Substation Reactive Power Regulation Strategy

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Abstract. With the increasing requirements on the power supply quality and reliability of distribution network, voltage and reactive power regulation of substations has become one of the indispensable ways to ensure voltage quality and reactive power balance and to improve the economy and reliability of distribution network. Therefore, it is a general concern of the current power workers and operators that what kind of flexible and effective control method should be used to adjust the on-load tap-changer (OLTC) transformer and shunt compensation capacitor in a substation to achieve reactive power balance in situ, improve voltage pass rate, increase power factor and reduce active power loss. In this paper, based on the traditional nine-zone diagram and combining with the characteristics of substation, a fuzzy variable-center nine-zone diagram control method is proposed and used to make a comprehensive regulation of substation voltage and reactive power. Through the calculation and simulation of the example, this method is proved to have satisfactorily reconciled the contradiction between reactive power and voltage in real-time control and achieved the basic goal of real-time control of the substation, providing a reference value to the practical application of the substation real-time control method.

Keywords: Substation; Voltage and reactive power regulation; Fuzzy logic; Variable-center nine-zone diagram control

1. Introduction
Voltage is an important indicator to measure power quality, and to ensure that the user voltage is close to the rated value is the basic task of power system operation scheduling. The system’s reactive power has a great impact on the voltage, as insufficient or excessive reactive power both will cause drop or rise of the system’s voltage. On the contrary, if the voltage is too low, reactive power can only be maintained in a worse environment. This may result in excessive active power loss caused by reactive power, affecting the economic operation of the system [1-5]. Therefore, voltage and reactive power control problems have attracted more and more attention.

The basic principle of substation voltage and reactive power regulation [6] is: to ensure that the voltage is satisfactory, reactive power is basically balanced, and the number of adjustments is minimized. Accordingly, the substation voltage and reactive power compensation is a multi-limit (including the number of daily main transformer tap changer adjustments, the number of daily capacitor switching times, voltage upper and lower limits, power factor (reactive) upper and lower limits, active power upper and lower limits, and user-specific requirements), multi-objective (satisfactory voltage, satisfactory power factor, and minimum network loss) optimal control issue.

Based on the above principles and laws, many automatic control strategies have been put forward at home and abroad. To sum up, there are several ways: 1. Combined adjustment according to the power
factor [7] and voltage [8]; 2. Based on the traditional nine-zone diagram method [9]; 3 Based on artificial intelligence nine-zone diagram method [10]; 4. Artificial intelligence regulation methods [11].

Although the above methods use different technologies with different emphases, they all inherit the basic principles of voltage and reactive power integrated control. At the same time, as the requirements for the flexibility and real-time performance of real-time algorithms of substations are increasing, the advantages of intelligent algorithms have become more apparent, which however, still have some shortcomings. It is still a common issue that how to combine the traditional algorithms with intelligent methods better and give full play to the advantages of both methods based on the basic principles of voltage and reactive power integrated control to guarantee the real-time performance and accuracy of control [11]. Secondly, as the power system is an interconnected and coordinated network structure, the regulation and state changes of any subtle part will more or less affect its upper- and lower-level networks. Sometimes mere local regulation may lead to further unbalanced reactive power of the whole grid even though the local voltage and reactive power can temporarily meet the requirements, affecting other regions. From the perspective of overall operation benefit, it is not economical [12].

Through the above analysis and the comparison of the above methods, it is found that most of the substations' voltage and reactive power real-time algorithms are based on the real-time load and voltage data, which may result in the frequent adjustment of equipment due to the randomness and dispersion of data. Therefore, an improved fuzzy variable-center nine-zone diagram control method is proposed based on the traditional one and the concept of delay is introduced. Using this method, a real-time control strategy of substation voltage and reactive power is established. The effectiveness of the algorithm is verified by an example analysis.

2. Control Process

The overall structure of substation reactive power regulation strategy proposed as shown in Figure 1 includes four parts: control strategy library, real-time database, real-time control module, and controlled object.

1. Real-time database: the real-time database stores the real-time data and part of the control system’s parameters:

2. Control strategy library: the control strategy library stores the basic control rules required for real-time control, which are the main basis for real-time regulation, including the basic regulation principles of real-time algorithm module and the basic rules of fuzzy algorithm design.

