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An Adaptive Load shedding Method Based on the Underfrequency and Undervoltage Combined Relay

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Abstract: The conventional UVLS (undervoltage load shedding) relay and the UFLS (underfrequency load shedding) relay, designed separately without considerations on load characters and mutual influences of the voltage and the frequency, may result in excessive or insufficient load curtailments. This paper proposes a new adaptive load shedding method based on the underfrequency and undervoltage combined relay. With considerations on influences of frequency and voltage dynamics on the load active power, this method uses real-time measured local responses to calculate the amounts of underfrequency load curtailments and undervoltage load curtailments, respectively, and adopts the larger one as the practical amount of load curtailments. Furthermore, this method transmits the practical amount of load curtailments to the underfrequency and undervoltage combined relay, thus triggering local successive load shedding. Simulation results of IEEE 39-bus system have shown that the new method, compared with the conventional one, can adapt better to load characters and disturbance types, thus guaranteeing the frequency stability and the voltage stability more effectively.

Key Words: Frequency, Voltage, Load Shedding, Combined Relay, Stability

1. INTRODUCTION

The frequency stability and the voltage stability have attracted much attention due to worldwide blackouts [1]. The UFLS (underfrequency load shedding) and the UVLS (undervoltage load shedding), as the last defense line for guaranteeing the security and the stability of the power system, are widely studied in recent years [2-4].

The conventional decentralized load shedding method executes UFLS and UVLS respectively without considerations on mutual influences of the voltage and the frequency [5]. Therefore, it is of great importance to provide a new load shedding method to coordinate the UFLS control and the UVLS control.

Alireza Saffarian tried to enhance the power system stability by using adaptive combinational load shedding methods which starts load shedding from the locations with higher voltage decay for longer period of time [6]. Hou Yuqiang proposed a new method of UFLS and UVLS by applying multi-agent technology [7]. Moreover, with the wide applications of PMU (phasor measurement unit) [8], K. Seethalekshmi used the index VSRI to choose the load shedding locations, thus proposing a synchrophasor assisted frequency and voltage stability based load shedding scheme for self-healing of power systems [9]. Tang Junjie proposed an adaptive load shedding scheme based on combined frequency and voltage stability assessment with considerations on both the reactive power and active power by using synchrophasor measurements [10].

Although scholars have done much work on designing the coordinated underfrequency and undervoltage load shedding scheme, it needs further study for cooperating UFLS with UFLS on the basis of the frequency dynamic, the voltage dynamic and the load characters [11].

In addition, the conventional decentralized load shedding method requires two separated relays to execute UVLS and UFLS respectively at the chosen locations, which costs much. However, the load shedding just requires one underfrequency and undervoltage combined relay if it is possible to obtain an integrated amount of load curtailments by cooperating UFLS with UVLS.

This paper proposes a new adaptive load shedding method based on the underfrequency and undervoltage combined relay. With considerations on influences of frequency and voltage dynamics on the load active power, this method uses real-time measured local responses to calculate the amounts of underfrequency load curtailments and undervoltage load curtailments, respectively, and adopts the larger one as the practical amount of load curtailments. Furthermore, this method transmits the practical amount of load curtailments to the underfrequency and undervoltage combined relay, thus triggering local successive load shedding. Simulation results of IEEE 39-bus system have shown that the new method, compared with the conventional one, can adapt better to load characters and disturbance types, thus guaranteeing the frequency stability and the voltage stability more effectively.

2. ANALYSIS OF THE FRQUENCY AND VOLTAGE CHARACTERS OF LOAD

The active power of load, which is proportional to system frequency and load voltage, can be expressed by the following power function load model:

$$P_{\mathrm{L}} = P_{\mathrm{L0}}(\frac{V}{V_{\mathrm{L0}}})^{\alpha} \times (\frac{f}{f_0})^{\beta} \tag{1}$$

where P_{L} and P_{L0} denote the practical and rated load active power respectively, V and V_{L0} are the practical and rated load voltage respectively, f and f_0 (50Hz) are the practical and rated system frequency respectively, exponent α is between 0.5~2 while exponent β is between 1.5~6. In practical power system, the value of α and β can be obtained by statistical data, steady state experiment and the real-time measured information. As shown in Eq.(1), the load active power changes with the system frequency and load voltage due to load's frequency and voltage characters.

