshore wind power projects with a total installed capacity of 657.88 MW were built in China. Additionally, several large-scale wind farms with the capacity of more than 10 GW are planned to be built in Northwest China in the near future.

The UFLS (For detailed meanings of abbreviations, refer to Table A3 of Appendix A) is a regular operation of the defense plan under the severe frequency decline conditions. It can restore the frequency to the reasonable value and prevent wide blackout [3]. Large-scale wind power penetration will greatly change the system frequency dynamics and increase significant issues in operation and control of the power system, such as the UFLS [4]. However, those negative effects on the UFLS scheme have rarely been considered or researched in the available literature. Hence, the existing UFLS

strategies applied in traditional power systems should be reassessed with the presence of high wind power penetration.

There has been ample research about the UFLS in recent literature. The comparisons among traditional, semi-adaptive and adaptive schemes were conducted in [5]. For the traditional strategy, the number and size of load shedding steps are determined based on numerous trials to achieve an acceptable operation in the case of the worst probable failure. However, a specified quantity of load is curtailed without considering the power deficit value. Consequently, in most fault scenarios the quantity of load which is shed will be less or more than necessary, and this might lead to undesired damage or serious costs. Therefore, the adaptive method is proposed and a reasonable amount of load based on the calculated power deficit is shed in the specified steps. The approach to use the Rate of change of frequency (RoCoF) to calculate the power deficit in the UFLS was proposed in [6–9], and it is the first generation of adaptive UFLS. One defect of this approach is that the quantity of shed load does not have a linear relation with power deficit. As a result, using this method, the amount of shed load in consequence of two nearly equal power deficits may differ significantly.

With the rapid development of smart grid, more and more sophisticated and intelligent UFLS algorithms based on the traditional strategy and the first generation of adaptive UFLS have recently been designed. A case study of UFLS strategy that coordinated with the intelligent appliances in a cyber-physical power system can be found in [10]. [11–13] respectively transformed the UFLS problem into the optimization problems, which are subsequently solved by integer programming [11] method, decoupled method [12] and genetic algorithm [13]. In [14], the probabilistic approach was used in order to quantify the performance of various configurations of traditional UFLS (varied both in the number of shedding steps as well as their capacity) in the whole variety of operating conditions. However, the inherent drawback of the traditional UFLS type is that the excessive economic losses resulted by the load over-shedding still cannot be addressed. Based on the wide area measurement system (WAMS), a sensitivity study was given in [15] to optimize the location and related amount of load to be curtailed. The above methodologies do not analyze the impacts of wind power while the large-scale wind farms become a salient feature in the modern power grid. Hence, a lacking of adaptability is expected inevitably, and it may bring about frequency instability under some fault scenarios that the wind power output fluctuates extremely. So, the adaptive UFLS scheme with prediction abilities in [16,17] are carried out to cope with some kind of predictive uncertainty. Thus, it is able to be utilized for managing unpredictable wind farm power variations. However, this scheme still has its shortcomings, such as the predictive method potentially failing when the extreme value of system-wide frequency gradient occurs and the great influences of wind power on the UFLS have not been analyzed.

Lately, some studies have been performed which consider the renewable energy generation. It was highlighted in [18] that the output power of photovoltaic and wind generation might change during the UFLS period, thus the power generation variations during the UFLS were considered. In [19], the authors proposed an improved UFLS in the islanded distribution network with high penetration of solar photovoltaic generation. Also, the approach of [20] focused on the effects of high photovoltaic penetration on the distributed system, but all of the simulations were carried out in the distributed grid. The frequency dynamic response of a realistic power system with reasonable integration of wind power was studied in [21]. However, few of these schemes above analyze the improvement direction of UFLS from the perspective of high wind power penetration.

Today, the demands of economical operation and reliability on power system are enhanced gradually, and this means the UFLS should keep the frequency stability better with most economical LS costs. So, a novel UFLS scheme is designed in this paper taking the high wind power penetration under consideration. There will be three major impacts on the UFLS when the wind generations are highly penetrated. These impacts are the fact that the system inertia time constant is not a fixed value; the low-frequency protection and the low voltage ride through of wind generator; the power output randomness of wind generation. We propose and integrate in our proposed scheme the solutions

for those major impacts. Furthermore, several key parameters, namely, the frequency threshold, the location and its amount of load to be curtailed, are also important. These parameters have not yet been optimized in the novel scheme. Besides, a locking criterion of LS is applied to reduce the probability of load over-shedding. Finally, various fault scenarios which consider the wind generation variation have been set up to verify the effectiveness of this scheme.

