

**RIGA TECHNICAL UNIVERSITY**  
Faculty of Electrical and Power engineering  
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Doctorand of the doctorate programme "Electrical technology computer control"

**ASYNCHRONOUS ELECTRIC DRIVE WITH  
FRONTAL PART WINDING AND CURRENT  
INVERTER**

**Dissertation**

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## Actuality of theme

The application of the cage rotor induction motor in variable speed electric drive systems is obstructed by the most difficult starting transient process of the simplest motor from all kinds of electric engines. During this process there are appeared the big oscillations of starting current and motor torque. The improving of electromechanical transient process is possible by utilization of frequency converter with complicated control methods and by sophistication of induction motor stator construction only, therefore it is actual question to develop such asynchronous drive system, which allows to realize the cage rotor induction motor transient process control using the simplest converters possible and minimum changes of stator construction.

## Purpose of work

The work purpose is to develop the new induction drive system with transient process control feasibility with achieving that simultaneously the cage rotor asynchronous motor construction could not be significant complexed and it could be possible to use the frequency converter with simplest possible power circuit, control system and its operation principle.

To get the purpose of dissertation there are solved the following tasks:

- has been made and experimentally tested the cage rotor induction motor with stator winding frontal part extension winding;
- has been made the drive system with induction motor with frontal part winding and current source net inverter;
- had done the development of induction motor with frontal part winding drive system and its separate blocks substitution schemes and operating regimes factor analysis.

## Research methods

To achieve the goals of dissertation there are used the solving of differential equations, function optimization and physical modeling methods. For experiments have been used the technical base and labour equipment of The Institute of Industrial Electronics and Electrotechnic and Institute of Electrical Machines and Apparatus by Faculty of Electrical and Power engineering of Riga Technical University.

## Scientific contribution and main results

The dissertation scientific contribution is:

- development of the new construction of asynchronous motor with frontal part winding;
- establishment of the current source net inverter;
- done the development of the asynchronous motor with frontal part winding substitution scheme;
- made the structure of asynchronous motor with frontal part winding and current source net inverter;
- analysis of the current source net inverter valves operation regimes;
- made the optimization of induction motor with frontal part winding power losses by slip.

The main results of work are:

- improving of motor energetic parameters;
- is possible the transient process control at dynamic and static regimes.

## Application of work

The practical value of work is connected with

- developing of the induction motor with frontal part winding drive system;
- establishing of the analyse principles of current source net inverter operation regimes;
- developing optimization method of motor losses by slip.

The realized researches allow to construct the asynchronous drive system with extended functional features at transient processes. The asynchronous drive with frontal part winding system experimental device is tested at labour base of The Institute of Industrial Electronics and Electrotechnic by Faculty of Electrical and Power engineering of Riga Technical University.

### Aprobation of work

The approbation of dissertation research results of the author has been made by taking part in international scientific-technical conferences:

- Asinhronās mašīnas pieres daļas ekvivalenta induktivitāte// 43. RTU studentu zinātniskās un tehniskās konferences materiāli// Rīga, 2002.
- Асинхронный двигатель с удлинёнными лобовыми частями статорных обмоток в электроприводе// Проблемы автоматизированного электропривода. Теория и практика// Харьков. 2003.
- Asinhronā dzinēja ar frontālās daļas tinumu mehānisko raksturlīkņu eksperimentāla pētīšana.// 44. starptautiskā zinātniskā konference// Rīga, 2003.
- Asinhronās elektriskās piedziņas ar pieres daļas tinumiem struktūrmezglu darbības īpatnības// Starptautiskā zinātniskā konference "Modernās tehnoloģijas enerģijas ieguvei un efektīvai izmantošanai"// Jelgava, 2004.
- The asynchronous Electric drive with frontal part winding// 11th International Power Electronics and Motion Control Conference "EPE-PEMC 2004" // - Riga, 2004.
- Bražis V., Greivulis J. Asinhrona dzinēja ar pieres daļas tinumu enerģētisko parametru optimizācija atkarībā no slīdes// "Enerģētika un elektrotehnika". 4. sēr., 13. sēj. -Rīga: RTU. 2004. - 88.-94. lpp.

### Structure of work

1. THE BASIC CHARACTERISTICS OF INDUCTION MOTOR IN OPEN-LOOP AND CLOSED-LOOP SYSTEMS
  - 1.1 The analysis of induction motor direct start
  - 1.2 The parametric control of induction motor

- 1.3 The frequency control features at induction motor starting process
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    - 3.3 The asynchronous drive with frontal part winding load estimation
    - 3.4 The optimization of induction motor with frontal part winding
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    - 4.1 The goal of experiment
    - 4.2 The asynchronous electric drive with frontal part winding experimental device
    - 4.3 Conclusions
- GENERAL CONCLUSIONS

The dissertation is dedicated to the control of induction motor transient processes, which allows the starting current restriction and the solution of problem by utilizing the new construction asynchronous motor with frontal part winding.

In the first chapter is wide examined the actual state of the induction motor starting difficulties and their overcoming.

In the second chapter is described the structure of drive system with frontal part winding, substitution scheme and the construction of motor.

In the third chapter were researched the operation features of current source type net inverter. There is offered the induction motor with frontal part winding losses optimisation from minimum slip value.

In the fourth chapter is analysed the motor mechanical and energetic parameter characteristics taken by experimental device.

## Amount of work

The dissertation consists of four chapters, conclusions, references and appendixes. The total amount of work is 261 pages. Dissertation contains 166 figures, 3 tables and 3 appendixes. The references list includes links to 57 bibliographical sources. 10 from it are author publications.

### 1. The basic characteristics of induction motor in open-loop and closed-loop systems

The 1<sup>st</sup> chapter includes big research about induction motor start theory main principles. This lets to analyse the facilities of practically widespread starting methods to influence the transient process parameters.

The asynchronous motor starting process is bound with big energy losses, therefore is necessary to perform the transient process analysis [15]. The mathematical description for this motor is very complex [14, 5, 9, 10], because starting transient process consists of infinity number of aperiodic [11], therefore the approximate calculations are used for transient proceses analysis [5, 9]. In [11] is offered the transient process dividing into still motor turn on overtransient and moving motor transient process, but in [9] is discussed the approximate method, which utilize the assumption that motor rotor lays non-rotating in viewed time period at constant static torque  $M_{st} = \text{const}$ . The omitting of electromagnetic transient process does not allowed [8], therefore is used the most precise description of proceses occurred in motor, which is obtained by converting the real motor to equivalent two-phase motor [5, 8, 9]. Such induction motor mathematical model is used in modern asynchronous drive control methods, where is realized the motor field oriented control. From analysing of induction motor transient process [5, 9, 10] is seen that historically oldest direct start by connecting the motor stator to

