

# Issues on Optimizing the Structural Parameters of the Induction Converter

Marinka K. Baghdasaryan, Siranush M. Muradyan, Avgen A. Gasparyan

**Abstract**—Analytical expressions of the current and angular errors, as well as the frequency characteristics of an induction converter describing the relation with its structural parameters, the core and winding characteristics are obtained. Based on estimation of the dependences obtained, a mathematical problem of parametric optimization is formulated which can successfully be used for investigating and diagnosing an induction converter.

**Keywords**—Induction converters, magnetic circuit material, current and angular errors, frequency response, mathematical formulation, structural parameters.

## I. INTRODUCTION

THE minimum error and the mass, the minimum sizes, the cost, the maximum operation reliability, the simplest structure from the standpoint of the adaptability to manufacture, the high maintenance qualities are the main requirements set to the induction converters [1].

It is obvious that no converter can simultaneously meet all the requirements mentioned above at the same time.

The induction converter quality mainly depends on the following factors [2]-[4]:

- an error conditioned by the dependence of the magnetizing field operating at the given moment not only on the existing, but also on the previous states of the magnetic circuit material [5];
- the current and angular errors;
- the frequency response of the induction converter;
- the converter mass.

Taking into consideration the factors mentioned above, the problem of optimizing the induction converter comes to the determination of the optimal structural parameters of the converter providing the minimum conversion errors at minimum mass and sizes.

Investigations of the known methods for the induction converter optimization mainly do not take into account the specific properties of the magnetic system of the converter. That is why; optimizing the structural parameters of the induction converter satisfying a number of optimization criteria simultaneously is an important problem [1], [6].

Marinka K. Baghdasaryan, Siranush M. Muradyan, and Avgen A. Gasparyan are with the Department of Electrical Engineering, Chair of Electrical Machines and Apparatuses, State Engineering University of Armenia (Polytechnic), Yerevan (phone: +374 9386 5022; e-mail: m.baghdasaryan@seua.am, bmarinka@yandex.ru).

## Statement of the Problem

The goal of the work is the theoretical and experimental investigation of the induction converter characteristics and the formulation of the optimization problem taking into account the structural parameters of the converter.

## II. INVESTIGATING THE MAIN CHARACTERISTICS OF THE CONVERTER AND SELECTING THE QUALITY CRITERIA

As the quality of the induction converter depends on the conversion error, a need for a comprehensive investigation of the change character of that error arises depending on the structural parameters. For that purpose, analytical dependences of the current and angular errors and the frequency response are obtained by us describing the relation with its structural parameters, and taking into account the non-uniform distribution of magnetic induction along the average length of the magnetic circuit [7], as well as the presence of technological clearances.

The determination of the angular and current errors, the amplitude-frequency and the phase-frequency characteristics of the converter has been carried out according to the equivalent circuit diagram as shown in Fig. 1.

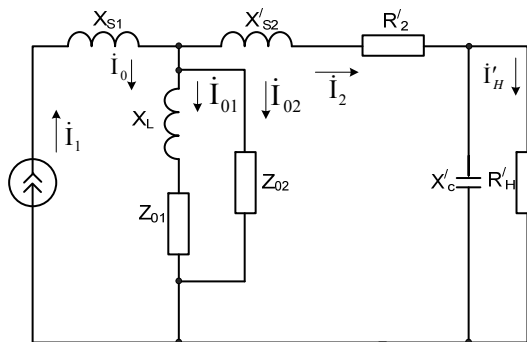


Fig. 1 Equivalent circuit diagram of the induction current

The current and angular errors of the converter describing the relation with its structural parameters, the core, the winding, and loading characteristics are as follows:

$$\delta_a = \frac{D_2 D_3 - D_1 D_4}{D_3^2 + D_4^2} 100 \text{ crad}, \quad \delta_l = \frac{D_1 D_3 - D_2 D_4}{D_3^2 + D_4^2} 100\%,$$