This paper is organized as follows: the significant impacts of high wind power penetration on the UFLS are analyzed and highlighted in Section 2. The solutions to handle these major impacts are presented in Section 3. The detailed parameter settings of the UFLS are proposed in Section 4. The setup of fault scenarios and the results and discussions of simulation are stated in Sections 5 and 6. Lastly, the conclusions are objectively drawn in Section 7.

2. The Major Impacts of High Wind Penetration on the UFLS Scheme

For the UFLS scheme, the high wind power penetration of the modern power system will have some great impacts on its effectiveness. The major influencing factors are concluded and categorized as follows under rigorous consideration: (a) In terms of the inertial response characteristics, there is a difference between the wind generator and the synchronous generator. For the wind generator with the virtual inertial control, its EIC owns some uncertainty; (b) The randomness of the wind power output. That is the wind output power that is intermittent and fluctuating; (c) The low frequency protection and low voltage ride-through of the wind generator.

2.1. Uncertainty of the Equivalent Inertia Constant

In the study of the dynamic frequency characteristics of the system with high wind power penetration, the analytic solution of EIC is a challenging task. In general, the inertia constant of the synchronous generators in the traditional grid is deterministic. However, for the wind generator with the virtual inertial control, its inertia constant is difficult to obtain [22]. Besides, the EIC would vary due to the uncertainty of wind generation and its virtual inertial control, thus this value is not fixed.

Generally, the existing adaptive UFLS strategies apply J_{eq} (For detailed meanings of nomenclature, refer to Table A4 of Appendix A) and RoCoF to calculate the power deficit of system under the disturbances or faults, as in Equation (1).

$$P_{def} = \sum (P_m - P_e) = \frac{J_{eq}}{f_N} \times \frac{df_{COI}}{dt}$$
(1)

The parameter f_{COI} can be calculated as in Equation (2).

$$f_{COI} = \frac{1}{J_{eq}} \sum_{i=1}^{n_G} J_i f_i \tag{2}$$

The accuracy of the LS is closely related to P_{def} , and the calculation of P_{def} is dependent on J_{eq} . Hence, the improved LS scheme needs to take the impact of the uncertainty of EIC into account.

2.2. Randomness of the Wind Power Output: Intermittent and Fluctuation

The wind speed often shows strong intermittency and fluctuation. Correspondingly, the wind power output is uncertain and it will vary randomly [23]. The fluctuation of wind power is caused by the pulse wind speed, and its intermittency is caused by the sudden change of the average wind speed, which means that the average value of wind speed in the geographical area is covered by the wind farm. The common changes in wind speed are as depicted in Figure 1. This paper argues that the great variations of wind speed depicted in (a) affect the effectiveness of LS (the icon ① and ② represents the process of wind speed increases and decreases in a sudden, respectively; the icon ③ and ④

respectively stands for the process of wind speed gradually rising and dropping), whereas the smooth fluctuations of wind speed which are identified as (b) do not need to be considered.



Figure 1. Diagram of the commons changes in wind speed: (a) Large fluctuation; (b) Small fluctuation.

If the wind speed varies greatly during the UFLS implementation, the unbalanced power of grid will change due to the variations of wind generator output. The power shortage will be mitigated when the output of the wind generator increases, then the amount of loads required to be shed should be reduced. In the opposite situation, the quantity of loads to be curtailed must be increased to avoid the rapid decline of frequency.

Nevertheless, most of the existing UFLS are based on the predefined LS parameters in case of the worst probable failure. In addition, the rest of these are only adaptive to the power deficit at the time of the disturbance. As a result, the dynamic changes of unbalanced power that may occur during the UFLS process are out of consideration [24]. Accordingly, the execution of these schemes may easily lead to load over-shedding or less-shedding under different failures of the grid with high wind power penetration. The former indicates the LS implementation is uneconomical, whereas the latter may even cause frequency collapse in some serious contingencies. Consequently, the randomness of the wind power output demands attention.

