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Examination of major factors affecting voltage variation on distribution feeders

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ABSTRACT

The main purpose of this paper is to investigate the major factors that affect the voltage variation on distribution feeders. This research focuses on the degrees of influence of major factors on the node voltage variations along distribution feeders. First, the definitions and related standards of power quality are introduced. Then, the major factors are identified, analyzed and compared, followed by a concise discussion and conclusion. The research results are of value to distribution engineers to improve operation and maintenance, and to design better distribution feeders.

1. Introduction

In recent years, the growing applications of electronic equipment and distributed generation (DG) have increased the interest in power quality. The recent growing impacts of power quality can be explained in two ways. First, equipment has become more sensitive to voltage disturbances. Second, the equipment used causes more and more serious voltage disturbances. Converter-driven circuits are widely used to drive modern equipment. However, the wide use of converter-driven equipment has led to a large increase in voltage disturbances. Thus, the modern electronic equipment is not only sensitive to voltage disturbances, but it also causes disturbances to other appliances.

In 1968, the oldest mention of the term “power quality” was published by Kajihara [1]. In the 1970s, high power quality was mentioned as one of the focuses of power system design. The term “power quality” is widely used to describe the potential power disturbance problem in industrial power systems. Power quality includes both voltage quality and current quality. Power quality is usually indicated by the node voltages, the line currents, and the system frequency. Among them, the voltage quality is one of the most important factors. Voltage quality measures the variance from the nominal voltage.

Some experts and scholars consider that the meaning of power quality is more general than voltage quality in industrial power systems, because the continuity of supplying power is included in power quality [2]. In recent years, many experts and scholars have investigated the different aspects of power quality. They have supposed that power disturbance phenomena consist of power interruption, waveform distortion, voltage flicker, frequency variation and voltage imbalance issues. Those are all related to voltage directly. The techniques for improving power quality in industrial power systems may involve state monitoring, reactive power compensation, noise filtration and system control.

In Ref. [3], a control strategy was proposed to expand the functionality of the existing nonlinear DG interface to not only control the active power, but also to manage the reactive power and mitigate harmonic, imbalance, and voltage fluctuations. In Ref. [4], some useful indices have been proposed to estimate short duration wave distortions which result from the sudden variations in nonlinear loads. The indices make it is possible to describe the system risk related to the burst occurrence and permit a suitable prediction of system behavior as a function of time. In Ref. [5], a building model of a typical Kuwaiti dwelling was presented to implement energy consumption analysis. The sensitivity analysis technique has been adopted to achieve building energy-saving through proper building design. In Ref. [6], a comparison between a simple artificial neural network (ANN) based model and a model based on physical principles as an auditing and predicting tool was presented to forecast building energy consumption.

In Ref. [7], an effective Energy Difference Multi-Resolution Analysis (EDMRA) method has been proposed for detection, localization and classification of different kinds of power quality disturbances.

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The functional relationship to the minimum decomposition level (MDL) was presented to avoid unnecessary computational cost. In Ref. [8], a simple short-duration disturbance classifying method without other classifier was proposed based on S-transform and maximum similarity by comparing the distances between S-transformed module time-frequency matrices (MTFMs) of standard and tested short-duration power quality disturbance (SDD). In Ref. [9], an approach for identifying the frequency and amplitude of flicker signals that impose on the nominal voltage signal has been proposed. It has succeeded in estimating the voltage flicker frequency and amplitude. In Ref. [10], an electrical energy analysis of the hybrid photovoltaic-hydrogen/fuel cell energy system was performed to evaluate the power quality of the hybrid energy system.

In Ref. [11], combined AC and DC distribution systems accompanied by distributed resources (DRs) have been presented to replace custom power parks for more simple and effective operation leading to high power quality for AC and DC loads. In Ref. [12], a simplified but accurate enough annual energy loss evaluation method for branch circuits or feeders of a dwelling unit or building was proposed. In this method, the time to time and season to season changes in active and reactive power consumption for each appliance are considered. Using only arithmetic calculations but considering the locations and characteristics of all connected appliances along the circuits of a home or building, makes the simplified method efficient and accurate enough. In Ref. [13], the authors addressed how uninterruptible power supply (UPS) can become an energy efficient solution in high tech buildings. It was found that the main problems for the equipment installed were harmonics and voltage sag (dip). In Ref. [14], a detailed power flow solution approach was presented to evaluate the energy loss of branch circuits or feeders by considering the characteristics of discrete loads along the circuits. The detailed power flow solution approach has resulted in the explicit energy loss evaluations for branch circuits or feeders of a dwelling unit or building and their corresponding determination of the daily, weekly, monthly and annual system electrical parameters. All the techniques mentioned above focus on voltage. For this reason, many experts consider that power quality problems are voltage quality issues actually, and the term “voltage quality” is more suitable than “power quality” in some situations.

