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Low-Voltage Comprehensive Management of Rural Distribution Networks based on MSVC and Line Voltage Regulator

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Abstract

Rural distribution networks, as important components of the electrical power system, are important basic conditions for economic development in rural areas. However, weak structure, large supply scope, abundant power supply terminals, and long line and low-voltage phenomenon are relatively common in rural distribution networks in China. A new low-voltage comprehensive management method for distribution networks based on magnetically controlled static var compensator (MSVC) and line voltage regulator was proposed in this study to solve low-voltage problems in rural distribution networks. The computing and MATLAB simulation model was constructed based on the 10 kV rural distribution network in Guangdong Province, China. Performances under different problem situations were compared by using voltage and power factor as the reference variables to verify the validity and feasibility of the new method. Results show that, the proposed comprehensive management method based on MSVC and line voltage regulator can improve the voltage and power factor of branch lines without influencing the voltage of other branch lines; thus, the voltage at different nodes satisfies the requirements (>9 kV) and increases the power factor to 0.96–0.98. This study proves that the proposed method has unique advantages in increasing voltage, power factor, and economical efficiency of the rural distribution networks. The study also provides effective references to low-voltage management in rural distribution networks.

Keywords: Rural distribution networks; low voltage; comprehensive management

1. Introduction

Rural distribution networks in China generally have long and radiated lines, complicated branch structures, many scattered loading points and evident seasonal characteristics of loads. Problems such as weak structures and lack of fundamental automatic facilities exist because of inadequate main power and material and financial resources in the early construction of rural distribution networks. Recently, the electricity consumption demand has grown rapidly due to the sudden social and economic development in rural areas. However, many power distribution equipment and lines in rural distribution networks are old, and abundant branch lines appear, thereby resulting in an extremely serious low-voltage phenomenon at the line terminals [1].

In rural distribution networks, the 10 kV distribution lines serve as an important link between the power system and users. The low-voltage phenomenon at line terminals becomes extremely serious because of the large quantity, complicated branch structure, large supply radius, and high network loss, thereby causing considerable influences to users. Building new transformer substations and changing the high-energy consumption transformer and the large-section wires can reconstruct rural distribution networks and address the above-mentioned problem [2, 3]. However, these methods are less feasible in many regions due to high cost and long construction period.

Under the premise of no large reconstruction of line structure and equipment, adding the reactive-load compensation equipment and voltage regulating equipment to the heavy-loaded lines is the main management method to address low-voltage problems in rural distribution networks. After installing the reactive-load compensation equipment (e.g. parallel capacitor) in the distribution networks, reactive power, which is consumed by inductive load, can be supplied. The reactive power that is supplied by the inductive load of the power source and transmitted by lines is reduced. Furthermore, the electricity loss caused by reactive power transmission in lines and transformer can decrease.

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Nowadays, the static var compensator (SVC) [4, 5], which is applied to practical engineering, has unique advantages in economic efficiency and technologies due to the short installing and debugging time and low cost. However, the independent use of SVC requires large-capacity distribution network terminals with heavy and large variation ranges of loads [6] . In addition, reducing the network loss of the system requires installation at multiple places with low economic efficiency. Moreover, load voltage regulator and one-line voltage regulator equipment can improve the line voltage quality of the distribution network to some extent. This approach is low cost. It can be regarded as a feasible method in low-voltage management of 10-kV rural distribution networks [7, 8]. However, for an electric system with inadequate reactive power, the voltage regulator can further increase the reactive vacancy of the system while improving the voltage of the accessed branches, thereby further decreasing voltage at points with lower voltage [9] . Therefore, the independent use of voltage regulator cannot be applied to rural distribution networks with large original reactive vacancy.

In this study, a collaborative management method based on MSVC and line voltage regulator was proposed. Moreover, the method can offset the disadvantages of MSVC and line voltage regulator while amplifying their advantages. A low-voltage management method was selected reasonably with comprehensive considerations for voltage and power factor based on the actual conditions of a 10 kV line in rural distribution networks in Guangdong Province, China. Consequently, the voltage level and power factor of relevant branch lines conform to regulations, thereby verifying the feasibility of the proposed method.

2. State of the art

Scholars have discussed voltage quality problems in rural distribution networks.

Huang [5] proposed the voltage adjusting and stabilizing method of distribution networks based on series capacitance compensation. They verified the feasibility of the proposed method by theoretical calculation and simulation. However, any failure of the parallel compensation devices will influence the accessed circuit, thereby resulting in poor reliability of the device.