2.3. Regulations: The Low Frequency Protection and Low Voltage Ride-Through of the Wind Generator

According to the "technical requirements for wind farm grid connection in Chinese grid" [25], the wind generator is required to run in the frequency range of $48.0 \sim 49.5$ Hz for 30 min at least in China. When the frequency is lower than 48.0 Hz, the wind generator can be tripped based on its minimum operating frequency. In addition, the wind generator is capable of the low-voltage ride through (LVRT). The LVRT characteristics in the Chinese regulations are depicted as Figure 2. That is: the wind generator should continue to run 625 ms when its bus-voltage drops to $0.2 U_N$, and the wind generator cannot be tripped when its bus voltage can restore to $0.9 U_N$ within 2 s. While the bus-voltage of wind generator drops below the red-line, it should be tripped.



Figure 2. The low voltage ride-through of wind generator in China.

Though the wind generator has the short time ability of LVRT, its protection standards of the low frequency and the low voltage are stricter compared to those of the synchronous generator. This means the wind generator is more likely to be tripped due to the low frequency or low voltage problem during the UFLS operation. Also, it will bring about greater power deficit, which will exacerbate the speed of frequency decay. As a consequence, the novel UFLS scheme should be able to effectively identify the adverse cases of the wind generator tripping. Moreover, the parameters settings of LS should be coordinated with the low frequency protection setting of the wind generator.

3. The Solutions for the Major Impacts of High Wind Penetration

3.1. Calculation of the EIC

The EIC J_{eq} is not actually fixed due to the fact that the power generating units are in a certain distribution throughout the power system which is integrated with high wind power penetration and their composition might change with time. Hence, the proposed scheme considers this factor and corrects the EIC value during the LS implementation.

The predefined initial value $J_{eq.0}$ is utilized to calculate the power shortage for the first step of LS; the determination of this parameter can be estimated by the empirical formula. Thus, in the process of the subsequent LS steps, the relation between the quantity of loads to be shed and the RoCoF can be acquired on the basis of Equation (1), as shown in Equation (3).

$$P_{\text{shed.}n} = P_{def.b} - P_{def.a} = \frac{J_{eq}}{f_N} \cdot \left(\frac{df_{\text{COI.b}}}{dt} - \frac{df_{\text{COI.a}}}{dt}\right)$$
(3)

According to Equation (3), the exact value of inertia constant $J_{eq.n+1}$ can be calculated, which is applied to solve the power shortage of n + 1-th step, and as shown in Equation (4).

$$J_{eq.n+1} = \frac{P_{shed.n} \times f_N}{f'_{COI.b} - f'_{COI.a}}$$
(4)

Based on Equation (4), the J_{eq} value can be acquired and utilized in each LS step (except the first step). In other words, the J_{eq} value provided in *n*-th step can be used in *n* + 1-th step. Therefore, the proposed UFLS scheme can be independent of the inertia constant.

3.2. Dynamic Correction of the System Power Deficit

For the system with high wind power penetration, there is a high probability of the random decrease of wind power output and the wind generator tripping under the serious fault. Accordingly, it is necessary to correct and update the power deficit value during the LS implementation in a timely manner.

Generally, voltage at some buses also decline instantaneously under the contingency, thus it decreases the active power consumption of load, in the early stage of disturbance (within 1~2 s) [8]. Hence, the calculation of power deficit which is used in the LS first step should be corrected; the correction is presented as in Equation (5).

$$P_{def.1} = \frac{J_{eq.0}}{f_N} \cdot \frac{df_{COI}}{dt} + \sum_{j=1}^M P_{L0,j}[(u_j/u_{0,j}) - 1]$$
(5)

Any sudden change of the power balance in the system appears as a step change in f'_{COI} value [18]. A step decrease in power deficit, which is resulted by the LS or the rise of generator output power, leads to an incremental sudden change in f'_{COI} value. Conversely, a step increase in power deficit, caused by a sudden decline of the generator output power, results in a step decrease in f'_{COI} value. Due to the presence of numerous wind generators in the system, the power imbalance state of system owns the uncertainty during the UFLS. Therefore, the power shortage value needs to be corrected

in a timely manner before the next step of LS when the output power of wind generator is reduced randomly or the wind generator is tripped. The correction of $P_{def.new}$ is given as Equation (6).

$$P_{def.new} = P_{def.old} + \frac{J_{eq}}{f_N} \cdot \Delta f'_{COI}$$
(6)

3.3. Locking Criterion of the Load Shedding Step

In the system of high wind power penetration, the high probability of random increase in wind power output should be taken into account. When the output power of the wind generator rises during the LS period, the power deficit will be reduced to some extent. Thus, the quantity of loads to be curtailed should be lowered, for the purpose of preventing the frequency overshoot caused by the load over-shedding. Meanwhile, it results in the reasonable decrease of LS costs.

