An Improved Method of Adaptive Under Voltage Load Shedding

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The conventional under voltage load shedding method only based on the local voltage information, and the method designed without considerations on load characters and mutual influences of the voltage and the frequency, this method may cause the instability of power system. This paper puts forward an improved method of adaptive under voltage load shedding based on two rounds of action. The improved method has considered on influences of frequency and voltage dynamics on the load active power, then used real-time measured electric parameters to calculate the amounts of under voltage load curtailments. In order to ensure the accuracy of the action, the method added an accelerated round to prevent the voltage drops rapidly. Simulation results of IEEE 39-bus system has shown the superiority of new method in calculating the amounts of curtailments.

Keywords: Load Shedding; Under voltage; Adaptive Stability Control.

1. Introduction

The frequency stability and the voltage stability are two important factors of power system stability. [1] With the development of power system, the stability control technology has attracted extensive attention of scholars domestic and overseas.

The UFLS (under frequency load shedding) and the UVLS (under voltage load shedding), as the last defense line, both of them are used to guarantee the security and the stability of the power system. [2,3]

However, compared with UFLS, the research on UVLS is still immature. The traditional UVLS scheme only based on the local voltage information,[4]this method will remove fixed proportion of load after a certain time delay when the system voltage is lower than the threshold value of each load shedding round. The traditional UVLS scheme did not consider the transient voltage response or voltage distribution characteristics of space as well as time. Due to the lack of information exchange between each relay that often leads to less load shedding or more load shedding, it’s difficult to guarantee the power system transient voltage stability when there occurs a serious fault. In addition, the traditional UVLS is not taken into the consideration of the frequency response of the power system, this
idea enabled the separation of UVLS and the UFLS. So, when there a sharp decline of load active power appears, the voltage of the power system will become unstable and the situation will lead to an unacceptable high frequency which may cause generator tripping and blackout.

Since the 20th century, foreign regions have configured different under voltage load shedding strategy, the TEPCO sends control signal based on the voltage stability.[5]During 10 seconds to minutes, they uses minimum square root to detect the situation that the voltage changes slowly, Alternatively, they calculated the voltage change rate to detect the situation that voltage changes fast in a second. The Quebec determined whether there cause long-term voltage instability problems by measuring average voltage of five 735kv substation.[6]New Mexico grid integrated two important substation’s information of voltage data and lines, then, taking different measures to disconnect the different target.[7]Southern Sweden takes control measures based on EMS, by detecting node voltage, generator current limiter and reactive power data to start the gas machine to switch the paralleling reactance, then remove the corresponding load.

Nowadays, several scholars have proposed frequency and voltage stability based adaptive load shedding schemes. There is a literature points out an adaptive load shedding method based on the under frequency and under voltage combined relay, [8]which considers the influences of frequency and voltage dynamics on the load active power ,this method uses real-time measured local responses to calculate the amounts of UFLS curtailments and UVLS curtailments.

Discussion from practical application, when low frequency occurs, the small offset of the frequency result in a big difference between the calculation of cutting load and the actual load demand. Therefore, effect of frequency on the actual UVLS strategy is very small, we have to seek a more practical method of reducing load.

Based on the analysis of the voltage, frequency and load information after system distribution, this paper proposes an improved method of adaptive UVLS which can calculate the unbalance active power of real-time system and suppress voltage drop quickly to ensure the stability of power system. With consideration on economical optimization strategy, this method can calculate the amounts of load shedding curtailments adaptively under the situation of regional power grid voltage instability, to provide real-time dynamic load shedding operation basis.

2. Analysis of the Voltage Characters of Load

The active power of load, which is proportional to system frequency and load voltage, it can be expressed by the following power function load model:
Where \( P_L \) denote the practical load active power, \( P_{L0} \) is the rated load active power, \( f \) and \( f_0 \) (50Hz) are the practical and rated system frequency. \( V \) and \( V_0 \) are the practical and rated voltage of load respectively. \( \alpha \) is a exponent that represents active power related to the voltage whose value is between 0.5~2, exponent \( \beta \) expresses the relationship between active power and frequency which is between 1.5~6. The value of \( \alpha \) and \( \beta \) always obtained by statistical data, steady state experiment and the real-time measured information. It should be noted that in practical power system, it is difficult to get exact parameters because of the complex composition of local load.

As it is known to all, the load active power changes with the frequency and load voltage of system because of load’s frequency and voltage characters. When the load voltage drops during disturbances, the load active power will decrease, thus accelerating the recovery of the voltage. However, if the UVLS is triggered due to severe drop of the voltage, the load active power will increase after load shedding, the increase of active power will weaken the effect of load shedding.