the full supply voltage does not provide the quality starting process because motor torque and current are not restricted at all. The induction motor parametric control includes the stator voltage control during start. In the second half of 20th century this method were researched by L. Petrov [10], V. Shubenko [13], I. Braslavskiy [13], J. Greivulis [6], L. Ribickis [6], I. Rankis and A. Zhiraveckaya. Although the stator voltage control at starting lets to control the transient process parameters, this method is not suitable for heavy loaded motor start-up [13] and causes electromagnetic compatibility problems [6]. The significant improving of transient processes is possible by frequency control scalar method [5], which does not the direct influence to machine torque. Induction motor torque control is possible by field oriented asynchronous motor starting techniques - vector control, published in 1971 by F. Blaschke and direct torque control (DTC), introduced in 20th century mid 90-s. Both mentioned methods could be efficiently used only at complicated drive systems with high speed microprocessor controlled frequency converter, which includes fully controllable switches. The vector control is not originated by precise speed and torque control at low speed range. The DTC is characterised by current and torque oscillations [1]. All above mentioned induction motor starting methods require to use the electronic switches in stator circuit. The asynchronous motor start conditions could be improved, if the number of stator phases is increased [23], however such solutions are connected with the relevant increasing of converter switch number. To get along stator side converter is possible by applying the induction motor with wound rotor. On the basis of this motor there are made the doubly-fed machine, which allows to return to the net the slip losses. The significant disadvantage of such drives is the construction with mechanical slip rings. The cage rotor asynchronous motor with double [22] requires only one stator side converter, however the motor construction is too complex. Except for the good transient process control facilities of all type multi-phase induction motor, wound rotor asynchronous motor and doybly-fed machine cascade, these drive systems are characterised by converter and (or) motor constructive complexity, which strongly limits the use of such drives for specific cases only, e.g., high voltage, permanent low speed operation applications.

The analysis of induction motor with frontal part winding starting methods lets conclude that the main problem of existent solutions is the impossible compromise situation between good transient process parameters and simple motor and converter for its control construction.

## 2. Asynchronous drive with frontal part winding block circuit

The solution which improves the start process is the new drive system with asynchronous motor with frontal part winding [2]. This solution lets to perform the transient process control, achieving that simultaneously the construction of cage rotor induction motor could not be complicated too much and could be used the semiconductor converter with most possible simplest power scheme, control system and its operation principle.

Commonly the base asynchronous motor frontal part is not used. To wide the induction motor functional features, the stator phase winding frontal part loops are threaded through the additional phase transformer core [15. 17]. There are used the separate transformers for each stator winding extension phase. Stator phase winding frontal part is used as transformer primary winding (fig. 2.1.).

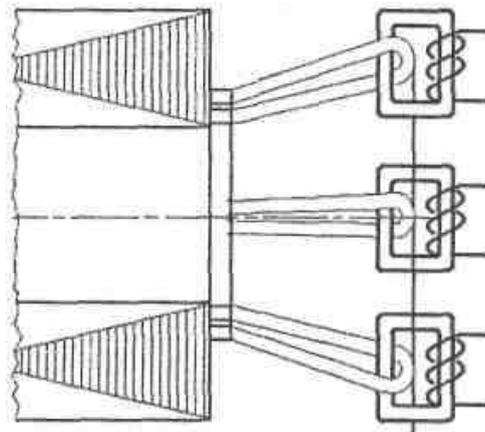


Fig. 1. Asynchronous motor frontal part winding construction

The transformer secondary winding is connected to the network through the converter. The induction motor frontal part resistance is mainly inductive [7, 16]. In this work the two layer winding frontal part reaktance value, which consists of axial and tangential parts sum is determined

$$x_f = x_a + x_t = \frac{24\pi}{10} f \frac{w^2}{p^2} \times \left\{ 2l'_n k_y^2 + (B-l'_n) \frac{y\pi - \sin y\pi}{y\pi} \cos \alpha + \frac{D}{2} y \sin \alpha \sin \frac{y\pi}{2} \left[ \lg \left( \frac{l'_n}{B-l'_n} + \frac{2}{y\pi} \lg \frac{y\pi}{4} \right) + 0.25 \right] \right\}. \quad (2.1)$$

The induction motor frontal part winding together with the additional transformer form the power control circuit. It gives the possibility to change not only static regime but mainly to form the transient process in accordance to given demands [18] with energy returning in the grid by applying the current source net inverter with variable angle  $\beta$ . When switching on the induction motor, there is formed not only the free part of starting current, but also forms the slow decaying aperiodic current. It is possible to return energy to the net during the transient processes without the trouble in asynchronous motor operation.

To determine the induction motor with frontal part winding electromagnetic torque and stator current, it is necessary to obtain the motor equivalent resistance from the T type equivalent circuit. When obtaining this resistance, the frontal part additional transformer equivalent scheme is included into asynchronous motor. The induction motor T type full equivalent circuit phase inductive resistance  $X_1$  is divided into three parts - the leakage main flux inductance  $X_g$ , the slot leakage flux inductance  $X_r$  and frontal connection leakage flux inductance  $X_{fs}$ . The additional transformer is connected parallel to the last inductance. Due to the common magnetic system of motor and frontal part transformer the stator winding frontal part resistance  $X_{fs}$  simultaneously is the additional transformer primary winding inductance

$X_{1tr}$  and therefore is included in transformer T type substitution circuit (fig. 2.2.).

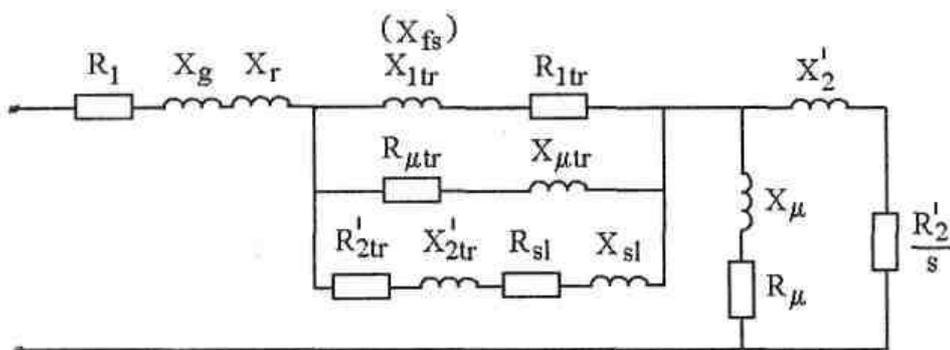


Fig. 2.2. The induction motor with extended winding single phase T type equivalent circuit

