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Modeling of asynchronous motor operation modes for the correct selection of voltage regulation devices

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Abstract. Many electrical appliances are used in production and in everyday life, 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. There are a number of technical solutions to solve this problem, one of which is the using of voltage control devices such as boost transformers. The principle of operation of booster transformers is the introduction of a longitudinal EMF into the electric circuit, which provides booster. The choice of voltage regulation devices consists in determining its power and the required transformation ratio. The latter needs some justification, because it cannot be formally accepted: if it is necessary to increase the voltage, for example by 5%, it is enough to introduce a longitudinal EMF of 5% of the nominal voltage into the electric circuit. This is due to the fact that with increasing voltage from the load side, the power consumption also increases, which causes an increase in voltage drop compared to modes in the absence of voltage regulation devices. Thus, the load will receive a slightly lower voltage level in comparison with the desired one.

1 Introduction

It is extremely difficult to maintain the voltage at the consumer unchanged and equal to the nominal. The characteristics of individual electrical receivers set the limits for voltage deviations.

Slow changes in power supply voltage (typically longer than 1 minute) are usually due to changes in electrical load.

Electric power quality indicators related to slow changes in the supply voltage are negative $\delta U_{(-)}$ and positive $\delta U_{(+)}$ deviations of the supply voltage at the point of transmission of electrical energy from the nominal value, %:

$$\delta U_{(-)} = \left[\frac{\left(U_0 - U_{m(-)}\right)}{U_0}\right]*100,\% ,$$

$$\delta U_{(+)} = \left[\frac{\left(U_{m(+)} - U_0\right)}{U_0}\right]*100,\% ,$$

where $U_{m(-)}$, $U_{m(+)}$ are the values of the power supply voltage, lower than U_0 and larger U_0, respectively, averaged over a time interval of 10 minutes in accordance with the requirements of State Standard 33073-2014 “Electric energy. Electromagnetic compatibility of technical equipment. Control and monitoring of electric power quality in the public power supply systems”[8].

U_0 - voltage equal to standard rated voltage U_n or matched voltage U_c.

The standard rated voltage U_n is 220V in low voltage electrical networks (between phase and neutral conductors for single-phase and four-wire three-phase systems) and 380V (between phase conductors for three- and four-wire three-phase systems). The following standards are established for the above-mentioned indicators of electric power quality: positive and negative voltage deviations at the electric energy transmission point must not exceed 10% of the nominal or agreed voltage value during 100% of the time interval of one week.

Permissible values of positive and negative voltage deviations at the points of common connection should be established by the network organization, taking into account the need to comply with the norms of this standard at the points of transmission of electrical energy.

Conditions must be provided in the consumer's electrical network under which the deviations of the supply voltage at the terminals of the electrical receivers do not exceed the permissible values established for them when meeting the requirements of this standard for the quality of electricity at the point of transmission of electrical energy.

Induction regulators, adjustable autotransformers, voltage boosting transformers and linear regulators can be classified as booster devices [20]. Such devices act on the resulting voltage at the consumer or receiver by creating additional EMF, the vector of which is superimposed on the main voltage according to, counter or at some angle, as is the case in some schemes of

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booster transformers that perform “transverse” regulation.

A booster transformer is a device that serves to regulate voltage and consists of two independent units, a “series” transformer, the primary winding of which is connected in series to the line cut, and a special control transformer or autotransformer. Booster transformer is mainly used for local voltage regulation. The voltage in the regulated line differs from the voltage of the mains by the amount of additional EMF serial transformer.

Typically, voltage regulation is carried out in steps; its smoothness depends on the number of control branches of the supply transformer. Booster transformer allows you to get additional EMF phase-shifted relative to the main voltage. The shear angle depends on the switching circuit of the control transformer and for the simplest schemes is 0°, 30°, 60° and 90°.

Transformers creating an additional voltage that coincides in phase with the main voltage are called boost voltage transformers with "longitudinal" regulation, and creating additional voltage, shifted by a certain angle, with "transverse" regulation.

The booster transformer is usually characterized by “throughput power”, i.e. power transmitted over the line into which the serial winding is included, and “own power" - the make-up device itself.

The operating mode of the power source, circuit resistance. Voltage deviations are not always in the range of acceptable values.

