Research on the Under-voltage Optimal Control Method of Analytical Sensitivity for Power Simulation Training

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Abstract: As China increasingly interconnecting power system, more and more factors are interfering with the stable operation of the power system. Due to the lack of system reactive power and the overload, resulting in the increasingly problem of low voltage amplitude. Voltage is a measure of whether the power system operation is basically normal index, the voltage level of the power network determines whether the whole power system is stable or not. The dispatcher and operator need to answer any specific challenges to solve the under-voltage in training simulator. In this paper, based on the analytical sensitivity method, the basic principle of the low voltage problem is solved by the method of load shedding and reactive power compensation. Then the low voltage control method is optimized from two aspects of the load shedding load and reactive power compensation. The reactive power compensation with high sensitivity is presented. If the voltage of the compensation is not returned to the allowable range of the state, cutting the load operation according to the magnitute of the load-sheddng sensitivity. Using power system simulation software to build a low voltage model of the IEEE-39 classic power system for the sensitivity index and the low voltage optimization control methods are analyzed and verified.

1. Introduction
With the gradual improvement and development of the power system, the low-voltage control technology is also constantly being updated. The dispatcher and operator need to answer any specific challenges to solve the under-voltage in training simulator. There are several method to solve the low-voltage problem, such as a new criteria of voltage stability margin for the purpose of load shedding[1], a minimum load shedding calculation algorithm[2], load shedding of trajectory sensitivities[3], emergency load shedding algorithm for power systems[4], a technique for load-shedding based on voltage stability consideration[5], load shedding method of analytical sensitivity[6]. These method are not very well to solve the low-voltage problem[7-9].

With the sharp increase of inductive load, the power factor in the power grid is reduced and the voltage is low. In recent years, low-voltage reactive compensation has been placed at the front end of research[10]. In [11], a multi-objective coordinated control method is proposed to overcome the lack
of coordination and large loss of the reactive power compensation device for the single compensation control method used in the current reactive power compensation device in 500kV substation. In [12], a dynamic reactive power compensation method for fast thyristor switching capacitors is proposed for power quality problems such as low power factor, voltage drop and flicker in power supply system caused by impact loads. The literature [13] is affected by the inductive reactive power demand of wind turbines, transformers and lines. The existing wind farms need to be equipped with reactive power compensation devices. The contradiction between the cost of the equipment and the compensation effect is the key factor for the selection of the type of compensation devices. It is proposed to use a capacitor bank and a static var compensator (SVC) to form a hybrid reactive power compensation system.

The sensitivity analysis method[14] are analyzed to solve the low-voltage with load shedding in this paper, and the perfect optimization processing are gotten on the existing scheme [6]. Aiming at the improvement proposal of low-pressure control optimization, the improved low-pressure optimization control method based on sensitivity analysis is improved. The existing system fixed parameters such as bus admittance matrix, bus impedance matrix, load power factor, etc. are analyzed before the system is run. When the voltage is too low when the system is actually running, the reactive power sensitivity analysis and load shedding are sorted according to the previous system parameters to select the optimal control point, and then the reactive power is optimally performed at this point. Compensate and load shedding operations. Due to the large increase of inductive load in the grid system, the power factor in the grid is reduced and the voltage is reduced. Therefore, some load bus can be compensated for necessary reactive power during the load shedding operation, so that the load shedding operation is performed, and the voltage is improvement and better.

2. Analytical sensitivity low-voltage optimization control theory

There is a load power network in a certain area[6], in which one bus is connected to a load bus i, and its bus voltage equation is as follows:

\[
\begin{bmatrix}
\dot{U}_1 \\
\vdots \\
\dot{U}_j \\
\vdots \\
\dot{U}_n \\
\end{bmatrix} = \begin{bmatrix}
K_{11} & \cdots & K_{i1} & \cdots & K_{1m} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
K_{i1} & \cdots & K_{ii} & \cdots & K_{im} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
K_{n1} & \cdots & K_{ni} & \cdots & K_{nm} \\
\end{bmatrix}
\begin{bmatrix}
\dot{U}_{k1} \\
\vdots \\
\dot{U}_{ki} \\
\vdots \\
\dot{U}_{km} \\
\end{bmatrix} - \begin{bmatrix}
Z_{11} & \cdots & Z_{i1} & \cdots & Z_{1n} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
Z_{i1} & \cdots & Z_{ii} & \cdots & Z_{in} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
Z_{n1} & \cdots & Z_{ni} & \cdots & Z_{nn} \\
\end{bmatrix}
\begin{bmatrix}
\dot{I}_1 \\
\vdots \\
\dot{I}_j \\
\vdots \\
\dot{I}_n \\
\end{bmatrix}
\tag{1}
\]

In the formula, the voltage vector of each bus in the network is represented; the voltage of the bus adjacent to the load bus i indicates the injection current vector of each bus; the matrix represents the intermediate conversion relationship, which mainly refers to the transformer non-standard transformation ratio.