When the system frequency or the load voltage drops during disturbances, the load active power decreases, thus accelerating the recovery of the frequency and the voltage. However, if the UFLS or UVLS is triggered due to severe drop of the frequency or the voltage, the load active power will increase after load shedding, which weakens the effect of load shedding. Therefore, it is necessary to consider the negative effect of load characters on load shedding control and adjust the amount of load curtailments according to the frequency and voltage dynamics.

3. ADAPTIVE LOAD SHEDDING METHOD BASED ON THE UNDERFREQUENCY AND UNDERVOLTAGE COMBINED RELAY

The underfrequency and undervoltage relay measures the voltage dynamic of the load bus and calculate the voltage, frequency and their velocities of variation in real time. Then it calculates the amounts of underfrequency load curtailments and undervoltage load curtailments, respectively, and adopts the larger one as the practical amount of load curtailments, thus triggering local successive load shedding.

3.1 Calculation on undervoltage load curtaillments

As it is known, the transient voltage can drop to a very low value in seconds after the disturbance such as system disconnection. In order to avoid voltage collapses, this paper calculates the undervoltage load curtailments without time delay when the load voltage satisfies Eq.(2), if the underfrequency and undervoltage combined relay has not executed load shedding before.

$$V_{\mathrm{L0}} - V > 0.1\, V_{\mathrm{L0}} \tag{2}$$

The amount of undervoltage load curtailments is calculated by

$$\Delta P_{\mathrm{LV}} = P_{\mathrm{L}} - P_{\mathrm{L}}(\frac{V}{V_{\mathrm{L0}}})^{\alpha} \times (\frac{f}{f_0})^{\beta} \tag{3}$$

where ΔP_{LV} is the undervoltage load curtailments, ΔP_{L} is the practical load active power. After load shedding, the load active power P_{LS} should be

$$P_{\mathrm{LS}} = P_{\mathrm{L}} - \Delta P_{\mathrm{LV}} = P_{\mathrm{L}}(\frac{V}{V_{\mathrm{L0}}})^{\alpha} \times (\frac{f}{f_0})^{\beta} \tag{4}$$

Supposing that the transmission capacity of the power system remains the same after load shedding, which means the amount of active power that the power system can transmit to the load is P_{L}, the load active power after load shedding P_{LS} should be equal to P_{L} after the transient process as shown by Eq.(5).

$$P_{\mathrm{LS}} = P_{\mathrm{L}} \tag{5}$$

Comparing Eq.(4) with Eq.(5), we can note that the voltage and the frequency should recover to the rated value after load shedding.

In addition, if the underfrequency and undervoltage combined relay has already executed load shedding, it takes time for the voltage to recover and we calculate the amount of undervoltage load curtailments using Eq.(3) only when the load voltage continues to drop or remains the same in the random continuous 0.5s after executing the previous load shedding, which means the load voltage should satisfy Eq.(6)

$$\frac{dV}{dt} \le 0 \quad t \in (t_{\mathrm{V}}, t_{\mathrm{V}} + 0.5s) \tag{6}$$

where t is the time, and t_{V} is the initial moment of triggering the UVLS.

3.2Calculation on underfrequency load curtaillments

This paper adjusts the threshold, the time delay and load curtailments of each round of UFLS off line according to the system capability and the operation mode. When the practical frequency drops below the settled threshold within the time delay, satisfying Eq.(7), we can obtain the determined underfrequency load curtailments according to corresponding threshold.

$$f < f_{K_{\mathrm{f}}} \qquad t \in (t_{\mathrm{f}}, t_{\mathrm{f}} + \Delta t_{\mathrm{f}}) \tag{7}$$

where f_{Kf} denotes the threshold of round K_{f}, t_{f} is the initial moment of triggering the UFLS, Δt_{f} is the time delay.

Furthermore, in order to weaken the negative effect of load characters on load shedding, this paper adds excessive load curtailments to the first round of UFLS. The excessive load curtailments are obtained by

$$\Delta P_{\mathrm{1F}} = P_{\mathrm{L}} - P_{\mathrm{L}}(\frac{V}{V_{\mathrm{L0}}})^{\alpha} \times (\frac{f_1}{f_0})^{\beta} \tag{8}$$

where ΔP_{1F} is the excessive load curtailments of the first round of UFLS, f_1 is the threshold of the first round of UFLS.