The transformer primary winding is substituted by resistances  $X_{1tr}$ . (in motor scheme  $X_{fs}$  is part of  $X_1$ ) and  $R_{1tr}$ . The transformer substitution scheme elements are marked with additional index "tr". The transformer T type equivalent circuit is reduced to single

equivalent resistance  $Z_{tr}$ , which is summed with stator active resistance  $R_1$ , un reactance  $X_1$ , components - the leakage main flux inductance  $X_g$ , and the slot leakage flux inductance  $X_r$ . Due to these considerations it is not recommended to label with  $Z_l$  the stator circuit resistance without additional transformer. The paralel branches resistances of the motor rotor  $Z_2$  and magnetising circuit  $Z_\mu$  are merged into one total resistance  $Z_{2\mu}$ . By adding the stator resistance  $Z_1$  to  $Z_{2\mu}$ , there is obtained the induction motor equivalent resistance, which is spliled into active and reactive component:

$$\begin{aligned}
 Z_{e,s} = R_1 + R_r + R_{2\mu} + j(X_g + X_r + X_{tr} + X_{2\mu}) = R_1 + \frac{(R_{1tr}R_{2tr}R_{2\mu} + R_{1tr}R_{2\mu}R_{2tr} - R_{2tr}X_{1tr}X_{2\mu} - \\
 - R_{2\mu}X_{1tr}X_{2tr} + R_{1tr}X_{2tr}X_{2\mu} + R_{2tr}X_{1tr}X_{2\mu} + R_{2\mu}X_{1tr}X_{2tr} + R_{2tr}X_{1tr}X_{2\mu})(R_{1tr} + R_{2tr} + R_{2\mu} + R_{2\mu}) + \\
 \dots \\
 \frac{(R_{1tr} + R_{2tr} + R_{2\mu} + R_{2\mu})^2 + (X_{1tr} + X_{2tr} + X_{2\mu} + X_{2\mu})^2}{\dots} \\
 + (R_{1tr}R_{2\mu}X_{2tr} + R_{1tr}R_{2tr}X_{2\mu} - X_{1tr}X_{2tr}X_{2\mu} - X_{1tr}X_{2\mu}X_{2tr} + R_{1tr}R_{2tr}X_{2\mu} + R_{2tr}R_{2\mu}X_{1tr} + R_{1tr}R_{2\mu}X_{2tr} + \\
 \dots \\
 + R_{2tr}R_{2\mu}X_{1tr})(X_{1tr} + X_{2tr} + X_{2\mu} + X_{2\mu}) + \frac{\left(\frac{R_2}{s} - X_2'X_\mu\right)\left(\frac{R_2}{s} + R_\mu\right) + \left(\frac{R_2X_\mu}{s} + R_\mu X_2'\right)(X_2' + X_\mu)}{\left(\frac{R_2}{s} + R_\mu\right)^2 + (X_2' + X_\mu)^2} + \\
 + j\left(X_g + X_r + \frac{(R_{1tr} + R_{2tr} + R_{2\mu} + R_{2\mu})(R_{1tr}R_{2tr}X_{2\mu} + R_{1tr}R_{2\mu}X_{2tr} - X_{1tr}X_{2tr}X_{2\mu} - X_{1tr}X_{2\mu}X_{2tr} + R_{1tr}R_{2tr}X_{2\mu} + \\
 + R_{2tr}R_{2\mu}X_{1tr} + R_{1tr}R_{2\mu}X_{2tr} + R_{2tr}R_{2\mu}X_{1tr}) - (R_{1tr}R_{2tr}R_{2\mu} + R_{1tr}R_{2\mu}R_{2tr} - R_{2tr}X_{1tr}X_{2\mu} - R_{2\mu}X_{1tr}X_{2tr} + \\
 \dots \\
 (R_{1tr} + R_{2tr} + R_{2\mu} + R_{2\mu})^2 + (X_{1tr} + X_{2tr} + X_{2\mu} + X_{2\mu})^2}{\dots} \right. \\
 \left. + \frac{(R_{1tr}R_{2\mu}X_{2tr} + R_{1tr}R_{2tr}X_{2\mu} - X_{1tr}X_{2tr}X_{2\mu} - X_{1tr}X_{2\mu}X_{2tr} + R_{1tr}R_{2tr}X_{2\mu} + R_{2tr}R_{2\mu}X_{1tr} + R_{1tr}R_{2\mu}X_{2tr} + \\
 \dots \\
 + R_{2tr}R_{2\mu}X_{1tr})(X_{1tr} + X_{2tr} + X_{2\mu} + X_{2\mu})}{\dots} + \frac{\left(\frac{R_2}{s} + R_\mu\right)\left(\frac{R_2X_\mu}{s} + R_\mu X_2'\right) - \left(\frac{R_2}{s} - X_2'X_\mu\right)(X_2' + X_\mu)}{\left(\frac{R_2}{s} + R_\mu\right)^2 + (X_2' + X_\mu)^2}\right)
 \end{aligned}
 \tag{2.2}$$

This expression lets to find out the current value, which is used for obtaining the electromagnetic torque equation of induction motor with frontal part winding:

$$M = \frac{m_1 \left[ \frac{U}{Z_2} \left[ 1 - \frac{Z_1}{R_1 + (R_{1lr} R_{2lr} R_{\mu r} + R_{1lr} R_{\mu r} R_{sl} - R_{2lr} X_{1lr} X_{\mu r} - \dots} \right] \right]}{\omega_{p,s} \dots}$$

$$\frac{-R_{sl} X_{1lr} X_{\mu r} + R_{1lr} X_{2lr} X_{\mu r} + R_{1lr} X_{\mu r} X_{sl} + R_{\mu r} X_{1lr} X_{2lr} + R_{\mu r} X_{1lr} X_{sl}) (R_{1lr} + R_{\mu r} + R_{2lr} + R_{sl}) +}{(R_{1lr} + R_{\mu r} + R_{2lr} + R_{sl})^2 + (X_{1lr} + X_{\mu r} + X_{2lr} + X_{sl})^2} \dots$$

$$+ (R_{1lr} R_{\mu r} X_{2lr} + R_{1lr} R_{\mu r} X_{sl} - X_{1lr} X_{2lr} X_{\mu r} - X_{1lr} X_{\mu r} X_{sl} + R_{1lr} R_{2lr} X_{\mu r} + R_{2lr} R_{\mu r} X_{1lr} + R_{1lr} R_{sl} X_{\mu r} + \dots$$

$$\frac{+ R_{\mu r} R_{sl} X_{1lr}) (X_{1lr} + X_{\mu r} + X_{2lr} + X_{sl}) + \left( \frac{R_2'}{s} - X_2' X_{\mu}' \right) \left( \frac{R_2'}{s} + R_{\mu}' \right) + \left( \frac{R_2' X_{\mu}'}{s} + R_{\mu}' X_2' \right) (X_2' + X_{\mu}')}{\left( \frac{R_2'}{s} + R_{\mu}' \right)^2 + (X_2' + X_{\mu}')^2} + \dots$$

$$+ j \left( X_{\nu}' + X_{\nu}' + \frac{(R_{1lr} + R_{\mu r} + R_{2lr} + R_{sl}) R_{1lr} R_{\mu r} X_{2lr} + R_{1lr} R_{\mu r} X_{sl} - X_{1lr} X_{2lr} X_{\mu r} - X_{1lr} X_{\mu r} X_{sl} + R_{1lr} R_{2lr} X_{\mu r} + \dots}{\dots} \right) \dots$$

$$\frac{+ R_{2lr} R_{\mu r} X_{1lr} + R_{1lr} R_{sl} X_{\mu r} + R_{\mu r} R_{sl} X_{1lr}) - (R_{1lr} R_{2lr} R_{\mu r} + R_{1lr} R_{\mu r} R_{sl} - R_{2lr} X_{1lr} X_{\mu r} - R_{sl} X_{1lr} X_{\mu r} +}{(R_{1lr} + R_{\mu r} + R_{2lr} + R_{sl})^2 + (X_{1lr} + X_{\mu r} + X_{2lr} + X_{sl})^2} \dots$$

$$\frac{+ R_{1lr} X_{2lr} X_{\mu r} + R_{1lr} X_{\mu r} X_{sl} + R_{\mu r} X_{1lr} X_{2lr} + R_{\mu r} X_{1lr} X_{sl}) (X_{1lr} + X_{\mu r} + X_{2lr} + X_{sl}) +}{\dots}$$

$$\left. \frac{\left( \frac{R_2}{s} + R_p \right) \left( \frac{R_2 X_p}{s} + R_p X_2' \right) - \left( \frac{R_2}{s} - X_2 X_p \right) (X_2' + X_p)}{\left( \frac{R_2}{s} + R_p \right)^2 + (X_2' + X_p)^2} \right\} R_2$$