Hingorani et al. [6] defined the concept of flexible AC transmission system (FACTS). They defined the system as the set of controllers based on thyristor. However, this proposal is only conceptual. Larsen et al. [7]continued to perfect this theory and classified FACTS controllers. Moreover, they performed deep explanations and updating of FACTS concept and facilitated the production of new equipment. Subsequently, scholars proposed their own understanding on the use of the new FACTS equipment in distribution networks. Gyurov [8] applied thyristor controlled series compensation (TCSC) to reactive compensation and voltage regulation in low voltage field by studying the basic characteristic capability of the TCSC. Bogovi Jerneja [9] proposed the three-phase static synchronous series compensator (SSSC) model based on the forward scanning algorithm, which is applied to distribution networks. Jaiswal Shiva Pujan [10] proposed a method that uses the unified power flow controller (UPFC) to minimize the distribution loss and improve voltage distribution at nodes. Gagandeep Singh [11] applied the proportional integral (PI) control based on the pulse-width modulation (PWM) and the dynamic voltage restorer (DVR) of hysteresis voltage control technology to middle and low voltages. However, single FACTS device cannot satisfy the complicated rural distribution networks. Yi [12] pointed out that none of the previous compensation devices of the distribution networks, such as SVC and thyristor controlled reactor (TCR), can adapt to sharp power changes of the distribution networks and realize instantaneous reactive power control. Therefore, the SVC of the distribution networks (D-STATCOM) was proposed. It could compensate capacitance or inductive reactive power dynamically and offers real-time compensation for instantaneous reactive power that changes rapidly. Geddada Nagesh [13] proposed the improved topological structure of the four-leg distributed SVC (D-STATCOM) for compensating non-equilibrium and nonlinear loads in the three-phase four-line distribution system. The D-STATCOM, which is connected in parallel with loads, offers reactive power and harmonic power required by non-equilibrium nonlinear loading. Li [14] analyzed the influences of voltage non-equilibrium of distribution networks on D-STATCOM from principles. At non-equilibrium three-phase network voltage, the output voltage of D-STATCOM developed negative sequence and third harmonic, which may cause overcurrent and burn the device under serious conditions. Thus, an improved switch function modulation method was proposed to improve the voltage output performance of D-STATCOM under asymmetric voltage of the distribution networks and to inhibit the third harmonic and negative-sequence current. At the same time, adding one negative-sequence voltage feedforward control link based on the double-closed voltage control method of D-STATCOM is suggested to inhibit the overcurrent caused by negative-sequence voltage. However, if the reactive compensation method causes concentrated compensation in rural distribution networks, the compensation capacity becomes extremely large, and the terminal effect of lines becomes serious due to the long lines. Moreover, in-situ compensation is impossible because of the massive and scattered branch lines and loading nodes in rural distribution networks.

Li [15] and Gu [16] pointed out that load voltage regulator and one line voltage regulating device can significantly improve line voltage quality of the distribution networks. However, in rural distribution networks with inadequate reactive power, the voltage regulator further increases the reactive vacancy in the network while improving the voltage of accessed branch lines, thereby decreasing the voltage at the low voltage point. The voltage regulator cannot be independently applied to rural distribution network lines with original large reactive vacancy.

Swarnkar [17], Ibrahim [18], and Wu proposed a high-efficiency algorithm for reconstruction of distribution networks to increase reliability and electricity quality of the distribution system. Liu proposed the one feeder reconstruction method. The relation curve between the overhead conductor with different cross areas and voltage loss percentage was revealed through the quantitative analysis on the voltage drop of feeder. He pointed out that given the small cross section area of wires, the voltage drop can be decreased effectively by increasing the cross section area of wires. However, rural distribution networks have massive and complicated branch lines. Such reconstruction method cannot be applied to voltage management in rural distribution networks.

These studies failed to propose an effective solution to the problems of rural distribution networks with long lines, complicated branch structure, massive and scattered loading point, and evident seasonal characteristics of loads. In this study, the collaborative management method based on MSVC and line voltage regulator was proposed to regulate line voltage and to compensate for the reactive power of lines simultaneously. The operating parameters of the actual lines were used as basis of the circuit model. The low-voltage management method was selected reasonably, considering voltage and power factor. Experimental results between different traditional methods and the proposed method were compared to provide effective references to low-voltage management of rural distribution networks.

The remainder of this study was organized as follows. Section 3 described the theoretical basis for the collaborative management method based on MSVC and line voltage regulator. The circuit computing and simulation model was constructed. Section 4 compared the simulation data. Section 5 draw the conclusions.

3. Methodology

3.1. Theoretical analysis of voltage drops in distribution networks

For a specific distribution network, the first-end voltage and first-end power of a known line were $\tilde{S} = P + jQ$ and $\dot{U}$, respectively. Therefore, the voltage loss of this line was obtained as follows [8]:

$$d\dot{U} = \Delta U + j\delta U \tag{1}$$

where $\Delta U = \frac{PR+QX}{U}$ and $\delta U = \frac{PX-QR}{U}$.Generally, the distribution networks with low voltage levels overlooked the vertical component of voltage drop. Thus, the calculation formula of voltage loss was simplified as follows:

$$d\dot{U} = \Delta U = \frac{PR + QX}{U} \tag{2}$$

Equation 2 indicated that the voltage loss of lines was related to line parameters, voltage level, and transmission power.

