Analysis and study of energy efficiency by the operation of a voltage stabilizer

R Ch Karimov1,2,3, A V Kuchkarov4, M Z Xodjalimova4, R K Makhamadjanov2 and A B Numonov2

1 Tashkent State Technical University named after Islam Karimov, 100095, Uzbekistan, Tashkent, University St. 2A
2 Almalyk branch of Tashkent State Technical University named after Islam Karimov, 110100, Uzbekistan, Almalyk, Mirzo Ulugbek St. 45
3 E-mail: raxmatillo82@mail.ru

Abstract. This article discusses the analysis and study of the energy efficiency of the operation of a voltage stabilizer using a non-contact voltage relay. In addition, the calculation of the energy efficiency from the use of the stabilizer is presented on the example of the enterprise of the Baysun district power supply of the Surkhandarya region. Summarizing the results of the analyzed and investigated energy efficiency of the prototype of the stabilizer, it can be stated that it fully meets the requirements for such devices and can ensure reliable operation of the power supply network of household electrical receivers with a voltage of 0.4 kV.

1. Introduction

In the Republic, indicators and standards for the quality of electrical energy are established by the State Standard of Uzbekistan O’zDSt 1044: 2003 and the Interstate Standard GOST 32144-2013 [1-2].

The current stage of development of the economy of the Republic requires a constant improvement in the quality and energy efficiency of the use of electrical energy, reducing the cost of products. For this purpose, the legislation of our republic adopted the Law on the Rational Use and Consumption of Energy (№421-I dated April 25, 1997). The law focuses on optimizing the modes of production and consumption of electrical energy [3].

In connection with the widespread automation of production processes, the introduction of automatic contactless control systems, the requirements for reliability, speed and durability of electrical devices and apparatus have significantly increased. These requirements are largely met by devices based on the use of properties and phenomena inherent in nonlinear resistive circuits. In the future, a significant expansion of the field of applications of nonlinear circuits as devices and devices with new qualitative properties is expected [1-4]. Therefore, the theory of nonlinear resistive circuits and systems is essential in the design of highly efficient non-contact voltage relays. On the basis of theoretical analyzes and experimental studies of nonlinear resistive circuits, it has been established that in order to ensure high-quality power supply to consumers, it is necessary to use such circuits as power contactless switching devices, current and voltage regulators. Circuits based on nonlinear resistive circuits allow switching power loads at the best dynamic modes, namely, when a sinusoidal current passes through zero, which improves the transient process mode [4-6].
As you know, power supply to household electrical consumers with voltage of 0.4 kV has its own characteristics associated with the specifics of household power consumption production, dispersed over a large area with low specific electrical loads, which, moreover, are of a constant nature. These circumstances determine the specific requirements for the construction of electric power systems for household electrical consumers as a whole [5-8].

At the same time, the high rates of development of household electrical consumers with a voltage of 0.4 kV at the present time lead to a continuous increase in electricity consumption, as well as to the widespread introduction of automatic control systems for technological processes and production complexes. The cost of violations of normal operating modes of such systems associated with deviations of power quality indicators, with sudden interruptions in power supply, due to emergency situations is extremely high [3-4, 8-10].

Currently, the direction of development of a voltage stabilizer using a non-contact voltage relay is relevant. Such systems increase the reliability of power supply for household electrical consumers with a voltage of 0.4 kV [5-6, 11-13].

As the level of industrialization of household power consumers increases, the voltage of 0.4 kV, the damage from interruptions in power supply and deterioration in the quality of electricity is steadily increasing. Interruptions in the power supply to household consumers, the quality of voltage decreases and related violations of the technology of household electrical receivers with a voltage of 0.4 kV. The level of damage largely depends on the type of household electrical appliances, its size and can exceed millions of sum [3-5, 14-17].

In addition, the power supply to household electrical consumers has its own characteristics. These features are influenced by the specificity of household electrical consumers, dispersed over a large area with low specific electrical loads, which, moreover, are of a constant nature. These circumstances determine the specific requirements for the construction of electrical power systems for household electrical consumers in general [5-7, 18-20].