3.3 Calculation on practical load curtaillments

This paper adopts the larger amount between the amounts of undervoltage load curtailments and underfrequency load curtailments as the practical amount of load curtailments according to Eq.(9), and then transmits the practical amount of load curtailments to the underfrequency and undervoltage combined relay, thus triggering local successive load shedding.

$$\Delta P_{\mathrm{L}} = \max\{\Delta P_{\mathrm{Lf}}, \Delta P_{\mathrm{LV}}\} \tag{9}$$

where ΔP_{L} is the practical amount of load curtailments, ΔP_{Lf} and ΔP_{LV} are the underfrequency load curtailments and the undervoltage load curtailments, respectively.

3.4 Flowchart of load shedding

Fig.1 shows the flowchart of the adaptive load shedding method proposed in this paper.

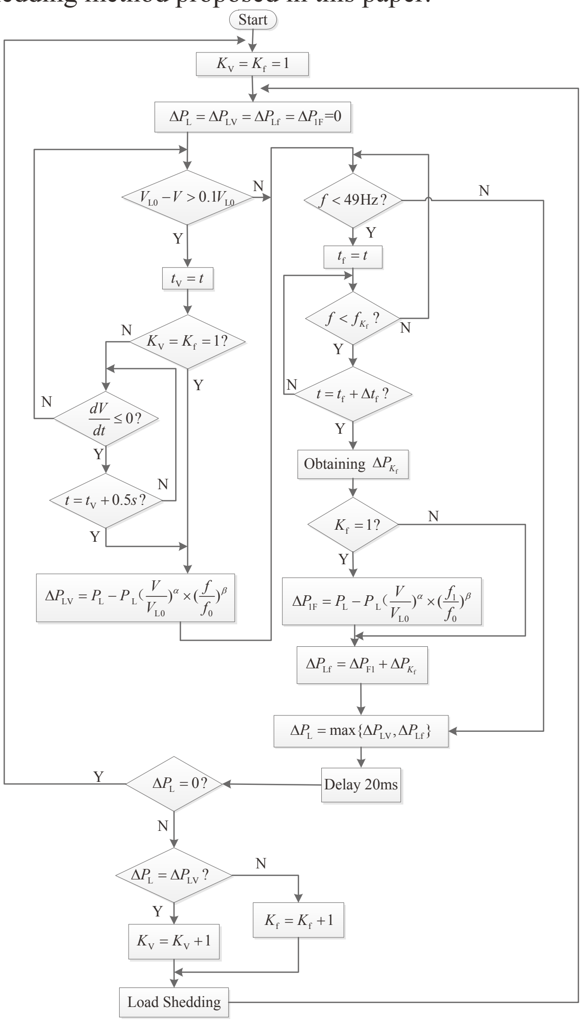

Fig 1. Flowchart of new load shedding method.

4. SIMULATIONS

To prove the effectiveness of the new method, this paper conducted simulations of different disturbance types such as low frequency, low voltage, low frequency and low voltage on IEEE-39bus system as shown in Fig.2 and compared the new load shedding method with the conventional one. In the simulations, the governor and the excitation regulator are considered, and the power function load model as shown in Eq.(1) is adopted with α=1，β=1.5.

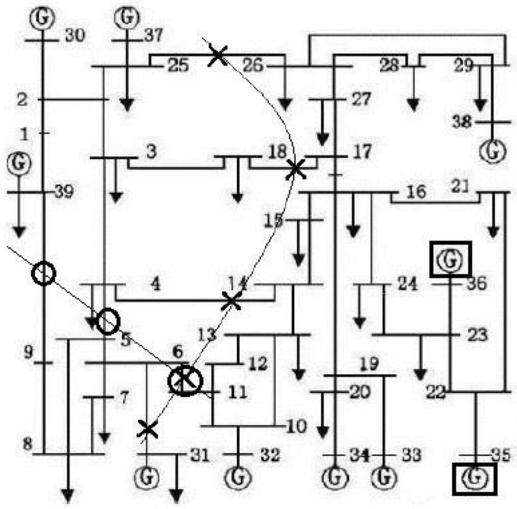

Fig 2. IEEE 39-bus system.

The conventional UFLS and UVLS schemes adopted in the simulations are shown in Table 1 and Table 2.