3.1.1. Effects of reactive compensation on voltage of the distribution networks

The formula for the voltage loss of the distribution lines was shown in 2 based on this analysis. When Qc capacity was compensated at the terminal of distribution lines, the voltage loss of lines changed into the following:

$$\Delta U' = \frac{PR + (Q - Q_C)X}{U'} \tag{3}$$

Equations 2--3 indicated that the reactive power was closely related to voltage loss. The reactive power determines the voltage loss directly, and the reactive compensation reduced the reactive power, which was transmitted in lines, thereby decreasing voltage loss in lines.

This analysis indicated that the reactive compensation mainly decreased the voltage loss by reducing reactive power, which flowed through the lines, thereby increasing voltage at the line terminals. Therefore, the reactive compensation method only achieved significant performance in lines with large reactive vacancy and low power factor.

In actual engineering projects, the loads on line change with time, and the terminal voltage of power lines also change. Therefore, the dynamic reactive compensation device had an outstanding effect. The magnetically controlled reactor (MCR) was applicable to a system of various voltage levels. It had low harmonic content output and good reactive output performances. MSVC is a dynamic reactive power compensation device composed by parallel connections of MCR and fixed capacitor (FC). The output reactive power of this device can change continuously from capacitance to inductance, enabling continuous smooth adjustment of voltage in the distribution network. The structure of MSVC is shown in Fig. 1.

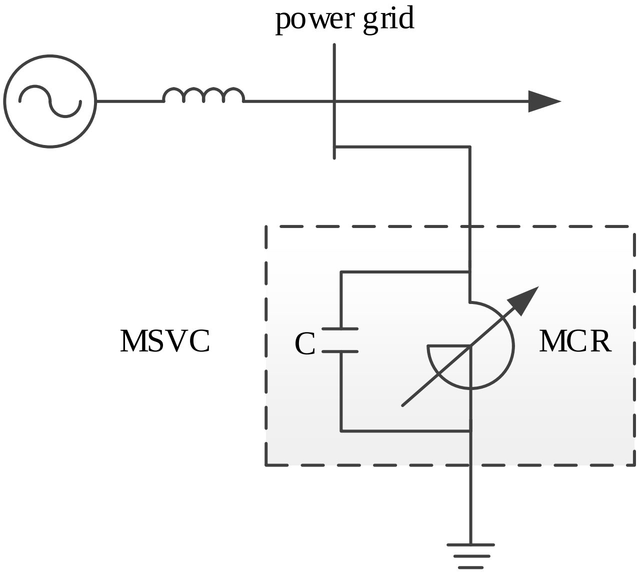

Figure 1: Structure of MSVC

Therefore, MSVC was used as the reactive compensator of lines in this study.

3.1.2. Effects of load voltage regulator on voltage of distribution networks

The load voltage regulator is an autotransformer with multiple tapping points. The basic principle of the load voltage regulator is to connect it to the line in parallel. When the voltage at the line nodes changes, it regulates the tapping points of the regulating wiring of the transformer according to the deviation between actual voltage and present reference voltage and changes the on-load voltage ratio of the transformer, thereby changing the voltage at the output end.

The specific structure of the load voltage regulator is shown in Fig. 2.

After the voltage regulator is applied, the controller can perform real-time detection of voltage at the output side and judge whether the output voltage is in the stable range. If the detected output voltage is out-of-limit, then the controller sends orders automatically to manage the aping points of the voltage regulator to switch gears and change the number of turns on the high voltage side. The voltage at the output side of the voltage regulator on the 10 kV line was stabilized in the setting range. Hence, for branch lines with high power factor, the voltage regulator can still relieve the relatively low voltage at line terminals to some extent. However, it can only regulate voltage at nodes after the installing points.

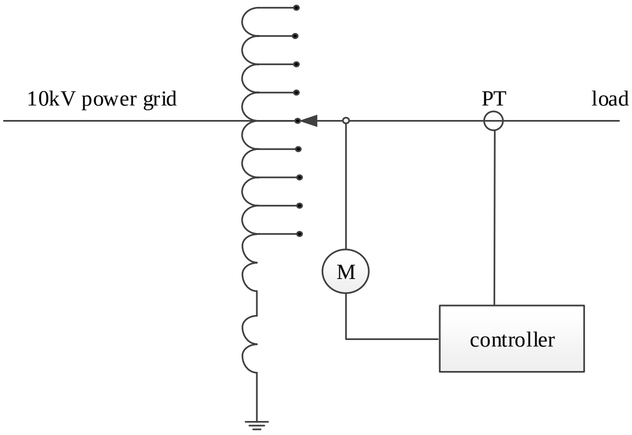

Figure 2: Structure of the voltage regulator

For lines with inadequate reactive power, the voltage regulation effect by the voltage regulator causes larger reactive power vacancy, thereby further decreasing the voltage. Hence, voltage regulator cannot be used independently in terminal lines of rural distribution networks.