To avoid the impact of the random increase in wind power output during the LS period, the locking criterion described as Equation (7) is triggered before the execution of each LS step [9].

$$\begin{cases} f'_{COI.n} < 0\\ \frac{f'_{COI.0} - f'_{COI.0}}{f'_{COI.0}} \times 100\% \ge LS_{n.total}\% \end{cases}$$
(7)

If the criterion Equation (7) is satisfied, the *n*-th step of LS should be locked. Since it means that the incremental outputs of wind power make the power imbalance of system decrease greatly. Also, the recovery of frequency stability can be ensured without the action of the *n*-th step of LS.

3.4. Consideration of the Wind Generator Low Frequency/Voltage Protection

The low frequency protection of the wind generator should be coordinated with the UFLS scheme. The minimal operating frequency of the synchronous generator is 47.5 Hz, and it is 48.0 Hz for the wind generator. So, the threshold of the last LS step should not be less than 48.0 Hz, and the LS ratio of the last step cannot be too large. Otherwise, it is likely that the minimum frequency is less than 48.0 Hz during the LS period.

Since the operation of wind generator has the higher demands on the frequency and voltage, the wind generator is more vulnerable than synchronous units in the event of failure. In this paper, the incident of wind generator tripping which is caused by its low frequency/voltage protection can also be obtained by the indicator of sudden decrease in f'_{COI} .

4. Detailed Parameters Setting of the UFLS Scheme

The parameters of the UFLS scheme include: (a) the frequency threshold and the corresponding LS ratio for each LS step; (b) the location and capacity model to locate and allocate the LS amount of each step. In this paper, the coordination of the low frequency protection of wind generator and the LS frequency thresholds is addressed. Moreover, the location and capacity model which considers the frequency regulation effect and active power-voltage characteristic of the loads is adopted to enhance the frequency recovery.

4.1. The Design of the Load Shedding Step: Frequency Threshold and Its Proportion

The regulation "technical requirements for wind farm grid connection in Chinese grid" [25] claims that the wind generator should continue to operate at least 30 minutes in the frequency range of 48.0~49.5 Hz. When the frequency descends to 48.0 Hz or less, the wind generator can be tripped. According to the "technical requirements for automatic under frequency load shedding in power system" of China [26], a higher value of frequency threshold should be chosen for the first LS step in order to delay the frequency decline. Meanwhile, the unnecessary LS actions resulted by the temporary frequency decrease ought to be avoided.

According to the above regulations of China, our UFLS scheme sets 4-level basic steps. And the frequency thresholds are chosen as 49.2, 48.8, 48.4 and 48.0 Hz respectively. The quantity of loads to be shed for the *n*-th basic step is $P_{shed.n}$, as provided in Equation (8).

$$P_{shed.n} = P_{def.n} \times R_n \% \tag{8}$$

 R_n are given as 30, 25, 25 and 20 respectively based on the requirements for UFLS in China [26].

In addition, one spare step of LS is designed in the proposed scheme. The returning frequency value for this spare step is given as 49.6 Hz, and its time-delay is set as 15 s. The amount of loads to be shed for the spare step is determined as the remaining unbalanced power, as in Equation (9). The LS spare step can guarantee the frequency restore to 49.6 Hz or more during the LS period.

$$P_s = P_{def} - P_{shed.t} \tag{9}$$

With the assistance of the basic steps and spare step of LS, the frequency regulation effect of system can be maximized to reduce the power shortage. That is to say, the total quantity of loads to be curtailed can be lowered.

4.2. The Location and Capacity Model of the Load Shedding

In order to determine the locations to shed load and the quantity to allocate during the LS period, the location and capacity model of the UFLS scheme should be constructed. The frequency regulation effect and active power-voltage characteristic of the loads are taken into consideration in this model. It is known from [12] that the prioritized shedding of the load buses with the smaller K_L and dv/dp is able to alleviate the power imbalance and make the frequency recovery better. The LS indicator F is defined as described in Equation (10), and the load buses with the lower value of F should be given priority to be curtailed.

$$F_j = \lambda_1 \cdot \frac{\mathrm{d}v_j/\mathrm{d}p_j}{\sum_{m=1}^M \mathrm{d}v_m/\mathrm{d}p_m} + \lambda_2 \cdot \frac{K_{\mathrm{L}j}}{\sum_{m=1}^M K_{\mathrm{L}m}}$$
(10)

The determination of the λ is deeply discussed in [12]. It is based on the load model of the power system. If the loads have strong ability of regulating frequency, which means the K_L is larger, the λ_2 should be larger. Similarly, if the load models are mainly composed of the constant power component, the λ_1 should be larger. This is due to the fact that the constant power component is more susceptible to the voltage changes.

