

# Definition of Static Voltage Characteristics of the Motor Load for the Purpose of Increase in Energy Efficiency of Coal Mines of Kuzbass

*Fedor Nepsha*<sup>1\*</sup>, and *Vladimir Efremenko*<sup>1</sup>

<sup>1</sup> T.F. Gorbachev Kuzbass State Technical University, 650000, 28 Vesennaya St., Kemerovo, Russia

**Abstract.** The task of determining the static load characteristics is one of the most important tasks, the solution of which is necessary for the correct development of measures to increase the energy efficiency of the Kuzbass coal mines. At present, the influence of electric receivers on the level of consumption of active and reactive power is not taken into account, therefore, the proposed measures to increase the energy efficiency are not optimal. The article analyzes the L-shaped and T-shaped circuit for the replacement of an asynchronous motor (AM), according to the results of which it is determined that the T-shaped replacement scheme is the most accurate for determination of static load characteristics. The authors proposed and implemented in the MATLAB Simulink environment an algorithm for determining the static voltage characteristics of the motor load.

## 1 Introduction

Electric receivers of the coal mine differ in permissible voltage deviations, depending on the operating mode and their individual properties. The change in the power consumed by the electric receiver when the voltage is changed is usually characterized by a regulating effect. It's expressed as a percentage of the load change when the voltage is changed by 1%.

In the center of the shaft supply and load nodes there is a different combination of different electric receivers, differing in their static load characteristics, which determine the dependence of the power (energy) consumed by the receivers on the voltage, and accordingly the values of the regulating effect. The overall regulating effect of the load depends on the static characteristics of individual electric receivers, the share of each electric receiver, the configuration and parameters of the power supply system of the coal mine.

In the conditions of coal mines, this effect is primarily due to changes in losses in asynchronous electric motors and the power they develop, as well as losses in transformers and networks. To a lesser extent, it is determined by the change in lighting and electric heaters, as well as welding transformers.

It should be noted that the practical results in the thesis of Professor Konyukhova E.V. proves the need to take into account the static voltage load characteristics in the control of normal regimes. The proposed method for determining the rational voltage levels and the degree of reactive power compensation, taking into account the voltage reference voltage,

---

\* Corresponding author: [nepshafs@gmail.com](mailto:nepshafs@gmail.com)

was introduced at the enterprise “AMO ZIL”. As a result the active maximum load in the power supply system of the mechanical assembly shop was reduced by 18%.

In addition, the effectiveness of voltage regulation at mining enterprises to manage the level of electricity consumption is noted in the dissertations written under the supervision of Professor Abramovich B.N.

The research of individual and general static load characteristics on the voltage of electric receivers is relevant in the context of solving the problem of increasing the energy efficiency of the Kuzbass coal mines. Currently, all activities aimed at improving energy efficiency are developed without taking into account the specific features of the topology of power supply system, electric receivers to the level of consumption of active and reactive power. Also, to a proper extent, voltage regulation devices are not involved. Because of it the algorithms of their work do not have interrelations with each other.

The motor load on a coal mine has a significant share and is about 60-70% therefore, it is decisive in the development of measures for voltage regulation.

However, at present there are no studies in the field of determining the static voltage characteristics of the engines load used in the coal mines of Kuzbass. In connection with this, the development of a technique for determining the static characteristics of the motor load of a coal mine is an actual scientific and technical task.

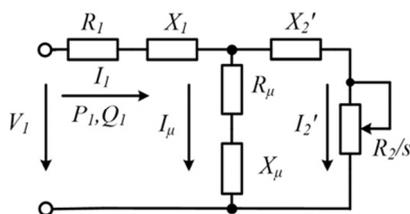
The voltage deviation at the AM clips affects the power consumption in a rather complicated way which is confirmed by literary sources and experimental data. These sources show that the consumption of reactive power varies unambiguously: as the voltage decreases, the reactive power consumption decreases. The consumption of active power is characterized by a more complex dependence. With a weak load of AM with a decrease in voltage, the consumption of active power decreases. With the increase in the load factor, the graph approaches a straight line, and as the nominal load is approached, the consumed active power remains practically unchanged.