where

$$D_1 = -I_1 R'_2 T_2 \rho_{x2} - I_1 R'_2 T_1 \rho_{x1} + \omega^2 L L_S T_1 - U'_H T_1 \rho_{x1} + \\ + \omega L_S I_1 T_1 \rho_{R1} + \omega L_S I_1 T_2 (\rho_{R2} + \ell_3 / \ell_4) - U'_H T_2 \rho_{x2},$$

$$\begin{aligned}
D_2 &= \omega L I_1 R_2' - I_1 R_2' T_2 (\rho_{R2} + \ell_3 / \ell_4) - U_H' T_1 \rho_{R1} \\
&- I_1 R_2' T_1 \rho_{R1} - \omega L U_H' - \omega L_S' I_1 T_2 \rho_{x2} - \omega L_S' I_1 T_1 \rho_{x1} - \\
&- U_H' T_2 (\rho_{R2} + \ell_3 / \ell_4), \\
D_3 &= I_1 \left( \frac{T_1 T_2 \rho_{x1} \rho_{x2} + R_2' T_1 \rho_{x1} + R_2' T_2 \rho_{x2} - \omega^2 L L_S' -}{(\rho_{R2} + \ell_3 / \ell_4) (T_1 T_2 \rho_{R1} + \omega L T_2 + \omega L_S' T_2) -} \right), \\
D_4 &= I_1 \left( \frac{T_1 T_2 \rho_{R1} \rho_{x2} + \omega L T_2 \rho_{x2} + \omega L R_2' - R_2' T_1 \rho_{R1} -}{- \omega L_S' T_1 \rho_{x1} + (\rho_{R2} + \ell_3 / \ell_4) (T_1 T_2 \rho_{x1} + R_2' T_2) +} \right), \\
T_1 &= \frac{2\omega S}{\ell_w (\rho_{R1}^2 + \rho_{x1}^2)}, \\
T_2 &= \frac{2\omega S}{(\ell/2 - \ell_w) ((\rho_{R2} + \ell_3 / \ell_4)^2 + \rho_{x2}^2)}, \\
\ell_4 &= \mu_o (\ell/2 - \ell_w).
\end{aligned}$$

The following notations are used in the formulae:  $I_1$  - the current of primary winding,  $U_H'$  - the introduced loading voltage,  $R_2'$  - the introduced active resistance of scattering,  $L$  - the winding inductance,  $L_S'$  - the leakage inductance,  $\rho_{R1}, \rho_{x1}$  - the active and reactive specific resistances respectively on the parts of the magnetic circuit under windings,  $\rho_{R2}, \rho_{x2}$  - the active and reactive specific resistances on the parts of the magnetic circuit free from windings,  $\ell_3$  - the clearance length,  $\ell_w$  - the winding length,  $\ell$  - the average length of the magnetic circuit.

The importance of investigating the frequency response for an induction converter is conditioned by the fact that the converter consists of complex resistances ( $L, L_S', C_2'$ ), and its resonance frequency is

$$f_r = 1 / 2\pi \sqrt{C_2' L}.$$

To select adequate parameters of the converter providing its normal operation in a certain range of frequencies, it is necessary to investigate the frequency characteristics.

In the same way, based on Fig. 1 analytical dependences for amplitude-frequency  $\delta_f$ , and phase-frequency  $\varphi(\omega)$  characteristics are obtained:

$$\begin{aligned}
\delta_f &= \frac{1}{D_3^2 + D_4^2} \sqrt{(D_3^2 + D_4^2 - D_3 D_5 - D_4 D_6)^2 + (D_4 D_5 - D_3 D_6)^2}, \\
\varphi(\omega) &= \arctg \frac{D_4 D_5 - D_3 D_6}{D_3 D_5 - D_4 D_6},
\end{aligned}$$