Table1. Conventional Scheme of UFLS

Round	Threshold/Hz	Time Delay/s	Load Curtailments/%
1	49.0	0.2	7
2	48.8	0.2	7
3	48.6	0.2	7
4	48.4	0.2	7
5	48.2	0.2	7
6	48.0	0.2	7
7	49.0	10	5

Table2. Conventional Scheme of UVLS

Round	Threshold/pu	Time Delay/s	Load Curtailmetns/%
1	0.90	0.5	6
2	0.85	0.5	6
3	0.80	0.5	6
4	0.75	0.5	6
5	0.70	0.5	6
6	0.65	0.5	6
7	0.90	10	5

In addition, the thresholds, the time delay and the load curtailments of UFLS in the new method are settled as the conventional UFLS scheme shown by Table1.

4.1 Scenario1: low frequency and low voltage

It is assumed in this scenario that the power system in Fig.2 is distributed to two parts from point X. After the disconnection, the left power system has 1273.8MW mismatch power, thus resulting in low frequency. Moreover, the load voltage in the left power system drops quickly because the load is far away from the generators. Therefore, the UFLS and the UVLS are both triggered.

Adopting the new method, the relay executes 1271MW load curtailments by 5 rounds, while round 1-6 of UFLS and round 1-2 of UVLS execute 964MW load curtailments when adopting the conventional method. The load shedding effects are shown in Fig.3 and Fig.4. The frequency stays below 48.5Hz and the lowest load voltage recovers slowly when using the conventional method. However, because the new method shed 307MW more loads than the conventional method does due to the considerations of the load characters, the frequency can reach to 50Hz in 30s after the disturbance and the lowest load voltage can recover to the rated value in 15s after the disturbance with fewer rounds of load shedding.

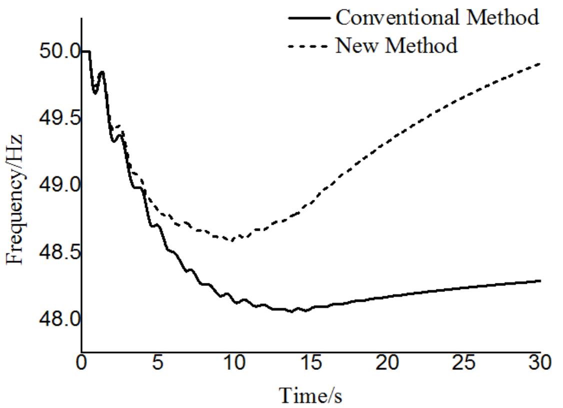

Fig 3. Frequency dynamic after load shedding.

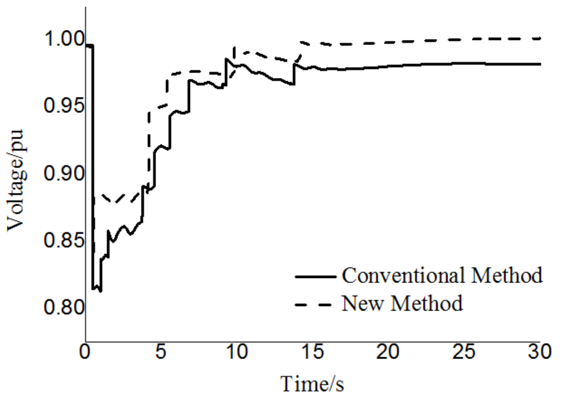

Fig 4. Lowest voltage dynamic after load shedding.

In addition, to study the adaptability of the new method to the load characters, this paper adopted different value of exponent α in Eq.(1) while assuming β=1.5 because the voltage decay is more serious than the frequency decay. The simulation results are shown in Table3 and Table4.

Table3. Load Shedding Results of Conventional Method

α	UFLS		UVLS		Total Load Curtailments /MW
	Load Curtailments/MW	Rounds	Load Curtailments/MW	Rounds	
0.5	784	6	180	2	964
1.0	784	6	180	2	964
1.5	784	6	118	2	902
2.0	784	6	75	1	859

Table4. Load Shedding Results of New Method

UFLS	UVLS	Total Rounds	Total Load Curtailments /MW
Load Curtailments /MW	Load Curtailments /MW		
939	189	5	1128
972	299	5	1271
722	380	4	1102
774	447	4	1221

From Table3, we can note that the conventional UFLS executes the same magnitude of load curtailments by the same rounds when the exponent α changes. As for conventional UVLS, the load curtailments should have increased with the increasing value of exponent α because the negative effects of load characters are more serious when the value of α is higher. However, the conventional UVLS executes less load curtailments when the value of α increases.