Nevertheless, there is no generally accepted technique for determining the static characteristics for the motor load, and the question of the mathematical model that can be used for this purpose has not been resolved.

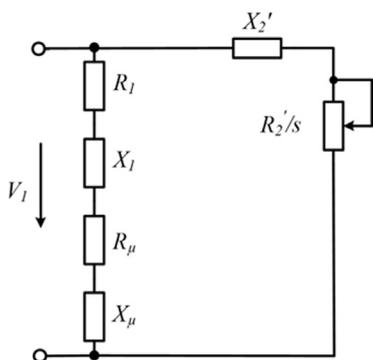
## **2 Materials and methods**

In practical calculations the L-shaped equivalent scheme is used to simplify the calculations (fig. 2). This simplification is made on the basis of an analysis of the relationship between the parameters of the T-shaped and the L-shaped equivalent scheme. In the transition from the T-shaped equivalent scheme to the L-shaped, the magnetization branch is transferred to the place of application of the supply voltage using the conversion coefficient. In this case, when the load changes, the magnetizing current does not change, therefore, in the nominal mode, the magnetizing current is overestimated. However, the most complete characteristics of AM can only be transmitted using a T-shaped circuit for replacing an asynchronous machine (fig. 1). In the article of Plankov A. A. it is noted that the transition to a simplified L-shaped equivalent scheme leads to an error of 3-5% in determining the rotor current strength. Comparison of the results of calculation of the parameters of AM and its characteristics with the use of three equivalent schemes (T-shaped, L-shaped and simplified L-shaped) shows that in the transition from the T-shaped scheme for replacing the AM to the L-shaped scheme in current calculations of AM there is an error of up to 5.8% and up to 7.6% when calculating the overflows of reactive power. In thesis of Professor Konyukhova E.V. the absence of data on resistance of a rotor and a magnetizing branch is resulted as the reason of application of the L-shaped equivalent scheme. Nevertheless, the formulas for calculating the parameters of the T-shaped replacement circuit presented in the literary sources allow us to determine the rotor and stator resistance from the catalog data. Data on the parameters of

the magnetizing branch can be obtained from the magnetization curve of the steel used to make the rotor or using the idling characteristic of the motor. Thus, when studying the static characteristics of the voltage of asynchronous motors it is advisable to consider the T-shaped equivalent scheme.



**Fig. 1.** T-shaped equivalent scheme for AM



**Fig. 2.** L-shaped equivalent scheme for AM

It is important to note that a sufficient amount of time has passed since the writing of the thesis of Professor Konyukhova E.V. and new software tools for modeling asynchronous motors have appeared. In particular the authors consider it necessary to single out MATLAB Simulink. In this software complex it is possible to sufficiently accurately simulate an asynchronous motor taking into account the magnetization curve.

The above analysis made it possible to compile an algorithm for determining the static characteristics of the motor load voltage using MATLAB Simulink (fig. 3). This algorithm allows to determine the static voltage characteristics for a number of asynchronous motors.

The algorithm for determining the static characteristics of the motor load voltage is as follows:

## 2.1 Input of initial data

The initial data for calculating the parameters of AM are the following:  $V_{nom}$  - the nominal line voltage [V];  $P$  - rated power [W];  $f_1$  - main frequency [Hz];  $p$  - number of pole pairs;  $n$  - rated speed [rpm];  $\eta$  - the coefficient of efficiency;  $\cos\varphi$  - power factor;  $I_{nom}$  - rated stator current [A];  $k_I$  - multiplicity of the starting current [pu units];  $M_{st}$  - the multiplicity of the starting torque;  $M_{max}$  - the multiplicity of the maximum moment;  $J$  - the moment of inertia [ $\text{kg} \cdot \text{m}^2$ ].

Initial data of the moment of resistance of the mechanism:  $M_{fr}$  - initial moment of friction ( $s = 1$ ) [N · m],  $\beta$  - load factor of AM;  $\alpha$  - an exponent that determines the nature of the load on the shaft.