3.2. Calculation of the equivalent circuit simulation model

In the Guiding Principle of China Southern Power Grid for Planning of Distribution Networks below 110 kV, the length of 10 kV distribution lines in rural (F type) areas satisfied the requirements on voltage quality at terminals. The line length in the supply region was controlled within 15000 m, whereas the length of the low-voltage distribution lines was controlled at lower than 500 m. In the Management Methods on Voltage Quality and Reactive Electricity of Power System in Guangdong Grid Company, the supply voltage at the user end allows some deviation, as follows: “the sum of the positive supply voltages and absolute values of the negative deviation of users with 35 kV or higher shall be controlled within 10% of the rated voltage. The allowable deviation of the three-phase supply voltage with 20 kV and lower is ±7% of the rated voltage. The allowable deviation of the 220 V single-phase supply voltage is +7% and -10% of the rated voltage”. Hence, some voltage management measures must be adopted for low or high system voltage.

Table 1: Power and three-phase voltage current data of one typical transformer on the line at different periods

Time	Active power, kW	Reactive power, kVar	Power factor
Summer (07.01)	44.33	32.97	0.802405
Summer (07.15)	57.1	41.2	0.810941
Winter (02.01)	2.97	2.93	0.711884
Winter (02.15)	2.93	2.23	0.795743

The branches in a 10 kV rural distribution network in Guangdong Province, China were used as the research object. The line layout is shown in Fig. 3 The red line indicated that the trunk line was one typical rural distribution network line. It was characterized by a large supply radius and many branches. This line had many special transformers. Therefore, the loads on this line had evident seasonal characteristics and great peak-valley gaps. The power and voltage current data of one typical special transformer in summer and winter are shown in Table 1.

Table 1 shows that this line has low power factor and violent voltage changes. In summer, when the demand for electricity was the highest, the line had heavy loads and the voltage at the line terminal drops sharply. In winter, the power factor was extremely low with low loads, and continuous growth of line terminal voltage was observed. In addition, this branch line, which had concentrated load types, was a special transformer of breeding users. The load changes evidently from day to night and from winter to summer. The dynamic reactive compensation device realized automatic compensation effectively. However, Fig. 3 shows that the studying branch lies in the terminal of the trunk line and other branches with heavy loads exist at the terminal. The monitoring data of the transformation station revealed that the voltage of this branch is lower than 0.9 p.u. in summer. Thus, the terminal voltage of the branch failed to satisfy the increasing requirements. If the voltage of this branch was only increased by adding a reactive compensation device, then high capacity was required to compensate for the reactive power of all heavy-loaded lines at the terminals to increase the voltage at the head end of the branch.

Therefore, a comprehensive management method that adds MSVC and line voltage regulator at the head end of the line was proposed for the distribution network with several heavy-loaded lines. The method can increase the volt-

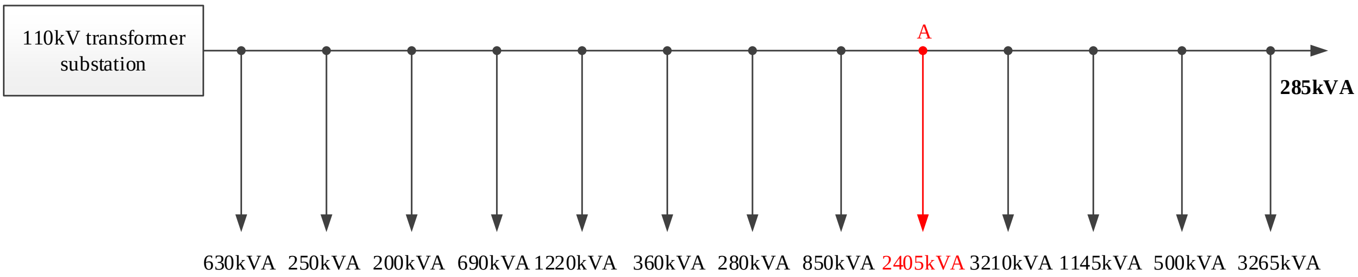

Figure 3: Structure of a trunk line on one rural distribution network in Guangdong Province

age of the studying branch without affecting the voltages of other branches on the trunk line. The proposed method was compared with other methods, which verified its validity.

The low-voltage management method was analysed by a branch in a 10 kV rural distribution network in Guangdong Province. The MSVC and voltage regulator was installed at the head end of the studying branch, that is, at point A in Fig. 3. Finally, the voltage of the entire branch was stabilized between 9 and 10.7 kV through a certain control strategy, thereby reducing low-voltage problem effectively and increasing voltage quality as well as supply reliability.