The paper is organized as follows: Section 2 introduces the definitions and related standards of power quality, Section 3 identifies and analyzes the major factors affecting voltage variation of distribution feeders, and Section 4 presents test cases and results. In Section 5, a concise conclusion is drawn.

2. Definitions and related standards of power quality

The main objective of this section is to introduce the definitions and the related standards of power quality.

2.1. Definitions of power quality

The term “power quality” is widely used to describe the electromagnetic phenomena in the power system. In IEEE Std. 1159 [15], power quality is defined as the concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment. In IEEE 1159-1995, several aspects of power quality issues can be cataloged as transients, short duration variations, long duration variations, waveform distortion, voltage imbalance, voltage fluctuations and power frequency variations.

In a power distribution system, the operation voltages are not always in their desired ranges due to variations of loads along the feeders, actions of tap-changers of the substation transformers and switching of capacitor banks or reactors. The small variation from its corresponding desired value is so called voltage deviation or variance.

The short duration variation category is used to refer to voltage sag, voltage swell and short interruption. Besides, the long duration variation category is used to refer to sustained interruption, undervoltage and overvoltage.

2.2. Related standards of power quality

In a power distribution system, the control of power quality mainly focuses on the node voltages along the feeders. The standards in power quality area are applied to maintain the node voltages along the feeders within a permissible range. The related power quality standards are listed in this paper in order to provide available resource information for making particular power quality decisions, as shown in Table 1.

The standards released by IEEE, ANSI, NFPA and UL are involved in this table and the definitions of voltage quality can be found in IEEE Std. 141, 519, 1100 and 1159. In general, each country has its own national regulations for steady-state voltage tolerances, for example, ANSI has constructed certain standards for the voltage variation problems of the power system in the U.S.

The voltage variation related ANSI standards are classified into two groups: one is ANSI C84.1 for nominal voltage rating above 100 V through 230 kV [16], and another one is ANSI C92.2 for nominal voltage rating above 230 kV [17]. Electrical power suppliers in the U.S. generally accord with ANSI C84.1 for delivery of electrical power.

3. Factors affecting voltage variation of distribution feeders

In general, most voltage quality-related standards mainly aim at the steady-state voltage variations. In this paper, to understand the degrees of influence of the major factors that affect the steady-state voltage deviations in the primary distribution feeders, the major factors are discussed as follows.

3.1. System short-circuit capacity

The system short-circuit capacity stands for the short-circuit capacity on the high-voltage side of substation transformers. The system driving-point impedance is inversely proportional to the system short-circuit capacity. Usually, if the system short-circuit capacity is larger than 2000 MVA, the system driving-point impedance will be much smaller than the impedance of the substation transformer. Therefore, the effects of the system short-circuit capacity on node voltages along the feeders will be less than that of the impedance of a substation transformer. The system short-circuit capacities distributed at the nodes along primary distribution feeders are mainly varied with the locations of the nodes and the design of configuration of distribution feeders. Moreover, the configuration of primary feeders is mainly determined by the reliability and security concerns of system operation, not the voltage variations.

3.2. Rated capacity of substation transformer

The variance of node voltages along the feeders can be lessened by increasing the rated capacity of their feeding substation transformer. That is, the larger the transformer capacity is, the lesser voltage variation arises. However, one of the major disadvantages for increasing rated capacity of substation transformer is the rise in the short-circuit fault current level on the secondary side of a substation transformer.

Table 1
Power quality standards by topic (referred to IEEE Std 1159-1995).