Based on Equation (10), the method to allocate the quantity of loads to be shed can be obtained, as described in Equation (11). Namely, the load buses with the lower value of indicator F should be allocated more LS quantity.

$$\begin{cases} \alpha_j = \sum_{m=1}^M F_m / F_j \\ \Delta p_{jn}(\Delta p_{js}) = \frac{\alpha_j}{\sum_{m=1}^M \alpha_m} \cdot P_{shed.n}(P_s) \end{cases}$$
(11)

4.3. Implementation Process of the UFLS Scheme

In summary, the implementation process of the proposed UFLS scheme is as follows and the flowchart is depicted in Figure 3.

- (a) Set the initial value of the load shedding parameters and n = 1;
- (b) When the frequency drops to the threshold f_{thn} , both the basic step and the spare step should be triggered simultaneously. The power deficit is calculated using Equation (5) if the n = 1. The loads to be shed of *n*-th basic step can be obtained based on R_n ;
- (c) Apply the criterion in Equation (7) to judge whether or not to lock the *n*-th basic step. If so, n = n + 1, otherwise proceed to the next;

- (d) Determine the location and capacity of *n*-th basic step to locate and allocate the corresponding LS amount, based on Equation (11). Then *n*-th basic step should be operated;
- (e) Update J_{eq} with Equation (4) and correct P_{def} by Equation (1);
- (f) Judge whether f'_{COI} sudden decrease or not. If so, update P_{def} with Equation (6);
- (g) The load shedding strategy stops when all basic steps are operated or the spare step is implemented. Otherwise, return back to stage (b).



Figure 3. Flowchart of the load shedding scheme.

As depicted in Figure 3, the basic steps and spare step of the LS scheme should be triggered simultaneously when the frequency variations of the system are satisfied. Meanwhile, the spare step own the time-delay of 15 s, which means the spare step will be implemented only if the corresponding conditions are met.

5. Simulation Setup

The simulations are carried out in the PSD-BPA[®] v1.0 of China Electric Power Research Institute. The IEEE-39 bus system integrated with high wind power penetration is applied for simulation and its structure is shown as Figure 4. The synchronous generators use the d-q biaxial model (i.e., transient model) that does not consider the damping windings. The wind generators adopt the pitch-variable

wind turbine model. The excitation systems apply the IEEE-F model. The governors adopt the reheat steam turbine. The load model is the composite model associated with frequency and voltage and its composition includes 40% constant power component, 40% constant impedance component and 20% constant current component. The importance of each bus is considered to be consistent. As the ability of load frequency regulation in this system is large and the constant power component accounts for 40% of the load composition, the weight coefficient λ_1 and λ_2 are chosen as both 0.5 to maximize the function of the indicator K_L and dv/dp during the frequency restoration.



Figure 4. Structure of IEEE-39 bus system integrated with wind generators.

As in Figure 4, large-capacity wind generators are installed in Bus-30, 32, 33, 36 and 37. The operating point of the wind generators is set at 90% of the rated output, so that the remaining 10% can be used as the reserve capacity which is provided by the pitch angle control. The wind speed model can simulate the stable speed, the gust and gradually changing speed. The rated power of this system is 6192.8 MW, while the wind generators are rated at 2632.5 MW. Therefore, the wind power penetration of this system is up to 42.5%.

It is assumed when t = 6.0 s, the generator in Bus-38 is tripped and stops its power output. Thus, the system is under a serious power imbalance situation, and the UFLS scheme is triggered. The conventional UFLS strategy (hereinafter referred to as CUFLS) [13] and an existing adaptive UFLS method (hereinafter referred to as AUFLS) [8] are adopted for comparisons, and their parameters setting can be found in Table A1 of the Appendix A. As described in Table 1, four fault scenarios are set to analyze the impacts of high wind power penetration on the LS, and the effectiveness of the proposed scheme in each scenario can be verified.

