Full compensation of reactive power in electric networks 0.4-10kV

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Abstract. The most important task in electric networks is to reduce energy losses. According to Network Company, in distribution electric networks with a voltage of 0.4-10 kV, they account for 62% of the total number of losses. One way to save energy is reactive power compensation. From Order of the Ministry of Energy of the Russian Federation dated June 23, 2015 No. 380 “On the Procedure for Calculation of the Ratio of Consumption of Active and Reactive Power for Individual Energy Receiving Devices (Groups of Energy Receiving Devices) of Electric Power Consumers” at a voltage of 0.4 kV, the reactive power coefficient should not exceed the value 0.35, and on the side of 10 kV - values of 0.4. In practice, in distribution electric networks, reactive power compensation devices are not installed in most cases, and the reactive power factor is 2-3 times higher than the standard values. Since compensating devices are expensive equipment, it is necessary to evaluate the feasibility of deep reactive power compensation, in the range of reactive power factor changes from its standard value to zero. The article discusses the economic and technical feasibility of deep reactive power compensation. The use of a generalized parameter of the electric network for determining the voltage at substations of distribution electric networks is proposed. The need for the coordinated use of reactive power compensation devices and booster transformers to ensure the quality of electricity is shown.

1. Introduction
At a voltage of 0.4 kV, the reactive power factor (tgϕ) should not exceed a value of 0.35, and on the side of 10 kV - a value of 0.4. However, in the distribution electric networks of urban and rural areas, reactive power compensation devices are not installed in most cases [1]. It is significant that regulatory documents specify only the upper limit tgϕ, without limiting its decrease, if it is economically profitable.

The lower the compensation level in the distribution electric networks, the more reactive power it is necessary to deliver from higher voltage networks to consumers. The higher the power loss in the networks, the lower the voltage levels, the throughput of lines and transformers, the stricter the restrictions on connecting new consumers to the networks, etc [2].

Reactive power compensation will allow: increase in throughput; reduction of active losses; reduction of voltage losses; reduction of equipment costs (smaller cross-sections of wires and cables, lower installed capacity of transformers). To reduce the distortion of the sinusoidal voltage, compensating devices with filters should be installed [3,8]. It is also necessary to monitor the technical
condition of the equipment in a timely manner using non-destructive testing methods [11-12].

According to some estimates, the optimization of the placement, power and degree of use of compensating devices and distributed active power sources in distribution electric networks would reduce the technical losses of power and electricity in them to 50% of the existing level [4-6]. To achieve this result, several features of reactive power compensation in distribution networks should be taken into account.

For low voltage, reactive power compensation is provided by:
1) Unregulated capacitor;
2) Automatic control devices or batteries, allowing continuous control when the load changes.

Permanent (unregulated) capacitor.

This circuit uses one or more capacitors to provide a constant level of compensation. Management may be:
1) Manual: by means of a switch or load switch;
2) Semi-automatic: by means of a contactor;
3) Direct connection to the load and switching with it.

Such capacitors are used:
1) At the terminals of inductive devices (motors and transformers);
2) On busbars supplying a number of small engines, and inductive equipment, for which separate compensation is too expensive;
3) In cases where the load level is quite constant.

Automatic compensation is used, since the block of capacitors is divided into a number of sections, each of which is controlled by a contactor.

Turning on the contactor turns on its section in parallel with other already working sections. Therefore, the capacity of the unit (battery) can increase or decrease stepwise by turning the control contactors on and off.

The control relay monitors the power factor of the controlled circuits and serves to turn on or off the corresponding contactors to maintain a sufficiently constant system power factor (within the tolerance specified by the value of each compensation battery). The current transformer for the monitoring relay must be on the same phase of the input cable supplying the monitored circuits.

The capacitor block, Figure 1, is a device for automatic power factor compensation, including static contactors (thyristors) instead of standard contactors.

![Figure 1. Automatic reactive power compensation device](image)

Static compensation is especially suitable for certain loads, including equipment with a fast cycle and / or high sensitivity to disturbance arising from transients.
Advantages of static contactors:

1) Instant response to any change in power factor (reaction time - 2 s or 40 ms depending on the controller);
2) An unlimited number of operations (operations);
3) Elimination of transients in the network when capacitors are turned on;
4) Silent operation.

A careful adjustment of the compensation to the level required by the load helps prevent overvoltages at low loads, i.e., preventing overvoltage conditions and possible damage to equipment. Overvoltages due to excessive reactive compensation depend, in part, on the value of the source impedance.

2. Experimental researches

In figure 2 shows typical diagrams of $\tan \phi$ changes observed on the tires of internal switchgears of three apartment buildings: a - three five-story residential buildings; b - three nine-story residential buildings; c - three fourteen-story residential buildings.
Figure 2. Change in reactive power factor per day in an apartment building

Figure 3 shows a distribution network with a transformer substation № 8142. Figure 4 presents typical diagram of tgo changes observed on low voltage buses of transformer substation № 8142 (installed in the countryside) during the day. The diagrams show that tgo is significantly overestimated relative to standard values, which leads to increased electricity losses.