Voltage regulation is the process of changing the voltage level in a characteristic accurate electrical system using special technical means. The historical development of methods and methods for regulating voltage and reactive power occurs from the lowest hierarchical levels of energy system control to the highest. In particular, voltage regulation in the central power supply networks of distribution networks - at regional substations [1, 4, 5], where the transformation coefficients (k_T) change - is supported by the voltage of consumers when changing their operating mode.

A large number of induction motors are used in agriculture and industrial enterprises. The change in the consumed active and reactive power when choosing voltage control devices has not been considered by anyone [7].

A mechanism with a “ventilatory” mechanical transmission was investigate in the work. The mechanism in which the coefficient of proportionality of speed and generalization of the results were used.

Consider the circuit diagram, figure 1. As a load, we consider three asynchronous motors with a capacity of 15 kW, 37 kW, 110 kW with a rated voltage U_n = 380V.

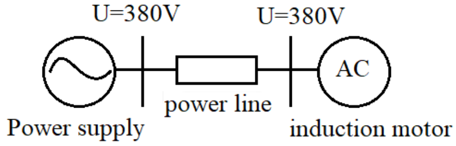

Fig. 1. Schematic diagram of connecting an induction motor.

The effect of voltage boosting depends on the ratio between the resistances of the power supply line and the load and generally acts to reduce the resulting voltage [2, 3].

2 Modeling induction motor

We model the circuit diagram in the MATLAB/ Simulink environment to plot the dependences of the power consumption on the voltage level, taking into account the different operating conditions of the induction motor [4-6].

The moment of resistance of an induction motor is represented by the formula:

$$M_c = M_{TP} + \left(k_{el} * M_{nom} - M_{TP}\right) * (\omega / \omega_{synch})^{\gamma}, \quad (1)$$

where M_{TP} is the initial moment at s = 1 or ω = 0, usually determined by friction forces; k_{el} is the engine load factor at synchronous angular velocity (the moment of resistance of the mechanism at ω = 1, expressed in fractions of the nominal moment of the engine); γ is an exponent characterizing this mechanism [9, 10].

The engine operation model for γ = 2 is shown in figure 2, for γ = 5 it is shown in figure 3. To determine the dependence of power consumption on engine load factor k_{el} which varies from 30% to 70%, and the initial moment of M_{TP} which varies from 10% to 50%.

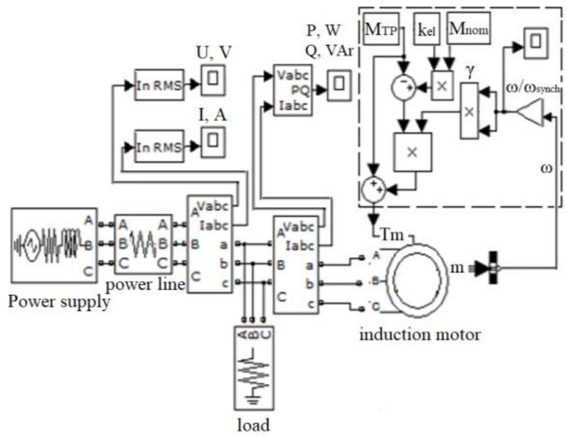

Fig. 2. Engine operation diagram for γ = 2, k_{el} = 30-70%, M_{TP} = 10-50%.

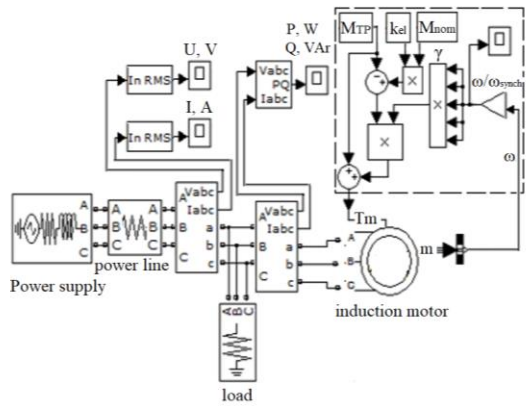

Fig. 3. Engine operation diagram for γ = 5, k_{el} = 30-70%, M_{TP} = 10-50%.