Scenario	Setting in the UFLS Period	Purpose
1	The wind power output retain stable	To verify the effectiveness of the LS parameters (thresholds and its proportions) and the superiority of the location capacity model
2	Set the step decrease of wind speed, causing the power output drop 200 MW	To verify whether the proposed scheme can obtain the step reduction feature of the RoCoF effectively
3	Set the gradual increase of wind speed, causing the power output grow 250 MW	To verify the ability to obtain the incident that the power shortage alleviate gradually. That is the effectiveness of the locking criterion.
4	Set the tripping of wind generator because of its relay protection	To verify the validity of the proposed scheme in the serious situation of wind generator tripping

According to the literature [23], in the time domain, the actual wind speed can be decomposed into the average wind speed in the large time scale (minute level) and the pulse wind speed in the small

time scale (second level). And the former is mainly used to study the scheduling optimization and stability analysis, etc. Therefore, this paper considers the time scale of wind power randomness as the minute level. In order to simulate the most serious fault scenario, the correlation of wind power is not considered in the simulations.

6. Results and Analyses of the Simulations

This section provides the comparisons and analyses of system frequency recovery under the implementation of different UFLS schemes in each fault scenario. Figure 5 depicts the total LS amount and steady-state frequency of each strategy under various fault scenarios, and its detailed data can be found in Table A2 of the Appendix A.



Figure 5. The total LS amount and steady-state frequency of each strategy under various scenarios.

6.1. Scenario-1: The Wind Power Output Retain Stable

The wind power outputs retain stable in this scenario. Thus there is no step decrease of f'_{COI} in the period of LS, and the power imbalance state only changes along with the implementation of LS steps. The recovery of frequency with the support of each strategy is shown in Figure 6.



Figure 6. The frequency recovery process of each strategy under scenario-1.

Figure 6 shows that the frequency can be restored to the satisfied range and the frequency accident can be avoided under the assist of each scheme. In addition, it is known from Figure 5 that the total LS quantity of the proposed scheme is minimal (i.e., the costs are the lowest). Furthermore, owing to the reasonable settings of the LS thresholds and ratios, the rotation reserves of generators can be exerted fully. Besides, the application of the location and capacity model also improves the effect of frequency recovery in comparison with other two schemes.

6.2. Scenario-2: The Wind Power Output Step Decrease

In this case, the wind power output in bus-32 has a sudden decrease because of the gust. The power output in bus-32 reduces 200 MW at 8.0 s and it conduces to incremental power shortage during the LS period. The frequency recovery with the aid of each strategy is presented in Figure 7.



Figure 7. The frequency recovery process of each strategy under scenario-2.

It is seen from Figure 7 that both CUFLS and AUFLS methods cannot respond to the increase of power deficit. The total LS quantity of AUFLS still remains at the level of scenario-1. Compared to the scenario-1, CUFLS operates a more LS step under this case, resulting in load over-shedding and frequency overshoot. However, the proposed scheme can obtain the incident of step decrease in f'_{COI} and timely update the loads to be shed. Correspondingly, the stability of frequency can be ensured and the LS costs can be lowered.

6.3. The Wind Power Output Increase Gradually

This scenario is dedicated to analyze the impact of wind power output gradual increase on the effect of LS. Within 10.0~20.0 s, the wind power output in bus-32 gradually rises about 250 MW, due to the variable wind speed. It means that during the LS period, the severity of power imbalance will be alleviated gradually. Accordingly, the loads to be shed should be corrected. Under this condition, the frequency recovery curves after the implementation of each strategy are declared in Figure 8.



Figure 8. The frequency recovery process of each strategy under scenario-3.

Through the analysis for Figure 8, it can be observed that CUFLS and AUFLS both cannot acquire the significant info that the power shortage is reduced. So these two schemes are still in accordance with the parameters of serious accident to operate and the frequency overshoot resulted by the load over-shedding cannot be avoided. In this scenario, only two basic steps of the proposed scheme are activated. Because when the frequency drops to the threshold 48.4 Hz, the third step of LS is locked due to the satisfaction of Equation (7). After the operation of proposed scheme, the frequency stabilized at 49.86 Hz finally.

6.4. Scenario-4: The Wind Generator Tripping Because of Its Relay Protection

This scenario is committed to analyzing the serious case of wind generator tripping during the LS period. At 16.0 s, the wind generator in bus-32 is tripped due to its low frequency or low voltage protection, thus the power imbalance of system becomes more serious. The recovery of frequency after the support of each scheme is shown as Figure 9.



Figure 9. The frequency recovery process of each strategy under scenario-4.