2. Discussion of the energy efficiency from the use of a voltage stabilizer

The modern electrical load of a one-story residential building is characterized by a wide range of household electrical consumers, which, according to their purpose and effect on the electrical network, can be divided into the following groups: passive consumers of active power (incandescent lamps, heating elements of irons, stoves, heaters); electrical receivers with asynchronous motors operating in single-phase mode (pumps - in the water supply and heating systems, drive of compressors of refrigerators, washing machines, and others); electrical receivers with collector motors (drive of vacuum cleaners, electric drills and others); AC and DC welding units (for repair work in the workshop and others); rectifying devices (for charging batteries and others); radio electronic equipment (televisions, computer equipment and others); LED lighting lamps [3-5, 19-22].

The impact of each individual household electrical consumer is insignificant, while the aggregate of electrical consumers connected to the 0.4 kV buses of the transformer substation has a significant effect on the supply network. In the case of the presence of an electrical network, the power of the substation in a suburban village or in a place where the household electrical receiver is not infinite. Accordingly, the quality of power supply during peak hours is reduced [6-8, 20-23].

In the introduction of an energy-efficient voltage stabilizer, who want to get a high-quality stable power supply and save a significant part of energy resources. The stabilizers showed the greatest efficiency when working with household electrical appliances [5-6, 24-26].

Currently, industrial enterprises, office and shopping centers are faced with the task of reducing energy costs. Lighting costs account for 25% to 35% of total energy costs. At the same time, the transition to energy-efficient lighting systems of the new generation, such as LED lamps, is very costly and has a long payback period. Therefore, to solve the problem of reducing energy consumption, we have developed voltage stabilizers using a non-contact voltage relay [5, 14-15, 27-28].
Voltage fluctuations have a significant impact on the operation of single-phase asynchronous motors, which are the most common receivers of electricity in agriculture. In addition, a decrease in voltage also worsens the conditions for starting an electric motor, since this reduces its starting torque [3, 29].

Incandescent lamps are characterized by nominal parameters: power consumption, luminous flux, luminous efficacy (equal to the ratio of the luminous flux emitted by the lamp to its power) and average nominal service life. These indicators largely depend on the voltage at the terminals of the incandescent lamps. With a decrease in voltage, the luminous flux decreases. When the voltage rises above the nominal, the luminous flux, lamp power and luminous efficiency increase, but the service life of the lamps sharply decreases and as a result they quickly burn out. In this case, there is an overspending of electricity [21, 29-31]. Changes in voltage lead to corresponding changes in luminous flux and illumination, which ultimately affects productivity and human fatigue.

Fluorescent lamps are less sensitive to voltage fluctuations. With an increase in voltage, the power consumption and luminous flux increase, and with a decrease, they decrease, but not to the same extent as with incandescent lamps. At a reduced voltage, the ignition conditions of fluorescent lamps deteriorate, therefore, their service life, determined by spraying the oxide coating of the electrodes, is reduced both with negative and positive voltage deviations. With voltage deviations of 10%, the service life of fluorescent lamps decreases on average by 20-25%. A significant disadvantage of fluorescent lamps is their consumption of reactive power, which increases with increasing voltage supplied to them [1-2, 11, 19-21, 32].

Voltage deviations negatively affect the quality of work and the service life of household electronic equipment (radios, televisions, telephone and telegraph communications, computer equipment) [1-2].

The strict requirements of the standard for deviations in the frequency of the supply voltage are due to the significant effect of frequency on the operating modes of electrical equipment, the course of production processes [25, 28-32].

The electromagnetic component of the damage is caused by an increase in active power losses in electrical networks and an increase in the consumption of active and reactive power (a decrease in frequency by 1% increases losses in electrical networks by 2%) [1-2, 14, 30-32].

The technological component of the damage is mainly caused by the under-production by industrial enterprises of their products and the cost of additional work time for the enterprise to complete the task. According to expert estimates, the value of technological damage is an order of magnitude higher than the electromagnetic one [16, 32].

The operation of household electrical receivers with the best technical and energy indicators (high efficiency, reliability, electromagnetic safety, etc.) is possible only with small voltage deviations at their terminals. For most household electrical appliances, the negative and positive voltage deviations should not exceed 5% of the rated voltage [5-6, 20-22].