In the presence of initial data within the program, saturation of AM steel can be taken into account. The parameters of the magnetization curve of the AM are entered in the parameter block of the AM parameters "[i; v] (pu)" in the MATLAB Simulink environment. The magnetization curves  $V = f(I_\mu)$  are determined from the current-voltage characteristic of the motor or reference data.

## 2. 2 Calculation of the parameters of AM equivalent scheme

The process of determining the exact value of the calculated coefficient C is realized by solving the following equation:

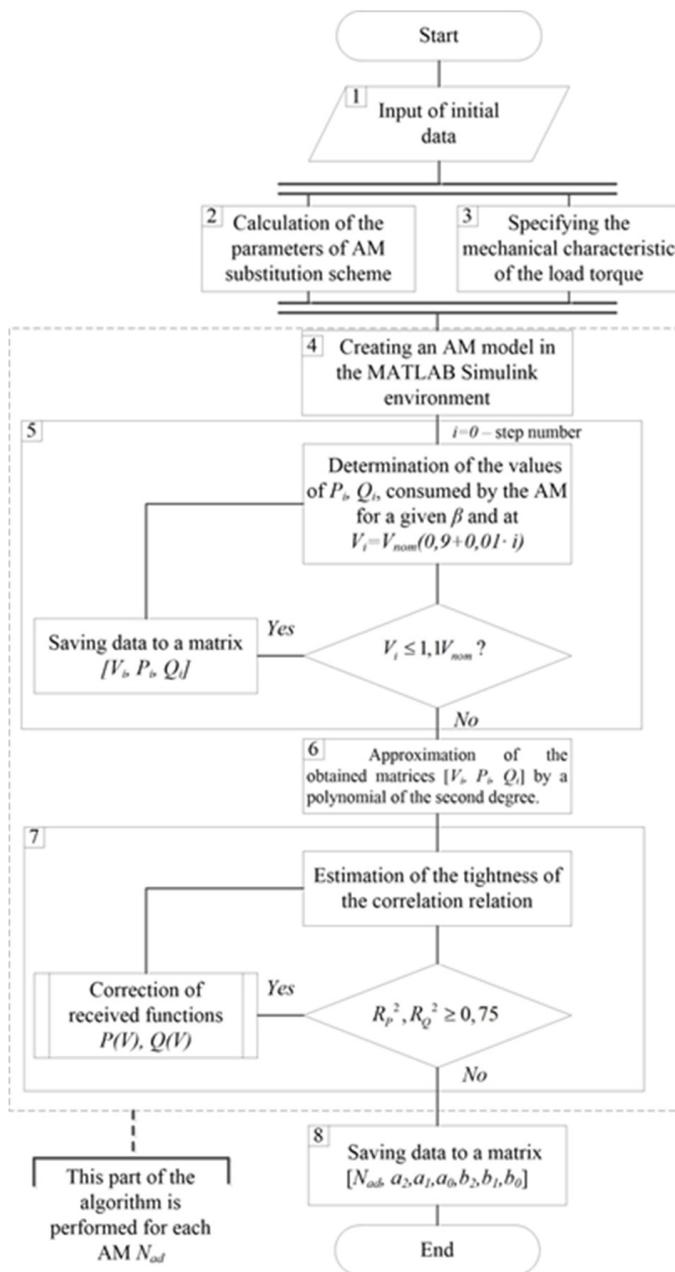
$$0 = 1 + \frac{\sqrt{\left[ \left( \frac{V_{nom}}{\sqrt{3}} \right) / (k_I \cdot I_{nom}) \right]^2 - \left( \frac{1}{2} \frac{V_{nom}^2 \cdot (1 - s_{nom})}{C(1 + C/s_k) m_{max} (P_{nom} + \Delta P_{mec})} + R_r \right)^2}}{4pf_1} - C, \quad (1)$$

$$L_s - \frac{\sqrt{\left[ \left( \frac{V_{nom}}{\sqrt{3}} \right) / (k_I \cdot I_{nom}) \right]^2 - \left( \frac{1}{2} \frac{V_{nom}^2 \cdot (1 - s_{nom})}{C(1 + C/s_k) m_{max} (P_{nom} + \Delta P_{mec})} + R_r \right)^2}}{4pf_1}$$

where  $s_k$  - critical slip;  $\Delta P_{mec}$  - mechanical losses [W];  $R_r$  - rotor resistance [Ohm];  $L_s$  - stator inductance [H].