As in Figure 9, the CUFLS and AUFLS methods lead to the frequency collapse and the unstability of frequency respectively, due to the insufficient quantity of loads to shed. By contrast, the sudden decrease of f'_{COI} can be identified effectively under the operation of the proposed scheme. Then, its amount of loads to shed can be corrected in the condition of wind generator tripping, making the frequency restore to stability range.

6.5. Analyses for the Simulation Results

The values of EIC and calculated power deficit of the proposed scheme in the above fault scenarios are shown in Table 2. It is seen that the calculation accuracy of the power deficit is high, thus it reduces the error of LS action. This is due to the fact that the proposed scheme takes the uncertainty of the EIC into account and corrects it timely.

Table 2. Power deficit calculation errors of the proposed strategy in different scenarios.

Scenarios	Jeq	Calculated P _d /MW	Actual <i>P_d</i> /MW	Errors (%)
1	66.74	830.7	832.4	0.21
2	68.41	1026.5	1030.9	0.43
3	67.82	578.4	580.7	0.39
4	70.53	1465.7	1482.8	1.15

From the analyses of the above four fault scenarios, it can be concluded that the CUFLS and the AUFLS have difficulty adapting to the various changes of wind generator during the LS period; their performances are susceptible to the impacts of high wind power penetration. Under the application of CUFLS, the load over-shedding occurs in the scenario-2 and 3, and the frequency collapses in the scenario-4. After the operation of AUFLS, the steady-state frequency of more than 50.2 Hz is achieved as a result of the load over-shedding in the scenario-3. It will increase the burden of accident handling, because the over-frequency generator-tripping scheme will be triggered when the frequency exceeds 50.2 Hz. Besides, the satisfied recovered frequency cannot be obtained in the scenario-4, and it may cause a cascading failure in the practical grid. However, the effectiveness and robustness of the proposed scheme are verified in the simulations. With the help of the proposed scheme, the restored frequencies are satisfied in above fault scenarios. It is mainly due to the fact: (a) the effective identification of the changes in wind power output and the correction of the loads to be shed; (b) the reasonable setting of parameters in the UFLS scheme.

In addition, the analysis of Figure 5 declares the proposed scheme is more suitable to satisfy the requirements of economical operation and reliability in power grid of China. That is to say, it can restore the frequency stability better with most economical LS costs.

7. Summary

In this paper, a novel adaptive UFLS scheme considering the high wind power penetration is proposed. Through the simulations on the IEEE-39 bus system which is integrated with numerous wind generators, the advantages of the proposed scheme are analyzed and demonstrated. This scheme is able to obtain the EIC more accurately and thus can enhance the calculation accuracy of power deficit and reduce the error of LS. It is verified that our approach can identify the changes of wind power output and the incident of wind generator tripping. Correspondingly, the amounts of loads to be shed must be increased or decreased so as to ensure the recovery of frequency stability. In various fault scenarios, with the support of the proposed scheme, neither the frequency overshoot nor the unsatisfied steady-state frequency and the frequency collapse happen. Hence, it is concluded that this scheme can protect the frequency stability effectively, while taking into account the demands of economical operation and reliability in power grid at the same time.

As we know, the proposed scheme requires the fast calculation and data transmission of the power grid. However, with the vigorous development of the fourth generation power system, some controllable equipment like the WAMS have been developed and constructed in China so far. Thus, the methodology in this paper could be applied in a practical system in the near future.

Finally, it is pointed out that the actual wind speed is various and there exists correlations of wind power among different geographical areas. So, the applicability of the proposed scheme in the practical grids requires more experiments for proof. Besides, the flexibility of the conventional UFLS can be enhanced by increasing the number of predefined steps, so the more detailed comparisons between the proposed and the conventional scheme, under different constraints of the regulations, needs to be done in further work.

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Conflicts of Interest: All of the authors declare no conflict of interest.

Appendix A

CUFLS [13]			AUFLS [8]		
Step	f/Hz	P _{shed} /%	Step	f/Hz	P _{shed} /%
1	49.25	5.28	1	49.20	10.10
2	49.14	6.57	2	49.00	19.87
3	48.83	6.85	3	48.80	19.77
4	48.67	7.37	4	48.60	43.40
5	48.29	7.51	/	/	/
6	47.83	7.87	/	/	/

Table A1. The parameters setting of the CUFLS and the AUFLS.