The specified requirements for the voltage deviation in the electrical network and at the terminals of household electrical receivers necessitate voltage regulation in all types of electrical networks. Distinguish between centralized and local voltage regulation. With centralized regulation, the voltage is changed in the power center, which can be the busbars of the power plant, as well as the medium or low voltage busbars of the step-down substation [25-26, 29-31].

As the analysis of methods for regulating and maintaining voltage within acceptable limits has shown, the simplest way to provide high-quality electricity is to use voltage stabilizers using a non-contact voltage relay [1-3, 19-23, 32].

Voltage stabilizers are used to power various equipment, appliances, household and office equipment, special and other equipment in conditions of drops, understated or overvoltage of the mains, the need to filter interference. Such voltage instabilities and interference in the power grid occur quite often, can be long-term and lead to failures or breakdown of electrical equipment [31-32].

In this case, voltage stabilizers are able to provide equipment protection against sudden changes in voltage in the mains and impulse noise, help to increase the uptime of complex and expensive equipment and devices [15-17, 22, 30].
An important characteristic of a voltage regulator is its speed, i.e. the higher the speed, the faster the regulator will react to changes in the input voltage. Different types of stabilizers have different speed. Another important parameter is the accuracy of the output voltage stabilization. An important household consumer parameter is the ability to maintain the declared parameters during power overloads [6-7, 18, 29-31].

For the correct and efficient operation of the voltage stabilizer using a non-contact voltage relay, it is necessary to determine and take into account the total calculated power of all equipment in a residential building, which needs simultaneous voltage stabilization. The power rating of a voltage regulator using a non-contact voltage relay is determined using the tabular demand factor method [14].

Initial data for calculation: As an example of how to analyze and investigate the calculation of energy efficiency from the use of a voltage stabilizer using a contactless voltage relay, let us take a project of a private one-story residential building with a living area of 108 m$^2$. The house has 4 rooms, an entrance hall, a kitchen, a bathroom. There is a garage on the plot. All electricity consumers are single-phase. Recommended capacity values for residential consumers of a residential building [14].

The initial parameter to analyze and investigate the calculation of energy efficiency from the use of a voltage stabilizer using a contactless voltage relay is the installed power $P_{\text{inst}}$ of a group of household consumers, and the main calculated coefficients are $k_d$ (demand factor), $k_u$ (utilization factor) and $\cos \varphi$ (power factor) [14]. The load demand factor is used to adjust the rated load based on the assumption that at any given time, not all electrical equipment will consume power at full load [14].

| № | The name of household consumers | $P_{\text{inst}}$ | $k_d$ | $k_u$ | Note |
|---|-------------------------------|------------------|------|------|------|
| 1. | Electric lighting for living rooms | $35\div40$ W/m$^2$ | 0.8 | 0.8 | |
| 2. | Electric lighting of living rooms (bedrooms) | $25\div30$ W/m$^2$ | 0.6 | 0.6 | |
| 3. | Electric lighting for classrooms, libraries, playrooms and others | $30\div35$ W/m$^2$ | 0.6 | 0.8 | Luminaires with incandescent lamps |
| 4. | Electric lighting for the kitchen | $25\div30$ W/m$^2$ | 1.0 | 0.8 | |
| 5. | Electric lighting of halls, corridors and others | $20\div25$ W/m$^2$ | 0.8 | 0.8 | |
| 6. | Household outlet network (TV and radio equipment, refrigerators, vacuum cleaners, irons, sconces, floor lamps and others) | 100 W/socket | - | 0.7÷1.0 | 1 socket for 6 m$^2$ total area: $k_d=0.7$ – with more than 50 sockets; $k_u=0.8$ – with the number of outlets from 20 to 50; $k_u=0.9$ – with the number of outlets from 10 to 20; $k_u=1.0$ – with the number of outlets up to 10 |
| 7. | Washer | $0.2\div2.2$ kW | 1.0 | 0.6 | |
| 8. | Accumulation water heaters | $1.5\div2$ kW | 0.6 | 0.8 | |
| 9. | Conditioners | $1.5\div4$ kW | 0.7 | 0.8 | |
| 10. | Food processors, coffee makers, electric kettles and others (in total) | $4\div5$ kW per apartment | 0.3 | 1.0 | |
| 11. | Submersible pumps | $0.75\div1.5$ kW | 0.8 | 0.9 | |
| 12. | Personal computers | $0.4\div0.5$ kW | 0.6 | 1.0 | |