Figure 3. Distribution electric network 0.4kV.
Since compensating devices are expensive equipment [7-10], it is necessary to evaluate the feasibility of deep reactive power compensation, in the range of reactive power factor changes from its standard value to zero. For this, we consider a 0.4 kV line with a load of $P_H + jQ_H$, at the end of which a compensating device is installed. The voltage center of the transformer substation serves as the power center. The economic effect of the additional installation of the capacitor unit was calculated under the following initial positions: the average cost of compensating devices was taken based on open sources available on the Internet; the cost of electricity losses - 2 rubles / kWh; the number of hours of using the maximum load was taken to be 3200 hours. The line resistance was set in accordance with the cross section of the wire, which, in turn, was coordinated with the maximum permissible current.

Figure 5 shows the results of calculating the payback period of compensating devices of various nominal parameters. As can be seen from the graphs, the minimum is achieved in most cases with $\tan \phi$ values $\tan \phi$ of 0.1. Moreover, full compensation of reactive power, when $\tan \phi = 0$, slightly increases the payback period and may be appropriate to increase the voltage level at the substation. In general, the calculations show that the decisive factor determining the economic efficiency of deep compensation of reactive power is the remoteness of power receivers from the substation. For the boundary length, you can take 200 m, in this case, the payback speed does not exceed 6.5 years.
Next, we consider the technical effect of the full compensation of reactive power, which consists in increasing the voltage at the substation.

To do this, we consider the distribution electric network modeled in MATLAB Figure 6, in the circuit we used an AC 95 brand wire ($r_0 = 0.34 \text{ Ohm} / \text{km}$, $x_0 = 0.332 \text{ Ohm/km}$). The length of the power line between consumers and a power center $L = 10\text{km}$. The electrical power of the consumers is $0.5\text{ MW}$. The voltage in the power center is $U_{pc} = 10.5\text{ kV}$, the value of the factorization of the reactive power factor $\tan \phi = 0.4$.

![10 kV distribution network model](image)

**Figure 6.** 10 kV distribution network model

The calculation results for the model, Figure 6, are presented in Figure 7. To comply with the normative document GOST 32144-2013 "Electric energy. Electromagnetic compatibility of technical
equipment. Power quality limits in the public power supply systems", the voltage at the load should not decrease less than 9.5 kV.

![Voltage graph](image)

**Figure 7.** The voltage value at the load of the distribution electric network
1 - voltage until reactive power compensation; 2 - voltage after reactive power compensation; 3 - voltage after reactive power compensation using voltage regulation on power transformers

For power grid companies, compliance with the regulatory voltage value is an urgent task. In production and in everyday life, many electrical appliances are used, which include elements that are extremely sensitive to voltage deviations from acceptable values. Failure in their work can cause equipment failure or a breakdown in technological processes. The consumer has the right to demand not only the replacement of failed equipment, but also monetary funds for forfeit. Distributive electric networks with a voltage of 10 kV are characterized by a large number of step-down substations (up to 20-30 units per feeder) and distances to end consumers up to several tens of kilometers. Power lines designed for power consumption more than a decade ago no longer have the required bandwidth. As a result, consumer voltage decreases beyond acceptable values. For example, a voltage graph is shown at the power center and at the end of the section, Figure 8.
Figure 8. Voltage change during the day

From figure 8 it can be seen that the voltage in the power center has overestimated values, while at the end of the section the voltage does not correspond to standard values.

To solve the problem with voltage deviation, automatic voltage control points for a voltage of 10 kV are used. Automatic voltage control points consist of boost transformers. If booster transformers are installed in two phases, the voltage is regulated within ± 10%; if booster transformers are installed in three phases, the voltage is regulated within ± 15% (Information provided by the company "Power supply quality systems" SKE-Electro"), figure 9.
**Figure 9.** The inclusion of an automatic voltage control point in the electric network

The automatic control point is energized to perform the functions:
- automatically increase or decrease the voltage level on the power line at critical points of voltage drop or rise;
- automatically maintaining the voltage level within the specified limits for the forward and reverse direction of the power flow (reverse mode).

A significant impact on their quantitative composition has a level of compensation of reactive power.

![Diagram showing voltage levels and compensation](image)

a – to ensure the quality of electric power in terms of voltage, four sets of automatic voltage regulation points are used as part of three voltage boost transformers, reactive power factor $\angle \phi = 0.4$

![Diagram showing voltage levels and compensation](image)

b – to ensure the quality of electricity in terms of voltage level, three sets of automatic voltage regulation points are used, one of which consists of three boost boost transformers and two others of two, reactive power factor $\angle \phi = 0$

**Figure 10.** Change in voltage level depending on the remoteness of consumers
Figure 10 shows that with full compensation of reactive power, both the number of sets of automatic voltage control points and the number of boost boost transformers included in them are reduced. The economic effect of reactive power compensation in this case will be more than 10 million rubles.

3. Conclusion
The calculations show the economic efficiency of energy saving due to deep compensation of reactive power, provided that the consumer is further than 200 meters from the supply substations. Full compensation of reactive power leads to an increase in the quality of electricity. The methodology for determining the voltage level at substations with full compensation of reactive power by generalized network parameters is substantiated. The need for a coordinated choice of the number and parameters of boost transformers with a level of reactive power compensation is shown, which leads to a decrease in investment to ensure the quality of electricity.

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