Topics	Relevant standards				
Grounding	IEEE Std 446	IEEE Std 141	IEEE Std 142	IEEE Std 1100	ANSI/NFPA 70
Powering	ANSI C84.1	IEEE Std 141	IEEE Std 446	IEEE Std 1100	IEEE Std 1250
Surge protection	IEEE 62 series	IEEE Std 141	IEEE Std 142	NFPA 78	UL 1449
Harmonics	IEEE Std C57.110	IEEE Std 519	IEEE Std P159a	IEEE Std 929	IEEE Std 1001
Disturbances	ANSI C62.41	IEEE Std 1100	IEEE Std 1159	IEEE Std 1250	
Lift/fire safety	FIPS PUB 94	ANSI/NFPA 70	NFPA 75	UL 1478	UL 1450
Mitigation equipment	IEEE Std 446	IEEE Std 1035	IEEE Std 1100	IEEE Std 1250	NEMA-UPS
Telecommunications equipment	FIPS PUB 94	IEEE Std 487	IEEE Std 1100		
Noise control	FIPS PUB 94	IEEE Std 518	IEEE Std 1050		
Utility interface	IEEE Std 446	IEEE Std 929	IEEE Std 1001	IEEE Std 1035	
Monitoring	IEEE Std 1100	IEEE Std 1159			
Load immunity	IEEE Std 141	IEEE Std 446	IEEE Std 1100	IEEE Std 1159	IEEE P1346
System reliability	IEEE Std 493				

3.3. Percent impedance of substation transformer

Reducing the percent impedance of a substation transformer is also a good way to improve the quality of node voltages along the feeders fed by the transformer. The effect of the percent impedance of a substation transformer on the voltage deviation is commonly larger than that of system short-circuit capacity or the rated capacity of a substation transformer.

Reducing the percent impedance of substation transformer gains an advantage in lessening the voltage drop on a substation transformer. However, the percent impedance of the substation transformer is the key factor to affect the short-circuit current or the short-circuit capacity at the secondary side of the substation transformer. For this reason, the restriction on the short circuit currents on the secondary side of the substation transformer should also be taken into account.

3.4. Size of primary feeder conductor

If a larger size of primary feeder conductor is used, the impedance of feeder conductor is reduced. Therefore, the voltage drops along the studied feeder are reduced and the voltage magnitudes at the nodes along the considered feeder are proportionally increased.

For a radial-type distribution feeder, the magnitude of current is the greatest in the outgoing feeder segments at the substation. The magnitudes of currents in the downstream feeder segments are continually decreased toward the farthest end of a feeder from the substation.

Although the magnitudes of currents are continually decreased in the feeder segments along the feeder from the substation to the farthest end of the feeder, smaller size conductors can be selected for the downstream segments of the feeder theoretically. However, the related operation rules may restrict the possible reduction of the feeder conductor size along the feeder, that is, the ampacity or the thermal capability of the feeder conductor is not the only factor which needs to be considered when selecting the conductor size for a feeder. Generally, the factors affecting the selection of the feeder conductor size are load growth rate, load forecast, voltage drops, substation transformer rating, conductor rating, total cost, power losses and the reserves of feeder conductor according to the policy of the utility company.

3.5. Length of primary feeder

The series impedance of a feeder is linearly proportional to the length of the feeder. Therefore, the length of the primary feeder should also have a significant effect on voltage deviation. Some of the design, operation and plan aspects affecting the length of primary feeders are substation site selection, feeder routing, load density, physical barriers and land use regulations.

3.6. Loads on primary feeder

The currents in a feeder segment along the primary feeder are functions of the discrete loads connected to the downstream portion of the primary feeder. Although the current will not affect the feeder impedance, it does affect voltage deviation. Some factors affecting the loading design of primary feeders are feeder routing and the number of feeders.

3.7. Distribution of discrete feeder loads

The distribution of discrete feeder loads is a major factor that affects the voltage drops of feeder segments along the distribution feeder and the total voltage drop at the end of the feeder as well. In general, the distributions of discrete feeder loads can be classified into three types: increasingly distributed loads, decreasingly distributed loads and uniformly distributed loads. The different distributions of discrete feeder loads cause different current flow distributions in the feeder segments. Therefore, they will also affect the node voltage drops along a feeder.

3.8. Power factors of feeder loads

The power factor is the ratio of real power to apparent power. For two power systems transmitting the same amount of real power, the system with the lower power factor will have the higher reactive power current which should cause the higher voltage drop and produce the higher loss. Usually, the reactive power compensation is required to correct the power factor and therefore improve the node voltage variations and system efficiency.

3.9. Total loads of other feeders

For a given substation transformer and service area, addition of new feeders will lessen node voltage drops and variations along the feeders fed by the substation transformer if the loads in the service area of the substation transformer can be shared evenly by all feeders fed by the same substation transformer. That is, reducing the ratio of total feeder loads to total loads of other feeders will have a favorable effect on the node voltage drops and variations.