The CUFLS is the conventional UFLS strategy proposed in [13]. The first stage of this method is determination of the worst probable generation loss event which results in the highest initial rate of frequency decay. Then, the amount of load shedding which ensures that the frequency will not deviate below the minimum permissible value in this case should be specified. After that, the number and size of load shedding steps are determined based on trial and error to achieve an acceptable operation in case of the worst probable contingency. The parameters of CUFLS are shown in Table A1. The *f* is the frequency threshold and the P_{shed} value of CUFLS is the proportion of the total LS amount in system loads. AUFLS is an existing adaptive UFLS method proposed in [8]. In this method, the amount of power deficit is calculated based on the frequency derivative at the moment of disturbance occurs. There is no need to determine the worst probable contingency and a proper proportion of loads based on the calculated power deficit are shed in 4 specified steps which are shown in Table A1. The *f* is the frequency threshold and the P_{shed} value of the AUFLS is the proportion of loads based on the calculated power deficit. Besides, both of them do not take the setting of spare step into account and consider load characteristics in the design of location and capacity model.

Table A2. The total LS amount and steady-state frequency of each strategy under various scenarios.

Scenario	The Proposed		CUFLS [13]		AUFLS [8]	
Stenario -	f/Hz	P_{shed}/MW	<i>f</i> /Hz	P_{shed}/MW	f/Hz	P _{shed} /MW
Scenerio-1	49.84	664.3	49.89	733.9	49.96	829.1
Scenerio-2	49.81	824.7	50.14	1158.2	49.79	829.1
Scenerio-3	49.86	456.5	50.17	733.9	50.26	829.1
Scenerio-4	49.82	1285.6	Collapse	733.9	47.78	829.1

Abbreviation	Meaning
UFLS	under frequency load shedding
LS	load shedding
EIC	equivalent inertia constant
RoCoF	rate of change of frequency
WAMS	wide area measurement system
LVRT	low voltage ride-through
PSD-BPA	the software which is capable of the power flow and transient stability analysis
CUFLS	conventional UFLS strategy proposed in [13]
AUFLS	existing adaptive UFLS method proposed in [8]
FACTS	flexible alternative current transmission systems

Table A3.	The ab	breviation	and its	meaning.
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Nomenclature	Meaning
P_m	the active power generation of the system in MW
P_e	the active power consumption of the system in MW
Jeq	the EIC of the system in s
f_N	the rated frequency of the system in Hz
fсоі	the frequency of inertia center in Hz
n _G	the number of generator
J_i	the inertia constant of <i>i</i> -th generator in s
f_i	the frequency of <i>i</i> -th generator in Hz
$P_{shed.n}$	the LS amount of <i>n</i> -th basic step in MW
P _{def.b}	the unbalanced power before the operation of <i>n</i> -th basic step in MW
P _{def.a}	the unbalanced power after the operation of n -th basic step in MW
$f'_{COI.b}$	the RoCoF before the operation of n -th basic step in Hz/s
$f'_{COI.a}$	the RoCoF after the operation of n -th basic step in Hz/s
M	the number of load bus
$P_{L0.j}$	the active power of <i>j</i> -th bus before the disturbance in MW
$U_{0.j}$	the instantaneous voltage of <i>j</i> -th bus before the disturbance in p.u.
U_j	the instantaneous voltage of <i>j</i> -th bus after the disturbance in p.u.
P _{def.new}	the calculated power deficit value after correction in MW
$P_{def.old}$	the calculated power deficit value before correction in MW
$\Lambda f'$	the difference value of thebefore and after the sudden change of
^I COI	power shortage in Hz/s
$LS_{n.total}\%$	the ratio of the total loads, which need to be curtailed until the <i>n</i> -th LS step, in active power deficit
f'_{COL0}	the frequency derivatives at the time that power deficit occurs in Hz/s
¢l	the frequency derivatives at the time that immediately before the n-th
J COI.n	LS step in Hz/s
$P_{def.n}$	the calculated power deficit value of the <i>n</i> -th basic step in MW
R_n	the LS proportion of the <i>n</i> -th basic step
P_s	The LS amount of the spare step in MW
$P_{shed.t}$	the total LS amount before the action of the spare step in MW
λ_1/λ_2	the weights of dv/dp and K_L , respectively
dv _j /dp _j	the sensitivity index of <i>j</i> -th bus
K_{Lj}	the frequency regulation coefficient of <i>j</i> -th bus
α_j	the inverse parameter of F_j
$\Delta p_{jn} (\Delta p_{js})$	the LS amount of <i>j</i> -th bus in <i>n</i> -th basic step (spare step)

Table A4. The nomenclature and its meaning.

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