where

$$\begin{aligned}
D_5 &= -U_H' T_1 \rho_{x1} - U_H' T_2 \rho_{x2} + \omega^2 C_2' L U_H' T_2 \rho_{x2} + \omega^2 C_2' L R_2' U_H' + \\
&+ \omega C_2' U_H' T_1 T_2 \rho_{R1} \rho_{x2} + I_1 T_1 T_2 \rho_{x1} \rho_{x2} + (\rho_{R2} + \ell_3 / \ell_4) \omega C_2' R_2' T_2 + \\
&+ \omega^2 C_2' L_S' U_H' T_2 \rho_{x2} + \omega^2 C_2' L_S' U_H' T_1 \rho_{x1} + \omega C_2' R_2' U_H' T_1 \rho_{R1} + \\
&+ (\rho_{R2} + \ell_3 / \ell_4) (-\omega L I_1 T_2 - I_1 I_2 T_2 \rho_{R1} + \omega C_2' U_H' T_1 T_2 \rho_{x1}), \\
D_6 &= (\rho_{R2} + \ell_3 / \ell_4) (I_1 I_2 T_2 \rho_{x1} + \omega^2 C_2' L U_H' T_2 + \omega C_2' U_H' T_1 T_2 \rho_{R12} + \\
&+ U_H' T_2 + \omega^2 C_2' L_S' U_H' T) + \omega L I_1 T_2 \rho_{x2} + I_1 T_1 T_2 \rho_{R1} \rho_{x2} + \\
&+ \omega C_2' U_H' T_1 T_2 \rho_{x1} \rho_{x2} - \omega L U_H' - U_H' T_1 \rho_{R1} - \omega C_2' R_2' U_H' T_1 \rho_{x1} - \\
&- \omega C_2' R_2' U_H' T_2 \rho_{x2} + \omega^3 C_2' L_S' L U_H' + \omega^2 C_2' L_S' U_H' T_1 \rho_{R1}.
\end{aligned}$$

From the obtained expressions, it follows that the character of these values depends on the steel material of the magnetic circuit, its structural parameters, and the winding data of the induction converter, and each of these parameters has a different, often opposite influence.

Fig. 2 shows the character of change  $\delta_a, \delta_I$  depending on the magnetic circuit steel material properties, and the number of turns. It is obvious that the increase in the permeability of the magnetic circuit steel material leads to an increase in the absolute value of the current error, and a decrease in the angular error.

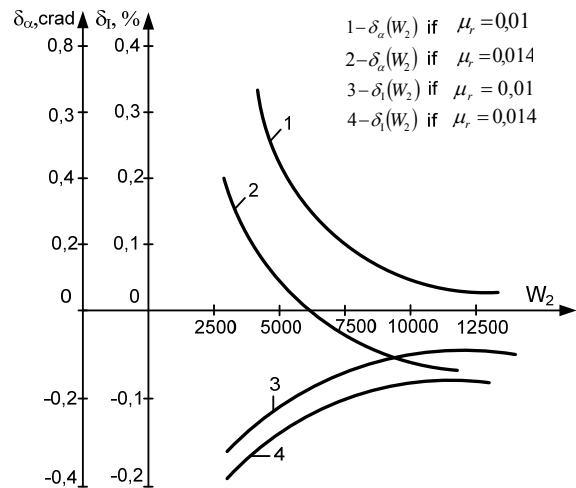


Fig. 2 Dependences of angular and current errors on the magnetic circuit steel material, and the number of the winding turns

The increase in the magnetic circuit steel material permeability at low frequencies leads to a decrease in the amplitude-frequency error and the phase shift, and at high frequencies - to their increase (Figs. 3, 4).