3.10. Imbalance of feeder loads

The three-phase loads, currents, voltages or impedances are inherently unbalanced in practical distribution systems. Balancing loads among three phases along a feeder can lessen the negative- and zero-sequence components of currents. Hence, the node

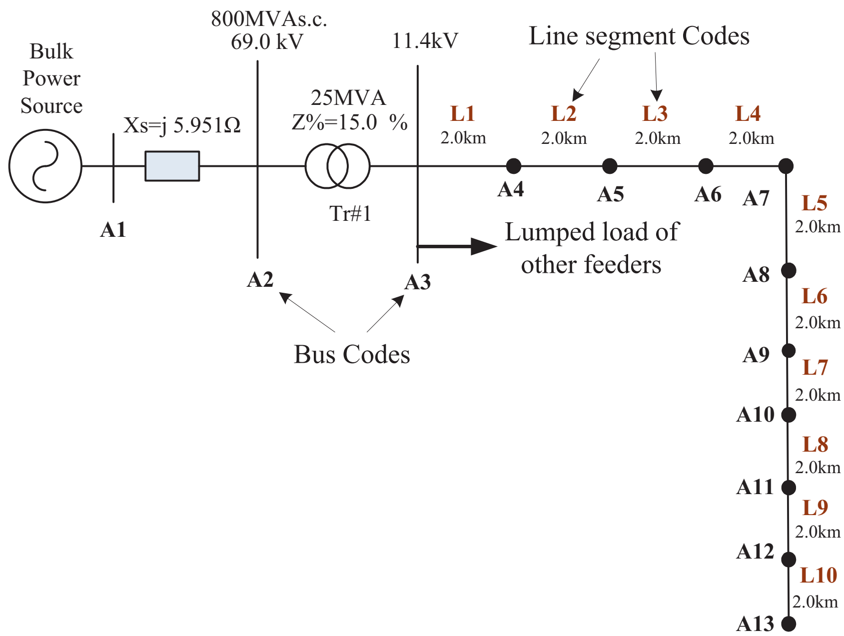

Fig. 1. Sample system.

voltage variations and power loss in the distribution feeder can be reduced considerably in many cases.

3.11. Voltage level of primary feeder

Although the allowable loading of a primary feeder is determined by the size of feeder conductor, the allowable loading of a feeder located at low-load density area is mainly restricted by the permissible voltage drop required by an electrical code. In contrast, a primary feeder located in a high-load density area is predominantly restricted by thermal constraints. In general, for a given feeder conductor size and percent voltage drop requirement, the feeder length and feeder loading are direct functions of the voltage level of the primary feeder. For the same percent voltage drop limitation and supplying the same power, if the voltage level of a feeder is doubled, the length of the service feeder can be extended four times. Hence, the selection of voltage level of feeder does affect the node voltage deviation. There are some factors affecting the decisions for selecting the voltage levels of the primary feeders, such as load projection, voltage drops, feeder lengths, sub-transmission voltage, power losses, equipment availability costs, adjacent substation and feeder voltages, company policies, etc.

The factors mentioned above have different levels of effect on voltage variation. The difference among them is only the degree of influence. In the next section, the degrees of influence of the major factors on the voltage variations will be examined.

4. Test cases and results

A 13-bus distribution system with radial-type feeders, shown in Fig. 1, is adopted as a sample system to investigate the major factors affecting the steady-state voltage deviations on primary feeders.

The feasible ranges of system parameters in practical Taiwan Power Company (Taipower) distribution systems are listed as follows:

(1) The system short-circuit capacities at the primary side of the substation transformer are typically between 400 and 8000 MVA.
(2) The voltage levels of the primary distribution system are 11.4, 22.8 or 34.5 kV. The 34.5 kV is not a standard nominal voltage in Taipower distribution networks. The use of 34.5 kV here is for expanding the application range of research results of this paper only.
(3) The percent impedances of the substation transformer are typically from 6% to 18%.
(4) The rated capacities of the substation transformer are 25, 30 or 60 MVA.
(5) The feeder conductors in Taipower distribution systems are 336, 477 and 795 MCM AAC overhead lines, with unit length impedances of 0.188 + j0.378, 0.131 + j0.364 and 0.0779 + j0.345 Ω/km. The 795 MCM AAC overhead line is not the standard size for Taipower distribution networks.
(6) The distribution circuits in the Taipower distribution systems typically have main feeders of 6–14 km in length.
(7) The total loads of a given feeder are assumed between 500 kW and 2.5 MVA, and the power factors of all loads are assumed between unity and 0.8 lagging. Furthermore, increasingly distributed, decreasingly distributed and uniformly distributed are applied.
(8) The total loads of the other feeders supplied by the same substation transformer are assumed between 3 and 15 MVA, and represented by a lumped-sum load connected to the secondary bus of the substation transformer. The power factor of this lumped load is assumed to be unity because the power factor is mostly corrected to near unity in the Taipower distribution systems.
(9) Three distributions of three-phase loads assumed are: three phase loads balanced, the ratio of three phase loads distributed at phase A, B, C is 2:3:4, and the ratio of three phase loads distributed at phase A, B, C is 1:3:5.

