Analysis on the Reason of Low Voltage Problem and the Effectiveness of Voltage Regulation in a Distribution Area

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Abstract. For the problem of low voltage, this paper took a 10kV low voltage line as the research object, summarized and classified the causes of low voltage on the line, analyzed the real reason for the problem of low voltage which combined with the actual situation of the line as the class, put forward many management suggestions. Combined with the actual situation of the line, line automatic voltage regulator would be installed. For automatic voltage regulator, its effectiveness was analyzed from the principle in this paper, 10kV line simulation model was established, this paper gave the simulation analysis of the effect of the line overload on the terminal user's voltage and the different control effects brought by the installation location of the voltage regulator, the research results provide a scientific basis for the management of the low voltage problem.

1. Introduction

At present, China's power grid is in a high-speed development stage, its scale continues to expand, the overall level of production construction, operation management and marketing services and so on has been continuously improved, and technology content has also been continuously enhanced, but the vast territory, the scattered living and relatively backward economy have resulted the unreasonable grid, lack of the power sources, the substations, the lines, the distribution transformers, reactive compensation configuration and long line power supply radius in some areas, especially in remote Midwest. In addition, network loads increases, some parts of the power grid have been unable to meet the current rapid economic and social development of the electricity demand, followed by low voltage qualification rate, high loss rate and series of results, the problem of voltage quality has become increasingly prominent. In the peak-load period, such as the Spring Festival, the Busy Season and the peak of every night, the voltage of the grid exists low (abbreviation as the problem of low voltage), seriously affects the normal production-life of the residents, is not conducive to the rapid development of economy and society [1], [2] and [3].

The problem of low voltage is becoming more and more important in the construction and development of distribution network. In order to eliminate the area of low voltage problem, the state has increased its investment in the distribution network construction, and the development of the distribution network has achieved remarkable results. Although the network structure, the equipment level and the comprehensive management level of distribution network improved significantly, there is
still a large gap relative to the international advanced level, develops imbalance between urban and rural regional, need to further improve the power quality. For this purpose the state has issued a number of relevant policy documents over the past year or so.

The problem of low voltage has become the livelihood issue, timely and effective solution to the problem of low voltage for improving the quality of power supply and enhancing the customer satisfaction is the social responsibility of each power supply company. In this paper, a 10kV line complained by the problem of low voltage was taken as the research object, the simple estimation method was introduced and seven causes of low voltage were summarized and classified, the analysis process of low voltage problem was in detail from the power supply radius, wire section, overload, unbalance, reactive power compensation in seven aspects, the corresponding measures and suggestions were given, combined with the actual situation of the line, a transitional scheme is adopted, that is, line automatic voltage regulator would be installed. For the voltage regulator, the principle and the application scope or the effectiveness for the problem of voltage control were analyzed, combined with the case of the user complaint low voltage line, the model based on MATLAB is built. The results show that the automatic voltage regulator is helpful to improve the problem of low voltage, but different installation positions have different effects on improving the terminal voltage, that is, the voltage regulator has an adaptive range for installation position and so on.

2. Overview of the problem of low voltage

The wiring diagram of the 10kV line for users complained the problem of low voltage, as shown in Fig.1. The mode of 10kV line power supply is single radiation and three sections, and the power source is an 110kV substation in the diagram, as can be seen from Fig.1. The trunk of the line has the total length of about 9.935km, the total of 109 base rods, the maximum power supply radius from #1 base rod to the terminal of the feeder 4 is 12.528km, and the specific distance of each section is shown in Fig.1. The trunk and the branch wire used in the 10kV line were LGJ-95 and LGJ-70 respectively, the total number of the transformer is 95, the total capacity is 11725kVA, including the number and the capacity of the Common Transformer (abbreviation as CT) were 49 and 4610kVA respectively, the remaining were the number and the capacity of Special Transformer (abbreviation as ST).