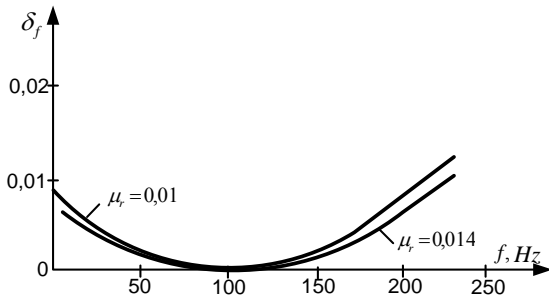


Fig. 3 Dependences of the amplitude-frequency response on the magnetic circuit steel material

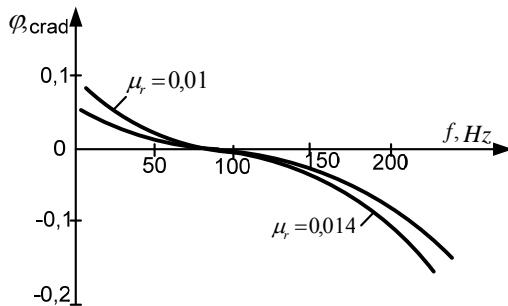


Fig. 4 Dependences of the phase-frequency characteristic on the magnetic circuit steel material

Fig. 5 shows that along with the magnetic circuit section, the absolute value of the current error decreases, whereas the value of the angular error first decreases up to certain dimensions of the magnetic circuit section, and later increases. At the same time, the magnetic circuit mass increases abruptly.

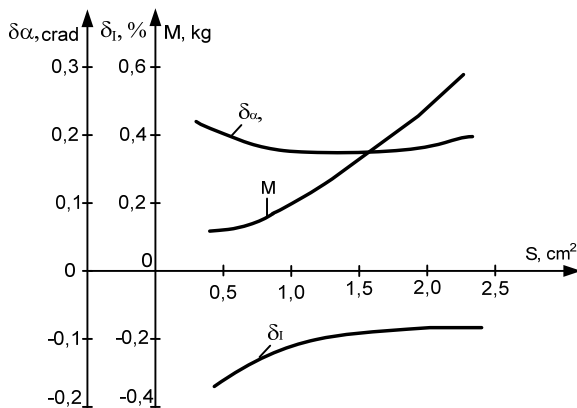


Fig. 5 Dependences of the angular and current errors and the converter mass on the magnetic circuit section

The investigation of the dependence  $\delta_\alpha$ ,  $\delta_I$ ,  $M$  on the diameter of the winding wire at other fixed parameters ( $\ell = \text{const}$ ,  $S = \text{const}$ ,  $\ell_w = \text{const}$ ) shows that along with the increase in the winding wire diameter, the angular error decreases regardless of the number of turns, however, the

absolute value of the current error at a small number of turns (up to 5000) decreases, and at a large number of turns, the increase in the diameter of the winding wire leads to the increase in the absolute value of the current error (Fig. 6). At the same time, the converter mass grows.

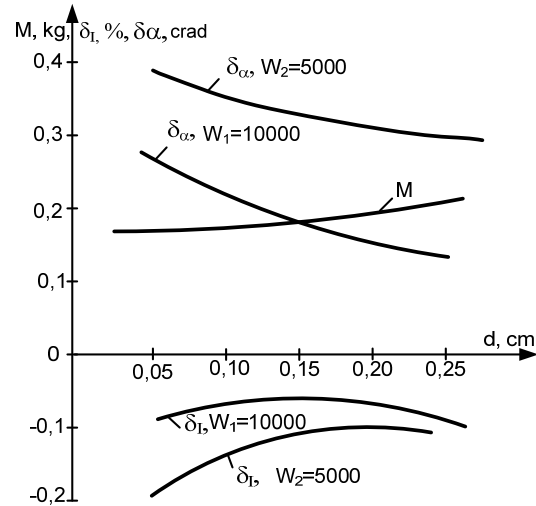


Fig. 6 Dependences of the angular and current errors and the converter mass on the winding wire diameter

The analysis of particular criteria of the angular, current, amplitude-frequency errors, phase-frequency characteristic, and the converter weight shows that they are interrelated and discrepant.

The interrelation and discrepancy of the mentioned particular criteria do not allow determining their minimum values in the optimization process simultaneously. It is also impossible to select the criteria of optimality which, to a great extent, characterize the properties of the converter, and which could be admitted as a quality criterion. Based on what is mentioned above, we propose the approach of generalized quality criteria.

