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Article

Investigation of Voltage Control at Consumers Connection Points Based on Smart Approach

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Abstract: More and more functions are performed automatically with the use of various electrical appliances and sophisticated control systems in all spheres of human life. In this regard, the demand for reliable and quality power supply is increasing. To date, low power quality, in particular unacceptable voltage levels, is an important deterrent for introducing technologies of smart electricity consumers (smart homes, smart companies, smart cities). This paper presents a comprehensive solution of this problem with the use of a voltage control system in the distribution grids, which is oriented on grids with a large number of heterogeneous loads and low level of Information Technology (IT) penetration. It is proposed to be installed on distribution substation special devices that perform continuous measurements of voltage levels, produce short-term forecasts and transmit the permissible ranges of voltage control to the power supply centers. The computing unit at the primary substation analyzes the data received from all distribution substations, and determines the optimum control actions to meet the requirements of all consumers. The proposed system was compared with conventional voltage control methods. The results have proved the effectiveness of the proposed approach.

Keywords: power quality; distribution electrical grid; voltage control; smart grid

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1. Introduction

The development of modern power distribution grids is attended by the increase of electric load, changes in energy consumption patterns, and the emergence of new types of consumers and power sources. Industrial and domestic consumers are beginning to pay more attention to cost savings and more efficient use of electricity, applying smart electrical control systems and installing distributed energy sources [1–3]. This leads to changes of load curves and the redistribution of power flows through the grid.

On the other hand, modern electrical receivers are sensitive to power quality. Violations of regulatory requirements often result in the failure of such equipment.

To date, the concept and technologies of smart electricity consumers have been developed in homes, factories and cities. The introduction of these technologies allows us to automate most of our routine work, but at the same time makes people more dependent on electricity. Power supply failure or the deviation of power quality indices from the permissible values lead to more serious consequences than they used to in the past.

Poor power quality is one of the limiting factors for the implementation of smart technologies for consumers as it requires the installation of additional stabilizing and backup equipment, i.e., entails substantial additional costs.

All this sets new challenges for regime control in distribution grids. Nowadays, control means used in the distribution grids are not sufficient to fully provide the desired voltage level for all consumers [4–7].

At the present time, voltage control in the distribution grids is carried out at the primary substation. Power consumers with different load profiles are connected to one primary substation. These consumers have different requirements for voltage regulation. Non-coordination of voltage control and actual requirements of consumers lead to the fact that in many parts of the grid, voltage is outside of the permissible range.

Daily voltage regulation in distribution grids of 6–20 kV is performed by on-load tap changers (OLTCs) of the power transformers installed on the primary substations. OLTCs are controlled by an automatic voltage regulator (AVR), which commands them to change tap position.

The AVR determines the new tap position as a result of the voltage measurement at 6–20 kV at transformer side of the primary substation and load currents of the outgoing lines or the total transformer current [8,9].

Since voltage control is performed on the basis of voltage and current measurements at the primary substation, consumers' actual voltage levels are not taken into account. Therefore, results of voltage control may not meet the requirements of consumers.

On this basis the actual problem emerges—to ensure the required voltage level at the connection points of end consumers through smart management of existing means of voltage regulation.

To solve this problem, the information-technical system is offered which implements the functions of monitoring and analysis of the actual voltage levels at the connection points of consumers, predicting their profiles and creating preventive control actions for control devices.

2. Comparison with Analogues

A number of international companies such as ABB, Schneider Electric, and Alstom are currently developing such systems. These systems vary widely in the algorithms used, the requirements for information and technical infrastructure, and the functions they perform. Products of these companies are focused on either grids with existing IT (Information Technology) infrastructure and advanced modern power equipment or on grids where these technologies will be implemented in conjunction with the reconstruction of the grids.

Systems for regime monitoring and control in the distribution grids by ABB and Schneider Electric suggest the presence of information channels with high bandwidth. Such systems have a rigid hierarchical structure. All information is transmitted from the control points to the control center where it is processed. Based on the results the centralized management of the entire grid is performed [10,11].