To evaluate and compare these methods, the power flow calculation of MATLAB/Simulink simulation software was analysed. The calculated results of the power flow showed that the voltage and power factor at the relevant nodes of this branch verified the performance of the method in the voltage and power factor regulation. The equivalent circuit in Fig. 4 was used for analysis and computation. The power is the voltage at the head end of the 10 kV side of the distribution network, and the load is a time-dependent variable. The load changes of the line under peak and valley conditions were simulated due to the randomness of these load changes. The starting time and working time were almost consistent, given that the load of this branch had the same type. Hence, the load changed from valley to peak at 1 s and worked simultaneously.

The voltage regulation effect of the line was analysed by the simplified equivalent circuit in Fig. 4. U_S is the system voltage. Z_S is the equivalent impedance of the system. S_1 and S_2 are load branches on the trunk line before the study. S_3 is the load branch on the trunk line after the study. S_4 and S_5 are the distribution transforming load on the studied branch. Z_1–Z_5 are the impedances on the line. U_1–U_5 are the main monitoring points of the line voltage. Specifically, U_1 is the head end voltage of the trunk line, U_2 is the head end voltage of the studied branch, and U_3 is the voltage behind the installation point of the compensator (voltage regulator). U_4 and U_5 are the terminal voltages of the branch at the installation point of the compensator (voltage regulator). MATLAB was used for simulation analysis. The simulation circuit is shown in Fig. 5.

When no reactive compensator and voltage regulator were added, the voltage at different nodes changed continuously when the loads change continuously with time. The voltage at different nodes and the head end power factor of the line, where the compensator (voltage regulator) lies are shown in Fig. 6.

4. Result Analysis and Discussion

The simulation analysis revealed that the voltage of the branch dropped successively from U_2 to U_3 and then to U_5 due to line loss and loads. The voltage at U_5 was lowest. As the load changed from valley period to the peak period, the voltage at different points declined gradually. At the head end of this branch, the voltage dropped from the peak 10.3 kV to the valley 8.9 kV, and the terminal voltage reached the minimum at 8.7 kV.

Therefore, effective management of low voltage was performed. The power factor at the head end of the branch was mainly maintained at approximately 0.88–0.89. The sharp change was mainly related to the sampling period of the simulation calculation during load changes. An impact on the sharp change of loads was observed from the steady state. Under heavy loads, the voltages at all nodes of the branch failed to reach the regulations, and measures were adopted to control the voltage.

Therefore, management performance of low-voltage problems on this line was analysed by using three methods, as follows:

Method 1: reactive power compensation based on independent use of MSVC.

Method 2: voltage regulation based on independent use of voltage regulator.

Method 3: comprehensive voltage regulation based on the combination of MSVC and load voltage regulator.

4.1. Independent use of MSVC

Method 1 used MSVC independently for reactive power compensation and voltage regulation. In the calculation of power flow, if all voltages of the branch satisfied the requirements, MSVC increased the capacity to at least 2300 kVar. Therefore, the capacitor and the magnetically controlled reactor with the same capacity were equipped.

MSVC was installed at point U_3, as shown in Fig. 6. The voltage and power factor of the nodes on the line are shown in Fig. 7.