The calculated demand and utilization factors are taken according to table 1, and the power factors according to table 2. Household consumers of occasional use (№ 10 of table 1) are taken into account in the total power of the outlet network. Accordingly, the demand coefficient of these consumers is defined as for the outlet network [14].
Based on the initial data in table 3, we draw up a calculated load table [14].

We group household electrical consumers into groups, observing the following rules:

- we combine household consumers of the same type into groups (for example, lighting and others);
- the installed capacities of the same type of household consumers are summarized;
- we combine consumers of equal power (there should not be in a group of consumers with very different nominal capacities);
- consumers of continuous operation of increased power (for example, a washing machine and others) are included in a separate group.

### Table 3. Initial data on the installed electrical equipment with reference to the premises.

| №  | Premises | Square, m² | Installed household appliances                                                                 | Rated (installed) power, kW | Note            |
|----|----------|------------|---------------------------------------------------------------------------------------------|-----------------------------|-----------------|
| 1. | Kitchen  | 15         | Electric lighting 2 sockets for a current of 10 A 1 socket for a current of 16 A             | 0.36                        | Table 1 note 4  |
|    |          |            |                                                                                             |                             | Table 1 note 6  |
|    |          |            |                                                                                             | 1.5                         | Table 1 note 10 |
| 2. | Hallway  | 10         | Electric lighting 1 socket for a current of 10 A                                           | 0.1                         | Table 1 note 5  |
|    |          |            |                                                                                             |                             | Table 1 note 6  |
| 3. | Bathroom | 8          | Electric lighting 1 socket for a current of 10 A Washing Accumulation water heaters         | 0.1 2.0 1.5                 | Table 1 note 5  |
|    |          |            |                                                                                             |                             | Table 1 note 6  |
|    |          |            |                                                                                             |                             | Table 1 note 7  |
|    |          |            |                                                                                             |                             | Table 1 note 8  |
| 4. | Living room | 20          | Electric lighting 4 socket for a current of 10 A                                        | 0.4 0.4 1.5                 | Table 1 note 1  |
|    |          |            |                                                                                             |                             | Table 1 note 6  |
|    |          |            |                                                                                             |                             | Table 1 note 9  |
| 5. | Canteen  | 14         | Electric lighting 2 socket for a current of 16 A Fridge                                   | 0.22 0.6                    | Table 1 note 4  |
|    |          |            |                                                                                             |                             | Table 1 note 10 |
|    |          |            |                                                                                             |                             | According to passport data |
| 6. | Cabinet  | 10         | Electric lighting 2 socket for a current of 10 A Personal Computer                        | 0.2 0.5                     | Table 1 note 3  |
|    |          |            |                                                                                             |                             | Table 1 note 6  |
|    |          |            |                                                                                             |                             | Table 1 note 12 |
| 7. | Bedroom  | 16         | Electric lighting 3 socket for a current of 10 A                                        | 0.2 0.3                     | Table 1 note 2  |
|    |          |            |                                                                                             |                             | Table 1 note 6  |
| 8. | Garage  | 24         | Electric lighting 2 socket for a current of 10 A Submersible pump                        | 0.1 0.2 0.75               | Table 1 note 6  |
|    |          |            |                                                                                             |                             | Table 1 note 11 |
| **Total:** |          |            |                                                                                             | **13.43**                   |                 |

The calculated active power of each group of household electrical consumers is determined by the

### Table 2. Power factors of individual household consumers.

| Types of household consumers | $\cos\phi/tg\phi$ |
|------------------------------|-------------------|
| Incandescent lamps           | 1.0/0.42          |
| Fluorescent lamps            | 0.92/0.426        |
| Refrigerators                | 0.65/1.168        |
| Pumps, fans, air conditioners up to 4 kW | 0.75/0.882 |
| Saunas                       | 1.0/0.0           |
| Jacuzzi                      | 0.8/0.75          |
| The same for engine power over 4 kW | 0.85/0.62 |

Based on the initial data in table 3, we draw up a calculated load table [14].