The equation is solved using the fzero command built into MATLAB to find the zeros of a function of one variable.

At the end of the calculation, the parameters of the equivalent scheme for each engine under investigation are displayed in the form of a matrix in the working environment of the program.



**Fig.3.** Algorithm for determining the parameters of static voltage characteristics for the motor load voltage using MATLAB Simulink

### 2.3 Specifying the mechanical characteristic of the load torque

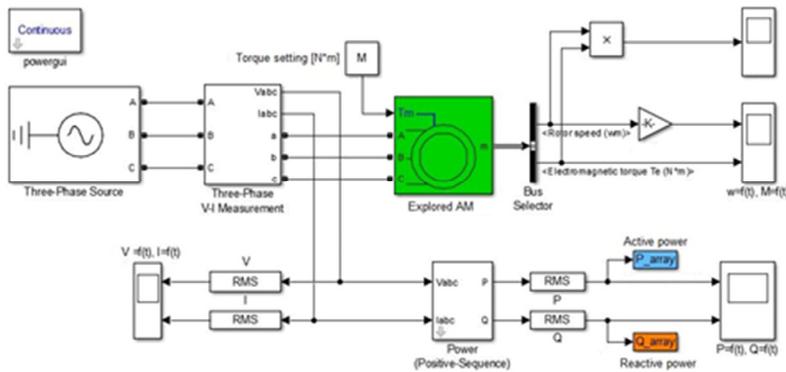
The mechanical characteristic of the moment of load resistance is given by the formula:

$$M_{st} = \beta M_{nom} \left( M_{fr} + (1 - M_{fr}) \cdot \left( \frac{1-s}{1-s_{nom}} \right)^\alpha \right), \quad (2)$$

The exponent  $\alpha$  which takes into account the change in the speed of rotation of the engine is determined by the type of mechanism.

## 2.4 Creating An AM Model In The MATLAB Simulink Environment

The AM model is created using the MATLAB Simulink toolkit. The parameters defined in items 2-3 are entered in the model parameters. The appearance of the model is shown in Fig.4.



**Fig. 4.** Model for determining the parameters of static voltage characteristics of motor load

The model can be adjusted depending on the type of motor and the mode of operation of the neutral of the simulated network.

## 2.5 Determination of the values of active and reactive powers consumed by AM at a different voltage level.

For each engine under investigation, the electric regime is calculated until the steady state is established. The calculation is performed for a voltage range of  $0.9-1.1V_{nom}$  (the calculation is performed 20 times with a resolution of  $0.01V_{nom}$ ). The upper and lower limits of the simulation are determined by the permissible voltage level deviations at the motor terminals determined by GOST 52776-2007. The obtained data on the change in the consumption of active and reactive power (blocks  $P\_array$ ,  $Q\_array$ ) are stored in the MATLAB working environment. Also the matrices  $[V_i, P_i, Q_i]$  are formed for each simulated AM.

## 2.6 Approximation of the obtained matrices $[V_i, P_i, Q_i]$ by a polynomial of the second degree.

Approximation of the obtained dependencies is performed using the polyfit function built into MATLAB. As a result for each AM a second-degree polynomial is formed in the form:

$$P(V) = P_{nom} P_*(V) = P_{nom} \left[ a_0 + a_1 \cdot \left( \frac{V}{V_{nom}} \right) + a_2 \cdot \left( \frac{V}{V_{nom}} \right)^2 \right], \quad (3)$$

$$Q(U) = Q_{nom} Q_s(U) = Q_{nom} \left[ b_0 + b_1 \cdot \left( \frac{V}{V_{nom}} \right) + b_2 \cdot \left( \frac{V}{V_{nom}} \right)^2 \right], \quad (4)$$

Where  $P_{nom}$  and  $Q_{nom}$  are the active and reactive power of the AM at the nominal voltage;  $P^*(V)$  and  $Q^*(V)$  are the static voltage characteristics of AM in relative units;  $V_{nom}$  - the nominal voltage of the AM or network;  $a_0, a_1, a_2, b_0, b_1, b_2$  are the coefficients of the polynomial of degree 2.