These technologies cannot be applied in the Russian power grids without a large-scale renovation. Considering limited funding for utilities, currently such solutions are not feasible.

The system proposed in this paper is focused on the current state of Russian distribution grids and requires minimal implementation costs. In the first phase, the basic functions of monitoring and voltage control are implemented; in the future these functions can be expanded and will become more complex. This system has a modular structure with an extensible set of features. It is a base for the further development of smart distribution grids.

3. System for Smart Voltage Control

The system for smart voltage control (SSVC) monitors grid regimes and controls voltage levels at the connection points of the end customers by means of OLTCs [3,4].

The system consists of interconnected blocks which implement the following functions:

1. voltage level monitoring at the connection points of end consumers;
2. generation of an archive of voltages in the load nodes;
3. voltage forecast in load nodes;

4. producing the control actions based on the actual and predicted voltage levels in the load nodes;
5. implementation of control actions.

Functions 1–3 are provided by installation of intelligent measuring devices at the control points of the grid. These devices are called "a measurement point".

Function 4 is performed in the computer center (CC), connected to other devices by the Internet.

Function 5 is performed directly in the OLTC control unit.

The record of phase voltage values is made at each measurement point. On the basis of these values the fundamental direct sequence voltage is calculated, which is controlled [12].

The received values of the basic frequency direct sequence voltage are averaged over one-minute intervals, and then are processed and added to the archive. Data verification is held, accidental perturbations and errors of registration are eliminated. Subsequently, data are adjusted in a way such that the load profile would not contain the results of the regulating influences. The received values reflect the dependence of the node voltage of the grid from the load variation of customers. The admissible control actions are defined on the basis of this information.

The Control unit generate inquiries to the measurement points and process received information. For a reduction of requirements to an information channel, only information about admissible ranges of transformer tap positions is transferred through the network.

These ranges are calculated for the actual and expected values of the voltage. All control points transfer these lists at the demand from the computer center.

The choice of tap position is carried out by analysis of the actual voltage at the control points and the forecast of its change. If few regimes are within the required voltage range, then one is chosen which requires fewer control actions.

Mathematically it can be described as a minimization problem of the objective function:

$$\min\left(F(N)\right) \to N; \tag{1}$$

$$F(N) = k_1 \sum_{i=1}^{n} \left(dN_{(+)\,i} + dN_{(-)\,i}\right) + k_2 \sum_{i=1}^{n} \left(dN^f_{(+)\,i} + dN^f_{(-)\,i}\right) + k_3 \left|N_0 - N\right|; \tag{2}$$

$$\begin{gathered} dN_{(+)\,i} = \begin{cases} N_i - N_{\mathrm{ul}\,i}; & N_i > N_{\mathrm{ul}\,i} \\ 0; & N_i \leqslant N_{\mathrm{ul}\,i} \end{cases}; \\ dN_{(-)\,i} = \begin{cases} N_{\mathrm{ll}\,i} - N_i; & N_i < N_{\mathrm{ll}\,i} \\ 0; & N_i \geqslant N_{\mathrm{ll}\,i} \end{cases}. \end{gathered} \tag{3}$$

where

$F(x)$ is the objective function;

N is the OLTC tap position;

$dN_{(+)\,i}$, $dN_{(-)\,i}$ is a deviation of the current tap position from the desirable one for i measurement point. It is calculated on the basis of the actual voltage level;

$dN^f_{(+)\,i}$, $dN^f_{(-)\,i}$ is a deviation of the current tap position from the desirable one for i measurement point. It is calculated on the basis of the predicted voltage level;

N_0 is the current tap position;

$N_{\mathrm{ul}\,i}$ is the upper limit acceptable tap position for i measurement point calculated on the basis of the actual voltage level;

$N_{\mathrm{ll}\,i}$ is the lower limit acceptable tap position for i measurement point calculated on the basis of the actual voltage level;

$N^f_{\mathrm{ul}\,i}$ is the upper limit acceptable tap position for i measurement point calculated on the basis of the predicted voltage level;

$N^f_{\mathrm{ll}\,i}$ is the lower limit acceptable tap position for i measurement point calculated on the basis of the predicted voltage level;

k_1 is the weight coefficient for the actual current level;
k_2 is the weight coefficient for the predicted voltage level;
k_3 is the weight coefficient for the number of control actions.