A 3-Phase Source block (designed to simulate a three-phase voltage source) is used as a power center, which includes three voltage sources connected to a star with a neutral wire [13-16]. The Three-Phase Series RLC Branch block was used as the power line because the inductive resistance of the line is neglected in the 0.4 kW network due to the small length [17-19]. The block in our case models a three-phase circuit consisting of three active resistances. An asynchronous motor is represented by the Asynchronous Machine block simulating an asynchronous electric machine in a motor mode [11,12]. The operation mode is determined by the law of the electromagnetic moment of the machine. The block contains several preset models of the induction motor. As an asynchronous motor we use an asynchronous motor with a power of 15 kW, 37 kW, 110 kW and a rated voltage of 380V and a frequency of 50 Hz specified by the MATLAB / Simulink program. The Tm port is designed to provide a moment of resistance to movement. The moment of resistance to movement is given by formula (1).

Define the synchronous angular velocity:

$$\omega_{synch} = \eta * \frac{2*\pi}{60},$$

where η is rotational speed of an induction motor.

Define the rated torque at a synchronous speed for the considered induction motors:

$$M_{nom.s} = \frac{P_m}{\omega_{synch}}$$

where P_m is the rated engine power indicated in the engine model of the MATLAB/Simulink program.

For an induction motor with a rated power of P_M = 15kW: η = 1460 rpm, $M_{nom.s}$ = 95.49 N*m, for an induction motor of P_M = 37kW: η = 1480 rpm, $M_{nom.s}$ = 235.56 N*m, for an induction motor P_m = 110kW: η = 1487 rpm, $M_{nom.s}$ = 700.28 N*m.

The load factor for active and reactive power is determined by:

$$k_l = \frac{P_{mw}}{P_n},$$

where P_{mw} is the active power consumed by an induction motor at various levels of operating voltage, U_w, which is calculated relative to the nominal (0.7-1.1*U_n) with the condition that k_{el} = 30-70% and M_{TP} = 10-50%; P_n is the rated active power of the engine.

The dependence of k_l on the supply voltage for two variants of mechanisms is presented in figures 4 and 5.

Figures 4 and 5 show that engines of different power, initially equally loaded, have approximate dependencies that slightly depend on the voltage level, this suggests that for them it is possible to take the load factor the same within a few percent of the error.

Also from figures 4 and 5 it can be seen that the M_{TP} value has little effect on the load factor, which makes it possible to group the motors in one equivalent exactly by the value of this coefficient.

Determine the resistance at rated voltage by the formula:

$$r_{nb} = \frac{U_n^2}{P'_{mk}}$$

where U_n is the rated voltage, P'_{mk} is the consumed active power at the rated voltage U_n and under various conditions of change M_{TP} = 10-50%, k_{el} = 30-70%.

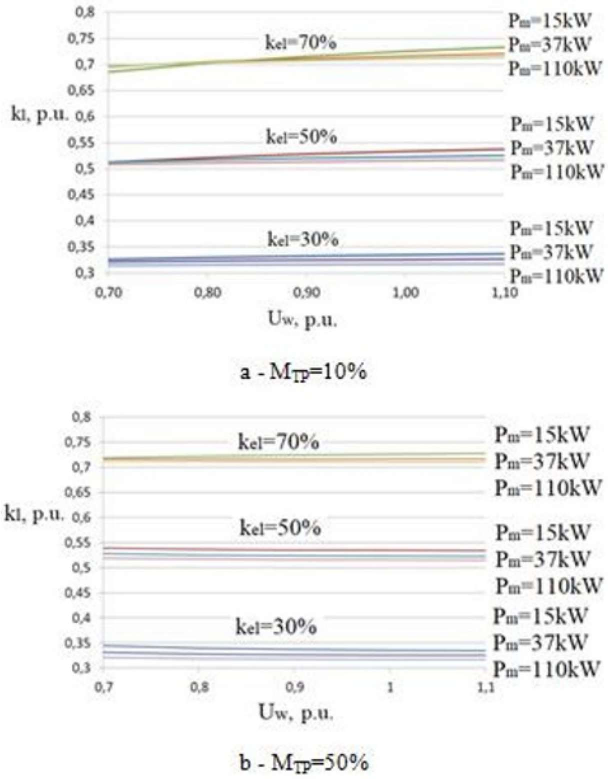

Fig. 4. The dependence of the load factor of the active power on the mains voltage for an induction motor γ=2.