![Figure 1. Wiring diagram of a 10kV line.](image)

Recently the ST4 customer of 10kV line complained that his factory often suffered from the problem of low voltage, couldn’t be seriously affected the normal production. Through the verification of voltage monitoring system, it is found that the first and the terminal of annual accumulative voltage qualification rate are 86.57% and 77.44% respectively. Second Side of a CT at the terminal of the line has been appeared to as low as 317V. In order to find out the real reason of low voltage of the line, firstly the analysis method of low voltage problem is introduced, and then research and analysis are carried out in many aspects combining with the measurement data of ST1~4, some corresponding measures and suggestions are put forward at last.
3. Analysis of the causes of low voltage

Based on the vector diagram of the line of power system, a simple estimation expression of voltage loss is obtained [4] and [5], as shown in formula (1).

$$\Delta U(\%) = \frac{PR + QX}{U^2} \times 100\% \approx \frac{PL}{AC} \times 100\%$$  \hspace{1cm} (1)

In the type, P and Q stand for active power and reactive power of the transmission line respectively. R and X stand for the resistance and the reactance of the line respectively, generally the line takes 0.35–0.4Ω/km, L stands for transmission distance or power supply radius, A stands for the cross-section of the conductor, C is the coefficient of voltage loss, the value of the copper wire is 85 and the one of the aluminum is 50 when the system is three-phase 4-wire power supply and each phase load is uniform.

The causes of low voltage at the terminal of the line obtained from the formula (1) are mainly low voltage of 10kV bus of the substation, overload, and long power supply radius, unreasonable distribution transformer running tap, small wire cross-section, load unbalance and lack of reactive power compensation and so on. The specific causes of low voltage of the line are shown in Fig.2.

![Figure 2. Schematic diagram of the cause of low voltage of the line.](image)

Next then the causes of low voltage of 10kV line are analyzed in detail from the power supply radius, the cross-section of the wire, overload and another four aspects.

1) The power supply radius: according to the regulations of the power supply radius “Guidelines for the planning of China Southern Grid Corporation 110kV and below distribution network” [6], the length of 10kV distribution line should meet the requirements of the terminal’s voltage quality, and the line length of various power supply areas should be controlled in the corresponding range, as shown in Fig.3. The line is mainly for urban power supply, belongs to the class E of power supply area, as seen from Fig.1, the length of the main trunk is close to the range of the guidelines, the longest of power supply radius is excess to the specified rang of the guidelines. On the whole, the power supply radius of the line is in the critical state.

![Figure 3. Selection of power supply radius for various power supply areas.](image)
(2) The wire cross-section: according to the regulations of 10kV wire cross-section “Guidelines for the planning of China Southern Grid Corporation 110kV and below distribution network” [6], as shown in Table 1. The wire cross-section of the line trunk is 95mm², below the minimum requirements of the main trunk in Table 1, the one of the line branch is 70mm², which meets the requirements of Table 1. Thus it can be seen that the cross-section of the main trunk is too small, which is one of the causes of low voltage problem at the 10kV line.

Table 1. Selection of 10kV wire cross-section.

| Classification of power supply areas | Overhead line (mm²) |
|------------------------------------|---------------------|
|                                    | Main Trunk | Secondary trunk | Branch |
| A, B, C, D                         | 240, 185   | 150, 120        | 95, 70 |
| E, F                               | 185, 150, 120 | 120, 95         | 50     |

(3) Overload: the model of 10kV main trunk conductor is LGJ-95, and its continuous allowable current is 335A. The Metering Automation System showed that the currents of A, B, C three-phase loads reached the maximum values on that day complained by the user, 316.8A, 321.6A and 318.4A respectively, the annual average were 146.8A, 149.1A and 146.5A, is close to continuous allowable current limit value of 10kV line, the line is overload at the seasons and the periods of peak power consumption. As a result, the overload of the line is also one of the causes of low voltage problem at the 10kV line.

(4) Three-phase unbalance: From the Metering Automation System, the qualified rate of 10kV bus three-phase voltage balance at 110kV substation is 100% all the year round, one of three-phase current balance rate is 100%. The measurement results showed that 4 STs’ three-phase voltage unbalances were 0.43%, 0.41%, 0.45% and 0.47%, which are in the standard range and three-phase average values are relatively close, whose maximum are at the same time. Therefore, it is considered that three-phase unbalance is not the cause of the low voltage problem of the line through comprehensive analysis and judgment.

(5) Reactive power compensation: In normal operation, power factors of ST1’s and ST3’s users have once reached 0.67 and 0.46 respectively, and users of ST1~4 are all equipped with reactive power compensation devices, overall power factors of these users are so high during the measurement period. From the Metering Automation System, the annual average power factor of the line is 0.91. Therefore, low power factor is not the cause of the low voltage problem in the line [7] and [8].