. (2.3)

For simplifying the motor equivalent resistance expression, some assumptions are allowed. The accuracy of equivalent resistance determination is not deteriorated by elimination of motor magnetization circuit active resistance and assumption that during the start slip is constant  $s = 1$ . At stationary regime, when transformer does not realize the control, it has been described as choke with ignoring the transformer secondary circuit parameters.

In the computations of induction motor with frontal part winding it is not useful to utilize the  $\Gamma$  type substitution scheme, because the stator and additional transformer common resistance is included into both branches of  $\Gamma$  type scheme. This caused the total equivalent scheme significant bigger than the analogic  $T$  type substitution scheme. There is possible to make the approximately description of asynchronous motor  $\Gamma$  type scheme, if the assumption, that additional transformer and motor has separate magnetic systems, is used. In this case the frontal part transformer resistance must be considered as the series connected to induction motor additional resistance. This approximation will be give the precise results for induction motor with separate current transformer [19].

The current source net inverter output voltage is proportional to the motor stator winding current. It is possible to construct the separate current transformer, which is not bound with the frontal part extension and doesn't require the alternation of motor construction [19]. The energy transferred to the net could be controlled by changing the relation  $U = kI$ , and inverter angle  $\beta$  in time. With the help of the stator phase winding extension additional transformer there is possible to affect the transient processes at all working regimes. The stator current conversion to voltage  $kI_s = U$  ensures the current source inverter operation in the case of low stator current load changes. Asynchronous electric drive system with frontal

part winding is expedient to use in electric drives with frequently start and braking. For the research of induction motor transient processes there is estimated the motor substitution scheme [15, 19].

### 3. The analysis of asynchronous drive with frontal part winding current source net inverter structure operation regimes

The components of asynchronous motor with frontal part winding electric drive system [ 19, 24] power control circuit (fig. 3.1.) are operating at power supply from current source mode, because the current flowing through frontal part transformer secondary circuit is noticeably smaller than stator winding current  $I_{2r} \ll I_1$  which forms the current source. The three-phase rectifier, included in electric drive block scheme (fig. 3.1.). is rectifying the frontal part transformer secondary winding currents, which are proportional to the induction motor stator current [19]. After current rectifying in the three-phase bridge rectifier and pulsation smothering with choke, the power has been transfered to the net inverter, which realizes the power control with further transferring to the grid the additional transformer secondary winding power  $P_d = I_d U_d$ . As the net inverter current value is proportional to the induction motor current, it means, that not only rectifier, but the inverter too is working in current source mode [20]. It forces to look the rectifier and inverter (fig. 3.1.) operation together with common substitution scheme (fig. 3.2.).

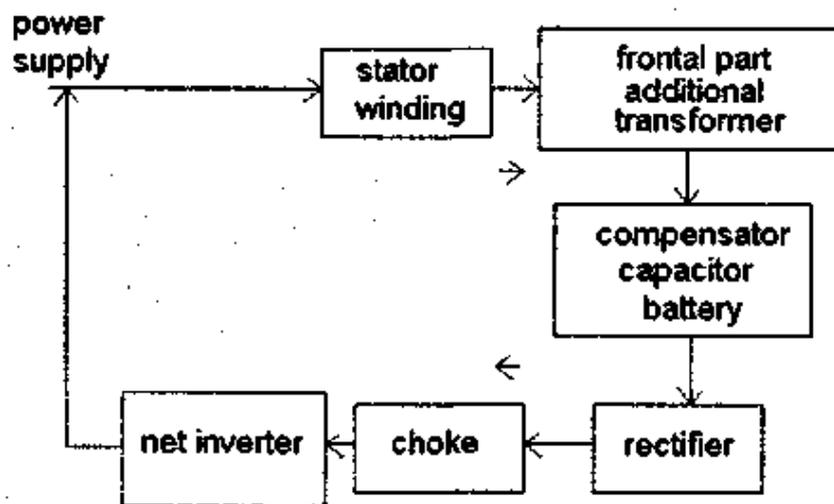


Fig. 3.1. Electric drive with frontal part winding block scheme

The three phase rectifier is supplied from current source - additional transformer secondary winding. As the rectifier load is used the three-phase net inverter which is connected by two half period scheme with neutral point. The inverter is substituted by resistive-inductive load with series connected opposite electromotive force [12] at given angle of inversion and inverter transformer equivalent scheme (fig. 3.2.). The net inverter transformer is substituted by simplified T type substitution scheme, where is excluded the magnetisation circuit [12]. In the result there is obtained the simplified inverter substitution scheme, which is connected to the three-phase rectifier output. The rectifying regime from induction motor frontal part additional transformers includes six periods of rectifier equivalent operation. At the condition  $0 \leq \frac{X}{R} \leq 1,73$  the rectified current shape is the same as in the case of resistive load, if opposite EMF provides that rectified voltage unachieves zero. At the condition  $\frac{X}{R} > 1,73$  occurs the rectifier bridge zero-voltage mode. The rectified current value depends from the load impedance module  $z$  and load opposite EMF value. The rectifier operation basic mode that must be used is at load parameter relation

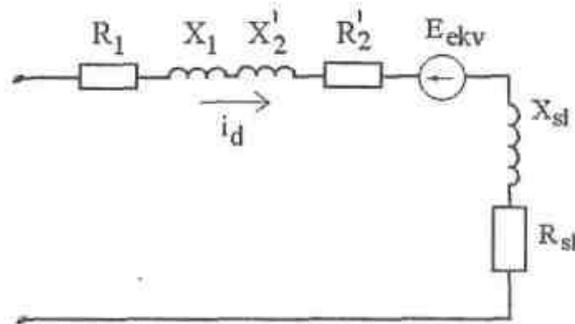


Fig. 3.2. The current source net inverter equivalent scheme

$0 \leq \frac{X}{R} \leq 1,73$ . Rectifier is characterised by two working regimes, which according currents and voltages are shown on fig. 3.3.:

- 1) output zero-voltage mode (fig. 3.3., b);
- 2) rectifying mode (fig. 3.3., a).

The periods of rectifier equivalent operation in rectifier mode are shown on fig. 3.4.