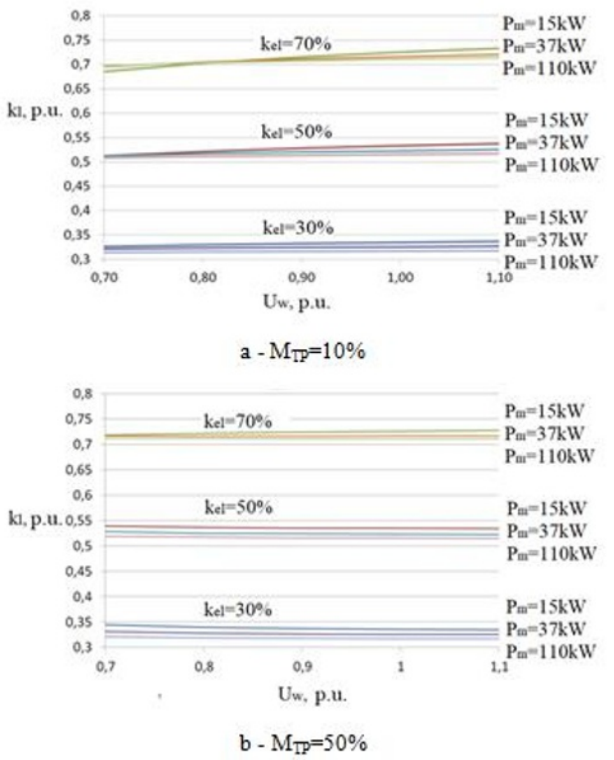

Fig. 5. The dependence of the load factor of the active power on the mains voltage for an induction motor γ = 5.

We determine the active resistance under the condition U_w= 0.7-1.1*U_n by the formula:

$$r_w = \frac{U_w^2}{P_{mw}}$$

Figure 6 shows a graph of resistance changes versus voltage level. From which (figure 6) it is seen that the active resistance at various values of M_{TP} = 10-50%, k_{el} = 30-70% and engine power varies according to one law and is within 5% of the error, and varies significantly from the voltage level. The actual resistance value can be determined by the formula:

$$r_w = \frac{r_{U_w}}{r'_{U_w}} * r'_w , \quad (2)$$

$$x_w = \frac{x_{U_w}}{x'_{U_w}} * x'_w , \quad (3)$$

where r'_{U_w}, x'_{U_w} are the load resistance at U_p, expressed in p.u. .; r_{U_w}, x_{U_w} - load resistance at U_P, expressed in named units; r'_p, x'_p - load resistance at U_n, expressed in p.u.

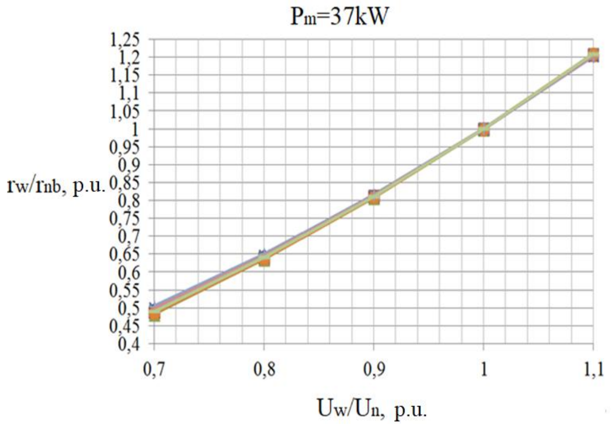

Fig. 6. Graph of changes in active resistance against voltage at M_{TP} = 10-50% and k_{el} = 30-70%.

It is necessary to determine tgϕ_n to determine the correction coefficient k_P. The tgϕ_n change diagram is shown in figures 7 and 8.