(6) Transformer running tap: At present Power Supply Company cannot provide the running tap information of the distribution transformer, and has never carried out adjusting the tap of the line transformer. Reasonably setting up the tap of distribution transformer is the most economical way to solve the problem of low voltage, and can achieve an immediate effect of voltage regulation within a certain range at the same time. Currently the tap of the transformer does not change, so it is impossible to automatically adjust its tap according to the actual voltage situation.

(7) Bus voltage of the substation: Table 2 is the annual statistical voltage data of the line. As can be seen from Table 2, 10kV bus voltage of 110kV substation does not exist the time on crossing the floor level, and only does a small amount of time on exceeding the upper limits, its voltage qualified rate is higher [9].

Table 2. Annual statistical voltage data of 10kV line.

| Phase | Time of upper limit (min) | Time of lower limit (min) | Voltage qualified rate (%) | Average values (kV) |
|-------|---------------------------|---------------------------|---------------------------|---------------------|
| A     | 360                       | 0                         | 99.87                     | 5.931               |
| B     | 480                       | 0                         | 99.81                     | 5.988               |
| C     | 120                       | 0                         | 99.96                     | 5.910               |
Fig. 4 is the trend of 10kV bus voltage variation from August to October. The maximum, the minimum and the average of 10kV bus voltage at 110kV substation are 10.62kV, 10.09kV and 10.38kV respectively during the above three months, its voltage is within the reasonable range. Therefore, bus voltage of the substation is not the cause of the low voltage problem in the line.

Through the above analysis, the causes of the problem of low voltage in the line is not three-phase unbalance, bus voltage of the substation and power factor of the line, but line overload and small wire cross-section, in addition that the power supply radius is in the critical condition and the ST’s users at the terminal of the line are more concentrated, which is the result of the combined effects of various reasons. The measures should be taken to control as follow: (I) In the future it should be scientifically evaluated and taken measures to avoid heavy load or even overload if the line is loaded with large users. (II) The tap of distribution transformer should be comprehensively checked, and then their records should be made. The records should be updated in time for the change of the tap of distribution transformer, so as to provide the reference for the problem of low voltage in the future. (III) Timely attention should be paid to power factor of the ST in the line, power supply company should inform users in time for rectification when power factor is lower. (IV) In the long term, fundamental solution on low voltage of the line should be reconstruction for the line (e.g. increasing wire section) under necessary conditions, or transfer for the users’ loads of the line and reduce the distance for power supply according to the planning for new substations. (V) According to the investment plan, line corridor and other actual characteristics of the line, the installation of voltage regulator is a transitional solution that can be chosen at present. It can play an immediate role in voltage regulation within a certain range.

4. Principle and validity of Automatic Voltage Regulator

Automatic Voltage Regulator is composed by three parts, which are the auto-transformer, the load tap changer and automatic voltage controller. Fig. 5. is the schematic diagram of the voltage regulator.
The auto-transformer is a transformer with only one winding and nine taps (voltage difference between each tap is 2.5%, the total voltage range is 20%, and larger voltage range can be customized according to the requirements). It is divided into three parts, which are series excitation coil, shunt coil and control coil. Series excitation coil is connected with different contacts of the load tap changer to achieve the voltage-regulating function, the main connection on the power supply side can be switched from tap 1 to tap 9 through the switch of load voltage-regulating, and the main connection on the load side determines the fixed connection according to the range of voltage, refer to Table 3. The shunt coil is a three-phase common winding coil, which is mainly used to generate magnetic fields for transmitting energy. The control coil of three-phase triangle connection is mainly used to eliminate 3th harmonic, and provides independent working power for the automatic controller and the load voltage-regulating switch. The load tap changer can switch with the load and change the joint position of the connector, ensure the continuity of power supply. Automatic voltage controller is the core part of the line voltage regulator, the voltage signal on the load side of phase A and phase C is equipped with a voltage transformer, the current signal on the load side of phase A and phase C is provided with a current transformer through the internal differential. By comparing the output voltage with the setting value, the corresponding control instructions are sent to the load tap changer, and the operation of the voltage-regulating is implemented automatically to meet the requirements of voltage quality [10], [11] and [12].