We group household electrical consumers into groups, observing the following rules:

- we combine household consumers of the same type into groups (for example, lighting and others);
- the installed capacities of the same type of household consumers are summarized;
- we combine consumers of equal power (there should not be in a group of consumers with very different nominal capacities);
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formula:

\[ P_{\text{cal}} = P_{\text{ins}} \cdot k_d \cdot k_a, \text{kW} \]  \hspace{1cm} (1)

Full design power of each group of household consumers:

\[ S_{\text{cal}} = \frac{P_{\text{cal}}}{\cos \phi}, \text{kVA} \]  \hspace{1cm} (2)

Taking into account that all loads are single-phase, the calculated current is determined by the formula:

\[ I_{\text{cal}} = \frac{P_{\text{cal}}}{U} / \cos \phi = \frac{S}{U} \]  \hspace{1cm} (3)

here, at the house input \( I_{\text{cal}} = \sum S_{\text{cal}} / U \).

3. The results of energy efficiency from the use of a voltage stabilizer
The calculation results \( P_{\text{cal}}, S_{\text{cal}}, I_{\text{cal}} \) are given in the calculated table of loads (table 4) [14].

**Table 4. Calculation table of loads.**

| Consumer group | Household consumer group name | \( P_{\text{ins}}, \text{kW} \) | \( k_d \) | \( k_a \) | \( \cos \phi \) | Calculated power | \( I_{\text{cal}}, \text{A} \) |
|----------------|-------------------------------|-----------------|---------|---------|---------|-----------------|----------------|---------|
| gr.1           | Lighting                      | 1.12            | 0.7     | 0.8     | 1.0     | 0.63            | 0.63             | 2.85    |
| gr.2           | Socket network                | 5.4             | 0.3     | 0.8     | 0.8     | 1.30            | 1.62             | 7.36    |
| gr.3           | Kitchen lighting              | 0.36            | 1       | 0.8     | 1.0     | 0.29            | 0.29             | 1.31    |
| gr.4           | Kitchen sockets               | 1.8             | 0.8     | 0.8     | 0.9     | 1.15            | 1.15             | 5.24    |
| gr.5           | Bathroom lighting             | 0.1             | 1       | 1       | 1.0     | 0.10            | 0.11             | 0.51    |
| gr.6           | Bathroom sockets              | 0.1             | 1       | 1       | 0.9     | 0.10            | 0.11             | 0.51    |
| gr.7           | Washer                        | 2.0             | 1       | 0.6     | 0.8     | 1.20            | 1.50             | 6.82    |
| gr.8           | Accumulation water heaters    | 1.5             | 0.6     | 0.8     | 1.0     | 0.72            | 0.72             | 3.27    |
| gr.9           | Garage lighting               | 0.1             | 0.8     | 0.9     | 1.0     | 0.07            | 0.07             | 0.33    |
| gr.10          | Garage sockets                | 0.2             | 1       | 0.9     | 0.9     | 0.18            | 0.20             | 0.91    |
| gr.11          | Submersible pump              | 0.75            | 0.8     | 0.9     | 0.8     | 0.54            | 0.68             | 3.07    |
| **Total:**     |                               | **13.43**       | -       | -       | -       | **6.28**        | **7.08**          | **32.17** |

The main parameters of a voltage stabilizer using an optoelectronic proximity voltage relay: full power, \( S=10 \text{kVA} \); input voltage change limit, \( U_{\text{inp}}=160\div250 \text{V} \); output voltage change limit, \( U_{\text{out}}=205\div235 \text{V} \); control system voltage, \( U_{\text{con}}=18 \text{V} \); frequency, \( f=50 \text{Hz} \); Power factor, \( \cos \phi=0.95 \). Total power of household consumers, \( S_{\text{house}}=7080 \text{VA} \). Average length of the supply line to the consumer, \( l \approx 0.1 \text{km} \). Cross-section of aluminum wire - \( 4 \times \text{A}-35, F=4 \text{mm}^2 \); \( r_0=4.6 \text{Ohm/km} \). Based on these data, we calculate the active resistance of the wire:

\[ R = r_0 \cdot l = 4.6 \cdot 0.1 = 0.46 \text{ Ohm} \]  \hspace{1cm} (4)