## 2.7 Estimation of the tightness of the correlation relation

To estimate the reliability of the obtained polynomials of the second degree (3,4), the determination of the determination coefficient is carried out:

$$R_p^2 = 1 - \frac{\sum_{i=1}^{20} (P_i - P_{scli})}{\sum_{i=1}^{20} (P_i - \bar{P})}, \quad (5)$$

$$R_q^2 = 1 - \frac{\sum_{i=1}^{20} (Q_i - Q_{scli})}{\sum_{i=1}^{20} (Q_i - \bar{Q})}, \quad (6)$$

where  $P_i, Q_i$  are the active and reactive power values obtained as a result of simulation;  $P_{scli}, Q_{scli}$  - the values of active and reactive powers, obtained from (3,4),  $\bar{P}, \bar{Q}$  - average values of active and reactive power.

If  $R_p^2, R_q^2 \geq 0,75$  the obtained functions (3,4) have a strong correlation with the data obtained in the MATLAB Simulink. Otherwise, the received functions are corrected (3,4).

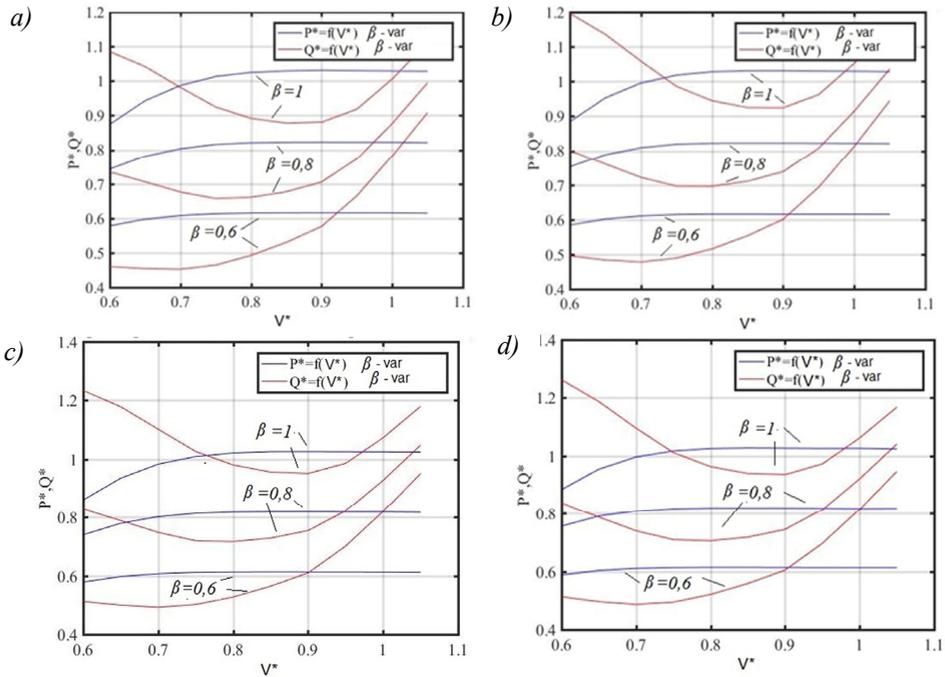
## 2.8 Obtaining the final values of the coefficient of the polynomial of the second degree.

The data is output in the form of a form matrix  $[N_{ad}, P_2, P_1, P_0, Q_2, Q_1, Q_0]$  ( $N_{ad}$  - the number of AM) and can be used to generate a database for setting the motor load when calculating the electrical regimes of a coal mine power supply systems or for the subsequent determination of the generalized static characteristics of mine loads.