3. Real-time control module: The real-time control module is the core of this algorithm. As changes in grid operating conditions will cause changes in substation supply voltage and real-time load, adjustment is needed in time to meet the grid’s requirements for voltage and real-time load, so the adjustment will be conducted by each substation’s real-time control module.

4. Controlled object: the control signal generated by the real-time control module is output to two controlled objects: the transformer’s tap changer and capacitor, to control the tap lifting or the capacitor switching.

The traditional nine-zone diagram is the main principle of in-situ real-time operation of substation for the operators. The voltage and reactive (or power factor) power are used as boundaries to divide the operation area into nine zones. The adjustment strategy is usually given by zone. Zoning principle is: the substation’s rated voltage and the predetermined power factor requirements are taken as the center of the nine zones, and the boundaries are given by the operating personnel based on their experience according to the reactive power control objectives. The control strategy derived from the nine-zone diagram is used for in-situ control of the substation to adjust the on-load tap-changer transformers and capacitors. This method is still relatively economical, practical and easy to understand [13-17].

Therefore, it is proposed that the substation voltage and reactive power value given by the operator based on experience be taken as the center point of the nine-zone graph and the voltage reactive power limits described by fuzzy linguistic variables according to the requirements of Technical Guidelines for Power System Voltage and Reactive Power as the boundaries fixed relative to the center. This ensures the flexibility of the nine-zone diagram with the center point which changes over time. When the
real-time operating status is not regulated in the central area of the nine-zone diagram, the regulation strategy of the substation meets the requirements. When the real-time operating status is not in the central area of the nine-zone diagram, the regulation device is under real-time correction to reach as close to the required operating conditions as possible. In this way, the rationality and accuracy of regulation have been improved.

At the same time, in order to overcome the problem of frequent equipment switching caused by the relatively fixed boundaries of the nine-region graph, the advantage of the fuzzy algorithm in dealing with the indefinite phenomenon is used to describe the voltage and reactive power limits of the nine-zone graph using fuzzy language variables of voltage and reactive power. In this way, the operating area of the traditional nine-zone diagram has been refined due to the use of fuzzy linguistic variables, so that it is possible to simulate the experience of experts to identify the areas where the voltage is closely or loosely related to the reactive power. Decoupling control method is adopted in the area of loose relation, that is, the capacitor or transformer is controlled separately; in the area of close relation, the integrated control method is adopted. In this way, it is possible to assign the authority of each device and action time more clearly.

Based on the basic design ideas of the real-time control module, the basic structure of real-time control module can be obtained. It includes four parts: operating status zoning mechanism, voltage fuzzy control sub-module, reactive power fuzzy control sub-module and integrated control sub-module.

The operating status zoning mechanism determines its deviation from the operating point based on the fuzzy variable-center nine-zone diagram, according to the real-time data of the substation’s secondary side bus voltage deviation $V_2$ and the reactive power $Q$ to identify the area where the operating status of the system is, thus determining which sub-module: voltage fuzzy control sub-module (which controls OLTC transformer’s tap), reactive power fuzzy control sub-module (which controls the capacitor), integrated control sub-module (which performs integrated control of the tap and capacitor), will be used to generate control strategy to achieve reactive power real-time control.

The traditional nine-zone diagram divides the operating area with the effective values of voltage deviation and reactive power as the boundaries [38]. The fuzzy variable-center nine-zone diagram divides the operating area according to the fuzzy linguistic variables of voltage deviation and reactive power input. Table 1 shows the fuzzy linguistic variables of voltage deviation and reactive power input.

### Table 1. Fuzzy language variables of voltage deviation (reactive power)

| $\Delta U_{\text{min}}$($Q_{\text{min}}$) | $\Delta U_{\text{max}}$($Q_{\text{max}}$) |
|------------------------------------|------------------------------------|
| Very Relatively Zero RelativELY Positively Very |
| negatlvely y ely positively tive |
| active negative positively tive |
| nb nm ns zo ps pm pb |
Table 2. Fuzzy variable-center nine-zone diagram

|   | 11 | 12 | 13 | 14 | 15 | pm  | pn |
|---|----|----|----|----|----|-----|----|
| 6a| 7a | 8a | 9a | 10a| pb | pm  | pn |
| 6b| 7b | 8b | 9b | 10b| nb | pm  | pn |
| 6c| 7c | 8c | 9c | 10c| ns | pm  | pn |
| l | 2  | 3  | 4  | 5  | nm | nb  | pm |
|   | nb | ns | zo | ps | pm | pb  |   |