Table 3. Main connection position table of voltage regulator at load side.

| Range       | Position | Tap |
|-------------|----------|-----|
| 0~+20%      | Tap 1    | One |
| -5~+15%     | Tap 3    | Three |
| -10~+10%    | Tap 5    | Five |

The principle of line voltage regulator is similar with load voltage-regulating transformer according to the analysis and the judgement of the data and the signal collected by the automatic voltage-regulating controller, the tap position of the winding coil can be changed through the load tap changer to achieve the purpose of regulating voltage [12]. The output and the input of the line voltage-regulating are the part of common coil, the voltage can be reduced if the tap is adjusted to less than the common coil, and instead the voltage can be boosted if the tap is done to more than that paper [12].

Line voltage-regulating device can be directly equivalent to the line connected to a transformer, in order to improve the voltage quality of next stage, reduce the voltage deviation and ensure that the voltage deviation is within the allowable range, is one of 10kV common voltage-regulating means. After the line is equipped with the voltage regulator, its equivalent circuit is shown in Fig.6.

![Figure 6. Schematic diagram of line voltage regulator.](image)

In the figure, the line voltage regulator expresses as the symbol of the transformer, its ratio is $k$, $E_s$ is the equivalent voltage, $I$ is the load current, $V_t$ is the terminal voltage, $Z_s$ and $Z_D$ are the system equivalent impedance and the load equivalent impedance before and after the line voltage regulator respectively, $P_g$ and $Q_g$ are the active power and the reactive power of the load respectively.
The secondary side of the equivalent impedance of the transformer is converted to the primary side, the system current can be obtained.

\[ Z_s = \frac{Z_L}{1 + \frac{k^2}{k^2} Z_D} \cos \phi \] (2)

The amplitude can be obtained by deducing.

\[ I = \frac{k^2 E_s}{\sqrt{k^4 Z_L^2 + 2k^2 Z_D \cos (\theta - \phi) + Z_D^2}} \] (3)

The current is normalized by short-circuit.

\[ \frac{I}{I_{sc}} = \frac{k^2 x}{\sqrt{k^4 x^2 + 2k^2 x \cos (\theta - \phi) + 1}} \] (4)

In the type, \( x = \frac{Z_L}{Z_D} \), short-circuit \( I_{sc} = \frac{E_s}{Z_L} \).

The voltage at the load side can be calculated.

\[ V_k = \frac{k E_s}{\sqrt{k^4 x^2 + 2k^2 x \cos (\theta - \phi) + 1}} \] (5)

The relation between the load and the ratio of the transformer is

\[ \begin{align*}
    P_k &= \frac{k^2 E_s^2 \cos \phi}{Z_L} \left( k^2 x + 2k^2 x \cos (\theta - \phi) + 1 \right) \\
    Q_k &= P_k \tan \phi
\end{align*} \] (6)

When \( x = 1/k^2 \) (that is \( Z_D = k^2 Z_L \)), there is a limit of the active power of the load.

\[ \begin{align*}
    P_{k\text{max}} &= \frac{E_s^2 \cos \phi}{2Z_L \left[ 1 + \cos (\theta - \phi) \right]} \\
    Q_{k\text{max}} &= P_{k\text{max}} \tan \phi
\end{align*} \] (7)

When the power of the load is close to the limit, there will be a morbid flow. Similarly, the relationship between the voltage and the ratio of load terminal is as follow.

\[ V_k = \frac{k}{\sqrt{k^4 x^2 + 2k^2 x \cos (\theta - \phi) + 1}} \] (8)

When \( k = 1/\sqrt{\gamma} = \sqrt{Z_D/Z_L} \), \( \frac{d(V_k/E_s)}{dk} = 0 \) and \( V_k \) would appear the limit, at the same time the increasing the ratio of the voltage regulator has no effect on voltage regulation. Therefore, the effectiveness of the voltage regulator is closely related with \( Z_L/Z_D \). When \( \cos \phi = 0.9 \) and
\[ \theta = \arctan(10) \], the relationship between the ratio \( k \) and \( V_s/E_s \) is under different conditions, as shown in Fig.7.