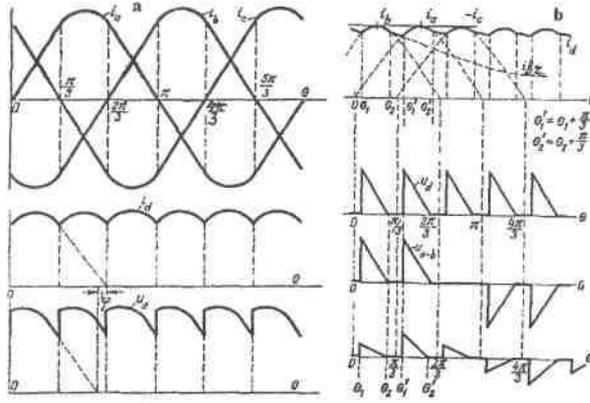


Fig. 3.3. Currents and voltages if  $\frac{X}{R} < 1,73$  (a) and  $\frac{X}{R} > 1,73$

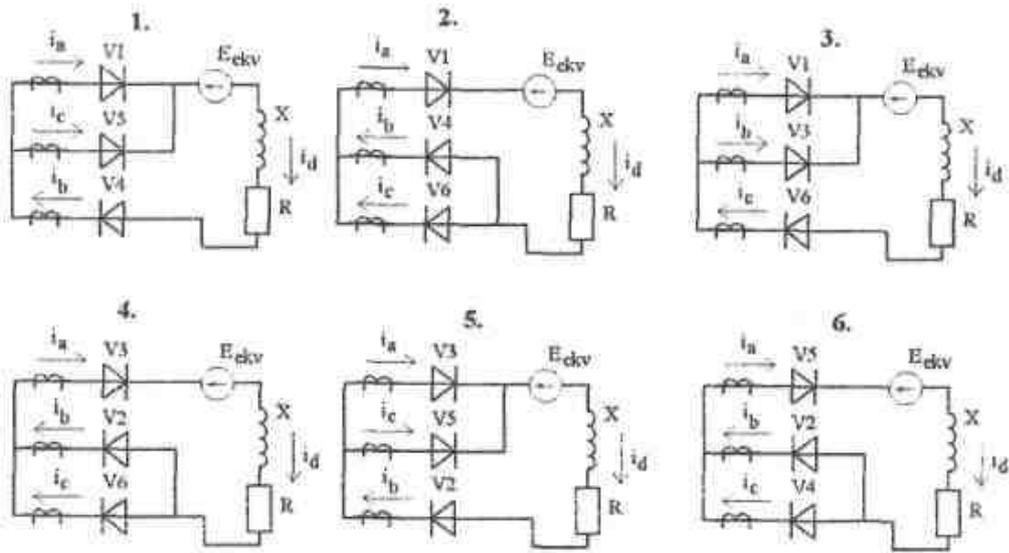


Fig. 3.4. Rectifier operation at rectifying mode

In zero-voltage mode the additional transformer secondary circuit rectifier input current is equal to zero. The additional transformer each phase secondary winding current  $i_n$  divides into compensator capacitor current  $i_{Kn1}$  and rectifier input current  $i_n$ , where  $n = A, B, C$  - phase number. The voltage at rectifier input is equal to the sum of rectifier output voltage and net inverter opposite EMF:

$$\begin{aligned}
u_d - E_{av} &= -U_{CBH} - U_{CCH} = -(U_{KBH} + U_{KBI}) - (U_{KCH} + U_{KCI}) = -\left(\frac{1}{X_c} \int_0^{\frac{\pi}{3}} \sqrt{2} I_{KO} \sin(\theta + \varphi) + \right. \\
&+ \left. \left(-\frac{\sqrt{2} I_{KBH}}{X_c} 2 \cos^2\left(\frac{\theta_1 + \varphi}{2} - \frac{\pi}{3}\right)\right) - \right. \\
&- \left. \left[ \frac{1}{X_c} \left\{ \int_0^{\frac{\pi}{3}} \frac{\sqrt{2}}{2} I_{BH} \sin(\theta + \varphi) + \int_0^{\frac{\pi}{3}} \sqrt{2} I_{KO} \sin(\theta + \varphi) \right\} + \left(-\frac{\sqrt{2} I_{KCI}}{X_c} 2 \cos^2\left(\frac{\theta_1 + \varphi_1}{2} - \frac{2\pi}{3}\right)\right) \right] = \\
&= -\frac{1}{X_c} \left( -\sqrt{2} I_{KO} \cos\left(\frac{\pi}{2} + \varphi\right) - \sqrt{2} I_{KO} \cos(\theta_1 + \varphi) \right) - \frac{\sqrt{2} I_{KBH}}{X_c} 2 \cos^2\left(\frac{\theta_1 + \varphi}{2} - \frac{\pi}{2}\right) - \\
&- \left[ \frac{1}{X_c} \left\{ -\frac{\sqrt{2} I_{BH}}{2} \cos\left(\frac{\pi}{3} + \varphi\right) - \frac{\sqrt{2} I_{BH}}{2} \cos(\theta_1 + \varphi) + \left(-\sqrt{2} I_{KO} \cos\left(\frac{\pi}{3} + \varphi\right) - \sqrt{2} I_{KO} \cos(\theta_1 + \varphi)\right) \right\} \right] - \\
&- \frac{\sqrt{2} I_{KCI}}{X_c} 2 \cos^2\left(\frac{\theta_1 + \varphi_1}{2} - \frac{2\pi}{3}\right) = \frac{\sqrt{2} I_{KO}}{X_c} \cos\left(\frac{\pi}{3} + \varphi\right) + \frac{\sqrt{2} I_{KO}}{X_c} \cos(\theta_1 + \varphi) - \\
&- \frac{\sqrt{2} I_{KBH}}{X_c} 2 \cos^2\left(\frac{\theta_1 + \varphi}{2} - \frac{\pi}{3}\right) + \frac{\sqrt{2} I_{BH}}{2 X_c} \cos\left(\frac{\pi}{3} + \varphi\right) + \frac{\sqrt{2} I_{BH}}{2 X_c} \cos(\theta_1 + \varphi) + \\
&+ \frac{\sqrt{2} I_{KO}}{X_c} \cos\left(\frac{\pi}{3} + \varphi\right) + \frac{\sqrt{2} I_{KO}}{X_c} \cos(\theta_1 + \varphi) - \frac{\sqrt{2} I_{KCI}}{X_c} 2 \cos^2\left(\frac{\theta_1 + \varphi}{2} - \frac{2\pi}{3}\right) = \\
&= \frac{\sqrt{2} I_{KO}}{X_c} \cdot 2 \cos\left(\frac{\pi}{3} + \varphi + \theta_1 + \varphi\right) \cos\left(\frac{\pi}{3} + \varphi - \theta_1 - \varphi\right) - \\
&- \frac{\sqrt{2} I_{KBH}}{X_c} 2 \cos^2\left(\frac{\theta_1 + \varphi}{2} - \frac{\pi}{3}\right) + \frac{\sqrt{2} I_{BH}}{2 X_c} 2 \cos\left(\frac{\pi}{3} + \varphi + \theta_1 + \varphi\right) \cos\left(\frac{\pi}{3} + \varphi - \theta_1 - \varphi\right) + \\
&+ \frac{\sqrt{2} I_{KO}}{X_c} 2 \cos\left(\frac{\pi}{3} + \varphi + \theta_1 + \varphi\right) \cos\left(\frac{\pi}{3} + \varphi - \theta_1 - \varphi\right) - \frac{\sqrt{2} I_{KCI}}{X_c} 2 \cos^2\left(\frac{\theta_1 + \varphi}{2} - \frac{2\pi}{3}\right) = \\
&= \frac{\sqrt{2} I_{KO}}{X_c} 2 \cos\left(\frac{\pi}{3} + \theta_1 + 2\varphi\right) \cos\left(\frac{\pi}{3} - \theta_1\right) - \frac{\sqrt{2} I_{KBH}}{X_c} 2 \cos^2\left(\frac{\theta_1 + \varphi_1}{2} - \frac{\pi}{3}\right) + \\
&+ \frac{\sqrt{2} I_{BH}}{X_c} \cos\left(\frac{\pi}{3} + \theta_1 + 2\varphi\right) \times \cos\left(\frac{\pi}{3} - \theta_1\right) + \frac{2\sqrt{2} I_{KO}}{X_c} \cos\left(\frac{\pi}{3} + 2\varphi + \theta_1\right) \cos\left(\frac{\pi}{3} - \theta_1\right) - \\
&- \frac{\sqrt{2} I_{KCI}}{X_c} 2 \cos^2\left(\frac{\theta_1 + \varphi_1}{2} - \frac{2\pi}{3}\right)
\end{aligned}$$