The greatest weight coefficient corresponds to the current voltage level. Thus, first of all, the regulation for the normalization of the existing violations of the voltage level is performed. If in the current regime the voltage is within admissible range, then it checks the possibility for voltage violation in the future on the basis of the forecast and implements a predictive regulation.

The short-term forecast is implemented by means of neuron networks, as it has proved itself as the most effective for such tasks.

The neural network of a multilayered perceptron type with three layers is constituted for each measurement point. The layers are entrance, hidden and output.

The forecast is performed for the hour ahead on the basis of voltage values in the last two hours, averaged by one-minute intervals.

Thus, the neural network contains 120 neurons in the input layer and 60 neurons in the output layer. The best results of forecasting become available with the hidden layer, consisting of 10 neurons. Training of a network is carried out by the particle swarm method. The constant check of the error level of forecasting is carried out when the neural network operates. In case of the excess of the 2% error level, the added training of the network is carried out.

4. Experiments and Results

The test grid for this work was developed on the basis of analysis of existing distribution networks in the Moscow region. The fragments of the network were reduced for the compact form of representation. The resulting scheme is shown in Figure 1.

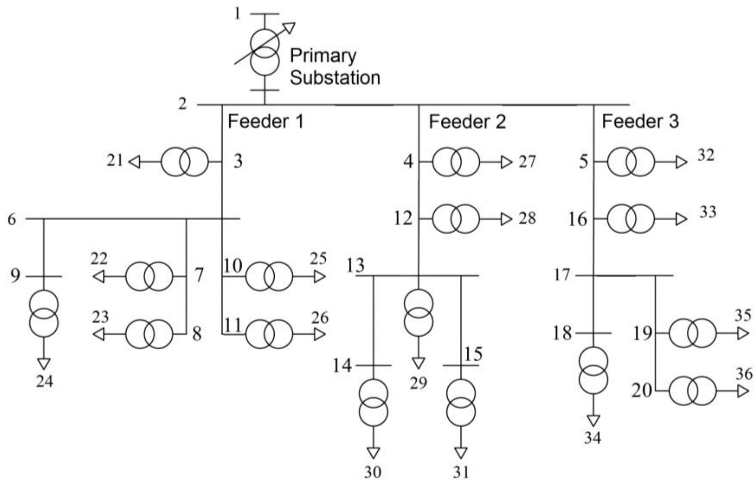

Figure 1. The test network.

Load of the nodes is modeled by week (7 days) profiles of active and reactive power, averaged over one-minute intervals.

Regime control in the distribution networks is aimed at providing a desirable voltage level at the connection points of consumers; at the same time, voltage levels are monitored on the low voltage side of the distribution transformers.

The local and international power quality standards (IEEE Std. 1159:1995, IEEE Std. 1346:1998, EN 50160:2010, GOST 32144:2013) define different voltage limits on supply terminals.

In the Russian local standard (GOST 32144:2013), the limit voltage overdeviation and underdeviation are equal to 10%. Voltage drop in the distribution networks does not exceed 5%. Thus, for support of the lower admissible limit of the most distant customers, the voltage on the side 0.4 kV of the distribution transformers should not be lower than 95% of the rated value. The closest customers can be directly connected to the distribution transformers; therefore, the upper voltage limit on the side 0.4 kV of distribution transformers should not be greater than 110% of the rated value.

Consequently,

- the upper limit is defined by the closest customers and is equal to 110% of the rated voltage;
- the lower limit is defined by the most distant customers and is equal to 95% of rated voltage.

The goal of the voltage regulation system is to provide a voltage level on the side 0.4 kV of distribution transformers in the range of 0.95–1.10 Un.

In spite of a broad range of admissible values, these requirements are often violated. It is typical for long-length distributive grids to have a large number of heterogeneous loads.