## 3 Results and discussion

On the basis of the developed algorithm, the authors wrote a program in the MATLAB environment which allows automatic calculation of the static characteristics parameters for the voltage of asynchronous motors.

With the use of the program, the static characteristics of the voltage of the pumping station motors of different power for various load factors have been determined. The obtained static characteristics of the motor load are shown in fig. 5.



**Fig. 5.** Static voltage characteristics of the pump station motors: *a* - VAO2-280S4 (132 kW), *b* - VAO2-280L4 (200 kW), *c* - VAO2-315M4 (250 kW), *d* - VAO2-315L4 (315 kW).

The resulting static voltage characteristics of the motors were approximated. As a result the coefficients of the polynomial of the second degree are obtained which are given in the table.

**Table 1.** The obtained values of the coefficients of the polynomial of the second degree for the engines of the pump station of various powers

Brand AM	$P_{nom}$ , kW	$\beta$	Coefficients of a polynomial of degree 2					
			by active power			by reactive power		
			$a_2$	$a_1$	$a_0$	$b_2$	$b_1$	$b_0$
VAO2-280S4	132	0,6	-0,3783	0,6847	0,3089	3,5638	-4,9391	2,1541
		0,8	-0,7927	1,4423	0,1730	4,0222	-6,1293	2,9819
		1,0	-1,5265	2,7930	-0,2350	4,3627	-7,2569	3,8993
VAO2-280L4	200	0,6	-0,3123	0,5633	0,3645	3,8119	-5,3456	2,3436
		0,8	-0,7184	1,2980	0,2428	4,4146	-6,8276	3,3250
		1,0	-1,4689	2,6715	-0,1711	4,9666	-8,3894	4,4728
VAO2-315M4	250	0,6	-0,3577	0,6442	0,3265	3,8225	-5,3867	2,3813
		0,8	-0,7999	1,4509	0,1686	4,4239	-6,8826	3,3840
		1,0	-1,6213	2,9629	-0,3137	4,8723	-8,2884	4,4880
VAO2-315L4	315	0,6	-0,2652	0,4755	0,4030	3,9123	-5,5402	2,4401
		0,8	-0,6545	1,1785	0,2953	4,6627	-7,2989	3,5536
		1,0	-1,4536	2,6339	-0,1530	5,3910	-9,2094	4,8770

From the analysis of the obtained data it follows that the voltage change at the terminals of the pump station motors practically does not lead to a change in the consumed active power regardless of the load factor of the engine and its rated power. When the voltage level rises by 1%, the reactive power consumption increases by 2-4%, depending on the load factor of

the engine and its rated power. At the same time with a decrease in the rated power and the load factor of the engine, the efficiency of reducing the reactive power consumption increases.

The use of the developed algorithm is also possible to determine the static characteristics of the voltage of synchronous motors under the condition of replacing the model AM in the MATLAB Simulink model with the SM model.

## 4 Conclusions

When determining the static voltage characteristics of AM, it is necessary to use the T-shaped equivalent scheme which is much more accurate than the L-shaped equivalent scheme. Under these conditions to determine the static voltage characteristics, it is most expedient to use the AM models presented in the MATLAB Simulink library.

The proposed algorithm makes it possible to obtain reliable data on the static voltage characteristics of the motor load with respect to voltage taking into account the change in the voltage and the moment of resistance.

The data obtained can be used to optimize the operation mode of the coal mine power supply system by voltage according to the criterion of minimum consumption of active power as well as in the development of measures to increase the energy efficiency of power supply systems of coal mines.

## References

1. P. Krause, O. Wasynczuk, S. D. Sudhoff, Steven Pekarek, *Analysis of Electric Machinery and Drive Systems*, (IEEE Press, 2013)
2. C.D. Pitis, M.W. Zeller, EPEC, **1:3**, (2008)
3. H. Auinger, *Energy efficiency Improvements in Electric Motors and Drives*, 284 (Springer-Verlag, 1997)
4. *Simulink Design Optimization. User's Guide. User's Guide*, (The Math Works, Inc. New Hampshire, 2015)