Rated current at rated voltage:

\[ I_1 = \sum S_{\text{cal}} / U_n = 7080 / 220 = 32.14 \text{ A} \]  \hspace{1cm} (5)

Power losses in the line at rated voltage:

\[ \Delta P_1 = I_1^2 \cdot R = 32.17^2 \cdot 0.46 = 476.9 \text{ W} \]  \hspace{1cm} (6)
Annual loss of electricity in the line at rated voltage:
\[ \Delta E_1 = \Delta P_1 \cdot T = 476.9 \cdot 10^{-3} \cdot 8760 = 4178.1 \text{ kW·hour} \]  
(7)

Rated current when voltage drops to 180 V:
\[ I_2 = \sum S_{\text{eq}} / U_{\text{dec}} = 7080/180 = 39.3 \text{ A} \]  
(8)

Power losses in the line with voltage drop:
\[ \Delta P_2 = I_2^2 \cdot R = 39.3^2 \cdot 0.46 = 710.5 \text{ W} \]  
(9)

Annual loss of electricity in the line when voltage drops:
\[ \Delta E_2 = \Delta P_2 \cdot T = 710.5 \cdot 10^{-3} \cdot 8760 = 6223.7 \text{ kW·hour} \]  
(10)

The difference in power losses:
\[ \Delta E_{\text{diff}} = \Delta E_2 - \Delta E_1 = 6223.7 - 4178.1 = 2045.6 \text{ kW·hour} \]  
(11)

From TP № GKTP-35 \( S_p=250 \text{ kVA}, U_n=10/0.4 \text{ kV} \), the Baysun district power supply enterprise receives electricity \( n=103 \) (Fig.1) from consumers from the population, then the difference in annual losses for all energy consumers:
\[ \Delta E_{\text{z}} = \Delta E_{\text{diff}} \cdot n = 2045.6 \cdot 103 = 210696.8 \text{ kW·hour} \]  
(12)

Electricity losses in monetary units for all consumers of TP № GKTP-35, Baysun district power supply enterprise:
\[ C = \Delta E_{\text{z}} \cdot \beta = 210696.8 \cdot 295 = 62155556 \text{ sum ($5814.65)} \]  
(13)

here, \( \beta=295 \text{ sum/kW·hour} - \text{electricity tariff for consumers – population.} \)

**Figure 1.** Single-line power supply diagram for household power consumption with a voltage of 0.4 kV.

According to figure 1, legend, where GKTP - main complete transformer substation; 1, 2, 3, 4, 5, … - numbering sign for supports; 2xA-25, 3xA-35, 4xA-35, 5xA-35 - wire cross-section; \( \Phi-1 \) - cell number (feeder); TP - transformer substation.

**4. Conclusions**

Based on the analysis of the developed voltage stabilizer using a non-contact voltage relay, made using a low-power transformer and optoelectronic elements, device circuits are proposed for contactless switching on and off of the booster transformer winding.
Experimental studies of the developed AC voltage stabilizer based on a contactless voltage relay have shown that the stabilizer operates with the required accuracy and provides a stable voltage at the output within ±5% of $U_n$.

A methodology and a computer calculation program for designing a booster transformer voltage stabilizer using a contactless voltage relay has been developed. The test results of the manufactured sample of the booster transformer voltage stabilizer based on the calculation results showed that the proposed technique is sufficiently accurate and acceptable for practical use.

Thus, the damage from reducing the voltage to 180 V for the example of TP № GKTP-35 ($S_n=250$ kVA, $U_n=10/0.4$ kV), the enterprise of the Baysun district power supply of the Baysun district of the Surkhandarya region is 62.16 million sum ($5814.65$).

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