A traditional approach to the voltage regulation in distributive grids by means of OLTCs is based on local measurements of current and voltage at a primary substation.

In the domestic distribution grids, the most common type of regulation is voltage stabilizing when the voltage on the low voltage side of the primary substation maintains a constant level.

Voltage diagrams of the most specific nodes of the grid in the case of voltage stabilization at the primary substation are represented in Figure 2. These diagrams are plotted for the 0.4 kV side of distribution transformers 10/0.4 kV.

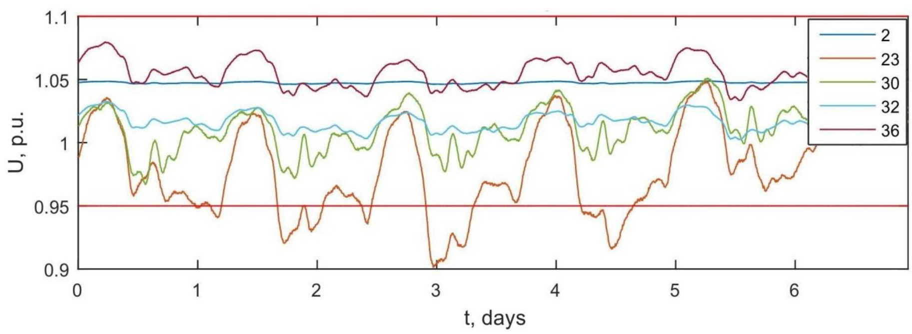

Figure 2. Voltage profiles in the case of voltage stabilization at the primary substation.

Figure 2 shows that there are number of customers with unacceptable voltage levels.

In the case of opposite regulation, the voltage level at the primary substation varies proportionally to the total current through the transformer. Application of the opposite regulation method considerably reduces the number of voltage violations in the network. Voltage diagrams in the case of opposite voltage regulation are represented in Figure 3.

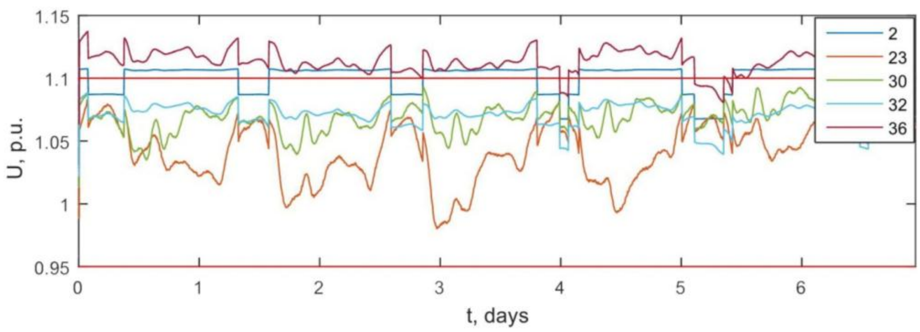

Figure 3. Voltage profiles in the case of opposite voltage regulation at the primary substation.

The effectiveness of opposite voltage regulation depends on the accuracy of the initial setup which includes the choice of coefficients of proportionality between the current through the transformer and the voltage level on the low voltage side of the primary substation. As a rule, the results of week measurements are not enough for the correct setup of a control system on the basis of the opposite regulation method; therefore, this method is seldom used in practice.

Figure 4 shows voltage profiles in the network with SSVC. In this case, voltage regulation is based on the described approach.

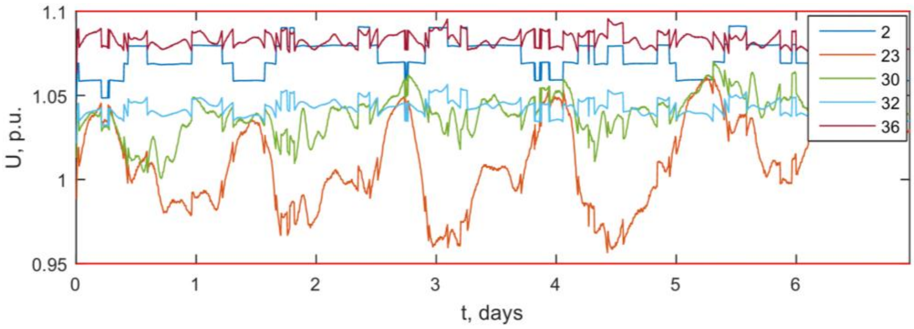

Figure 4. Voltage profiles in the network with SSVC.