As shown in Table 1, the fuzzy linguistic variables of voltage deviation (reactive power) are defined as "very negative" (nb), "negative" (nm), "relatively negative" (ns), "zero" (zo), "relatively positive" (ps), "positive" (pm), and "very positive" (pb). By corresponding "very negative" (nb) and "negative" (nm) to a zone of the original nine-region diagram, and "relatively negative" (ns), "zero" (zo), and "relatively positive" (ps) to a zone, and using the fuzzy linguistic variables of voltage deviation as abscissa and the fuzzily linguistic variables of reactive power as ordinates, a fuzzy variable-center nine-zone diagram similar to the original is formed.

Of course, on the setting of the universe of discourse, it is necessary to ensure that the operating point falls in the central region of the region of fuzzy variable-center nine-zone diagram, that is, the voltage deviation of the operating point and the vague linguistic variables of reactive power all correspond to "zero" (zo).

The system operates in different zones of the fuzzy variable-center nine-zone diagram, corresponding to different control modes. The corresponding relationship between operating area and control mode is shown in Figure 3-3. Among them, the horizontal axis is the reactive direction, and the vertical axis is the voltage deviation direction. The definition of each area in the figure is the same as that of the areas in Figure 3-2. None indicates normal state, and the device does not need action and does not start the sub-module; Cap indicates to reactive power fuzzy control module to switch capacitor; Tap indicates to start voltage fuzzy control module to adjust the OLTC transformer’s tap; Both indicates to start the integrated control sub-module to perform integrated control of the tap and capacitor. In this way, the voltage (reactive power) fuzzy control module uses a separate control mode, while the integrated control module uses integrated control.

Table 3. Corresponding relationship between operating area and control mode

| Both | Both | Tap | Tap | Both | pm  | pn |
|------|------|-----|-----|------|-----|----|
| Cap  | Cap  | None| Tap  | Both | ps  |    |
| Cap  | None | None| None | Cap  | zo  |    |
| Both | Tap  | None| Cap  | Cap  | ns  |    |
| Both | Tap  | Tap | Both | Both | nm  | nb |
| nb   | nm   | ns  | zo  | ps  | pm  | pb |

3. Example Analysis

Based on the voltage and reactive power regulation strategy of substation proposed in this paper, VB programming language was used to simulate the voltage and reactive power of a substation on one day. The comparison of the control results obtained using the proposed method and the traditional methods
shows that the proposed algorithm regulated the control strategy of the transformer tap and capacitor in real time, which not only meets the requirements of real-time control, but also makes the cooperation between the two more reasonable, effectively reducing the number of device actions, improving the voltage pass rate, and reducing power consumption.

Transformer parameters: 2 x three-phase double-winding transformers; model: SFZ7-120000 / 220; capacity: 120MVA; voltage on high and low voltage sides: 220 ± 8 × 1.5% / 69KV, impedance reduced to the low voltage side: 0.146 + j5.205Ω. Load loss ΔP₀ = 441.6KW; no-load loss ΔP₀ = 92KW; impedance voltage Uk% = 12.65; no-load current I₀% = 0.427; connection group: YN, d11.

Capacitor parameters: There are four capacitors on each bus; model: BFF19-334-1W; rated voltage: 19KV; rated capacity: 334Kvar; rated capacitance: 2.95uF.

The curve of the preset reactive load value and real-time reactive load value, and the curve of the preset primary voltage value and real-time primary voltage of 1 # main transformer 24 hours a day at 96 time points are shown in Figure 4 (a) & (b) below.

Still using the above real-time data, the control strategies of the traditional nine-zone diagram control method and the proposed algorithm are shown in Tables 4 and 5.

![Figure 1. Substation main wiring diagram](image1)

![Figure 2. Reactive load and primary voltage data curve](image2)
In Figure 2 (a), the blue solid line is the real-time reactive load, and the black solid line is the preset reactive load; in Figure 2 (b), the blue solid line is the real-time primary voltage, and the black solid line is the preset primary voltage.

It can be seen that using the proposed real-time algorithm can obviously reduce the number of regulations of the device, make the regulation more centralized, and reduce the unnecessary device actions in the traditional nine-zone diagram method. However, for the mechanical regulating device, there is the condition of regulation of two tap positions in the adjacent regulation periods.