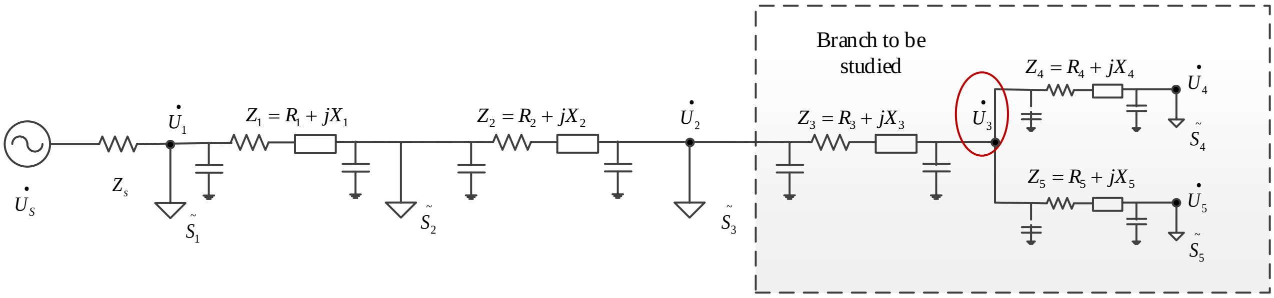

Figure 4: Equivalent circuit of the system

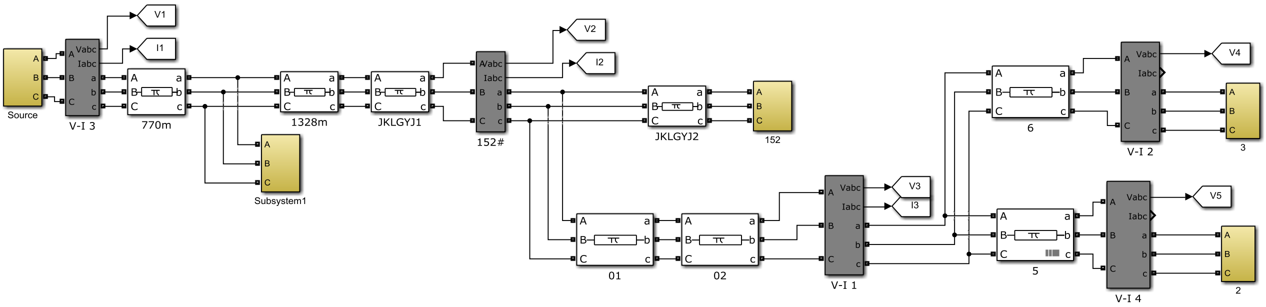

Figure 5: Simulation circuit

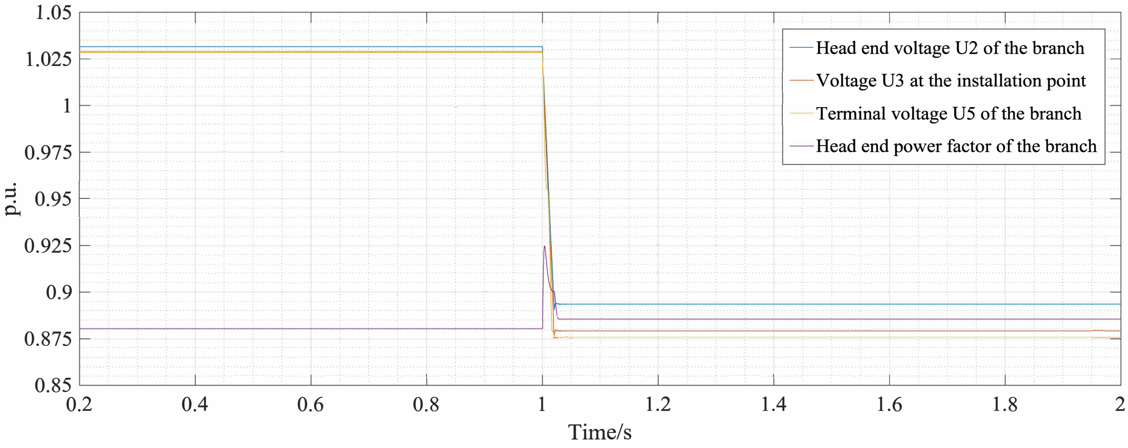

Figure 6: Structure of MSVC

The voltage simulation waveform indicated that the voltage at different nodes on the line can satisfy the regulations before and after the load changes, ranging between 9.0 and 10.7 kV. The simulation waveform of the power factor revealed that the power factor varies between 0.88 and 0.886 before the compensation, 0.98–1 after the compensation. The power factor greatly increased and satisfied the requirement of higher than 0.95. The comparative analysis between voltage waveform and power factor revealed this finding. When MSVC was added, the voltage at different nodes and head ends of the line increased greatly, thereby satisfying the regulations.

The voltage of the trunk line during reactive power compensation increased based on MSVC independently due to the overall long lines in the distribution network. The voltage of the branch increased accordingly. The compensation capacity was extremely high for the overall distribution line. Besides, the occupational area was large.

4.2. Independent use of voltage regulator

Method 2 uses the load voltage regulator for voltage regulation. The load voltage regulator mainly uses the transformer to change the tapping points, thereby changing the

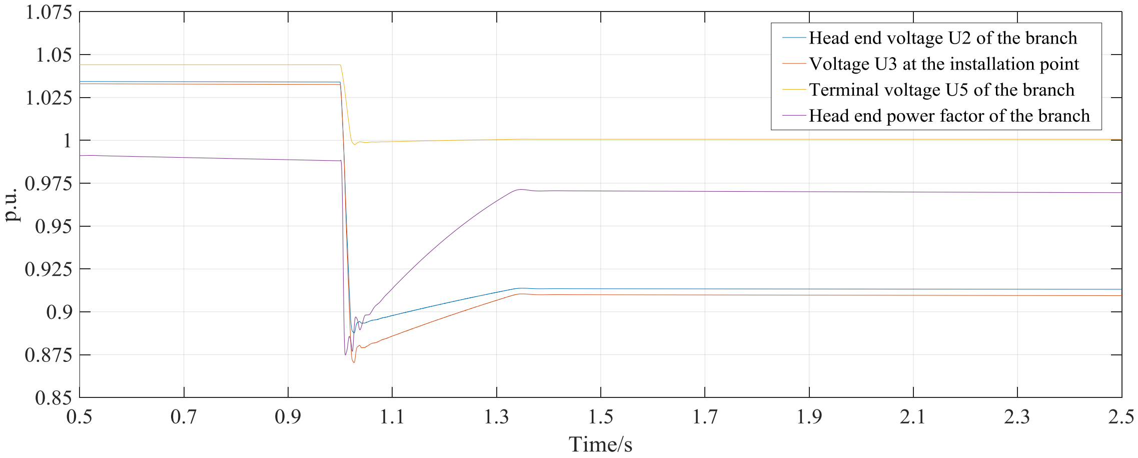

Figure 7: Voltage at different nodes and head end power factor of the line of method 1