The information about the actual consumers' voltage requirements makes it possible to optimize OLTC switching to meet the power demand for the maximum number of consumers. Figure 4 shows that the voltage levels of all network nodes are within the required range.

The schedule of the tap changer switching on the main substation with SSVC is shown in Figure 5.

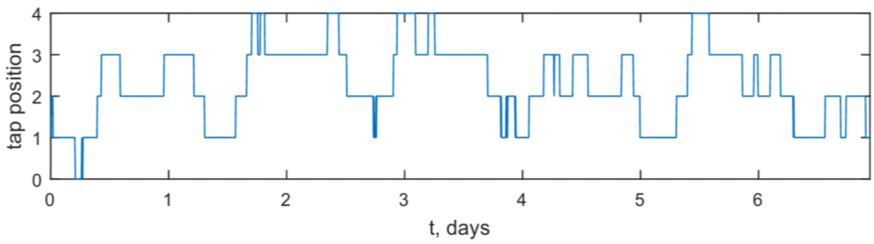

Figure 5. Schedule of tap changer switching.

The graphs above show that the SSVC operates the control devices to the fullest extent. That means that equipment is used effectively.

Figure 6 shows the relative time of the output voltage limit exceeded at all nodes of the range.

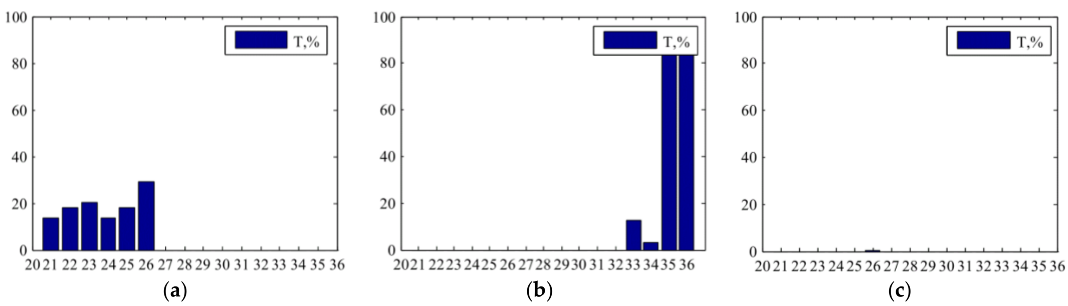

Figure 6. Relative time of the output voltage limit exceeded with different regulation methods. (**a**) Voltage stabilizing; (**b**) opposite voltage regulation; (**c**) grid with SSVC.

Configuration of the local voltage control equipment settings (no-load tap changer, booster transformer, reactive power compensator) is required in the case of the output voltage being out of range and it indicates the engineering incapability of normalizing stress in the power network.

5. Conclusions

The presence of unacceptable voltage levels in the power supply system is a deterrent to the introduction of smart technologies at the electricity consumer level. Voltage control using old approaches is not possible due to the nature of modern power consumers; therefore, a smart voltage control system is required.

The proposed voltage control system is designed for use in the Russian distribution grids. It is designed on the basis of a large-scale regime monitoring system, which is being implemented at the moment. The availability of information about the regime parameters in the most important nodes of the grid allows the implementation of the voltage control system, which will be focused on the actual voltage levels at the connection points of consumers. In this paper, a possible variant of such a system is proposed.

The proposed system measures the voltage level at the low voltage side of distribution transformers, and it collects and analyzes information. The system produces a voltage forecast on distribution transformers and determines the permissible range of tap positions on the basis of archived information. The system applies the control actions before actual voltage values exceed the range, thus providing an optimal regime for the consumer.

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Conflicts of Interest: The authors declare no conflict of interest.

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