### III. MATHEMATICAL FORMULATION OF THE PROBLEM OF OPTIMIZING THE STRUCTURAL PARAMETERS OF AN INDUCTION CONVERTER

To form the efficiency function, the optimality criteria largely characterizing the converter properties are selected. The efficiency function is formed from the angular and current errors. Particular criteria, such as the mass and the frequency characteristics are formulated in the form of restrictions.

Among the parameters of the converter whose values can be changed in the optimization process in a certain range, the most constructive ones are the winding length ( $\ell_w$ ), the number of the winding turns ( $W_2$ ), the diameter of the winding wire ( $d$ ), the average length of the magnetic circuit ( $\ell$ ), and the magnetic circuit section ( $S$ ).

Taking into consideration what is mentioned above; the mathematical recording of the optimization problem and the structural parameters of the induction converter takes the

form:

$$F(\bar{x}) = \alpha_1 \left( \frac{\delta_\alpha(\bar{x})}{\delta_{\alpha \min}} - 1 \right)^2 + \alpha_2 \left( \frac{\delta_f(\bar{x})}{\delta_{f \min}} - 1 \right)^2 \rightarrow \min$$

$$\left\{ \bar{x} \in R^5; M(\bar{x}) < M_d, \delta_f(\bar{x}) < \delta_{fd}, \varphi(\bar{x}) < \varphi_d, \right.$$

$$\left. x_j^- \leq x_j \leq x_j^+, j = 1, 2, \dots, 5 \right\},$$

where  $\bar{x} = [\ell_w, W_2, d, \ell, S]$ ;  $\alpha_1, \alpha_2$  are the weight coefficients,  $\alpha_1 + \alpha_2 = 1$ ;  $x_j^-, x_j^+$  – the lower and upper limiting values for the j-th structural parameter,  $\delta_{\alpha \min}, \delta_{f \min}$  – the minimum values  $\delta_\alpha$  и  $\delta_f$ ,  $M_d, \delta_{fd}, \varphi_d$  – the admissible mass, the admissible phase shift, and the amplitude-frequency error respectively.

#### IV. CONCLUSION

The obtained analytical dependences for the angular and current errors allow revealing their interrelation with the structural parameters, thus creating prerequisites for formulating the optimization problem.

The proposed algorithm of the converter structural parameter optimization can be used to investigate and design an induction converter.

The analytical relationships of the angular and current inaccuracy and the frequency response describing the link with its structural parameters are obtained in which the non-uniform distribution of magnetic induction along the average length of the magnetic circuit and the presence of technological gap are taken into account.

#### ACKNOWLEDGMENT

This work was supported by State Committee Science MES RA, in the frames of the research project № SCS 13Ap\_2b008

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**Marinka Baghdasaryan** was born in 1960 in Armenia. She has 25 years of experience in the sphere of modeling and developing electromechanical devices and systems. Dr. Sci. Prof., Head of the Chair "Electrical Machines and Apparatus" of State Engineering University of Armenia (SEUA). She is an author of 110 scientific works, among them 2 monographies and 11 patents. Her investigations are devoted to the modeling and design of measuring devices, control of electromechanical systems. Since 2008, she has headed the scientific – research laboratory of Electromechanics and Electrical Radiomaterials. Since 2011 she has been the Editor-in-chief of the SEUA Proceedings – Series "Electrical Engineering and Energetics".

**Siranush Muradyan** was born in 1983 in Armenia. She has 7 years of experience in the sphere of investigating electrotechnical devices. PhD, Assistant Lecturer of the Chair "Electrical Machines and Apparatus" of State Engineering University of Armenia (SEUA). She is an author of 10 scientific works, among them 1 patent.

**Avgen Gasparyan** was born in 1942 in Armenia. He has 45 years of experience in the sphere of developing different electromechanical devices and relays. He has been the Head Engineer of the plant "Electrical Apparatus" for many years. PhD, Associate Professor of the Chair "Electrical Machines and Apparatus" of State Engineering University of Armenia (SEUA). He is an author of 67 scientific works, among them 7 patents.