The better way to understand the effects of the factors that affect the steady-state voltage deviations is to quantify the degrees of influence of these factors. The results for the degrees of influence of major factors are obtained by modifying the corresponding system parameters of the sample system and performing a series of power flow analyses. The degrees of influence of major factors that

Table 2
Degrees of influence of major factors on voltage quality of distribution feeders.

Factor	Influenced system parameter	Influenced scope	Application stage	Average degrees of influence of voltage at receiving-end of a feeder (pu)
System short-circuit capacity	Impedance	Entire distribution system	System planning	1.917×10^{-6}/MVAs.c.
Rated capacity of substation transformer	Impedance	Downstream distribution system of substation transformer	System design	2.857×10^{-4}/MVA
Percent impedance of substation transformer	Impedance	Downstream distribution system of substation transformer	System design	6.667×10^{-4}/1%
Size of primary feeder conductor	Impedance	Entire feeder	System design or as desired	1.024×10^{-5}/AAC
Length of primary feeder	Impedance	Entire feeder	System planning or as desired	1.25×10^{-3}/km
Loads on primary feeder	Current	Entire distribution system	System planning and operation	1.8×10^{-2}/MVA
Distribution of discrete feeder loads	Current	Entire feeder	System planning and design	6.0×10^{-3} for increasingly distributed load -3.0×10^{-3} for decreasingly distributed load
Power factor of feeder loads	Current	Entire distribution system	System design or as desired	4.333×10^{-4} for power factor of 0.01 lagging
Total loads of other feeders	Current	Entire distribution system	System planning, design and operation	8.333×10^{-4}/MVA
Imbalance of feeder loads	Current	Entire distribution system	System design, installation and maintenance	-4.0×10^{-4} for the ratio of 2:3:4 -1.9×10^{-3} for the ratio of 1:3:5
Voltage level of primary feeder	Current	Entire distribution system	System planning	8.0×10^{-3}/class

affect the steady-state voltage deviations on primary feeders of the sample distribution network are tabulated as Table 2.

The influence and possibility of the major factors affecting the steady-state voltage deviations are as follows:

(1) System short circuit capacity: The system short-circuit capacity is actually not a constant, and it will be varied with the system operation conditions. The short-duration variation of a system short-circuit capacity is usually very small for a large-scale power system. For a distribution network, the system short-circuit capacity is mainly a function of its feeder arrangement. And, the feeder arrangement of a distribution system is mainly determined by the design consideration of reliability or service continuity of the distribution system.
(2) Rated capacity of substation transformer: The rated capacity of the substation transformer is determined by the existing load demands, load characteristics and future load growth. The capacity cost for a substation transformer is usually extremely high. Hence, increasing the rated capacity of the substation transformer for improving node voltage variation along a feeder is not considered in usual circumstances.
(3) Percent impedance of substation transformer: Although reducing the percent impedance of a substation transformer can decrease node voltage drops along a feeder effectively, the short-circuit fault currents in downstream feeder segments will arise substantially. The interrupting capacity of protection devices should also be promoted and will cost a lot. Hence, reducing the percent impedance of a substation transformer is usually not a feasible way to improve node voltage variations along a feeder.
(4) Size of primary feeder conductor: For a radial-type distribution feeder, if the length of the feeder is not short, the size of the primary feeder conductor may have a significant effect on voltage variations.
(5) Length of primary feeder: The length of the primary feeder has a key effect on the network equivalent impedance at the end of a feeder. With the same loading conditions, the shorter the length of primary feeder is, the smaller equivalent impedance and the lesser power losses. Although shortening the length of the primary feeder can improve the voltage quality of feeders, it has to follow the route of a feeder.
(6) Loads on primary feeder: The loads of the primary feeder may affect the voltage profiles of the whole distribution system, but they may increase or decrease depending on customer demands. The loads of the primary feeder can be regulated by feeder reconfiguration under system planning and operation stage.
(7) Distribution of discrete feeder loads: In general, the distributions of discrete feeder loads can be classified into three types: increasingly distributed loads, decreasingly distributed loads and uniformly distributed loads. In these three conditions, the adverse effect on total voltage drop at the end of a feeder is the worst with increasingly distributed loads. In contrast, the favorable effect of total voltage drop at the end of a feeder is the best with decreasingly distributed loads. Hence, to minimize the node voltage variations and system power losses, the load center should be as close as possible to the substation. However, the distribution of discrete loads is mainly determined by the locations of the existing substations, the number of primary feeders and feeder routing.
(8) Power factors of feeder loads: To reduce the reactive currents and voltage drops in the substation transformer and primary-feeder mains, the power factors of feeder loads should be corrected to near unity. The fixed and switched capacitor banks or SVC (static var compensator) installed at feeders or substations are used to compensate for the reactive power required by feeder loads. The shunt compensating devices have a significant effect on voltage quality of upstream systems of device-connection points. Hence, correcting power factor of feeder loads is always a good method to reduce node voltage drops and variations along a feeder.
(9) Total loads of other feeders: It is hard to use this factor to improve voltage quality during system operation. In general, the arrangements of loads of the other feeders depend on long-term system planning or midterm design.
(10) Imbalance of feeder loads: To reduce the node voltage drops and variations along a three-phase primary feeder, the rearrangement of connection phases of discrete loads along a feeder is also effective. However, interrupting service continuity is unavoidable when changing the connection phases of distribution transformers to a feeder. Hence,

the rearrangement of connection phases of distribution transformers cannot be performed frequently.

(11) Voltage level of primary feeder: Upgrading the voltage level of the primary feeder is a good way to reduce line currents and node voltage drops along a primary feeder. However, it is part of a long term planning and is usually determined by the policy of a utility.

5. Conclusion

The purpose of this paper is to investigate various voltage affecting factors for a feasibility study of system voltage control of a distribution network. The existing voltage control techniques of a distribution feeder can be classified in two groups: system planning techniques and equipment control techniques. The system planning techniques consist of (1) the system short-circuit capacity, (2) the rated capacity of the substation transformer, (3) the percent impedance of the substation transformer, (4) the size of the primary feeder conductor, (5) the length of the primary feeder, (6) the loads on primary feeder, (7) the distribution of discrete feeder loads, (8) the power factors of feeder loads, (9) the total loads of other feeders supplied by the same substation transformer, (10) the imbalance of feeder loads and (11) the voltage level of the primary feeder.

The system planning techniques are only employed in system design and planning stages. Although the system planning techniques are not suitable for regulating the real-time feeder voltage, the effect of system planning techniques is overall.

The application of equipment control techniques is a good way to maintain the node voltages along a distribution feeder within a permissible range. The equipment control techniques can be applied to regulate the node voltages along a feeder in real-time system operation because of high state controllability.

Usually, the equipment control techniques applied to the voltage quality of distribution feeders consist of ULTC (under load tap changer) transformer, DVR (dynamic voltage restorer), AVR (automatic voltage regulator), SVC (static var compensator), SC (shunt capacitor) and so on [18–21]. The control equipment for network voltage described above can be classified in two groups: voltage control equipment and current control equipment. ULTC transformer and AVR that are used to regulate the voltages of primary distribution feeders belong to the first group, the voltage control equipment. DVR, SVC and SC that are applied to regulate the currents in feeder segments belong to the second group, the current control equipment.

The voltage control equipment can be adopted to regulate the node voltages of the feeders in the concerned region and the influenced area may cover an entire or a local area of a feeder. For example, if the tap position of a ULTC transformer is changed, its effect on the node voltages are from the busbar on the secondary side of the substation transformer to the end of a feeder. DVR and AVR do affect the voltages at the downstream systems of device-connection points. And, SVC and SC do affect the voltages in the vicinity of device-connection points. To maintain operation security and the voltage quality of a power system, the system planning techniques and the equipment control techniques are both required. The results of this paper are of value in understanding the effects of major factors affecting the voltage variation of primary distribution feeders.

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