principle of on-load voltage ratio to regulate the voltage. The voltage at the output end of the regulator was detected by using the controller and compared with the reference voltage. The working principle is shown in Fig. 8. When the voltage at the transformer output end is higher (or lower) than the reference value, the motor in the on-load tap-changer is delayed to rotate the tap-changer switch from one tapping point to another, thereby changing the on-load voltage ratio of the autotransformer to realize the on-load automatic voltage regulation.

For the 10 kV rural distribution networks, the reference values were mainly set at +7% and -10%. When the output voltage is higher than 1.07 p.u., the tapping point is downregulated, decreasing the voltage at the output side. When the output voltage is lower than 0.9, the tapping point is upregulated, increasing the voltage at the output side.

The voltage drop of the branch becomes relatively serious because of the long line. To further increase the line voltage, the goal of the low voltage management was realized. The voltage regulator was installed at U_3. The capacity of the voltage regulator was set at 2000 kVA by calculating the maximum load of the branch. The voltage and power factor of the nodes on the line, which were simulated by the method, are shown in Fig. 8.

To investigate the performances of the load voltage regulator at different nodes of the line, the upper and lower limits of the voltage were set at 10.7 and 9.5 kV, respectively. The voltage regulator upregulated the tapping point when the voltage is lower than 9.5 kV, but downregulated the tapping point when the voltage was higher than 10.7 kV. Fig. 8 shows that after the load voltage regulator is used, the voltage at different nodes increased greatly, satisfying the relevant regulations. However, the voltage is not increased, but decreased with the increase in level before the use of the voltage regulator. In addition, the voltage before the installation points of the voltage regulation device during peak periods did not satisfy the requirement. Moreover, the voltage regulator did not improve the power factor and further led to deterioration of the power factor of the branch relative to the requirements.

4.3. Comprehensive voltage regulation

The simulation analysis of the two methods revealed that both methods improved the low voltage. However, they had unique advantages and disadvantages. For this reason, these two methods were combined for comprehensive voltage regulation. To enhance the compensation of MSVC , it was installed at the output end of the voltage regulator. When the voltage did not satisfy the requirements, the voltage regulator initially acted to reach the satisfying voltage, and then, the MSVC effectively adjusted the power factor. In this method, the capacity of the voltage regulator was 2000 kVA, and the capacity of MSVC was 1000 kVar. The waveform of the voltage and power factor at different nodes, according to the simulation circuit, is shown in Fig. 9.

Fig. 9 shows that the combination of these two methods enabled the voltages at all nodes to satisfy the requirement, thereby exceeding 9 kV and even 9.5 kV after adding the voltage regulator. The voltage regulation performance was better than during the independent use of MSVC. In addition, the power factor increased to 0.96–0.98 after the combination of the two methods, thereby offsetting the disadvantages of the independent use of voltage regulator. The voltage of the trunk line branches was not affected. The comprehensive method effectively managed the low voltage problems of the branch independently.

4.4. Comparative analysis of different methods

Simulation analysis of the three methods was carried out. Results are shown in Table 2. All compensation methods realized the goal of low-voltage management. Method 1 used the dynamic reactive compensator MSVC.

MSVC enabled the voltage and power factor to satisfy the corresponding requirements, but required large capacity of