Converting the above formula (1) to an equation can be expressed as:

\[
\dot{U}_i = \sum_{j=1}^{n} K_{ij} \dot{U}_j - \sum_{k=1}^{m} Z_{ik} \dot{S}_{ik} i = 1,2,\ldots,n \tag{2}
\]

The current in equation (2) is changed to the apparent power representation to get a new expression:

\[
\dot{U}_i = \sum_{j=1}^{n} K_{ij} \dot{U}_j - \sum_{k=1}^{m} Z_{ik} \frac{S_{ik}}{U_k^*} i = 1,2,\ldots,n \tag{3}
\]

The vector in equation (3) is expressed in polar coordinates as follows:
Combining the data in equation (4) yields:

\[ U_i \angle \theta_{\theta_i} = \sum_{j=1}^{m} |K_{ij}| \angle \theta_{\theta_{ij}} U_{ij} - \sum_{k=1}^{n} |Z_{ik}| \angle \theta_{\theta_{ik}} S_{k} \angle \theta_{\theta_{ik}} \]

\[ i = 1, 2, ..., n \]  

(4)

\[ U_i = \sum_{j=1}^{m} |K_{ij}| \angle \theta_{\theta_{ij}} U_{ij} - \sum_{k=1}^{n} |Z_{ik}| \angle \theta_{\theta_{ik}} S_{k} \angle \theta_{\theta_{ik}} , i = 1, 2, ..., n \]  

(5)

The \( \theta_{\theta_{ij}} \) sum \( \theta_{\theta_{ik}} \) and in equation (5) can be expressed as:

\[ \theta_{\theta_{ij}} = \theta_{\theta_{ij}}^{KU} + \theta_{\theta_{ij}} - \theta_{\theta_{ij}} \]

(6)

\[ \theta_{\theta_{ik}} = \theta_{\theta_{ik}}^{ZUU} - \theta_{\theta_{ik}} + \theta_{\theta_{ik}} \]

(7)

The real and imaginary parts of equation (5) are split to obtain the expression of the bus voltage amplitude:

\[ U_i = \sum_{j=1}^{m} |K_{ij}| \cos \theta_{\theta_{ij}}^{KU} U_{ij} - \sum_{k=1}^{n} |Z_{ik}| \cos \theta_{\theta_{ik}}^{ZUU} S_{k} \]

\[ i = 1, 2, ..., n \]  

(8)

The parameter in (8) can be expressed by using the symbol instead:

\[ U_i = \sum_{j=1}^{m} S_{ij} \cos \theta_{\theta_{ij}}^{KU} U_{ij} - \sum_{k=1}^{n} S_{k} \cos \theta_{\theta_{ik}}^{ZUU} S_{k} , i = 1, 2, ..., n \]  

(9)

The sensitivity parameters are:

Reactive compensation sensitivity

\[ S_{ij}^{\text{react}} = |K_{ij}| \cos \theta_{\theta_{ij}}^{KU} \]  

(10)

Load-shedding sensitivity

\[ S_{k}^{\text{load}} = |Z_{ik}| \cos \theta_{\theta_{ik}}^{ZUU} \]  

(11)

It can be known from formula (9) that the amplitude of the bus voltage is mainly controlled by two data; one is the voltage amplitude of each bus in the system adjacent to the bus; the other is the magnitude of the load of each bus, indicating each bus. The degree of interference between the adjacent bus voltage amplitude and the voltage amplitude of the target bus expresses the degree of interference of the fluctuation of the load of each bus on the voltage amplitude of the target bus.

Since the reactive power compensation sensitivity is close to 1, they are processed as follows in order to easily see their size.

\[ S_{ik}^{\text{react}} = c \left( S_{ik}^{\text{react}} - \min \left\{ S_{ik}^{\text{react}} \right\} \right) \]  

(12)

Among them, the minimum value of the reactive compensation sensitivity in the selected reactive power compensation node. \( c \) is a constant, the value can be taken as 10, 100, and varies according to the value of the change, ensuring less than 1. It is a concept that is derived to more clearly reflect the magnitude of the load shedding sensitivity.