Admittedly, the coupling relationship of frequency and voltage can’t be neglected, the change of frequency can be used as an auxiliary reference factor for UVLS method to optimize the amounts of load shedding curtailment, nevertheless, the impact of relative to the voltage change, the influence of frequency is weaker. Therefore, it is necessary to design an adaptive function of UVLS which mainly based on the voltage change.

### 3. Calculation on Under Voltage Load Shedding Curtailments

As we all know that the transient voltage will drop to a low value in seconds after the disturbance of power system. In order to avoid voltage collapses, this paper calculates the under voltage load curtailments without time delay when the load voltage satisfies Eq. 2, if the UVLS has not operated before.

\[
V_{L0} - V > 0.1V_{L0}
\]  

(2)

The amounts of under voltage load curtailments is calculated by

\[
\Delta P_{LV} = P_L - P_{L0} \left( \frac{V}{V_{L0}} \right)^\alpha \times \left( \frac{f}{f_0} \right)^\beta
\]

(3)
Where $\Delta P_{LV}$ is the under voltage load curtailments, $P_L$ is the practical measured load active power. After load shedding, the load active power $P_{LS}$ should be:

$$P_{LS} = P_L - \Delta P_{LV} = P_L \left( \frac{V}{V_{L0}} \right)^\alpha \times \left( \frac{f}{f_0} \right)^\beta$$

(4)

Assuming that the transmission capacity of the power remains the same value after load shedding, in other words, the amounts of active power that the system can provide to the load is still $P_L$, then $P_L$ should be equal to $P_{LS}$ that be absorbed by load after the transient process.

$$P_{LS} = P_L$$

(5)

At this time, the frequency and voltage of load should return to rated value. As a complement, if UVLS has already operated, and 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. 2 and Eq. 6, only in this situation, we calculate the amounts of under voltage load curtailments by using Eq. 3.

$$\frac{dV}{dt} \leq 0, \quad t \in (t_V, t_V + 0.5s)$$

(6)

Where $t$ is the time, $t_V$ is the initial time of triggering under voltage load shedding.

4. Adaptive Under Voltage Load Shedding Method

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

The function of adaptive UVLS is configured to transformer, according to the operating condition of main transformer, the method can calculate the overload deficiency, then use the deficiency of load power, feeder load importance and feeder load's active power value to generate the export matrix of overload inter tripping.

UVLS is equipped with a basic round, the basic round is used to complete remove the corresponding load in different time delay when the voltage is at a low value. Another is accelerated round, which is used to prevent the system collapse by cutting load rapidly when the voltage drops quickly. In addition, accelerated
round must action after the basic round action, otherwise, the accelerated round will quit running automatically.

4.1. **Boot logic**

The UVLS method will start when the bus voltage satisfies Eq. 7 after a time delay which is $T_{ud}(0.1s)$ without blocking.

$$\max\{U_{ab}, U_{bc}, U_{ca}\} < U_{qd}$$  \hspace{1cm} (7)

Where $U_{ab}$, $U_{bc}$, $U_{ca}$ is the voltages of bus. $U_{qd}$ is the under voltage started value, it is two voltages more than the basic round value.

4.2. **Locking logic**

4.2.1. **Under voltage locking**

The UVLS will lock when the voltage satisfy Eq. 8, when the voltage recovery to the normal value, the under voltage locking will unlock automatically.

$$\min\{U_{ab}, U_{bc}, U_{ca}\} < 20V$$  \hspace{1cm} (8)
4.2.2. **Negative Sequence Voltage Locking**

When \( U_2 > 5 \text{V} \), the UVLS will lock instantaneously, when the voltage recovery to normal value, the under voltage locking will unlock automatically.

4.2.3. **Slip locking**

When the \(-dU/dt\geq\) under voltage slip locking value, the UVLS will lock instantaneously, the slip locking will relieve until the \( \text{MIN}[U_{ab}, U_{bc}, U_{ca}] \) recovery to start value above confirm 0.1s or the 5S delay.

Alternatively, when the voltage drops quickly, which conform to \( du/dt \leq \text{under voltage accelerated value} \), the influence of time delay caused by data window when using transient measurement reckoning dynamic voltage measurement should be considered. Therefore, it requires compensation for the voltage in Eq. 2

\[
V_{(aftercompensation)} = V_{(dynamic)} + (dv/dt) \times T
\]  

Where \( V_{(dynamic)} \) is the measured voltage in Eq. 1. \( dv/dt \) is the measured rate of bus voltage’s change. \( T \) means the transient signal gathering time delay, generally take \( T/2 \) be the label position to calculate the \( V_{(dynamic calculation value)} \) by using the Fourier algorithm.

When the voltage drops meets \( du/dt \geq \text{under voltage accelerated value} \), the time delay caused by dynamic voltage calculation process is shorter, there is no need to compensate the voltage in Eq.1, in order to avoid the calculation error of \( du/dt \) enlarge the calculation error of the amounts of load shedding curtailments.