![Figure 7](image)

**Figure 7.** The relationship between the ratio \( k \) and \( V_s/E_s \) under different conditions.

According to the graph, the larger the value \( Z_L/Z_D \), the earlier the extreme value of the curve, the less the effect of the voltage regulator is. From the practical view, the longer the distribution line, the greater the impedance of the line \( Z_L \), the greater of the load, the smaller the value \( Z_D \), at the same time the greater the value \( Z_L/Z_D \), the more the disadvantage of the installation of voltage regulator on the line. Under this condition, the installation of voltage regulator is not recommended when the value \( Z_L/Z_D >0.9 \). Therefore, the magnitude and the phase of the system equivalent impedance and the load equivalent impedance should be calculated synthetically, and the relationship between the secondary voltage and the ratio of voltage regulator is calculated according to the formula (7), in order to judge the validity of voltage regulator.

5. Simulation and analysis

Users of ST4 often complained the problem of low voltage. After testing and analysis, a transition solution at present was given, that is, the voltage regulator was installed within a certain range to achieve immediate effect of voltage regulation. In order to explain the effectiveness of the automatic voltage regulator and the corresponding installation position, this paper proposed 10kV simulation model based on MATLAB software. The short-circuit capacity of the line which is connected to 10kV bus in 110kV substation was 250MVA, the power factor of whose line was 0.9. When the current of the line changed, four users of ST1~4 appeared in accordance with their complaints and the details are shown in Table 4.

| Current of 10kV line (A) | Voltage of secondary side (V) |
|-------------------------|-------------------------------|
|                         | User of ST1 | User of ST2 | User of ST3 | User of ST4 |
| 129.79                  | 223.6       | 222.5       | 223.2       | 207.3       |
| 198.32                  | 213.9       | 213.1       | 213.2       | 194.7       |
| 291.37                  | 206.6       | 198.7       | 199.6       | 177.34      |

In the table, when the current of the line was increased to approximately 300A, the voltages of four ST users were obviously decreased in the normal operation of reactive power compensators, the voltage of ST4 was reduced to 177.34V, far lower than national standard limits.
In order to solve the problem of low voltage of the ST4, the installation adopts the principle of proximity, a line voltage regulator was to install near the 97# pole in this paper. Before the installation of the voltage regulator, the voltage of the user at the ST3 near 97# pole was 198.01V, the voltage of the user at the terminal of the branch 4 was 195.43V, after the installation of the voltage regulator, and their voltages were increased to 222.65V and 220.32V respectively. But it was also noticed that the effect of voltage regulator was closely related to the power factor, the rate of the load and the installation position in the simulation. For that the average power factor of the line was high, its influence was not considered in this paper. The simulation analysis of two installation positions of 93# pole and 97# was carried out, the results of the simulation was shown in Fig.8.

![Figure 8. Comparison among voltage-regulation effects of different installation positions of automatic voltage regulator.](image)

The simulation results showed that the coefficient k of the voltage regulator increased, the voltage regulator was installed either in the 93# pole or in the 97# pole, the effect of voltage regulator was gradually increasing, and however the effect of voltage regulator was gradually decreasing with the rate of the load from 30% to 100% at front of the installation position. Under the same conditions, the installation position had a great influence on the effect of voltage-regulating, which is consistent with the conclusion of the third section of this paper. Therefore, before the voltage regulator would be installed, the optimal of the installation position, the installation capacity and the voltage regulation coefficient should be calculated by comprehensive simulation.

6. Conclusion
The paper took a 10kV line which was complained for the problem of low voltage as the research object, introduced a simple method for estimating the voltage loss, and summarized seven cases on the cause of low voltage and detailed analysis process, at the same time, some measures and suggestions were put forward. In combination with the actual situation of the line, the automatic voltage regulator was adopted. For the automatic voltage regulator, its principle and the scope or effectiveness of the control of low voltage problem were analyzed. The model of the line of low voltage based on MATLAB software was established, the simulation results showed that the voltage regulator could help to improve the problem of low voltage, however, different installation positions had different effects on improving the terminal voltage, that is, the voltage regulator had a suitable range for the installation position. Therefore, before the voltage regulator would be installed, the optimal of the installation position, the installation capacity and the voltage regulation coefficient should be calculated by comprehensive simulation.

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