3. Low pressure control measures

It can be known from formula (3) that when the voltage of a certain bus in the system is low, the voltage of the bus close to the bus can be increased by reactive power compensation, and a part of the load close to the bus can also be removed.

3.1. Reactive power compensation

It can be known from equation (10) that the reactive compensation sensitivity is related to the value of . Each bus has a different reactive compensation sensitivity corresponding to this voltage offset point.
When reactive power compensation is applied at the point with the highest sensitivity, it is most effective to improve the voltage improvement of the bus voltage to the target bus. Therefore, the first step should be choose the best reactive compensation point.

The first step is to find the abnormal bus with low voltage, determine the set of bus directly connected with it as the preliminary set of reactive compensation points, and then calculate the reactive compensation sensitivity using the formula (10) for the selected bus set. And the power factor of each bus. In the bus set, find the bus with low power factor, and perform reactive compensation processing on these bus until the voltage of the target bus returns to within the allowable deviation specified by the rated voltage of the bus. If the power factor of each bus in the bus set has reached a high level and the voltage has not returned to the normal range, the load removing operation is performed.

3.2. Load shedding
It can be known from formula (11) that the magnitude of the load-shedding sensitivity parameter is mainly related to the three parameters of the bus voltage amplitude of the cut point, the mutual impedance between the bus at the load shedding position and the target bus, and the power factor of the load shedding point. When the voltage of a bus is abnormal, each bus has a different load--shedding sensitivity corresponding to this voltage offset point. When the load is removed at the point with the highest sensitivity, the voltage improvement degree of the target bus is most effective. Therefore, you should first choose the best load shedding point. In the power system, the impedance matrix is sparse matrix, and the impedance between the point that is not directly connected to the target bus and the target bus is zero, that is, when the load shedding point is not directly connected to the target bus, the load-shedding sensitivity is zero; The load point set is reduced to several bus near the target bus. Therefore, the sensitivity is further selected from the power factor and the bus voltage amplitude.

Therefore, screening the optimal load-removing point should be screened in two steps. The first step is to find the abnormal bus with low voltage, and determine the set of bus directly connected with it as the initial set of load points to be removed, and then filter the bus. The set (11) is used to find the load shedding bus with the maximum value of the load-shedding sensitivity, and the bus is subjected to load shedding processing until the voltage of the target bus returns to the allowable deviation specified by the national rated voltage of the bus to stop the load shedding operation. The amount of load shedding should be considered as the boundary of the load shedding constraint based on the load size constraints specified in the actual case, and the imbalance relationship of each bus in the power network should always be considered to prevent other faults from occurring due to excessive load removal.

The first step is to find the abnormal bus with low voltage, determine the set of bus directly connected with it as the preliminary set of load points to be removed, and then use the formula (11) to find the maximum value of the load-shedding sensitivity. The load shedding bus performs load shedding on the bus until the voltage of the target bus returns to within the allowable deviation specified by the national rated voltage of the bus to stop the load removing operation.

4. Example simulation and data analysis
Using the IEEE-39 classic example to simulate, by adjusting the IEEE-39 raw data, the voltage of the bus 18 and their adjacent bus is low. The wiring diagram of the 10 machine 39-bus standard test system is shown in Figure 1. Low-voltage control measures mainly include load shedding and reactive power compensation. The low-pressure optimization control measures are mainly to combine the two.
Figure 1. IEEE 39 standard test system.

4.1 Remove load then reactive power compensation
In view of the low voltage of bus 18, the optimal control measures are taken. Firstly, the load-removing operation is performed at the bus with high load-sensing sensitivity at bus 18, and then the reactive power compensation operation is performed at the bus with high sensitivity of 18-bus reactive power compensation.

The load-shedding sensitivity is calculated by Equation 11, as shown in Table 1. The 17 bus have no load, so the load-carrying operation is performed on the 18th and 3rd bus, and the 18MW and 40-bus 40MW loads are sequentially removed. The 1-33 bus voltage change after the load shedding operation is performed is shown in Fig. 1, and the 18-bus voltage standard value is as shown in Fig. 1. Table 1 shows. It can be seen from Table 1 and Figure 2 that although the 18-bus voltage is increased after the load removing operation, the increase is slow. After the reactive power compensation operation, the 18-bus voltage is significantly increased. The 18th bus’s voltage value is as shown in Table 2 after performing low-voltage control measures, the 18th bus’s voltage is better from compensate for 3-bus and 18-bus of reactive power than from load of 3-bus and 18-bus be removed.