Table 4. Comparison of capacitor action strategy

| Time | Action strategy | Current number of groups |
|------|-----------------|--------------------------|
| 2:00 | Switch on       | 4                        |
| 3:00 | Switch off      | 2                        |
| 5:00 | Switch off      | 1                        |
| 6:00 | Switch on       | 2                        |
| 8:00 | Switch on       | 3                        |
| 9:15 | Switch on       | 4                        |
| 12:00| Switch off      | 3                        |
| 13:00| Switch off      | 2                        |
| 14:00| Switch on       | 3                        |
| 19:00| Switch off      | 2                        |

Table 5. Comparison of transformer tap action

| Time | Action strategy | Current tap position |
|------|-----------------|----------------------|
| 2:00 | Lift up         | 3                    |
| 3:00 | Lower down      | 2                    |
| 5:00 | Lower down      | 1                    |
| 10:00| Lift up         | 2                    |
| 11:45| Lift up         | 3                    |
| 12:00| Lower down      | 2                    |
| 16:15| Lower down      | 1                    |

Table 4. Comparison of capacitor action strategy

| Time | Action strategy | Current number of groups |
|------|-----------------|--------------------------|
| 2:00 | Switch on       | 4                        |
| 3:00 | Switch off      | 2                        |
| 5:00 | Switch off      | 1                        |
| 6:00 | Switch on       | 2                        |
| 8:00 | Switch on       | 3                        |
| 13:00| Switch off      | 2                        |
| 14:00| Switch on       | 3                        |
| 19:00| Switch off      | 2                        |

Table 5. Comparison of transformer tap action

Comparison of the regulation effects of the two methods is shown in Figures 5.
Figure 3. Corresponding secondary voltages of the two methods
In the figure, the blue solid line is the secondary voltage obtained by using the proposed algorithm, and the black solid line is the secondary voltage obtained by using the nine-zone diagram method.

Figure 4. Corresponding reactive power flowing through the transformer of different methods
In the figure, the blue solid line is the reactive power flowing through the transformer obtained by using the proposed algorithm, and the black solid line is the reactive power flowing through the transformer obtained by using the nine-zone diagram method.

It can be seen from the above simulation results that the proposed algorithm are obviously better in control strategy than the traditional nine-zone diagram method. Using this algorithm, the number of capacitor switching times and the number of transformer tap regulations are significantly reduced, and the coordinated control of capacitors and transformer tap is more reasonable, reducing the switching oscillation (frequent action of equipment).

In the control effect, the regulation of voltage and reactive power is superior to the traditional nine-zone diagram method. Its defects have been overcome in the principle. More attention is paid to the coordinated control of capacitors and transformer tap, that is, the sensitivity and effectiveness of device to the adjustment of actual operating conditions. At the same time, it takes advantage of the delay to enhance the anti-interference ability of the system, solves the problem of the number of regulations required by the controller and the actual number of regulations allowed, and reduces the blind change to the sudden load, thus reducing the number of regulations, enhancing the security and stability of the system operation, and greatly extending the life.

4. Conclusions
Substation voltage and reactive power on-line regulation strategy is proposed in this paper. Based on the traditional nine-zone diagram method, the theory and techniques of fuzzy logic control are introduced to improve the traditional method, so that a real-time control algorithm based on fuzzy theory and traditional control principle is formed. Based on expert experience, the action strategies of each substation's control equipment for the next day and the operation status of each substation are scheduled, so as to exert influence on the real-time control of the substations to ensure that the real-time control is more instructive and comprehensive. The simulation results of the example show that the algorithm can set corresponding control system according to the specific equipment parameters and operating conditions of different substations, and can control multiple OLTC transformers and multiple groups of parallel capacitors. Real-time adjustment of the control strategy of transformer tap and capacitor not only can meet the requirements of real-time control, but also can make the cooperation between the two more reasonable, so as to effectively reduce the number of device actions, improve the voltage pass rate, improve the power factor, reduce the network loss, and reduce the cost of operation and maintenance of control equipment. This can serve as a guide of real-time control for substation operators. The proposed algorithm is obviously superior to the traditional nine-zone diagram control method, which can be used
as a basic module of online closed-loop control. However, the problems such as data acquisition and output control involved in the real-time control module in the paper still need further solution and improvement, and a great deal of work needs to be done before practical application.

5. References
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