Finally, after calculated the amounts of UVLS curtailments, remove the load in sequence.

Make a description to the reaction time delay, which is a recovery time for system at the end of the UVLS, waiting for the next under voltage criterion of the load shedding again.

Above all, this paper increases cyclic load shedding scheme to make the results better, this issue will be discussed in more detail in next chapter.

5. **Simulations**

In order to verify the effectiveness of cyclic load shedding scheme, this paper conducted simulations of different result between the original method and improved method on IEEE-39 bus system as shown in Fig.2. In the simulations, the governor and the excitation regulator are considered.
In the original method, the strategy only operated by one round after disturbance. The improved method proposed in this paper only remove 50% of the total load curtailments in first round, then, use voltage, frequency and residual power to calculate the amounts of load that still need to remove after 200ms.

Assuming that the IEEE-39 power system in Fig.2 is distributed to two parts from point O in 0.5s, the fault leads to the lower left corner isolated. Voltage's instability triggers the UVLS action.

As follow the specific operation data: the power system faults occurs in 0.5s, $a=1, b=1.5, \Delta t=0.01s$, considering the transmission delay, use the power, voltage, and frequency at 0.52 to calculate, then we get the amounts of curtailments is 252.21MW.

Table 1. Load shedding results of original method.

<table>
<thead>
<tr>
<th>Load</th>
<th>V/pu</th>
<th>F/pu</th>
<th>P</th>
<th>dv/dt</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.672</td>
<td>0.996</td>
<td>32</td>
<td>-0.6</td>
</tr>
<tr>
<td>8</td>
<td>0.675</td>
<td>0.996</td>
<td>38</td>
<td>-0.596</td>
</tr>
<tr>
<td>31</td>
<td>0.727</td>
<td>0.998</td>
<td>33</td>
<td>-0.596</td>
</tr>
</tbody>
</table>

Table 2. Power, voltage, and frequency changes.

<table>
<thead>
<tr>
<th>Load</th>
<th>Power</th>
<th>Voltage</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>233.8</td>
<td>0.996</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>522</td>
<td>0.996</td>
<td>0.02</td>
</tr>
<tr>
<td>31</td>
<td>9.2</td>
<td>0.998</td>
<td>0.33</td>
</tr>
</tbody>
</table>
The original method only removes the load in one round, the curtailments is 252.21MW. The steady-state voltage is 0.99633pu and the frequency is 1.001pu after load shedding.

Table 2. Load shedding results of new method.

<table>
<thead>
<tr>
<th>Load</th>
<th>V/pu</th>
<th>F/pu</th>
<th>P</th>
<th>Load curtailments/MW</th>
<th>Second round total load curtailments/MW</th>
<th>dv/dt</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.842</td>
<td>0.99</td>
<td>913</td>
<td>132.849</td>
<td>69.35</td>
<td>-0.022</td>
</tr>
<tr>
<td>8</td>
<td>0.840</td>
<td>0.99</td>
<td>913</td>
<td>295.527</td>
<td>47.44</td>
<td>-0.022</td>
</tr>
<tr>
<td>31</td>
<td>0.858</td>
<td>0.99</td>
<td>915</td>
<td>5.96</td>
<td>0.85</td>
<td>-0.021</td>
</tr>
</tbody>
</table>

The improved method just removes 50% of the curtailment, which is \( 252.21 \times 0.5 = 126.1 \text{MW} \), and the second round’s curtailments is 69.35MW, so the total curtailments is \( 126.1 + 69.35 = 195.46 \text{MW} \), after load shedding, the steady-state voltage is 0.97763 pu and the frequency is 0.99792 pu.

The voltage of No.8 bus after original method UVLS is shown in Fig. 3, the voltage of No.8 bus after improved method’s first round operated is shown in Fig. 4, and the voltage of No.8 bus after improved method’s second round operated is shown in Fig. 5.

![Figure 3. the voltage of No.8 bus after original method operated.](image)
The result shows that the cyclic load shedding scheme removes less loads than the original plan, but the steady state voltage and frequency were slightly lower than the original plan. After further analysis, the method extended the time of load removal, which makes the voltage regulator devices action and have an effect on reducing the amounts of load shedding curtailments.

6. Conclusions

This paper puts forward an improved method of adaptive UVLS based on two rounds of action. The improved method has considered on influences of frequency and voltage dynamics on the load active power, then uses real-time measured electric parameters to calculate the amounts of under voltage load curtailments. In order to ensure the accuracy of the action, the method adds an accelerated round to prevent the voltage drops rapidly. Simulation results of IEEE 39-bus system has shown the superiority of new method in calculating the amount of curtailments. Compared with the conventional one, the improved method can
adapt better to load characters and disturbance types with fewer relays, thus guaranteeing the voltage stability more effectively.

References