(3.1)

The number of induction motor repeated switch on could be increased, because the electric energy losses at starting process  $\Delta A$  decreases, which is provided by current source net inverter by returning power to the net.

The energetic parameters of induction motor are high enough only if the motor is working with rated load. To obtain the good efficiency factor and power factor values at small loads, it is necessary to vary the motor supplied voltage, which value could be optimised. The induction motor with frontal part winding has wider control features and losses power could be returned to the net. therefore in this dissertation there is reviewed the parameter optimisation only to this type of motor. Independently from the asynchronous motor and its control form, the main task of optimisation is to determine the slip, at which the losses values are minimal.

The induction motor energetic parameters - efficiency factor  $\eta$ ; and power factor  $\cos\phi$  deteriorates with motor shaft load decreasing. A lot of widespread mechanisms (lifting, extrusion and metal working devices) are characterised by permanent drive operation with small load or idle running. In this regimes the drive energetic parameters are low. The induction motor efficiency and power factors could be increased by stator voltage varying [14]. The asynchronous motor with hard mechanical characteristic and frontal part winding at low torques has the optimal slip

$$s_{opt} = \frac{R_2}{X_{\mu}} \cdot \sqrt{\frac{R_{1ekv}}{R_2 + R_{1ekv}}}, \quad (3.2)$$

with minimum of power losses. It is obtained from the  $T$  type equivalent circuit (fig. 2.2.) for the motor with frontal part winding. The induction motor energetic parameters improving at the case of low mechanical load in the small slip value range is realized by utilising the stator voltage varying [21]. This method advisability increases, because the utilising of induction motor with frontal part winding allows more efficiently to use such construction wider control possibilities given advantages.

#### 4. Experimental researches

The main tasks of experiment were proposed as follows:

- 1) taking the mechanical characteristics of induction motor with frontal part winding [18];
- 2) checking the current source net inverter operation possibility;
- 3) taking the frontal part winding transient process characteristics.

The asynchronous motor with frontal part winding mechanical characteristics at additional transformer secondary circuit inverter load (fig. 4.1.) have been compared with conventional industrial same brand base motor characteristic 4. If the power is controlled by inverter, the mechanical characteristics 1,2,3 drop more rapid than in the case of base motor 4 and the maximum torque is approximately half from rated value independently from number of additional transformers in phase, used rectifier neutral wire circuit and filter parameters. The stiffness of induction motor characteristics 2,3 is greater, when two transformers per phase are mounted instead of one, therefore further research was made with device, which has two transformers at each phase. By adding the compensator filter capacitors with  $10\mu F$  phase capacity, the mechanical characteristic 2 stiffness considerably increases. At the beginning of these curves the differences from these characteristics is impossible to determine due to the unprecise available measuring apparatus. By increasing the filter phase capacity to  $30\mu F$  and connecting the circuit with neutral wire, the mechanical characteristic 3 becomes softer than with less capacity filter (curve 2). The mechanical characteristic of drive system with great filter capacity 3 is placed higher than for system with small capacity curve 2.

By analysing the transferred power characteristics (fig. 4.2.). it seems, that with the frontal part winding transferred power increasing the revolutions are decreasing at all reviewed load cases. By increasing the compensator filter capacity. With increasing the compensator filter capacity the transferred power increases which is visible by compare the curve 3 with related curve 2.

The experimentally obtained characteristic  $\eta = f(P_2)$  showed that efficiency factor at low compensator capacity in the case of small loads is higher (fig. 4.3. curve 1). The high filter capacity decreases  $\eta$  (curve 2). In the case of low filter capacity the  $\eta$  minimal value is observed at power approximately 400W. farther the efficiency factor increases. At the case of high compensator filter capacity  $\eta$  grows practically lineary with increasing of power (curve 2). At small loads the efficiency factor of induction motor with frontal part winding is higher than base motor (curve 4).

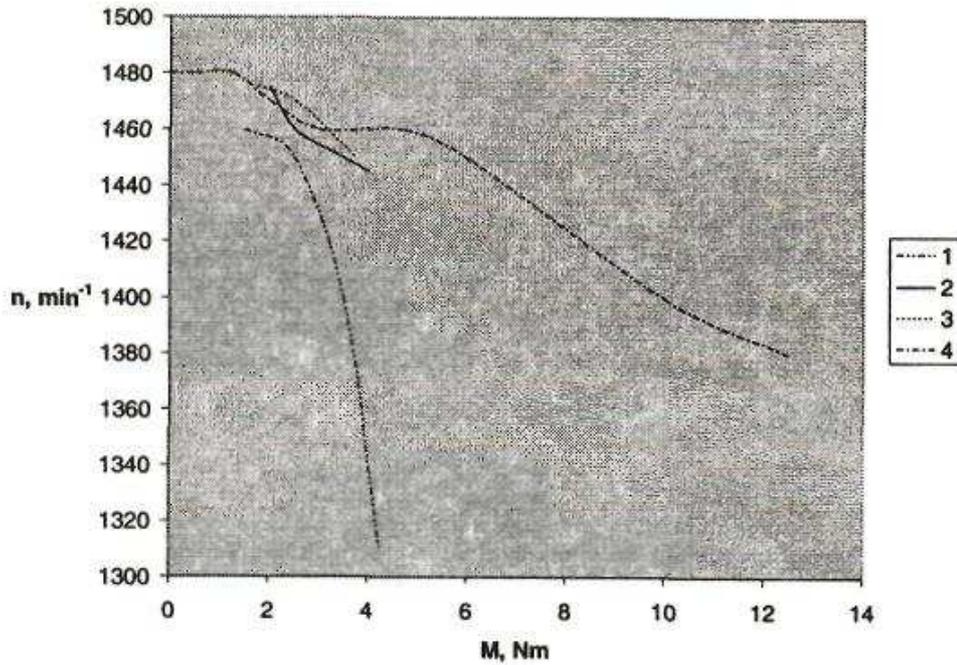


Fig. 4.1. Induction motor with frontal part winding mechanical characteristics for:

1. induction motor with single frontal part winding additional transformer per phase at inversion angle  $\beta_{max} = 64,29^\circ$ ;
2. induction motor with two frontal part winding additional transformer per phase and scheme with rectifier filter capacity  $10\mu F$  at inversion angle  $\beta_{min} = 28,29^\circ$ ;
3. induction motor with two frontal part winding additional transformer per phase and scheme with rectifier filter capacity  $30\mu F$  at inversion angle  $\beta_{min} = 28,29^\circ$ ;
4. base motor

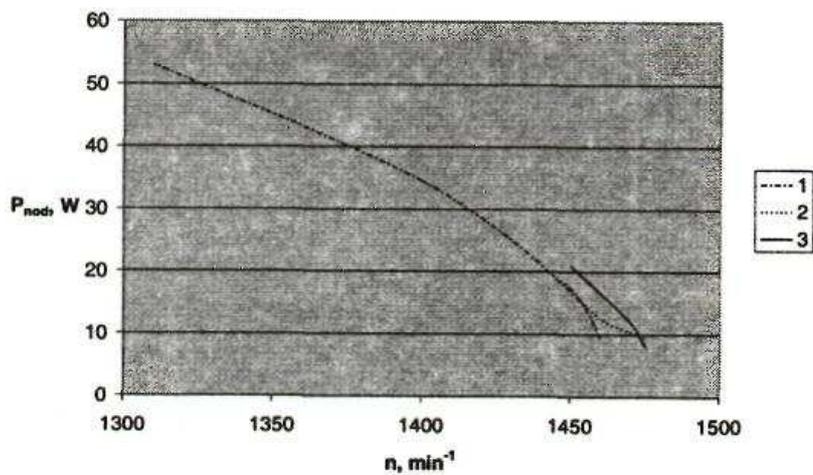


Fig. 4.2. Frontal part transformer transferred power (curves numbers refers to fig. 4.1.)

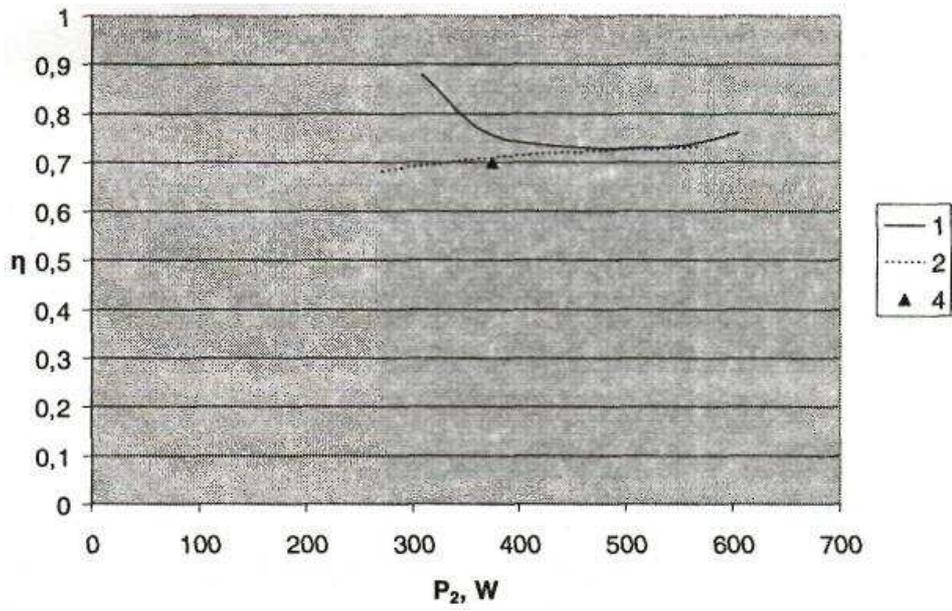


Fig. 4.3. Efficiency factor relation from mechanical power (curves numbers refers to fig. 4.1.)

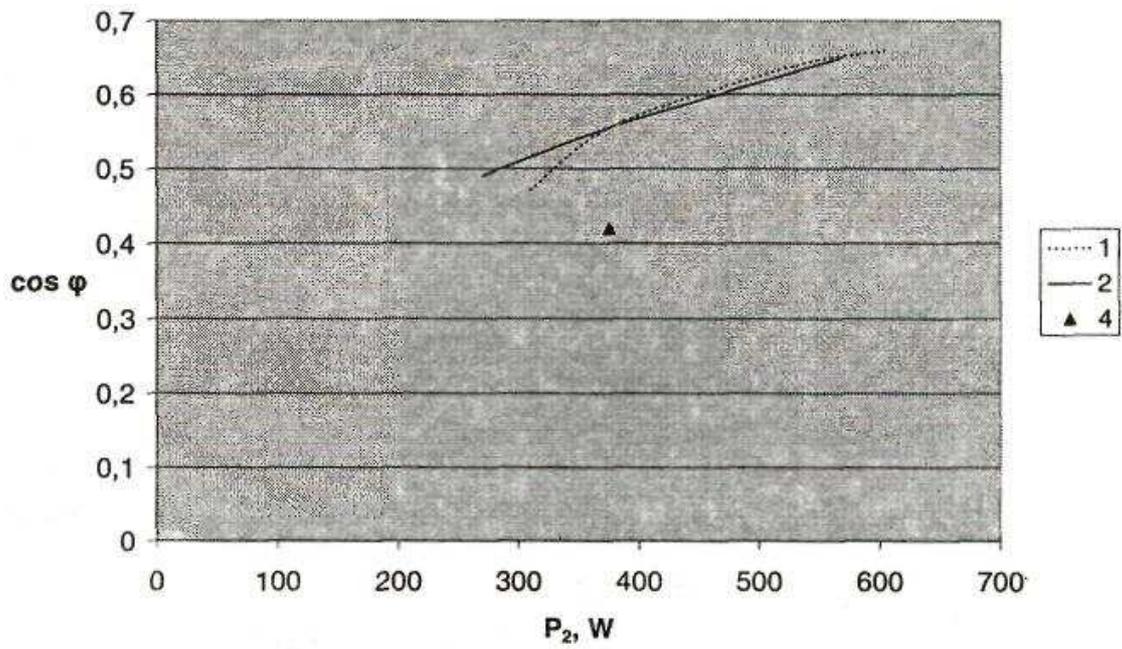


Fig. 4.4. Power factor relation from mechanical power (curves numbers refers to fig. 4.1.)