Figure 2. Bus voltage curve.
Table 1. The load-removing sensitivity of the 18th bus

| Bus k | Load-shedding sensitivity |
|-------|---------------------------|
| 18    | 0.091382                  |
| 3     | 0.054408                  |
| 17    | 0.029898                  |

Table 2. The 18th bus’s voltage value after performing low-voltage control measures

| Low pressure optimization control measures      | 18-bus voltage |
|-------------------------------------------------|----------------|
| Load 40MW of 18-bus be removed                   | 0.931          |
| Load 40MW of 3-bus be removed                    | 0.933          |
| Load 80MW 18-bus be removed                      | 0.938          |
| Compensate for 3 and 18 bus of reactive power   | 0.974          |

4.2 Compensate reactive power then load removed

For the same original data, when performing low-voltage optimization control measures, the reactive power compensation operation is performed first at the bus with high sensitivity of 18-bus reactive power compensation, and then the load shedding operation is performed at the bus with high sensitivity of 18-bus load shedding and the above optimization. The voltage improvement effect after the measure is compared.

Taking the 18-bus as the center, the reactive compensation sensitivity is calculated by formula (10), and sorted, as shown in Table 3. After considering the bus with high sensitivity of reactive power compensation, it is also necessary to check whether the power factor of the bus is within a reasonable range. If it is high enough, the reactive power compensation measure cannot be performed. Therefore, no reactive compensation measures are performed. In summary, the bus 18, 4, and 3 with higher reactive power compensation sensitivity are selected, and the reactive power compensation operation is sequentially performed. The curve of the bus voltage after reactive power compensation is shown in FIG. 1. It can be seen from Fig. 3 that the effect of 18-bus reactive power compensation is significant, and as the sensitivity of reactive power compensation decreases, the effect of reactive power compensation is gradually reduced. After the 27 bus compensated for reactive power, the 40MW load was removed at the 18th and 3rd bus, and the 18-bus voltage increased, but it did not change much.

Table 3. The 18th bus’s reactive power compensation sensitivity

| Bus k | Reactive power compensation sensitivity | Power factor |
|-------|-----------------------------------------|--------------|
| 18    | 0.2833                                  | 0.88         |
| 17    | 0.2763                                  | No load      |
| 15    | 0.2708                                  | 0.95         |
| 4     | 0.2632                                  | 0.89         |
| 16    | 0.2631                                  | 0.99         |
| 3     | 0.2629                                  | 0.89         |
| 27    | 0.266                                   | 0.92         |
| 33    | 0                                       | 0.94         |
Comparing Fig. 2 and Fig. 3, combined with the power factor of the bus in Table 3, it can be seen that in the IEEE 39 bus system, when the bus reactive power is insufficient, the load removing operation is performed on the low voltage bus, and the bus can be improved. Voltage, but the improvement is not obvious. However, at this time, the reactive power compensation is performed on the bus with high sensitivity of reactive power compensation, and the bus voltage improvement effect is very obvious. When the reactive power of the node is sufficient, the bus load-removing operation bus voltage improvement effect is obvious. The 18th bus’s voltage value is shown in Table 4 after performing low-voltage control measures.

Table 4. The 18th bus’s voltage value after performing low-voltage control measures.

| Low pressure optimization control measures       | 18-bus voltage |
|------------------------------------------------|----------------|
| Compensation 18-bus reactive power              | 0.946          |
| Compensation 4-bus reactive power               | 0.951          |
| Compensation 3-bus reactive power               | 0.957          |
| Compensation 27-bus reactive power              | 0.964          |
| Removing 18, 3 bus 40MW load                    | 0.971          |

5. Conclusion
There are any specific challenges need to be answered to solve the under-voltage for dispatcher and operator in training simulator. In this paper, the basic principles of low voltage reactive power compensation and load-shedding sensitivity calculation based on analytical sensitivity method are studied. The reactive power compensation sensitivity and load-shedding sensitivity parameters and their influencing factors are derived. Starting from the influencing factors, the method based on analytical sensitivity reactive power compensation and load shedding is further determined. Firstly, the fault point is studied, and the reactive power formula is used to screen the reactive power compensation point and the load shedding point. The order of the low-voltage control measures is verified. The result proves that the necessary reactive power compensation is performed at the load bus with high reactive power compensation sensitivity. If the low-voltage voltage fails to return to the normal level after the reactive power compensation, then The load reduction point is reduced by a certain amount of load, and the low voltage control method has a more significant voltage improvement effect.

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