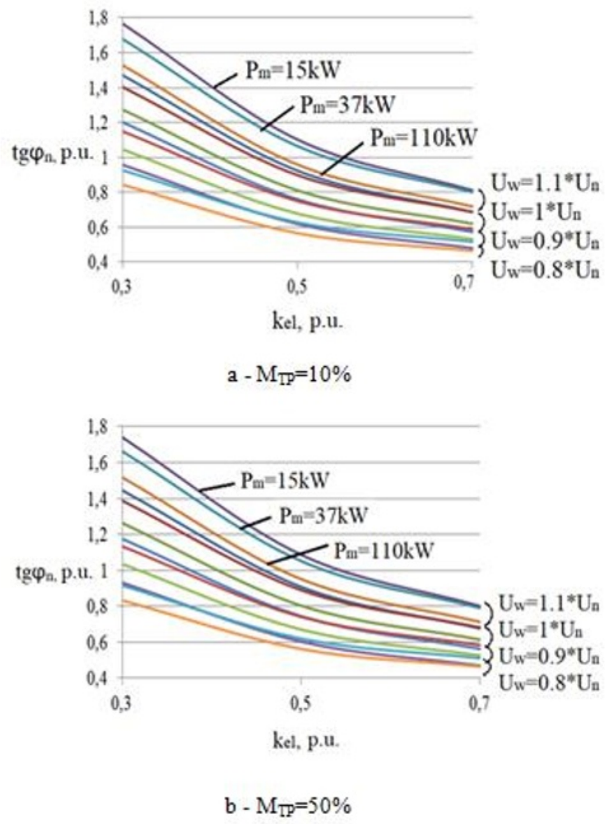

Fig. 7. . Change in tgϕn at different levels of U_P relative to k_{el} for different values of M_{TP} for an induction motor γ = 2.

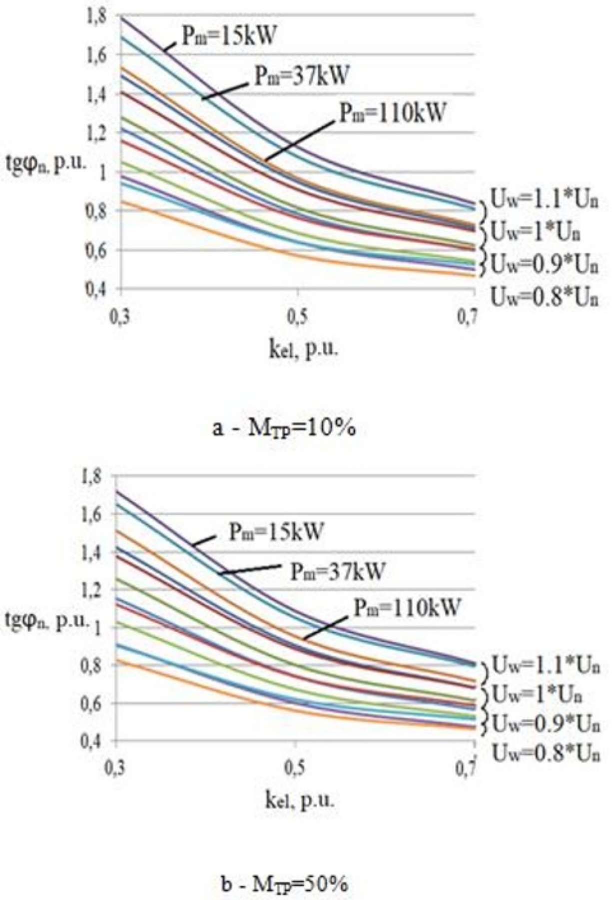

Fig. 8. Change in tgϕ_n at different levels of U_P relative to k_{el} for different values of M_{TP} for an induction motor $\gamma = 5$.

It can be seen from figures 7 and 8 that with increasing voltage, the value of tgϕ_n also increases.

The change in tgϕ_n obeys one law with the variation of k_{el}, M_{TP}. In order to generalize the obtained tgϕ_n values for various values of M_{TP}, we use the least squares method.

As a result, generalized characteristics are obtained that make it possible to determine tgϕ_n for engines of different powers, neglecting M_{TP}.

To determine k_w, all parameters are known, and k_w is determined by expression (4).

$$k_w = \left|\frac{r_{nb}*(1+jtg\phi_n)}{(r_{l0}+jx_{l0})*k_l*l+r_{nb}*(1+jtg\phi_n)}\right| = \left|\frac{(1+jtg\phi_n)}{(\alpha+j\beta)*k_{kl}+(1+jtg\phi_n)}\right|, \quad (4)$$

where $\alpha = r_{l0}/r_{nb}$; $\beta = x_{l0}/r_{nb}$, $k_{kl} = k_l * l$.

From formula (4) it can be seen that the ratio between the network and load resistances affects the magnitude of the voltage boost.

In real conditions, to determine k_{el}, tgϕ_n, r_{nb}, you can use clamp meters with the function of measuring power.

3 The choice of voltage regulation device

The problem of choosing the transformation coefficient (k_T) of voltage regulation devices is to correctly take into account the value of the consumer load power, which changes with voltage [9,10,19].