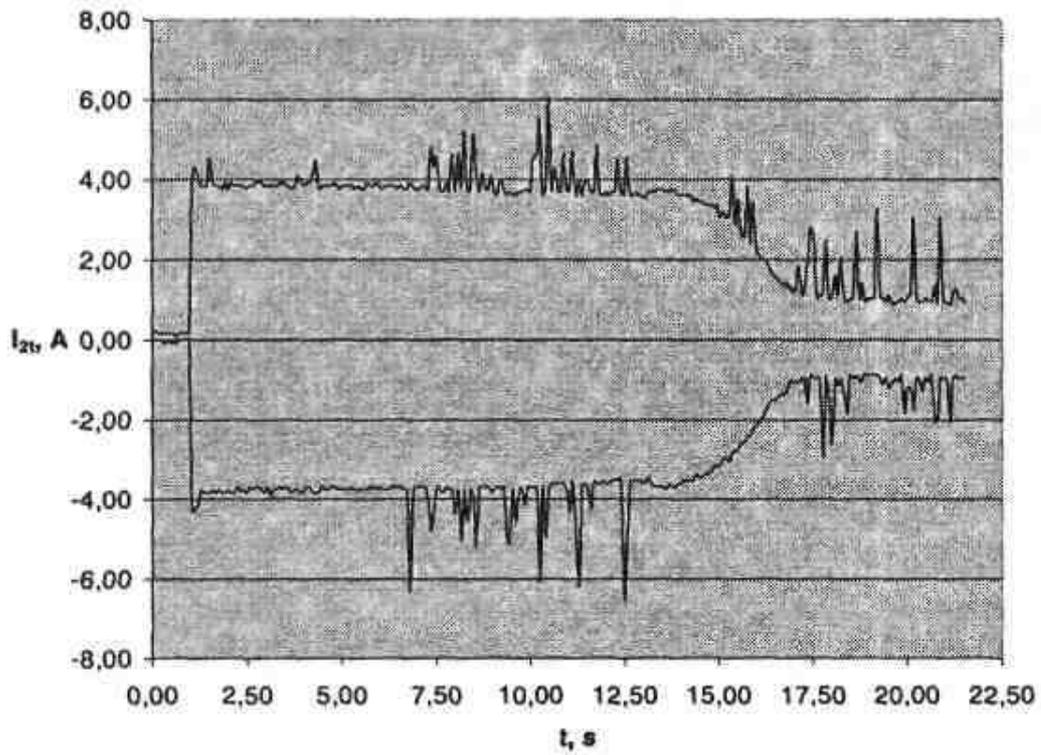


Fig. 4.5. Additional transformer output current at induction motor starting regime at inversion angle  $\beta_{\max} = 64,29^\circ$

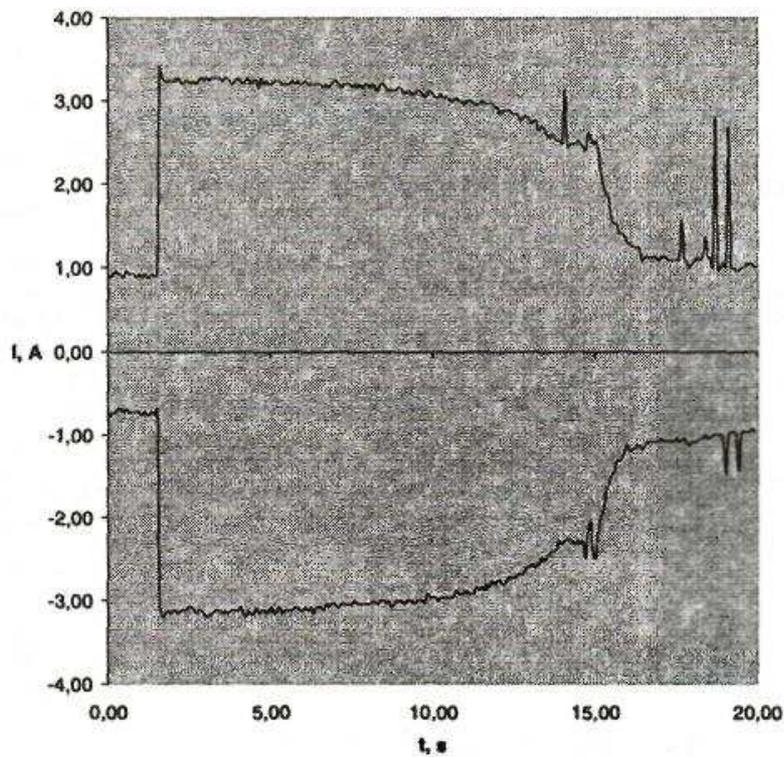


Fig. 4.6. Inverter output current at motor starting regime at inversion angle  $\beta_{\min} = 28,29^\circ$

In the case of small filter capacitance (fig. 4.4. curve 1)  $\cos \varphi$  is higher at greater mechanical power values than in the case of high capacity (curve 2). Independently from the kind of inverter load the power factor of induction motor with frontal part winding is higher than for base motor at small mechanical loads (curve 4).

There are experimentally taken induction motor with frontal part winding rectifier input current oscillograms at motor and braking regimes, inverter output current and rotation speed transient process oscillogram. It's seen from the oscillogram (fig. 4.5.) that at the beginning of the loaded motor starting process predominate the little changing aperiodic component of current, but its varying exposes only at the end of transient process. At the beginning of starting the inverter output current decrease has an aperiodical character (fig. 4.6.). At the end of transient process the inverter current is slightly greater than transformer idle current.

The current source net inverter output voltage is proportional to the motor stator winding current. It is possible to construct the separate current transformer, which is not bound with the frontal part extension and doesn't require the alternation of motor construction. The energy transfered to the net could be controlled by changing the relation  $U = kl$ , and inversion angle  $\beta$  in time.

By varying the angle  $\beta$  it is possible to stabilize the induction motor operational point on mechanical characteristic. With the help of the stator phase winding extension additional transformer there is possible to affect the transient processes at all working regimes. The asynchronous motor mechanical characteristics are practically invariable if the frontal part extension winding is not loaded. The stator current conversion to voltage  $kl_s = U$  ensures the current source inverter operation in the case of low stator current load changes.

The results of experimentally taken induction motor with frontal part winding static mechanical characteristics verify the such drive system control possibility. The frontal part winding power control circuit includes the net inverter which operates in current source regime. For the affiliation of mechanical characteristics is used the electromagnetic brake, which creates the lineary growing torque.

The transient process characteristics taken in dynamic regime shows that motor revolutions are decreasing at great transfered power, which allows to realized the control of transient proceses. The experimentally taken capacitor braking transient process allows to conclude that occurs the power return to the grid.

## Conclusion

The results of dissertation allow to make the asynchronous drive system with frontal part winding, where is used the induction motor with frontal part winding and current source net inverter system, which lets to perform the asynchronous motor transient process control and power returning to the net.

The main conclusions shortly could be formulated as:

1. the basic theory of induction motor with frontal part winding operation is developed and the substitution scheme calculation theory is given;
2. the asynchronous drive system with frontal part winding and current source net inverter, where is realised the transferring of frontal part losses back to the net is established;
3. the current source net inverter with opposite electromotive force operation theoretical features are found out;
4. the drive system optimisation has done by determining of optimal working regime slip;
5. the practical test has carried out, to make sure that induction motor with frontal part winding could work and gain its characteristics at statical and dynamic regime;
6. asynchronous motor with frontal part winding is expedient to use in electric drives with frequently start and braking.

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