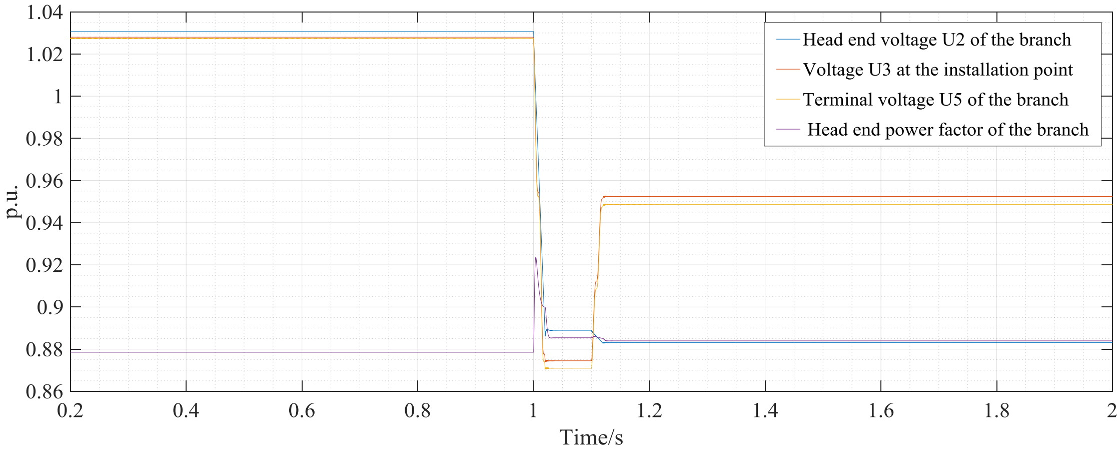

Figure 8: Voltage at different nodes and head end power factor of the line of method 2

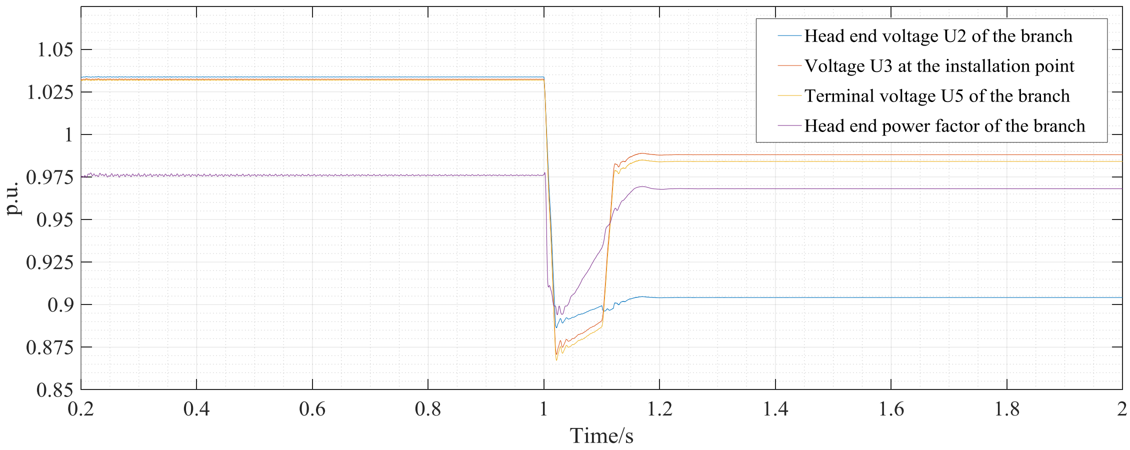

Figure 9: Voltage at different nodes and head end power factor of the line of method 3

Table 2: Comparison of different methods

Methods	Voltage	Power factor	Price	Area
Method 1	Satisfactory	Satisfactory	Highest	Maximum
Method 2	Unsatisfactory before and satisfactory after the use	Unsatisfactory	Lowest	Minimum
Method 3	Satisfactory	Satisfactory	Middle	Middle

the compensator and claims large area and construction volume. Method 2 enabled the voltage to respond to the requirement rapidly, but only regulated the voltage after the installation point and decreased the voltage before the installation point. The head power factor of the line was extremely low. Method 3 combined MSVC and voltage regulator for comprehensive voltage regulation. The method enabled the terminal voltage and head end power factor of the line to reach high levels.

For the terminal branch with heavy loads in the distribution band, Method 3 increased the voltage and power factor to the qualified range simultaneously. It had high economic efficiency and enforceability. This approach provided certain references to the voltage management of branches in rural distribution networks with large reactive vacancy and low voltage.

5. Conclusion

A comprehensive voltage management method based on MSVC and voltage regulator was proposed in this study to solve low-voltage problems in rural distribution networks. One branch of the 10 kV distribution network in Guangdong Province was used in the case study. The voltage and power factor were considered comprehensively. Three low-voltage management methods were compared. The validity of the proposed method was verified by the comprehensive comparison of the three methods through theoretical calculation and simulation analysis. Some major conclusions could be drawn as follows.

(1) For lines in the distribution networks, the voltage loss is related to the line parameters, voltage level, and transmitting power. The voltage loss can be reduced from these aspects.

(2) According to simulation result of three different low-voltage management methods, all methods can increase voltage. The comprehensive management method based on MSVC and voltage regulator has unique advantages in increasing power factor and economic efficiency. This method provides effective references to low-voltage problem management in rural distribution networks.

A new low-voltage problem management method in rural distribution networks was proposed by combining simulation experiment and theoretical study. The comprehensive management method based on MSVC and voltage regulator is more applicable to the complicated structure of rural distribution networks. This method can provide certain references for the subsequent studies. Actual monitoring data and simulation data after adding comprehensive voltage regulation devices should be combined and verified in future studies to clearly disclose the low-voltage management in complicated rural distribution networks.

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