Let's consider two options:

1. When the voltage of the consumer changes, they remain constant (r_n, x_n = const);

2. When the voltage changes, the consumer resistance changes.

Figure 9 shows a diagram based on the calculation results for tgϕ = 0.4

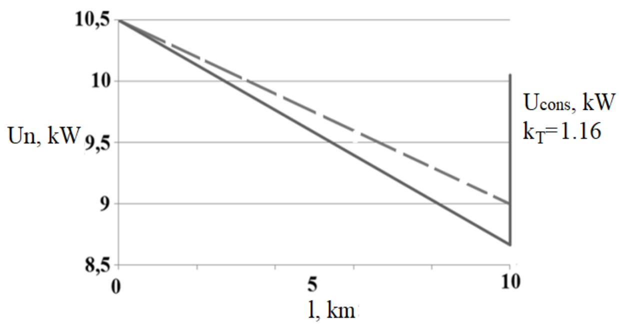

Fig. 9. The change in voltage (r_n, x_n = const).

In figure 9, the voltage drop for the initial values of the load power, provided that the consumer load is constant, k_T, = 1.1, is shown by a dashed line, and the voltage drop with a constant resistance (r_n, x_n = const) is shown by a solid line.

Figure 9 shows that when the voltage on the consumer increases with a constant load resistance of the consumer, the voltage drop increases: this indicates the need to increase k_T from 1.1 to 1.16. In this scheme, it will be necessary to install two nodes, two boost transformers.

Subject to voltage changes the consumer resistance changes. To determine the resistance under the condition U_{cons} = 10kV, we use the graph of the dependence of resistance on voltage in p.u., figure 6, for fan mechanisms with $\gamma = 5$ constructed using the MATLAB / Simulink simulation software.

As an example, consider the load represented by three asynchronous motors P = 110kW with k_l = 0.5, P = 37kW with k_l = 0.7, P = 37kW with k_l = 0.4, the length of the power line varies 10 km and is made by AS -16, figure 10.

We neglect the power loss and voltage drop in the power transformer.

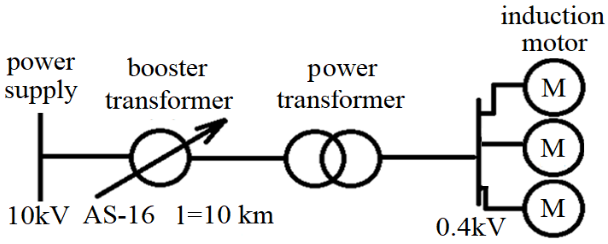

Fig. 10. Single line diagram.

To determine the resistance values at U_{cons} = 10kV, we use the formulas (2 and 3):

Having determined the resistance values using formulas (2-3), we calculate the power consumption at the beginning of the line at $U_{cons} = U_n$ = 10kV.

Based on the calculation results for tgϕ = 0.4, a diagram is constructed, figure 11.

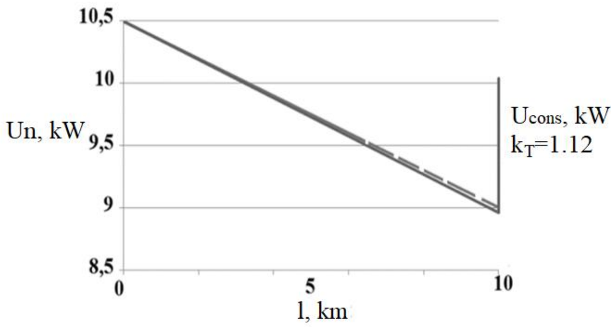

Fig. 11 Voltage change (r_n, x_n depends on U_{cons})..

From figure 11 it can be seen that to increase the voltage level to the nominal value, k_T should be equal to 1.12.

4 Conclusion

As can be seen from the results obtained, when choosing the coefficient of transformation of voltage regulation devices, the nature of the dependence of the load power on its voltage should be taken into account. So the transformation coefficient, calculated under the condition of constant power when the load voltage changes, will turn out to be somewhat underestimated, which does not provide the required voltage level in reality (since the magnitude of the load power changes with voltage change).

On the other hand, the calculation of the transformation coefficient of voltage regulating devices (resistance constant), when the supply voltage changes, will lead to the choice of an oversized transformation coefficient, this fact affects the number of boost transformers installed in one node (two or three), and the number of installed knots in a line.

The variant with which the load resistance depends on the voltage allows you to take into account the actual changes, which ensures the correct selection of the transformation coefficient.

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