From Table4, it is obvious that the load curtailments of UVLS increase with the increment of α when using the new method. Moreover, compared to the conventional method, the times of relay actions is much fewer when adopting this new method.

4.2 Scenario2: low frequency

It is assumed that the generator 35 and 36 (marked with the square) lose 1098MW in Fig.2. After the disturbances, the UFLS is triggered due to low frequency, while the load voltage is over 0.9pu.

Adopting the conventional method, round 1-2 and 7 of UFLS execute 742MW load curtailments, however, the new method only executes load shedding once with 717MW load curtailments. Fig.5 shows the frequency dynamic after load shedding by using these two methods. It is obvious that the frequency can recover faster with fewer load curtailments when using the new method.

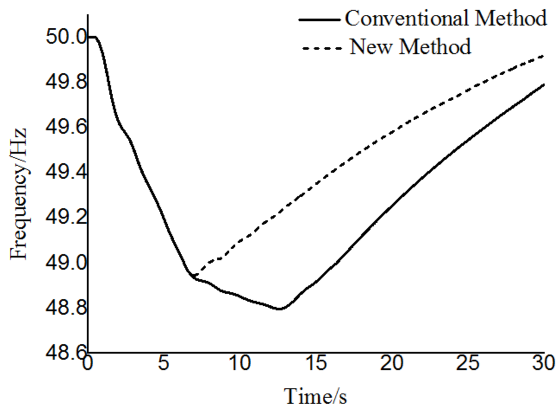

Fig 5. Frequency dynamic after load shedding.

4.3 Scenario3: low voltage

It is assumed that the power system in Fig.2 is distributed to two parts from point O. After the disconnection, the generator 31 can provide the load with enough active power, so the frequency can maintain around 50Hz. However, the UVLS is triggered due to serious voltage decay.

Adopting the conventional method, round 1-2 of the UVLS execute 92MW load curtailments if the excitation regular is considered, otherwise, round 1-5 and 7 of the UVLS execute 245MW load curtailments. Adopting the new method, the UVLS executes 241MW load curtailments by only one round with or without considerations of the excitation regular. Fig.6 illustrates the voltage dynamics when using the conventional method and the new method. It can be seen that the new method can bring the voltage back to almost the rated value in quite a short time with only one round of load shedding, even if the excitation regular is restricted. However, the control effect of the conventional method depends on the excitation regular. When the excitation regular is restricted, the conventional method, compared with the new method, executes larger amount of load curtailments with more rounds of load shedding, and results in slower recovery of the load voltage.

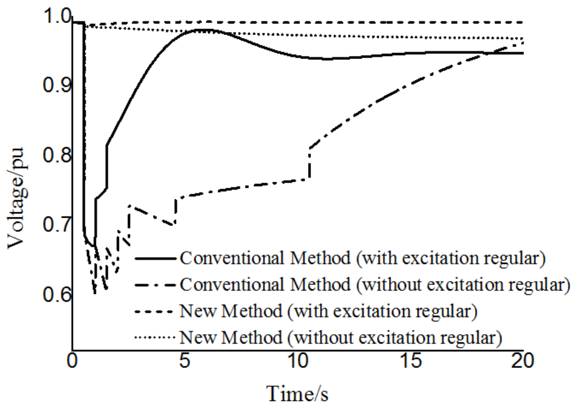

Fig 6. Lowest voltage dynamic after load shedding.

5. CONCLUSIONS

This paper proposes a new adaptive load shedding method based on the underfrequency and undervoltage combined relay. With considerations on influences of frequency and voltage dynamics on the load active power, this method uses real-time measured local responses to calculate the amounts of underfrequency load curtailments and undervoltage load curtailments, respectively, and adopts the larger one as the practical amount of load curtailments. Furthermore, this method transmits the practical amount of load curtailments to the underfrequency and undervoltage combined relay, thus triggering local successive load shedding. Simulation results of IEEE 39-bus system have shown that the new method, compared with the conventional one, can adapt better to load characters and disturbance types with fewer relays, thus guaranteeing the frequency stability and the voltage stability more effectively.

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